Dealing with Uncertainties in the Dutch Gas Sector

An Exploratory Modeling and Analysis Approach

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Delft University of Technology
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TABLE OF CONTENTS

SUMMARY ..... **v**

SAMENVATTING ..... **xiii**

CHAPTER I - INTRODUCTION

1.1. AN OVERVIEW OF THE DUTCH GAS SECTOR **1**
1.1.1. THE PAST 1
1.1.2. THE PRESENT 3
1.1.3. THE FUTURE 5
1.2. RESEARCH OBJECTIVE AND RESEARCH QUESTIONS **6**
1.3. OUTLINE OF THE THESIS **9**
1.4. REFERENCES **11**

CHAPTER II - PROBLEM DIAGNOSIS

2.1. A SYSTEMS ANALYTIC APPROACH **14**
2.2. POLICY GOALS **15**
2.3. SYSTEM OF INTEREST CORRESPONDING TO THE POLICY PROBLEM **17**
2.4. ACTORS AND PERSPECTIVES ON THE FUTURE **27**
2.4.1. MAIN ACTORS IN THE DUTCH GAS SECTOR 27
2.4.2. STAKEHOLDER PERSPECTIVES ON THE FUTURE 31
2.5. POLICY ALTERNATIVES AFFECTING THE DUTCH GAS SECTOR **33**
2.5.1. PAST AND PRESENT POLICIES IMPLEMENTED IN THE NETHERLANDS 33
2.5.2. POLICIES IMPLEMENTED IN OTHER COUNTRIES 36
2.5.3. POLICY ALTERNATIVES CONSIDERED IN THIS STUDY 37
2.6. UNCERTAINTIES REGARDING THE DUTCH GAS SECTOR **38**
2.6.1. A FRAMEWORK FOR IDENTIFYING AND COMMUNICATING UNCERTAINTIES 39
2.6.2. UNCERTAINTIES IN THE DUTCH GAS SECTOR 40
2.7. CONCLUSIONS **42**
2.8. REFERENCES **44**

CHAPTER III - RESEARCH METHODOLOGY

3.1. POLICY ANALYSIS **47**
3.1.1. MODEL-BASED POLICY ANALYSIS 49
3.1.2. POLICY ANALYSIS UNDER UNCERTAINTY 50
3.2. MODEL-BASED ANALYSIS FOR ENERGY POLICIES **52**
3.2.1. ENERGY SYSTEM MODELS 52
3.2.2. MODELS OF GAS PRODUCTION AND MARKET 57
3.3. EXPLORATORY MODELING AND ANALYSIS **60**
3.3.1. WHAT IS EXPLORATORY MODELING AND ANALYSIS? 60
3.3.2. WHY EXPLORATORY MODELING AND ANALYSIS? 62
3.4. SYSTEM DYNAMICS **63**
3.4.1. WHAT IS SYSTEM DYNAMICS? 64
3.4.2. WHY SYSTEM DYNAMICS? 65
3.5. CONCLUSIONS **66**
3.6. REFERENCES **67**

CHAPTER IV - A SUPPLY-DEMAND MODEL FOR THE DUTCH GAS SECTOR

4.1. OVERVIEW OF THE MODEL **75**
4.2. SUPPLY SIDE **77**
4.2.1. NATURAL GAS PRODUCTION 77

3A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

4.2.2. Renewable Gas Production ... 86
4.2.3. Imports ... 94
4.3. DEMAND SIDE ... 97
4.3.1. Natural Gas Demand of the Electricity Sector ... 98
4.3.2. Natural and Renewable Gas Demand except the Electricity Sector ... 102
4.4. MARKET ... 105
4.5. CONCLUSIONS ... 108
4.6. REFERENCES ... 109

CHAPTER V - ANALYZING THE MODEL BEHAVIOR

5.1. REFERENCE SIMULATION ... 111
5.1.1. Model Specification and Simulation Settings ... 112
5.1.2. Comparison of Model Behavior to Historical Data ... 113
5.1.3. Model Behavior in the Reference Scenario ... 116
5.2. EXPLORATION OF FUTURE DYNAMICS ... 118
5.2.1. Analysis Specification and Simulation Settings ... 118
5.2.2. Future Scenarios ... 119
5.3. FUTURE DYNAMICS FROM THE STAKEHOLDER PERSPECTIVES ... 121
5.3.1. Model-based Representation of the Stakeholder Perspectives ... 122
5.3.2. Exploring Future Scenarios in Each Perspective ... 125
5.4. CONCLUSIONS ... 139
5.5. REFERENCES ... 140

CHAPTER VI - A FRAMEWORK FOR ANALYZING POLICY EFFECTIVENESS AND ROBUSTNESS

6.1. METHODS USED TO ASSESS AND COMPARE THE POLICY ALTERNATIVES ... 142
6.1.1. Time Dimension ... 144
6.1.2. Robustness Metrics ... 145
6.1.3. Multi-criteria methods ... 151
6.2. CONCLUSIONS ... 154
6.3. REFERENCES ... 155

CHAPTER VII - SELECTION OF EXCHANGEABLE POLICY OPTIONS

7.1. ANALYZING THE PRODUCTION CAP POLICIES ... 157
7.1.1 Analyzing the Cap Policies with Static Metrics ... 158
7.1.2 Analyzing the Cap Policies Dynamically ... 166
7.1.3 Selecting a Cap Policy for Further Analysis ... 170
7.2. ANALYZING THE BIOMETHANE SUBSIDIZATION SCHEMES ... 170
7.2.1 Analyzing the Subsidization Schemes with Static Metrics ... 175
7.2.2 Analyzing the Subsidization Schemes Dynamically ... 183
7.2.3 Selecting a Subsidization Scheme for Further Analysis ... 186
7.3. CONCLUSIONS ... 188
7.4. REFERENCES ... 189

CHAPTER VIII - COMPARISON OF DIFFERENT POLICES FOR THE DUTCH GAS SECTOR

8.1. POLICY OPTIONS ... 192
8.2. VISUAL COMPARISON ... 194
8.3. ANALYZING THE POLICY OPTIONS ... 198
8.3.1. Lexicographic Ordering ... 198
8.3.2. Additive Utility Method with Equal Weights ... 201
8.3.3. Additive Utility Method with Uncertain Weights ... 203
8.3.4. Pareto Set ... 206
8.3.5. Discussion on the Preferred Policies ... 206
8.4. SCENARIO DISCOVERY FOR ANALYZING THE POLICY PREFERENCE CHANGES AND VULNERABILITIES 208
8.5. CONCLUSIONS ... 216
8.6. REFERENCES ... 217

3B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

CHAPTER IX - CONCLUSIONS AND REFLECTION

9.1. RESPONSES TO THE RESEARCH QUESTIONS 219
9.1.1. How can the policy problem of the Dutch gas sector be formulated within the systems analysis framework? 220
9.1.2. What is the performance of various policy options identified under a wide set of possible futures? . 223
9.2. POLICY RECOMMENDATIONS 226
9.3. REFLECTION ON THE RESULTS AND METHODOLOGY 230
9.3.1. Reflection on the policy-related results 230
9.3.2. Reflection on the methodology 234
9.4. LIMITATIONS OF THE STUDY 238
9.5. FUTURE RESEARCH 241
9.6. REFERENCES 242

APPENDICES TO CHAPTER II **245**

APPENDICES TO CHAPTER IV **246**

APPENDICES TO CHAPTER V **251**

APPENDICES TO CHAPTER VII **266**

APPENDICES TO CHAPTER VIII **289**

Acknowledgements **301**

About the author **303**

Dissemination **304**

4A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

4B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Summary

The Dutch Gas Sector and Uncertainty

Following the discovery of a vast natural gas field in Groningen more than 50 years ago, the Dutch energy sector experienced a radical change. With the rapid development of widespread infrastructure, Dutch households and industry took advantage of this abundant and convenient energy source, while exploration and production companies and the government benefited from high revenues. Although the oil crisis in the 1970s changed the perception of abundance and led to preservation policies, and the liberalization of the energy markets in the 2000s created opportunities for many actors to enter the market, natural gas has remained as the major energy source, accounting for 43% of the total primary energy consumption currently.

This role of natural gas in the Dutch energy system is expected to change in future, mainly because of the declining indigenous production, and the transition towards a renewable energy system where natural gas has a complementary role. Several technological, societal and political uncertainties regarding the supply, demand, market and infrastructure of gas make it difficult to estimate how the future can unfold. Moreover, there is ambiguity in the Dutch gas sector about the desired future state, which stems from the multiplicity of actors in the sector and the variety of their interests. These interests are often conflicting, for instance the high production goal of the natural gas producers contradicts with the renewable energy goal of the government and environmentalists.

Covering several of the actors' interests, the policy objective of the Dutch national government is to provide a secure, sustainable, and affordable gas supply. However, not only the inherent conflicts between these objectives but also deep uncertainties impede the achievability of these goals and obscure policy making. To aid decision making under these circumstances, the objective of this thesis is defined as

> *Providing policy recommendations to the Dutch government and to the key actors in the gas sector, based on a policy analysis study that investigates the long-term effectiveness of policy options to deal with conflicting interests and uncertainties.*

Policy Problem

In line with this research objective, the thesis starts with a systematic definition of the policy problem by identifying (i) the policy goals of the government and the outcome indicators representing these, (ii) a system representation of the Dutch gas sector, (iii) the actors related

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to this system and stakeholder perspectives, (iv) the past and present policies that have been implemented, as well as future policy alternatives, and lastly (v) the uncertainties associated with the system of interest and the policy goals. With regard to these elements, the problem investigated in this study is the assessment of *policy options* in terms of the states or behavior of the *outcome indicators* in the alternative futures created by *uncertainties*.

In this problem definition, the policy goals are grouped into three as social, economic and environmental goals. Social goals relate to security of supply, affordability and safety, and are represented by outcome indicators such as *Coverage of Domestic Gas Demand* (the ratio of total supply in the Dutch market to the total domestic demand), *Import Dependency*, *Average Consumer Gas Price* and *Societal Acceptance*. Economic goals relate to the public income obtained by natural gas production and the gas-related economic activity. The outcome indicators associated with these goals are *Total State Revenue* (from natural gas production) and *Transport Capacity Utilization Rate*. As for the environmental goals, which focus on reducing the greenhouse gas emissions and increasing the share of sustainable energy sources, the *Share of Renewables in the Energy Mix* and *Renewable Gas Percentage* are the outcome indicators derived from these goals.

To conceptualize the system of interest and define its boundaries, a supply-demand view is adopted. In this view, three main supply options are taken into account, namely domestically produced natural gas, imported natural gas, and domestically produced renewable gas. These supply options are matched with the gas demand from households and commercial buildings, industry, agriculture, transport, and electricity production sectors. Development and deployment of each of these supply and demand options are included in the system model. The interactions between these supply options and the competition between the options for market share are included as the key mechanisms in the system model, because they are considered the main drivers of future dynamics of the system.

Natural gas producers such as NAM, renewable gas producers, traders such as GasTerra, small and large scale consumers and the transmission system operator GasUnie are the main actors considered in this study, influencing the system of interest with their decisions and actions. As for the government's potential actions, i.e. the policy options components of the problem definition, this thesis includes a review of the policies which are currently or have been previously implemented in the Netherlands and in other countries, or can be potentially implemented in future. The final list of policies included in the analysis is composed of three natural gas policies (production cap on the Groningen field, permission for shale gas production and a higher State Profit Share in the natural gas profits), three renewable gas policies (subsidization, agreements with the industry to reach a certain production goal, obligatory renewable gas supply by utility companies), and two demand side policies (a lower energy levy for renewable gas consumption, and a higher value-added tax (VAT) for both types of gas).

The uncertainties which are identified to be potentially influential in the future of the gas sector are divided into three groups: The first group contains the factors external to the system, such as the availability of natural gas and biomass resources, characteristics of new energy technologies and gas demand. The second group includes uncertainties about the

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system structure, mainly associated with price changes and producer behavior. In the third group, uncertainties are related to the value system of the problem owner, namely how the policy goals are prioritized by the government.

Policy Analysis and Uncertainty

Many policy problems are characterized by high complexity and deep uncertainty. This requires taking uncertainties into account explicitly in policy analysis, and adopting a research methodology accordingly. This thesis follows the Exploratory Modeling and Analysis approach, which proposes to use computational experiments to generate and analyze a large set of future scenarios, instead of a single best-estimate future. This large set of scenarios is used for understanding the effects of uncertainties and for analyzing the effectiveness of policies.

With the exploratory modeling approach, a simulation model is developed. System dynamics is chosen as the modeling methodology for this simulation model. This model differs from the existing energy (or gas) system models in terms of its scope and the way it incorporates uncertainties. Regarding the scope, this model represents the system of interest outlined in the problem definition in a supply-demand balance view. The gas sector is the main focus of the model, and different types of gas, such as natural and renewable, are taken into account. The competition between these different supply options in the market is considered a major driver of future dynamics. Regarding the representation of uncertainties, the model includes several parametric and structural uncertainties, i.e. multiple alternatives of a model structure if it is subject to uncertainty due to several possible modelling assumptions.

Enabling experimentation with many different combinations of the alternative instances of uncertain elements, the model is used to explore a variety and a large number of dynamic future scenarios in a horizon of 50 years between 2012 and 2062. To systematically analyze and compare the performance of different policies across these scenarios, a framework is proposed. This framework addresses three aspects of decision making: (i) To deal with the uncertainty aspect, the robustness of each policy across the uncertainty space is computed, with various expectation-based, regret-based and statistical robustness metrics. (ii) To deal with the multiplicity of policy objectives, four different, but simple and transparent, multi-criteria methods are used, such as a lexicographic ordering, or the additive value of robustness values corresponding to each policy objective. (iii) Lastly, to deal with the time aspect, such multi-criteria problems are solved statically with metrics which aggregate the transient nature of scenarios into a single measure, and dynamically in each year in the scenario horizon. The reason behind the use of multiple robustness metrics and multiple multi-criteria methods in this framework was to explore the consequences of methodological uncertainty, since no single metric or method is deemed the most appropriate one and the results are expected to be dependent on such methodological choices.

Exploring the Future Scenarios

The scenario space is generated by simulating the computer model with different instances of uncertainties, and resulted in wide uncertainty ranges of the outcome indicators in a time horizon between 2012 and 2062. For instance, *Renewable Gas Percentage*, i.e. the ratio of

6A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

renewable gas in the total gas consumption, has a wide range from 0 to 40% at the end of the scenario horizon, namely in year 2062. Yet, in this wide range, the majority of scenarios is below 5%. Such uncertainty ranges of the outcome indicators and the density distributions of scenarios in these ranges are the basis of the robustness analysis conducted in the later stages according to the three dimensional framework summarized above.

This thesis also includes an investigation of the model-based scenario space according to stakeholder perspectives found in the Dutch gas sector by Cuppen and Di Ruggero (2014)[1]. These perspectives are derived from an application of Q-methodology and each of them describes how several aspects of the Dutch energy system are expected to look like in the future. Hence, each perspective is considered as a qualitative scenario, or a set of such scenarios, in this study. These stakeholder perspectives are simulated with the model by adjusting the uncertainty ranges of model inputs and outputs, depending on the vision and future expectations of stakeholders forming a perspective. Resulting from this partitioning of the scenario space, this step firstly explores the extent to which the views expressed in the perspectives are internally consistent and feasible. Then, the differences and similarities of the future views expressed by these stakeholder groups are demonstrated. For instance, in terms of the share of renewable energy in the total energy mix, the perspective that envisions a bright future for renewables shows a wide range of relatively high values, whereas the perspective that expects the gas sector to adapt to the future changes shows a narrower range but still high values. The perspective that expect a prominent role of natural gas in the future energy system and the perspective that envisions austerity conditions in future show the highest densities of low end state values for the share of renewables.

Besides, this analysis helps to understand the conflicting objectives and system elements in the gas sector in general. For instance, the perspective that envisions a prominent role for renewable energy in future expects a low share of natural gas in the power generation mix, and a high share of renewable gas in the total gas consumption. However, these two conditions do not occur simultaneously in many scenarios. The reason is that electricity prices increase when natural gas is replaced by renewables in the power mix, which makes the electricity sector more attractive to be used for the limited biomass resources. In this case, the remaining low biomass supply to the renewable gas production leads to a low renewable gas percentage in the gas consumption.

Groningen Cap and Subsidization Policies

The policy testing, which is based on the framework summarized above, included two stages in this study: The first stage analyzes different implementation schemes of the two main policies in the gas sector, namely the production cap on natural gas and the subsidization of renewable gas. After selecting one of the options for each of these policies, the second stage compares various policies targeting natural gas supply, renewable gas supply and demand to each other.

[1] Cuppen E, O Di Ruggero. 2014. Stakeholder perspectives on the future of gas in the Netherlands (Working paper), Delft University of Technology.

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Four implementation schemes are considered to limit the natural gas production from the Groningen field. These schemes involve different instances of the two levers of the cap policy, i.e. the duration and the maximum production volume. When these four options are compared to each other, it is observed that they do not significantly differ from each other in terms of several outcome indicators such as demand coverage and consumer prices, yet the results. i.e. the preferred policies, are highly method-dependent. In other words, the robustness metric, the multi-criteria method used, and where in time the comparison is made strongly influence what the most preferred cap option is. Still, the 'prolonged cap' option is selected to be compared to other policies, due to the high frequency of this option being the most preferred one across all robustness, time and multi-criteria methods, and in a longer duration.

As for the subsidization of renewable gas, the analysis compares eleven schemes, such as the variations of market-independent fixed feed-in tariffs or market-dependent variable price schemes, including the spot-market gap model currently implemented in the Netherlands, a long-term implementation of this scheme and a no-subsidization option. While these schemes have similar effects on many outcome indicators, the trade-off between high renewable gas production and high subsidization costs to the government is apparent in the results. Based on the framework which combines the performance on multiple outcome indicators and against uncertainty, the 'fixed cost percentage model' of subsidization results as the most preferable scheme. According to this scheme, the government pays the difference between a multiple of the unit production cost and the market price to producers as long as the market price is lower than the cost. This choice is not the result of a strong predominance of this scheme on the others, but due to its acceptable performance with most of the methodological options.

Policy Comparison

Following the analysis of different implementation schemes for the cap and subsidization policies, eight different policies are compared to each other using the three dimensional framework. These eight policies are grouped into three as the ones targeting the natural gas supply, gas demand, and renewable gas supply. In the first group, increasing the state share in the natural gas profits increases the state revenue, without causing a considerable adverse effect on other outcome indicators. A long-term cap policy does not perform differently (than other policies) in terms of increasing the demand coverage or reducing future import dependency, yet it provides a considerable opportunity for renewables to grow their market share both in the gas and in the total energy sector. Permission to produce shale gas is shown to increase state revenues and to lower import dependency without resulting in low societal acceptance (mainly due to modelling assumptions), but it results in worse outcomes for the share of renewables.

The second group of policies targets the demand side by changing the consumer price with two different taxation instruments such as the energy levy and the value-added tax, yet they do not lead to significant changes in the future. In the third group, obliging the utility companies to provide a portion of their supply as renewable gas does not result in a higher performance than the business-as-usual policy. However, subsidization and communicative policies to enhance renewable gas production demonstrate a distinctive effectiveness

7A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

especially in terms of the renewable gas percentage and import dependency, without worsening any of the other outcome indicators.

The framework-based analysis favors the two renewable gas policies, namely the subsidization and biomethane production goal policy, due to their positive impacts on the abovementioned outcome indicators, and their high robustness performance with many metrics. Still, the results are time-dependent. If the short-term performance is taken into account, then the business-as-usual policy is shown to be promising besides subsidization, whereas in the long-term, the biomethane goal policy is shown to be the most preferable one, followed by the shale gas policy.

These policies, especially the subsidization policy, are found to be most vulnerable to uncertainties associated with the market price and producer behavior. In particular, two uncertainties about the producer behavior are found to be highly influential on policy performance. The first one of these uncertainties is how renewable gas and electricity producers make capacity installation decisions. Based on this finding, it can be said that a short-term view of producers which considers only the current cost and price values for capacity installation makes both the subsidization and the biomethane goal policies less effective than they could be. A long-term view represented by an NPV-based decision, leads to a higher profitability perception of producers, higher investments in capacity installation, and higher shares of renewable gas and energy. The second influential uncertainty is how gas producers respond to market price changes, e.g. by increasing their desired market price or decreasing it. Despite the negative connotation from a consumer perspective, a price increase initiated by natural gas producers in response to increasing market prices stimulates renewable gas production by enhancing its competitiveness. However, a response of producers that decreases the prices of natural gas also reduces the competitiveness of renewable gas and leads to low renewable gas production.

In Conclusion

In conclusion, this thesis provides a systematic analysis of gas sector policies in terms of their long-term effectiveness on various conflicting policy objectives and their robustness against uncertainties. Given the large set of policy objectives, no single policy is found to have positive effects on all of them, yet the subsidization and communicative biomethane policies are found to assist in attaining the sustainability goals without negatively affecting the other goals.

The framework developed and used to analyze such policies is an attempt to combine robustness, multi-criteria and time aspects of decision analysis under uncertainty based on dynamic scenarios and with multiple methodological options. Within this multi-method framework, multiple robustness metrics are used for the quantification of uncertainty in the policy outcomes. This study does not involve an explicit experimental design to compare these metrics. Still, the observations obtained from using the metrics reveal that an analysis should include multiple metrics, yet not necessarily as many as the ones used in this study. It is suggested that metrics to be used should capture (i) various characteristics of the scenario space, such as the skewness towards more desired outcomes or the peakedness indicating a

7B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

narrow uncertainty range, and (ii) the tradeoff between the average value of outcomes and the dispersion around it. Moreover, method-dependence manifests itself in the relation between a particular prioritization of policy objectives (i.e. a weighting scheme) and the policies preferred according to this prioritization. Namely, a particular prioritization of policy objectives results in a set of policies to be preferred with a particular robustness metric, yet the result changes when a different metric is used. Therefore, it cannot be strongly argued that a policy is suitable for a particular prioritization of the policy goals.

This study showed that the major vulnerabilities of the favorable policies (e.g. the subsidization and biomethane goal policies) are related to the producer behavior which is represented as a structural uncertainty in the model. This finding emphasizes the importance of taking structural uncertainty into account instead of focusing only on parametric uncertainties. Besides, it shows that the policies are not most vulnerable to external factors, but to factors within the system boundaries.

Three major limitations of this study are discussed in this thesis. The first one is related to the scope, i.e. the elements of the energy system excluded from the system boundaries such as the mechanisms behind demand change. Secondly, two limitations of the exploratory modelling approach are observed. The first one is the lack of analysis tools for understanding the effects of uncertainties on dynamic behavior, where the current scenario discovery tools are not adequate. The second one is related to the validity of exploratory models. There is no specific definition of the validity in the context of exploratory models, and validation tests can help to establish credibility of the model are not thoroughly described. The last major limitation is related to the desire for compactness and understandability of the information provided that guided the development of the three dimensional framework. The framework aggregates the relationship between a single policy and an outcome indicator across many scenarios into a single value. As a result, the underlying assumptions are transparent for specialist analysts only, and richer insights may be lost.

Further research is suggested mainly to deal with these limitations. Investigating the demand side of the energy system is suggested as a point of departure for further studies to extend the scope of this study. Besides, analysis tools for the exploratory modeling approach can be developed and improved for understanding the effects of uncertainties on dynamic behavior, and for uncovering the information obscured due to the aggregation of robustness and multi-criteria performance of policies. Further iterations of policy testing, for instance by strengthening the chosen policies according to their vulnerabilities, is considered useful to reach robust policy strategies.

In short, the use of this framework showed a strong method-dependence of the results, and provided information about which policies are favored with which methodological choices. This multi-method framework is observed to be computationally costly, yet useful for informing the policy debate about which decision making approach leads to which policies to be preferred.

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Samenvatting

The Nederlandse Gassector en Onzekerheid

Sinds de ontdekking van een groot aardgasveld in Groningen meer dan 50 jaar geleden, heeft de Nederlandse energiesector een radicale verandering ondergaan. Door de snelle ontwikkeling van grootschalige infrastructuur, konden Nederlandse huishoudens en de industrie gebruik maken van deze overvloedige en gemakkelijke bron van energie, terwijl de exploratie- en productiebedrijven en de overheid geprofiteerd hebben van hoge opbrengsten. Hoewel de oliecrisis in de jaren 70 van de vorige eeuw de perceptie van overvloed veranderde en de liberalisering van de energiemarkt aan het begin van de 21ste eeuw kansen creëerde voor veel actoren om de markt te betreden, is aardgas de belangrijkste energiebron gebleven. Het primaire energieverbruik bestaat momenteel voor 43% uit aardgas.

De grote rol van aardgas in het Nederlandse energiesysteem zal naar verwachting in de toekomst veranderen, vooral als gevolg van de dalende binnenlandse productie en de transitie naar duurzame energie, naar een situatie waar aardgas een complementaire rol heeft. Verschillende technologische, maatschappelijke en politieke onzekerheden met betrekking tot de vraag, aanbod, de markt en infrastructuur voor gas maken het moeilijk te beoordelen hoe de toekomst zich kan ontwikkelen. Bovendien is er ambiguïteit in de Nederlandse gassector met betrekking tot de gewenste toekomstige situatie. Dit komt door de veelheid aan actoren in de sector en de diversiteit van hun belangen. Deze belangen zijn vaak tegenstrijdig. De hoge productiedoelstelling van de aardgasproducenten is bijvoorbeeld in tegenspraak met de duurzaamheidsdoelstelling van de overheid en de milieubeweging.

De overkoepelende beleidsdoelstelling van de Nederlandse overheid is om in een voldoende, duurzaam en betaalbaar gasaanbod te voorzien. Echter, niet alleen de inherente conflicten tussen deze doelstellingen, maar ook diepe onzekerheden belemmeren de haalbaarheid van deze doelstellingen en maken beleidsvorming ingewikkeld. Om de besluitvorming onder deze omstandigheden te ondersteunen, is het doel van dit proefschrift gedefinieerd als:

> *Het voorstellen van beleidsaanbevelingen aan de Nederlandse overheid en de belangrijkste actoren in de gassector, op basis van een beleidsanalyse waarin de lange termijn effectiviteit van beleidsopties in het licht van tegenstrijdige belangen en onzekerheden onderzocht wordt.*

Beleidsprobleem

In lijn met deze doelstelling begint het proefschrift met een systematische definitie van het beleidsprobleem door het identificeren van (i) de beleidsdoelstellingen van de overheid en de

9A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

bijbehorende uitkomstindicatoren, (ii) een systeemrepresentatie van de Nederlandse gassector, (iii) de actoren die betrokken zijn bij het systeem en perspectieven van belanghebbenden, (iv) huidige beleidsmaatregelen en maatregelen uit het verleden, alsmede mogelijke toekomstige beleidsalternatieven, en ten slotte (v) de onzekerheden die betrekking hebben op het systeem en de beleidsdoelstellingen. In termen van deze elementen, is het probleem dat onderzocht wordt een analyse van de invloed van *beleidsopties* op de *uitkomstindicatoren* in de alternatieve toekomsten die gecreëerd worden door *onzekerheden*.

In deze probleemdefinitie worden de beleidsdoelen gegroepeerd naar: sociale, economische en milieudoelstellingen. Sociale doelstellingen hebben betrekking op voorzieningszekerheid van energie, betaalbaarheid en veiligheid, en worden gerepresenteerd door uitkomstindicatoren als *Coverage of Domestic Gas Demand* (de verhouding van het totale aanbod op de Nederlandse markt tot de totale binnenlandse vraag), *Import Dependency* (import afhankelijkheid), *Average Consumer Gas Price* (gemiddelde consumentenprijs van gas) en *Societal Acceptance* (maatschappelijke acceptatie). Economische doelstellingen hebben betrekking op de publieke inkomsten verkregen door de productie van aardgas en aan gas gerelateerde economische activiteiten. De uitkomstindicatoren die samenhangen met deze doelen zijn *Total State Revenue* (inkomsten uit de productie van aardgas) en *Transport Capacity Utilization Rate* (benutting van transportcapaciteit). Met betrekking tot de milieudoelstellingen die zich richten op het verminderen van de uitstoot van broeikasgassen en het verhogen van het aandeel duurzame energie, zijn de uitkomstindicatoren *Share of Renewables in the Energy Mix* (aandeel hernieuwbare energie in de energiemix) en *Renewable Gas Percentage* (percentage hernieuwbaar gas) afgeleid van deze doelen.

Om het systeem te conceptualiseren en de systeemgrenzen te definiëren, is het systeem beschouwd vanuit een vraag-aanbod invalshoek. Er zijn vanuit deze visie drie belangrijke typen aanbod waarmee rekening wordt gehouden, namelijk: in eigen land geproduceerd aardgas, geïmporteerd aardgas en binnenlands geproduceerd hernieuwbaar gas. Het aanbod wordt gekoppeld aan de vraag naar gas van huishoudens en commerciële gebouwen, industrie, landbouw, transport en elektriciteitsproductie. De ontwikkeling van aanbod en vraag is gerepresenteerd in het systeemmodel. De interacties tussen de typen aanbod en de concurrentie tussen de typen aanbod om marktaandeel zijn sleutelmechanismen in het systeemmodel.

Aardgasproducenten zoals de NAM, producenten van duurzaam gas, handelaren zoals GasTerra, kleinschalige en grootschalige consumenten, en het gasinfrastructuurbedrijf GasUnie, worden beschouwd als de belangrijkste actoren in deze studie. Zij beïnvloeden het beschouwde systeem met hun beslissingen en acties. Voor wat betreft mogelijke acties van de overheid, d.w.z. de beleidsopties uit de probleemstelling, bevat dit proefschrift een overzicht van beleidsmaatregelen die momenteel worden toegepast of in het verleden zijn toegepast in Nederland of in andere landen, of die mogelijk in de toekomst kunnen worden toegepast. De lijst van maatregelen die is opgenomen in de analyse bestaat uit: drie aardgas opties (maximum productie uit het Groningenveld, toestemming voor de productie van schaliegas, en een hogere winstaandeel voor de Staat in de aardgasbaten), drie beleidsopties voor hernieuwbaar gas (subsidiëring, overeenkomsten met de industrie over een productie-doel,

9B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

verplicht aanbod hernieuwbaar gas door energiebedrijven), en twee opties voor de vraagkant (een lagere energieheffing voor hernieuwbaar gas, en een hogere btw voor beide soorten gas).

De onzekerheden, die zijn geïdentificeerd omdat ze potentieel van invloed zijn op de toekomst van de gassector, zijn verdeeld in drie groepen: de eerste groep bevat de factoren van buiten het systeem, zoals de beschikbaarheid van aardgas en biomassa, kenmerken van nieuwe energietechnologieën, en vraag naar gas. De tweede groep bestaat uit onzekerheden over de structuur van het systeem, die vooral te maken hebben met prijsveranderingen en gedrag van producenten. In de derde groep zijn de onzekerheden opgenomen die gerelateerd zijn aan de waarden van de probleemeigenaar, d.w.z. de prioritering van beleidsdoelen door de overheid.

Beleidsanalyse en Onzekerheid

Veel beleidsproblemen worden gekenmerkt door een hoge complexiteit en diepe onzekerheid. In een beleidsanalyse moet daarom expliciet rekening gehouden worden met onzekerheden en gebruik gemaakt worden van een onderzoeksmethodologie waarbij dat mogelijk is. Dit proefschrift volgt de *Exploratory Modeling and Analysis* aanpak, waarin computer-experimenten worden gebruikt voor het genereren en analyseren van een groot aantal toekomstscenario's, in plaats van één enkele verwachting van de toekomst. Deze grote verzameling scenario's wordt gebruikt inzicht te krijgen in de effecten van onzekerheid en voor het analyseren van de effectiviteit van beleidsmaatregelen.

Bij de *exploratory modeling and analysis* aanpak wordt eerst een simulatiemodel ontwikkeld. In dit onderzoek is *System Dynamics* gekozen als modelleermethode voor het simulatiemodel. Dit model onderscheidt zich van de bestaande energie (of gas) systeemmodellen voor wat betreft de scope en de manier waarop onzekerheden meegenomen worden. Ten aanzien van de scope, representeert het model het systeem dat in de probleemstelling omschreven vanuit de vraag-aanbod invalshoek. De gassector is de belangrijkste focus van het model, en de verschillende soorten gas, zoals aardgas en hernieuwbaar gas, worden meegenomen. De concurrentie tussen deze verschillende aanbodopties wordt beschouwd als een belangrijke motor van de toekomstige dynamiek. Met betrekking tot onzekerheden omvat het model verschillende parametrische en structurele onzekerheden, d.w.z. meerdere alternatieven van een modelstructuur als daar onzekerheid in zit.

Het model wordt gebruikt om een groot aantal dynamische toekomstscenario's over de tijdshorizon tussen 2012 en 2062 te verkennen, door te experimenteren met zeer veel verschillende combinaties van alternatieve waarden voor de onzekerheden. Om de prestaties van de verschillende beleidsmaatregelen in deze scenario's systematisch te analyseren en vergelijken, wordt een raamwerk voorgesteld. Dit raamwerk heeft betrekking op drie aspecten van besluitvorming: (i) Om rekening te houden met onzekerheid, is de robuustheid van elke maatregel in de onzekerheidsruimte berekend, met behulp van diverse robuustheidsmaten, die gebaseerd zijn op verwachting, spijt en statistische robuustheid. ii) Om rekening te houden met de veelheid aan beleidsdoelstellingen, zijn vier verschillende, maar eenvoudige en transparante, multi-criteria methoden gebruikt, zoals een lexicografische ordening en de additieve waarde van de robuustheidswaarden van elke beleidsdoelstelling. (iii) Tot slot, om

10A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

rekening te houden met het tijdsaspect, worden de multi-criteria problemen statisch opgelost met statistische maten die de tijdsafhankelijke scenario's aggregeren tot één waarde, en daarnaast dynamisch in ieder jaar van de scenario-horizon. De reden voor het gebruik van meerdere robuustheidsmaten en meerdere multi-criteria methoden is om de gevolgen van methodologische onzekerheid te onderzoeken, aangezien geen enkele maat of methode het meest geschikt wordt geacht en wordt verwacht dat de resultaten afhankelijk zijn van dergelijke methodologische keuzes.

Verkenning van de Toekomstscenario's

De scenario-ruimte wordt gegenereerd door het computermodel met verschillende combinaties van waarden van de onzekerheden te simuleren. Dit resulteert in grote onzekerheidsmarges van de uitkomstindicatoren over de tijdshorizon tussen 2012 en 2062. De *Renewable Gas Percentage*, de verhouding van hernieuwbaar gas tot het totale gasverbruik, heeft bijvoorbeeld een breed bereik van 0 tot 40% aan het einde van de scenario-horizon. Binnen dit brede bereik resulteren de meeste scenario's echter in minder dan 5%. De onzekerheidsmarges van de uitkomstindicatoren en dichtheidsverdelingen van de scenario's vormen de basis voor de verdere robuustheidanalyse met behulp van het driedimensionale raamwerk dat hierboven is samengevat.

Dit proefschrift bevat ook een onderzoek naar de scenario-ruimte volgens de perspectieven van belanghebbenden in de Nederlandse gassector die opgesteld zijn door Cuppen en Di Ruggero (2014)[2]. De perspectieven zijn ontwikkeld door toepassing van de Q-methodologie, en ieder perspectief beschrijft hoe wordt verwacht dat de verschillende aspecten van het Nederlandse energiesysteem er in de toekomst uit zullen zien. In deze studie wordt ieder perspectief beschouwd als een kwalitatief scenario, of een reeks van dergelijke scenario's. De perspectieven worden gesimuleerd in het model door de onzekerheidsranges van model-inputs en outputs aan te passen op basis van de toekomstverwachtingen die bij het perspectief horen. Als gevolg van deze opdeling van de scenario-ruimte, kan onderzocht worden in welke mate de standpunten in het perspectief intern consistent en haalbaar zijn. Vervolgens kan gekeken worden wat de verschillen en overeenkomsten zijn in de toekomstvisies van de verschillende groepen belanghebbenden. Het perspectief dat een positieve toekomst verwacht voor hernieuwbare energie, laat bijvoorbeeld een brede range zien aan relatief hoge waarden voor het aandeel hernieuwbare energie in de totale energiemix, terwijl het perspectief dat verwacht dat de gassector zich zal aanpassen aan toekomstige veranderingen een smallere range laat zien, maar wel met hoge waarden. Het perspectief dat een prominente rol voor aardgas verwacht in het toekomstige energiesysteem en het perspectief dat soberdere omstandigheden verwacht in de toekomst laten de hoogste dichtheden zien van lage waarden voor de eindsituatie van het aandeel hernieuwbare energie.

Deze analyse kan ook helpen om conflicterende doelstellingen en systeemelementen te begrijpen. Bijvoorbeeld, het perspectief dat een prominente rol voor hernieuwbare energie in de toekomst voorziet, verwacht een laag aandeel van aardgas in de elektriciteitsproductie mix

[2] Cuppen E, O Di Ruggero. 2014. Stakeholder perspectives on the future of gas in the Netherlands (Working paper), Delft University of Technology.

10B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

en een hoog aandeel hernieuwbaar gas in het totale gasverbruik. Echter, deze twee voorwaarden treden niet in veel scenario's gelijktijdig op. De reden is dat de elektriciteitsprijs stijgt wanneer aardgas wordt vervangen door hernieuwbare energie in de energiemix, hetgeen de elektriciteitssector aantrekkelijker maakt voor de beperkte hoeveelheid biomassa. In dit geval leidt het lage biomassa aanbod voor de productie van hernieuwbaar gas tot een laag percentage hernieuwbaar gas in het gasverbruik.

Maximum Productie Groningengasveld en Subsidiebeleid

Het testen van het beleid, gebaseerd op het raamwerk dat hierboven is samengevat, bestaat in deze studie uit twee fasen: De eerste fase analyseert verschillende opties voor implementatie van de twee belangrijkste beleidsmaatregelen in de gassector, namelijk het beperken van de aardgasproductie en de subsidiëring van hernieuwbaar gas. Na het selecteren van één van de implementatie-opties voor elk van deze beleidsmaatregelen, worden in de tweede fase verschillende maatregelen, die gericht zijn op aanbod van aardgas, aanbod van hernieuwbaar gas, en vraag, met elkaar vergeleken.

Vier opties zijn gekozen voor het beperken van de productie van aardgas uit het Groningenveld. Deze opties bestaan uit verschillende waarden van de twee "knoppen" waaraan gedraaid kan worden bij het beperkingsbeleid, namelijk de duur en het maximale productievolume. Wanneer deze vier opties vergeleken worden met elkaar, wordt duidelijk dat ze niet significant van elkaar verschillen op een aantal uitkomstindicatoren, zoals dekking van de vraag en de prijs voor de consument, maar de resultaten, dat wil zeggen de beleidsopties die de voorkeur hebben, zijn sterk methode-afhankelijk. Met andere woorden, de robuustheidsmaat, de gebruikte multi-criteria methode, en op welk tijdstip de vergelijking gemaakt wordt, zijn van sterke invloed op welke optie de voorkeur heeft. Toch is de optie '*prolonged cap*' (langdurig maximum) gekozen om te vergelijken met de andere beleidsmaatregelen, vanwege de hoge frequentie waarmee deze optie de voorkeur heeft over alle robuustheids-, tijd- en multi-criteria methoden, en van een langere duur.

Voor de subsidiëring van hernieuwbaar gas, zijn tijdens de analyse 11 opties onderzocht, zoals varianten van vaste feed-in tarieven of markt-afhankelijke variabele prijsopties, waaronder het model dat momenteel in Nederland toegepast wordt (*spot-market gap model*), een lange-termijn implementatie van deze optie en een geen-subsidie optie. Hoewel deze opties vergelijkbare effecten hebben op veel uitkomstindicatoren, is de trade-off tussen een hoge productie van hernieuwbaar gas en hoge subsidiekosten voor de overheid duidelijk. Op basis van het raamwerk, dat de prestaties op verschillende uitkomstindicatoren en onder onzekerheid combineert, heeft het '*fixed cost percentage model'* van subsidiëring de voorkeur. Bij deze optie, betaalt de overheid het verschil tussen een veelvoud van de productiekosten per eenheid en de marktprijs aan producenten, zolang de marktprijs lager is dan de kostprijs. Deze keuze is niet het gevolg van een sterke overheersing van deze optie boven de andere opties, maar vanwege aanvaardbare prestaties bij de meeste methodologische varianten.

11A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Vergelijking van Beleidsalternatieven

Na de analyse van de verschillende implementatie-opties voor de maximumproductie en het subsidiebeleid, worden 8 verschillende beleidsmaatregelen met elkaar vergeleken met behulp van het driedimensionale raamwerk. Deze 8 maatregelen zijn gegroepeerd in drie groepen die gericht zijn op: het aanbod van aardgas, de vraag naar gas, en aanbod van hernieuwbaar gas. In de eerste groep, verhoogt het vergroten van het staatsaandeel in de aardgasbaten de overheidsinkomsten, zonder dat het een aanzienlijk negatief effect heeft op andere uitkomstindicatoren. Een lange-termijn maximumproductiebeleid doet het niet anders (dan andere beleidsmaatregelen) in termen van het verhogen van de dekking van de vraag of het verminderen van toekomstige afhankelijkheid van import, maar het biedt een aanzienlijke kans voor hernieuwbare energie om het marktaandeel te laten groeien, zowel in de gas- als in de totale energiesector. Toestemming om schaliegas te produceren verhoogt de staatsinkomsten en om verlaagt de afhankelijkheid van invoer, zonder dat het resulteert in lage maatschappelijke acceptatie (komt vooral door aannames in het model), maar het leidt tot slechtere resultaten voor het aandeel van hernieuwbare energie.

De tweede groep maatregelen is gericht op de vraagzijde, door het veranderen van de consumentenprijs met twee verschillende fiscale instrumenten zoals de energieheffing en de btw, maar deze niet leiden tot significante veranderingen in de toekomst. In de derde groep, leidt de verplichting voor energiebedrijven om in een deel van hun aanbod te voorzien door hernieuwbaar gas, niet tot betere prestaties dan bij het business-as-usual-beleid. Echter, subsidiëring en communicatie-beleid om de productie van hernieuwbaar gas te verhogen zijn effectief in termen van het percentage hernieuwbaar gas en importafhankelijkheid, zonder verslechtering van één van de andere uitkomstindicatoren.

De twee beleidsmaatregelen op het gebied van hernieuwbaar gas, namelijk subsidiëring en beleid waarbij er een biomethaan-productiedoel gesteld wordt, komen positief uit de analyse met het raamwerk, vanwege de positieve effecten op de bovengenoemde uitkomstindicatoren, en hun hoge robuustheidsprestaties bij veel maten. Toch zijn de resultaten tijdsafhankelijk. Als de prestaties op korte termijn in aanmerking worden genomen, dan is het business-as-usual beleid veelbelovend naast subsidiëring, terwijl op de lange termijn het biomethaandoel de meeste voorkeur heeft, gevolgd door het schaliegas beleid.

Deze beleidsmaatregelen, en met name het subsidiebeleid, blijken het meest kwetsbaar voor onzekerheden die te maken hebben met de marktprijs en het gedrag van producenten. Twee onzekerheden met betrekking tot producentgedrag in het bijzonder, blijken zeer invloedrijk voor de uitkomsten van het van het beleid. De eerste van deze onzekerheden heeft betrekking op hoe producenten van hernieuwbaar gas en elektriciteit beslissingen nemen over de installatie van capaciteit. Op basis van deze bevinding, kan worden gezegd dat een korte-termijn visie van producenten die alleen de huidige kosten en de prijs meeneemt bij de installatie van capaciteit, zowel de subsidiëring als het biomethaandoel-beleid minder effectief maakt dan het zou kunnen zijn. Een lange-termijn visie, gerepresenteerd door een NPV-gebaseerde beslissing, leidt tot een hogere winstgevendheidsperceptie van producenten, hogere investeringen in de installatie van capaciteit, en grotere aandelen hernieuwbaar gas en energie. De tweede invloedrijke onzekerheid is hoe gasproducenten reageren op

11B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

veranderingen in de marktprijs, bijvoorbeeld door verhogen van hun gewenste marktprijs of door verlagen. Ondanks de negatieve connotatie vanuit consumentenperspectief, stimuleert een prijsverhoging die geïnitieerd wordt door aardgasproducenten in reactie op stijgende marktprijzen de productie van hernieuwbaar gas door het verbeteren van het concurrentievermogen. Echter, een reactie van de producenten die de prijzen van aardgas verlaagt, verslechtert ook de concurrentiepositie van hernieuwbaar gas en leidt tot lage productie van hernieuwbaar gas.

Concluderend

In dit proefschrift wordt een systematische analyse uitgevoerd van beleidsmaatregelen in de gassector, in termen van lange termijn effectiviteit in het licht van tegenstrijdige beleidsdoelstellingen en robuustheid tegen onzekerheden. Gezien het grote aantal beleidsdoelstellingen, is geen enkele beleidsmaatregel gevonden die een positief effect heeft op alle doelstellingen, maar de subsidiëring en communicatieve biomethaan beleidsmaatregelen kunnen een bijdrage leveren bij het bereiken van de duurzaamheidsdoelstellingen, zonder negatieve gevolgen voor de andere doelen.

Met het raamwerk, dat is ontwikkeld en gebruikt om de beleidsopties te analyseren, is getracht om robuustheids-, multi-criteria- en tijds-aspecten van besluitvorming onder onzekerheid te combineren, gebaseerd op dynamische scenario's en met verschillende methodologische varianten. In dit multi-methode raamwerk worden meerdere robuustheidsmaten gebruikt voor het kwantificeren van onzekerheid in beleidsuitkomsten. Dit onderzoek maakt geen gebruik van een expliciet experiment-ontwerp om deze maten te vergelijken. Echter, uit de resultaten die verkregen zijn door gebruik te maken van de statistische maten blijkt dat een analyse meerdere maten moet omvatten, doch niet noodzakelijkerwijze zo veel als gebruikt in deze studie. Voorgesteld wordt dat de gebruikte statistische maten (i) verschillende kenmerken van de scenario-ruimte zouden moeten weergeven, zoals de scheefheid (*skewness*) naar meer gewenste resultaten, of de piekvormigheid die wijst op een smalle onzekerheidsmarge, en (ii) de afweging tussen de gemiddelde waarde van de uitkomsten en de spreiding eromheen duidelijk moeten maken. Bovendien manifesteert methode-afhankelijkheid zich in de relatie tussen een bepaalde prioritering van de beleidsdoelstellingen (d.w.z. keuze voor gewichten) en de maatregelen die de voorkeur hebben volgens deze prioritering. Een bepaalde prioritering van de beleidsdoelstellingen resulteert namelijk in een verzameling beleidsmaatregelen die de voorkeur hebben bij een bepaalde robuustheidmaat, maar het resultaat verandert wanneer een andere robuustheidsmaat wordt gebruikt. Daarom kan niet worden gesteld dat een beleidsmaatregel geschikt is bij een bepaalde prioritering van de beleidsdoelstellingen.

Uit deze studie blijkt dat de belangrijkste kwetsbaarheden van de gunstige beleidsmaatregelen (bijvoorbeeld subsidiëring en biomethaandoel) zijn gerelateerd aan het gedrag van de producent, dat wordt gerepresenteerd als een structurele onzekerheid in het model. Deze bevinding benadrukt het belang van het meenemen van structurele onzekerheid in plaats van alleen parametrische onzekerheden. Bovendien blijkt dat het beleid niet het meest kwetsbaar is voor externe factoren, maar voor factoren binnen de systeemgrenzen.

12A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Drie belangrijke beperkingen van dit onderzoek worden besproken in dit proefschrift. De eerste heeft betrekking op de scope, namelijk de onderdelen van het energiesysteem die buiten de systeemgrenzen vallen, zoals de mechanismen achter de verandering van de vraag. Ten tweede, zijn twee beperkingen van de *exploratory modelling* aanpak duidelijk geworden. De eerste is het gebrek aan analyse-instrumenten voor het begrijpen van de effecten van onzekerheden op dynamisch gedrag, waar de huidige *scenario discovery tools* niet toereikend zijn. De tweede heeft betrekking op de validiteit van de *exploratory* modellen. Er is geen specifieke definitie van validiteit in de context van *exploratory* modellen, en validatietests die zouden kunnen bijdragen aan het beoordelen van de geloofwaardigheid van een model zijn niet grondig beschreven. De laatste grote beperking houdt verband met de wens die leidend was bij de ontwikkeling van het driedimensionale raamwerk, namelijk dat de informatie die verkregen wordt compact en begrijpelijk is. Het raamwerk aggregeert de relatie tussen een beleidsmaatregel en een uitkomstindicator over vele scenario's tot één enkele waarde. Hierdoor zijn de achterliggende aannames alleen transparant voor specialistische analisten, en diepere inzichten kunnen verdwijnen.

Aanbevolen wordt om verder onderzoek te doen naar manieren om met deze beperkingen om te gaan. Onderzoek naar de vraagzijde van het energiesysteem wordt voorgesteld als vertrekpunt om de reikwijdte van deze studie uit te breiden. Bovendien kunnen analysemethoden voor de *exploratory modeling* aanpak worden ontwikkeld en verbeterd, zodat de effecten van onzekerheid op dynamisch gedrag beter kunnen worden begrepen, en voor het zichtbaar maken van informatie die als gevolg van het aggregeren van robuustheids- en multi-criteria uitkomsten van beleidsmaatregelen niet meer transparant is. Verdere iteraties van het testen van beleidsmaatregelen, bijvoorbeeld door het versterken van de gekozen maatregelen naar aanleiding van de gevonden kwetsbaarheden, wordt zinvol geacht om tot robuuste beleidsstrategieën te komen.

Kortom, het gebruik van het ontwikkelde raamwerk toont een sterke methode-afhankelijkheid van de resultaten, en levert informatie over welke beleidsmaatregelen gunstigere resultaten geven bij welke methodologische keuzes. Alhoewel het multi-methode raamwerk rekenintensief is, kan het een zinvolle bijdrage leveren aan het debat over welke besluitvormingsaanpak leidt tot welke geprefereerde beleidsmaatregelen.

12B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

1

INTRODUCTION

1.1. AN OVERVIEW OF THE DUTCH GAS SECTOR

On a dry, sunny summer morning in 1959, a group of engineers working in a small village named Slochteren in the far north of the Netherlands have recorded the discovery of a huge natural gas field. This discovery initiated a radical change in the Dutch energy sector. On the one hand, Dutch households and industry took advantage of this abundant and convenient energy source for decades. On the other hand, the producers and government benefited from high sales revenues, which financed the social welfare system and large infrastructure projects such as the Deltaworks. In the current situation, natural gas is still the main energy source of the Netherlands, covering 43% of the primary energy consumption (CBS, 2014a). The future situation, however, is not known. This is mainly attributed to uncertainties such as future resource availability and consumption trends. Besides, the variety in the expectations of key actors (e.g. producers, consumers, policymakers) about the role of natural gas in the energy system plays an important role in unpredictability of the future situation. This section expands these past, present and future situations, and provides a brief overview of the Dutch natural gas sector in these three aspects.

1.1.1. The Past

The history of natural gas is usually divided into three periods (Warner, 2009; Correljé *et al.*, 2003). In this overview, we follow the same periodization, and present the past of the Dutch gas sector in three sections below.

The first period: From the discovery to the oil crisis

The period from the discovery in 1959 until the oil crisis in 1973 was marked by a rapid transition towards a gas-based energy system, due to successful policies of the government and the evident advantages of gas over oil and coal. Thinking that the future energy systems would be nuclear-based and natural gas would lose its importance, the government followed

13A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

an eager strategy to establish a domestic and international market for the Dutch gas. Despite their long distance from the production area, densely populated and highly industrialized regions were selected for initial network construction, which stimulated high sales revenues and further expansion. Moreover, natural gas use was intensely promoted to households and industrial consumers due to its cleanliness, ease of use, efficiency and flexibility. This promotion resulted in an extensive preference of gas over oil or coal even though the price of gas was not significantly lower than the others.

Besides the advantages of gas observed by consumers, another main reason for the rapid development was the certainty provided by the market structure for investors and producers (Correljé, 2011). In this structure named *Gasgebouw* (Gas building), the network operator and trader company GasUnie and the production company NAM (Nederlandse Aardolie Maatschappij) had monopolistic positions for a long time. GasUnie, owned by the state and NAM, purchased all the gas from producers with fixed and oil-linked prices and sold it to the different consumers with different prices and long-term contracts. In this respect, GasUnie had full control of the prices, which were acceptable by each party. GasUnie had no purpose of profit-making, and after the reduction of transportation costs and the corporate taxes, all the revenues of GasUnie were passed to the producers, who paid 70-90% of their profit to the government. On the producer side, owned by big, multinational companies Shell and Exxon, NAM had a wide experience in gas exploration and production. Particularly for the extraction from the Groningen (Slochteren) field, NAM participated with a 60% share in the company Maatschap Groningen, of which 40% was owned by DSM (Dutch State Mines) (Siegers).

The second period: From the oil crisis to liberalization

In the second period, i.e. from the oil crisis in 1973-1974 until the late 1980's, the perception of energy abundance disappeared, and the economy was affected by recession. The main reason of such a perspective change about the abundance of energy was the shortages due to the oil embargo imposed on the Netherlands, and the increasing oil prices. The secondary reason was the famous Limits to Growth study by the Club of Rome (Meadows *et al.*, 1972), which raised awareness about the depletion of natural resources. As for the economic recession, it was mainly caused by the phenomenon known as *Dutch disease*. The high export volumes of gas had made the Dutch currency very valuable, reducing the exports of other goods but easing imports. Although the state revenues from the gas production covered the actual budget deficit and enhanced the public sector for a while, the reduced competitiveness of the Dutch manufacturing industry led to an overall economic recession (Correljé et al., 2003).

To deal with future gas supply problems and economic recession, the policy strategy of the government had three main aspects in this period. Firstly, natural gas exports were reduced in quantity, and imports from especially Norway and Algeria were initiated. Also, export prices were increased to support this policy. Secondly, the domestic gas prices were increased with the intention of decreasing demand, and the large-scale industrial consumers were supplied with natural gas only if it brought an added value to their business compared to oil and coal. The third policy initiated in this period was the well-known "small fields policy". With this policy, the gas produced from small on and offshore fields was ensured to be purchased by

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GasUnie. This assurance tempted companies to explore and produce from fields other than the Groningen field, and eventually assigned a complementary role to the Groningen field, where it was used only to balance the seasonal demand fluctuations and preserved for future security of supply.

The third period: From liberalization to the present

The liberalization of European energy markets in the late 80's initiated a new period in the Dutch gas sector. Although the policy objectives for liberalization were outlined in 1995, they were transformed into new regulations eventually in 2000 with the Gas Act. Following that, with the Third Party Access (TPA) system, suppliers other than GasUnie were given access to the network and market. Large, medium and small scale consumers were given freedom to choose their suppliers in 1998, 2002 and 2004, respectively. The unbundling of transport and commercial activities of network operators resulted in the split up of GasUnie in 2005 into Gas Transport Services (GTS) as the network operator, and GasTerra as the trader. GasUnie remained the network owner. In 2003, GasUnie established the Title Transfer Facility (TTF), which is the virtual trading center for the functioning of the spot market.

After the liberalization, decarbonisation and market integration regulations of European Commission (EC) played an important role in the Dutch energy sector. The 'Energy 2020 Goals' set in 2007 aimed at the reduction of greenhouse gas emissions by at least 20% compared to 1990 emission levels (in the ETS sectors); the reduction of total EU energy consumption by 20% compared to 2020 consumption estimates; and the increase of the share of renewables by 20% in energy consumption and 10% in transport (EC, 2010). The Netherlands' national target for the renewable energy share in 2020 was set at 14%, whereas the emission level target for non-ETS sectors was adopted at the national level as 16% and the energy saving target was transformed into a 1.5% annual reduction. As for the market integration, the EC aimed at establishing a single European market both for gas and electricity, with harmonized prices and more choices for customers. The Netherlands responded to this with the 'Gas Hub strategy', namely with the goal of being the gas hub of the Western Europe.

1.1.2. The Present

In the current situation, the three indicators of the 2020 goals are still below the target values, but the Dutch government is ambitious to achieve these targets. In 2012, the CO_2 emissions were recorded as 93.26% of the 1990 levels and the share of renewables in the total energy consumption was 4.5% (EUROSTAT, 2014a). The average annual reduction rate of the total energy consumption between 2005 and 2013 were 1.2% (CBS, 2014a). Still, the National Reform Plan of 2014 states that the 2020 goals can be achieved with the current policy measures. These measures include the subsidization of renewable energy production, energy efficiency regulations and energy agreements with industry such as Energy Agreement for Sustainable Growth signed with the Social and Economic Council of the Netherlands (MEZ, 2014a).

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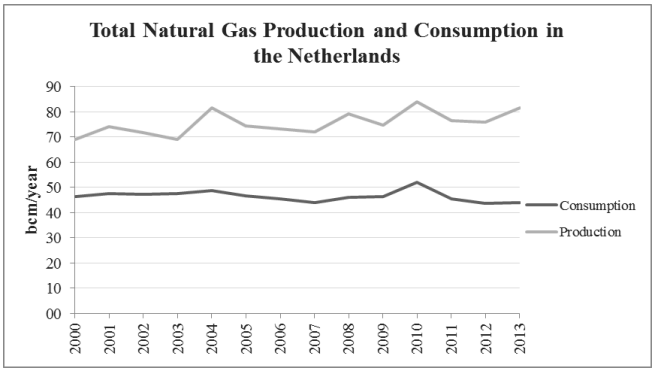


Figure 1.1: Natural Gas Production and Consumption in the Netherlands between 2000 and 2013 Source: (CBS, 2014b)

As for the indigenous natural gas consumption and production, the Netherlands still produces almost double of its consumption. In 2013, the total natural gas production from small fields and the Groningen field was 81.5 billion cubic meters (bcm), following a short declining trend seen in Figure 1.1, after the peak production in 2010, which was 83.9 bcm (CBS, 2014b). Still, the depletion of reserves is expected to result in production volumes decreasing significantly in a few decades, as Figure 1.2 shows (NLOG, 2014). The total natural gas consumption was 44.1 bcm in 2013. This value reflects the sum of volumes consumed by households and industrial users, as well as in the power generation, agriculture and transport sectors. The 2013 consumption is slightly higher than the consumption of 2012, which was 43.6 bcm and the lowest of the last decade (CBS, 2014b).

There are two major issues currently debated in the Dutch policy arena regarding the natural gas production. The first is the extraction of unconventional natural gas, which could change the expected production volumes drastically. The prospects of shale gas, which is the most common unconventional gas type found in the Dutch subsoil, are around 110,000 bcm (Muntendam-Bos *et al.*, 2009). However, due to the environmental damage of production and the social controversy about it, shale gas extraction is currently not allowed in the Netherlands. The government has announced that a decision about permission will be made in 2015 (MEZ, 2014b). The second issue is the earthquakes caused by the natural gas production in Groningen. The increasing number of earthquakes in the last few years has raised significant public opposition, and the government eventually had to reduce the production quota on Groningen for 2014-2016, despite the expected financial loss of 2.3 billion Euros in this period (MEZ, 2014c).

Whether conventional or unconventional, natural gas is no longer the only gas type in the gas grid and gas sector. Biomethane, also known as 'green gas' in the Netherlands, is the biogas that is upgraded to the natural gas quality and injected into the grid. Being a renewable alternative, biomethane not only reduces the CO_2 emissions, but also extends the use of the gas grid, which is under the risk of obsolescence if natural gas sources are depleted or renewable electricity replaces the natural gas consumption. Currently, the biomethane production covers only around 2% of the domestic gas demand, but the Dutch government has high ambitions for the future.

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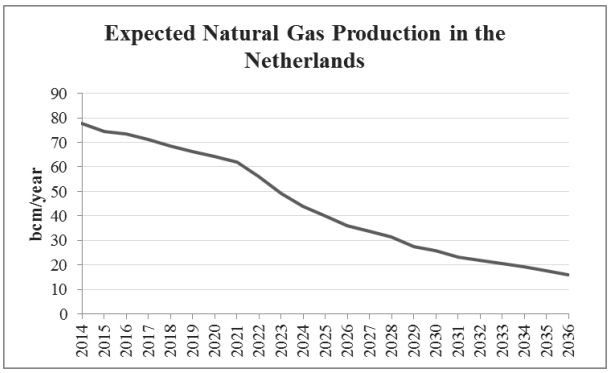


Figure 1.2: Expected Total Natural Gas Production from Small Fields and the Groningen Field
Source: (NLOG, 2014)

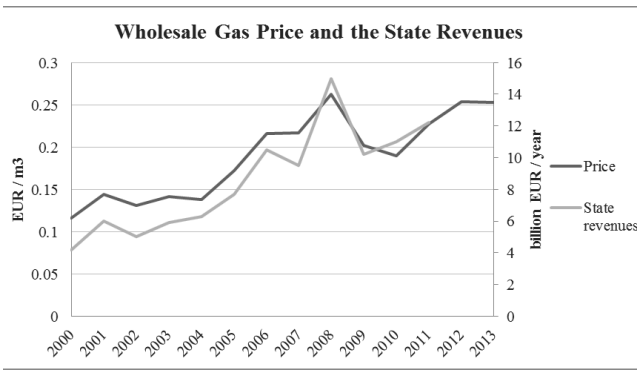


Figure 1.3: Wholesale Natural Gas Price in the Dutch Market and the State Revenues from Natural Gas Production between 2000 and 2013
Adapted from (CBS, 2014c) and (EBN, 2012)

The wholesale price of gas and the state revenues, corresponding to the production and consumption volumes stated above, showed an increasing trend in the past decade. In 2013, the price reached 0.25 EUR/m^3 (CBS, 2014c) whereas the state revenues were recorded as 12 billion EUR in 2012 (EBN, 2012), as seen in Figure 1.3. Having this high contribution to the government budget, on the one hand, especially small consumers carried the burden of high prices on the other. The average household gas price was 0.83 EUR/m^3 in 2013, whereas the European average was 0.69 EUR/m^3 (EUROSTAT, 2014b). Around 50% of this price is paid for transport costs and taxes in the Netherlands, posing a potential for consumer dissatisfaction.

1.1.3. The Future

Although the available data makes the present state certain to the extent that it is accurate and reliable, there is a high degree of ambiguity in the Dutch gas sector about the desired future state. This ambiguity stems from the multiplicity of actors in the sector and the variety of their interests. Certainly, there are some commonalities in these interests. For instance, high gas prices are favorable to both the producers and the government since they increase the sales revenues. However, there are many conflicts between these interests. One example is the high production goal of the natural gas producers, which contradicts with the renewable energy

15A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

goal of the government and environmentalists, because a high share of renewable energy is expected to degrade the role of natural gas in the energy system. Similarly, the interests of the producers and consumers are conflicting on the basis of price, since the consumers would like to have low prices and the producers would like to make profit with high prices.

In addition to such conflicting interests, the future of the Dutch gas sector is surrounded by many uncertainties. On the production side, the most important uncertainties are the amount of remaining conventional natural gas resources, the amount and recoverability of shale gas, the contribution of other gas types (e.g. renewable) to the gas supply, and how the societal acceptance of natural gas will develop and affect the production. On the demand side, the major unknowns are related not only to socio-economic consumption trends but also to where the ongoing energy transition towards renewables will lead the natural gas demand. Additional uncertainties include the natural gas prices in both domestic and international markets, infrastructure development, and import availability. These uncertainties are a major barrier to a reliable estimate of the future developments in the Dutch gas sector.

1.2. Research Objective and Research Questions

Policy problem

In the context of decision making, a problem is defined as "the occurrence of an undesired aspect of the current situation that creates a gap between what is occurring and what we would like to have occur" (Sage and Armstrong, 2000, p. 87). In other words, a "problem arises because someone feels that something in the real world situation needs changing, and decisions need to be taken to move it away from an unsatisfactory position"(Checkland, 1985, p. 152). As mentioned above, there are gaps between the futures desired by the actors in the gas sector and the current situation, either because the future goals are higher than the current values (e.g. renewable energy targets), or because the current situation cannot be maintained due to external factors (e.g. natural gas production). These gaps require finding solutions that lead to satisfactory futures, and create a decision making problem.

The national government is considered in this study as the owner of this decision making problem, because it is the actor who has the power to intervene in the whole energy system at the level of abovementioned interests. The Dutch government has the regulatory, financial and communicative tools to change the natural gas production, to influence the market in order to enable the use of various supply options, to stimulate renewable energy production, and to safeguard the consumer values such as the coverage of energy demand and affordability of prices. Therefore, the national government is the problem owner of this difficult policy making problem, which requires dealing with the uncertainties in future and the conflicting objectives of the government itself and the actors in the gas sector.

Research objective

A policy problem like the one defined above is complex by nature. Without a proper analysis, policy decisions intended to solve such a problem may turn out to be ineffective, or yield unintended and undesired consequences. To avoid such consequences, a policy analysis study

15B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

can assist the decision making process by providing a deeper understanding of the issue and information about the effectiveness of various policy options.

The Dutch government often consults research institutions such as Energy Center Netherlands (ECN) or Netherlands Organization for Applied Scientific Research (TNO) about potential policies, for instance regarding the natural gas production from the Groningen field, shale gas production or renewable energy subsidization. These studies provide useful information and insight about a particular problem, and aid the decision making process of the policymakers. Yet, these studies lack a systemic view, in which all main elements of the energy system and their interactions are considered simultaneously. They rather have a single focus, such as natural gas production or renewable energy goals. Besides, a tool to assess the long-term impacts of decision options, particularly in the context of the policy problem defined above, has not been developed yet, and uncertainties have not been systematically taken into account for the evaluation of decision options.

To address these issues, the objective of this study is determined as

Providing policy recommendations to the Dutch government and to the key actors in the gas sector, based on a policy analysis study that investigates the long-term effectiveness of policy options to deal with conflicting interests and uncertainties.

This research objective definition and the gaps that impede reaching it have led to the research questions that this thesis aims to answer. Prior to formulating these questions, the overarching policy analysis approach used in this study is introduced below, because the research questions are formed according to this approach.

Policy analysis approach

With the aim of providing recommendations to the decision makers, policy analysis studies adopt various approaches and methods. Mayer *et al.* (2004) proposes a framework to understand these approaches and methods, and identify six styles of policy analysis as *rational style, client advice style, argumentative style, participatory, process and interactive styles*. Although this study uses some elements of other styles as well, the rational style is the dominant style of this study. The main reason for adopting this style is its suitability for conducting an explicit and systematic study by using the available knowledge, and providing evidence-based recommendations, which are often desired by decision makers but cannot be easily obtained in the presence of uncertainty.

There are four main phases of a rational style policy analysis study (Quade, 1982; Walker, 2000):

i) Formulating of the problem which includes identifying the system boundaries, objectives and policy alternatives;
ii) building a model or framework for reflecting the effects of policy alternatives on the objectives;
iii) analyzing the impact of alternatives on the objectives, mostly by using a model, and
iv) evaluating the alternatives based on the analysis.

16A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The research questions of this study are formulated below, in a way to address these phases of a rational-style policy analysis study.

Research questions

Following the objective of the study, the main research question is formulated as:

Main Question: *Which policy options are effective in meeting the conflicting interests of the key actors in the Dutch (natural and renewable) gas sector and robust against uncertainties in the long-term?*

The research aimed at finding policy options that are effective in satisfactorily covering the gap between the current situation and the future situation, in a scope limited by the interests of the key actors in the gas sector. Since the gas supply is now, and expected to be, composed of both natural gas and renewable gas, 'the gas sector' refers to the industry and market of these two types of gas.

The main research question of this study is split into two questions and many sub-questions, in a way to address the elements and phases of a rational policy analysis approach. In accordance with these phases, the first question stated below aims at diagnosing the problem using a systems analysis approach (Thissen, 2013). The sub-questions 1.1-1.5 aim at identifying the elements of the systems analysis framework in the context of the Dutch gas sector. These elements are i) the system of consideration and its boundaries, ii) the actors, their interest and desired future situations (goals), iii) the outcome indicators (criteria) that refer to these future situations, iv) policy alternatives, and v) uncertainties.

Question 1: *How can the policy problem of the Dutch gas sector be formulated within the systems analysis framework?*

- *Question 1.1:* *What is the system of interest?*
- *Question 1.2:* *What are the interests, goals and perspectives of the key actors and stakeholders in the gas sector?*
- *Question 1.3:* *Which outcome indicators can be derived from these goals?*
- *Question 1.4:* *What present and future policy options do exist or can be thought of for this problem?*
- *Question 1.5:* *What are the uncertainties that will make a significant impact on the long-term development of the gas sector?*

Once the policy problem is diagnosed and the first question is answered, Question 2 pursues an analysis of the impacts of alternative policies on the outcome indicators, and an evaluation of options based on this analysis.

Question 2: *What is the performance of various policy options identified under a wide set of possible futures and for a variety of performance indicatros?*

16B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Question 2.1: *How can the system of interest identified for this problem be represented in a simulation model?*

Question 2.2: *How can the performance of a policy option under uncertainty be measured?*

Question 2.3: *What is the long-term impact of present and future policy options on the identified outcome indicators and what is their performance under uncertainty?*

Questions 2.1 and 2.2 seek a system model and a way, or ways, of measuring the performance of policies under uncertainty. In a single-actor but multi-focus view, Question 2.3 seeks for the governmental policy options that provide satisfactory results for the outcome indicators of the government (which are shared by many other actors, too). Once they are all answered, these questions clarify the policy recommendations that can be given to the government and other key actors, as well as the benefits and limitations of exploratory modeling and analysis.

1.3. OUTLINE OF THE THESIS

This thesis is organized in the order of the steps of a policy analysis study, as depicted in Figure 1.4. In addition to the steps followed, this figure also shows which research question(s) each chapter refers.

Chapter 2 delineates the problem that is dealt with in this thesis with a systems analytical approach. In addition to elaborating on the actors in the Dutch gas sector, the different perspectives and the outcome indicators derived from their interests, this chapter defines the system, hence the scope of the study. Besides, several past and potential policies affecting the gas sector in the Netherlands or in other countries are discussed in this chapter, as well as the uncertainties which constitute the focus of this policy analysis study.

Regarding the methods used in this study, this chapter briefly explained the use of a rational-style policy analysis approach and the use of systems analysis for problem diagnosis. **Chapter 3** further discusses these choices and the reasoning behind them, and provides an overview of the methodologies used in this research. Following a discussion on policy analysis, Chapter 3 presents a review of studies using quantitative models for energy policy problems, with the purpose of investigating the approaches used in these studies to deal with uncertainty. Then, Exploratory Modeling and Analysis is discussed, as a way of dealing with uncertainty in policy problems, and as the selected approach of this study. Lastly, the simulation modelling methodology used to develop the system model and why it is selected is explained.

Chapter 4 describes the simulation model developed to analyze the policy alternatives, which is a representation of the system described in Chapter 2 and enables the propagation of impacts of uncertainties to the outcome indicators.

Following the model description, **Chapter 5** presents and discusses the behavior of the model, i.e. the model output, in a base case, and explores a wide ensemble of scenarios generated by this model. This chapter also discusses the validity of the model, based on formal validation

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tests and expert consultation. Additionally, Chapter 5 provides a scenario-based analysis of the stakeholder perspectives, and their comparison to each other.

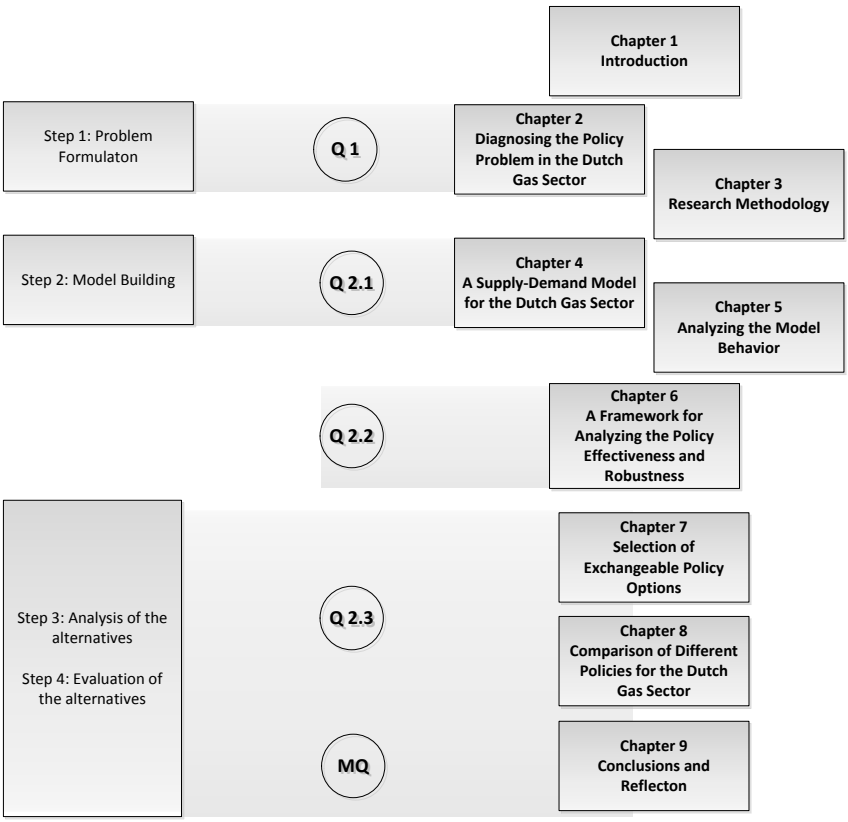


Figure 1.4: Outline of the thesis

Chapter 6 introduces the framework used for analyzing the alternative public policies identified in Chapter 2 with respect to their impacts on the outcome indicators derived from the interests of actors, and their effectiveness under a wide set of possible futures generated by simulations. This chapter also clarifies how this framework takes uncertainties related to methodological choices into account.

The analysis of policies based on this framework and in government's view is presented in two separate chapters. **Chapter 7** presents and discusses the selection of an option for a policy that can be implemented in many different ways. The policies focused in this chapter are the production cap on the Groningen field, and the subsidization of renewable gas. Using the findings of Chapter 7, **Chapter 8** compares different policies to each other for the purpose of generating policy recommendations.

Chapter 9 presents the policy recommendations derived from the analyses in the previous chapters, conclusions and limitations of the study, as well as future research opportunities. This chapter also provides a discussion on the benefits and shortcomings of the main research

17B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

methodology, namely Exploratory Modeling and Analysis, derived from this particular study on the Dutch gas sector.

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18A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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Earlier we closed old coal power plants. That provided an unexpected growth in the share of sustainable energy. […]Remember that we, as the Netherlands still possess large gas reserves. We are not like Germany, dependent on Russian gas. However, Russian gas can eventually be an option in the energy mix.[3]

Henk Kamp, Minister of Economic Affairs, 2015

2

PROBLEM DIAGNOSIS

Chapter 1 briefly introduced a policy problem in the Dutch gas sector, with reference to conflicting interests of multiple actors and future uncertainties. Yet, this problem is not comprehensively delineated to establish a basis for policy analysis. In this chapter, as the first step of a policy analysis study, the problem is thoroughly diagnosed, with the systems analysis approach.

Following an explanation of what systems analysis is in Section 2.1, the chapter is structured as follows, corresponding to the elements of a systems analysis: Section 2.2 provides an overview of the policy objectives, and outcome indicators derived from them. Section 2.3 presents the system of interest, i.e. the main elements considered, the relationships between them, and system boundaries, so that a basis is formed for the system model described in Chapter 4. Section 2.4 introduces the key actors in the problem context related to the system definition of Section 2.3, and stakeholder perspectives. Section 2.5 provides an overview of policies affecting the gas sector, implemented in the Netherlands or neighboring countries with a similar market structure, in the past or currently. This overview leads to the policy alternatives to be tested in the analyses presented in Chapters 7 and 8. Lastly, Section 2.5 examines the uncertainties in the Dutch gas sector, with a prior discussion on what uncertainty is, and how it can be identified and communicated. Section 2.6 concludes the chapter.

[3] This statement is originally published in NRC as "Eerder besloten we al oude kolencentrales te sluiten. Daar staat tegenover een voorziene groei van het aandeel duurzame energie. Er zijn twee opties: gas kan via pijpleidingen worden ingevoerd uit Rusland of in vloeibare vorm per tanker uit andere landen. Bedenk dat wij als Nederland nog steeds een grote gasvoorraad bezitten. We zijn niet zoals Duitsland afhankelijk van Russisch gas. Maar in de energiemix kan Russisch gas uiteindelijk een optie zijn." (Remie, 2015)

19A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

2.1. A SYSTEMS ANALYTIC APPROACH

A *policy problem* is briefly defined as "an unrealized need, value, or opportunity which, however identified, may be attained through public action" (Dunn, 1994, 85). Regardless of the technique used, Dunn (1994, 151) sees the identification and structuring of a policy problem as being crucially important, because policy analysis studies fail usually due to solving the wrong problem instead of the right one. The obvious reason for the importance of problem structuring is the need to avoid resource misallocation and public frustration, as Guess and Farnham (2011, 23) argue.

Among several terms such as problem structuring, formulation, framing, etc., Thissen (2013) prefers 'problem diagnosis' based on the argument that the former terms imply a single or best definition of a problem, whereas the latter one includes the exploration of the problem context, rather than a narrow formulation. According to Thissen (2013), there are three aspects of problem diagnosis: Substantive aspects, actors and network characteristics and institutional characteristics, and a systems analytic approach can be used to address these aspects. This approach enables the diagnosis of substantive aspects, and provides a basis for diagnosing the other two aspects, namely the actor and network, and institutional characteristics.

Systems analysis emerged from operations research (OR) in the 1950's, for ill-structured problems embedded in larger sociotechnical systems than OR problems, and later evolved into policy analysis in 1960's and 1970's (Majone, 1985, 35-48). The main elements of a systems analysis are listed as *objectives*, *alternatives*, *consequences* (impacts) of alternatives on objectives, *criteria* providing a way to relate objectives, alternatives and consequences, and a *model* or models for assessment of consequences (Findeisen and Quade, 1985, 118-119). These elements were adopted by policy analysis, too (Quade, 1982, 45-47), and evolved into a depiction known as 'system diagram' (Walker, 2000; de Haan, 2007; Van der Lei *et al.*, 2011; Thissen, 2013). Figure 2. illustrates a system diagram, with 5 main components. These components are (1) *Value systems (W)* of the stakeholders and policymakers which include objectives and preferences, (2) *Outcome indicators (O)* that are determined based on the objectives of stakeholders and help assessing the performance of policies, (3) *Policy variables (P)* that are used to intervene in the system and improve the outcomes, (4) *External factors (X)* that affect the system and (5) the *System model (R)* representing the system within certain boundaries.

In order to diagnose the policy problem in the Dutch gas sector, this chapter presents a study of these 5 components in the following sections. It must be noted that this study particularly focuses on uncertainties as the fifth component of the problem. These uncertainties are associated with not only the external factors (X) but also the system (R) and values (W). The investigation of these five problem components was based on a review of policy documents and strategy reports of the Dutch government, previous policy analysis reports, and informal interviews with the representatives of the key actors and stakeholders. The list of these interviewees can be seen in Appendix 2.1.

19B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

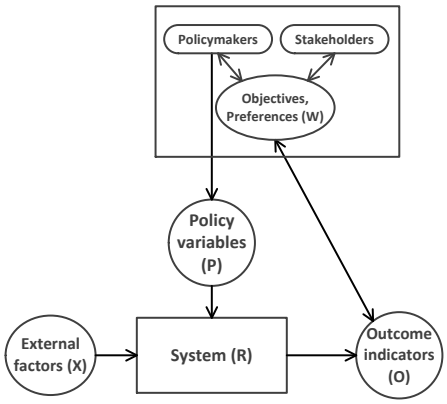


Figure 2.1: A system diagram with major elements of problem diagnosis, adapted from (Walker, 2000)

2.2. POLICY GOALS

This section focuses on the first two components of the system diagram, namely the *value system (W)* of the problem owner and the *outcome indicators (O)*. Therefore, this section describes the policy objectives from a single-actor perspective, and the outcome indicators derived from them. Besides this section, Section 2.4 will introduce the main actors in the Dutch gas sector corresponding to the system components discussed in Section 2.3, their interests and preferences related to the policy objectives of the government.

In 2001, the Dutch government adopted a 'transition management' (Rotmans *et al.*, 2001) approach and launched a transition towards a sustainable energy system with the Fourth Dutch National Environmental Policy Plan (NMP4) (VROM, 2001). Despite the conclusion of Kern and Smith (2008) that the transitions approach is impeded by the dominance of regime actors, the government still holds the long-term ambition of switching to sustainable, low carbon energy supplies by 2050 (MEZ, 2015). Under this energy policy strategy, the policy goals regarding the gas sector include three aspects of sustainability, namely the social, economic and environmental aspects.

The main social goal of the Dutch gas policy is providing consumers with security of supply. Both the Gas Act (MEZ, 2000) and the European regulations (Regulation (EU), 2010) mention the security of gas supply as an important pillar of national energy policy. Although the technical responsibility of providing security of supply is given to the Transmission System Operator (Gas Transport Services) the Gas Act states that the ultimate responsibility lies with the Minister of Economic Affairs. The Dutch government sees the diversity of supply sources and independence of imports from politically unstable countries as important contributors to supply security (MEZ, 2011, 9, 22).

Another social goal is to safeguard the affordability of gas by the consumers (MEZ, 2015), implying that consumer prices should be at a level acceptable by consumers so that the basic needs of households can be afforded and the industrial consumers do not lose their competitiveness. Ensuring safety is another concern of especially the natural gas policies. The

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earthquakes which have occurred in Groningen in recent years and the resulting distress of local residents showed the importance of this issue, and led the government to take extra measures regarding the natural gas production (MEZ, 2014).

The economic goals of the government regarding gas policies address two main issues. Firstly, maintaining the government income from natural gas production is important since it constitutes an important addition to the government budget, which is around 12 billion Euros per year (EBN, 2012). Secondly, the government aims to make the Netherlands the 'gas hub' of the Northwestern Europe to maintain the economic activity in the gas sector, hence the employment opportunities, and to recover the large investments made in the gas infrastructure (MEZ, 2011, 18).

The abovementioned energy transition goals reflect the environmental policy goals of the government regarding the gas sector. Switching to sustainable, low carbon sources is still the major goal not only for the entire energy system, but also for the gas sector.

Table 2.1 presents the policy goals listed above, and the corresponding operational and quantifiable outcome indicators. The main factor considered in selecting these outcome indicators is their representativeness of the policy goals. However, since the higher the number of these indicators, the more complicated the decision problem is, the number of outcome indicators and their independence from each other are also taken into account in forming this list. Hence, the 8 outcome indicators listed in Table 2.1 are selected as the proxies of the policy goals.

Table 2.1: Policy goals of the government and the corresponding outcome indicators

	Policy Goal	Outcome Indicator	Objective
SOCIAL	*Security of supply (SoS)*	*Coverage of Domestic Gas Demand*	*Maximization*
		Import Dependency	*Minimization*
	Affordability	*Average Consumer Gas Price*	*Minimization*
	Safety	*Societal Acceptance (Groningen)*	*Maximization*
ECONOMIC	*Public income*	*Total State Revenue from NG production*	*Maximization*
	Gas hub	*Transport Capacity Utilization Rate*	*Maximization*
ENVIRONMENTAL	*Emission reduction*	*Share of Renewables in the Energy Mix*	*Maximization*
	Sustainable sources	*Renewable Gas Percentage*	*Maximization*

The security of supply goal is represented by the *Coverage of Domestic Gas Demand*, which is the ratio of total supply in the Dutch market to the total domestic demand, and *Import Dependency*, which is the percentage of imports in the total domestic consumption. *Average Consumer Gas Price* represents affordability, as the average of prices for four consumer groups, that is, households, industry, agriculture and transport. *Societal Acceptance* (of the natural gas production in Groningen) is the outcome indicator related to safety and social distress, and its quantification will be explained in Chapter 4 in more detail.

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The public income goal is directly matched to the *Total State Revenue from NG production*, which is the total of the corporate income tax and State Profit Share the government collects from the natural gas producers. The utilization rate of the international transport capacity (import, export and transit), namely the *Transport Capacity Utilization Rate*, is selected to represent the extent of being a gas hub, since it indicates the economic activity in the gas sector, and the recovery of infrastructure investments even though the domestic natural gas production diminishes.

As it has been already operationalized by the European Union and the national government, the *Share of Renewables in the (total) Energy Mix* is the main indicator of environmental goals, both in terms of reducing the CO_2 emissions and switching to sustainable sources. The Dutch government aims to increase the share of renewables particularly in the gas sector, too (Scheepers, 2013), not only because of environmental reasons but also to enhance the security of supply and utilization of the infrastructure. Therefore, *Renewable Gas Percentage*, which is the ratio of renewable gas in the total national gas consumption, is included as an indicator of environmental policy goals.

These policy goals and the outcome indicators derived from them are to be used in the assessment of future scenarios and potential policies in the following chapters of this thesis. In this chapter, the next section discusses the system of interest, i.e. the important aspects of the gas sector relevant for the future of these outcome indicators.

2.3. SYSTEM OF INTEREST CORRESPONDING TO THE POLICY PROBLEM

A system is defined as "a group of components that work together for a specified purpose" (Sage and Armstrong, 2000, 5), or as "a part of the reality that is being studied as a result of the existence of a problem or the suspicion thereof" (Enserink *et al.*, 2010, 52). In this section, as the system of interest, a part of the reality relevant for the studied policy problem in the Dutch gas sector is presented, with its main components and the relationships between them. In addition to understanding the system of interest, this section aims to demarcate the scope of the study, and provide the basis of the system model presented in Chapter 4. Therefore, this section explains how the system works and (in bordered text blocks) which parts of the real system are included in the system model.

Figure 2.2 illustrates the Dutch gas market. In the technical layer, natural gas flows from the *production* (upstream), via the *transport* and *distribution networks* (midstream) to the *consumption* (downstream). In the economic layer, producers and the corresponding production sources are shown at the left, whereas the two groups of consumers, and the utility companies linking the small consumers to the wholesale market are placed at the right. The midstream is composed of the transmission system operator (TSO), distribution system operators (DSO's) and the traders in the wholesale market. The wholesale market involves a spot market named Title Transfer Facility (TTF) and a bilateral market where long-term contracts are made between the producers and traders.

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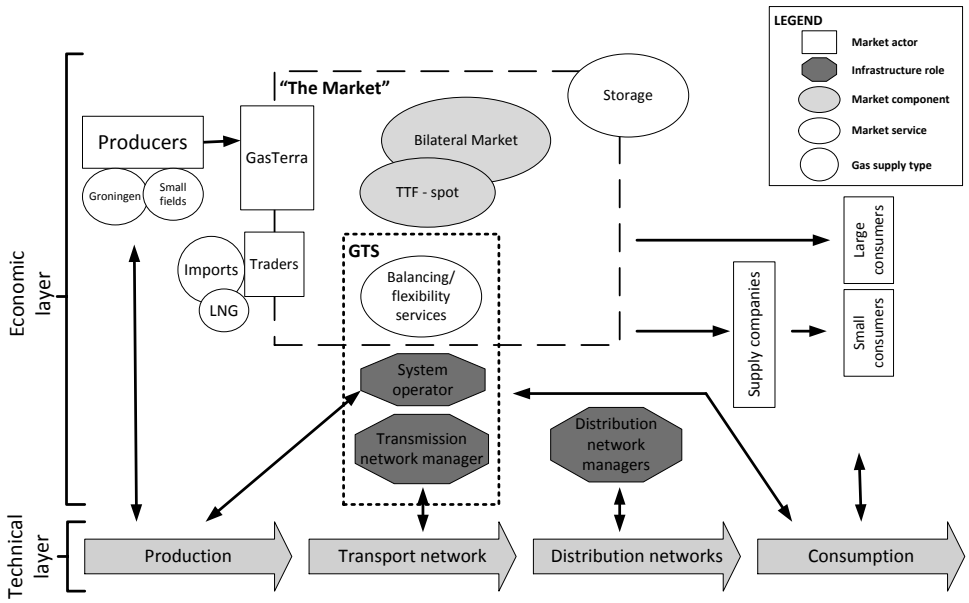


Figure 2.2: The structure of the Dutch gas market after liberalization – Adapted from (Correljé, 2011)

Based on this decomposition of the Dutch gas market, and the policy goals and outcome indicators identified in the previous section, this study adopts a supply-demand perspective to define the system. More clearly, some outcome indicators such as *Coverage of Domestic Gas Demand*, *Import Dependency* or *Share of Renewables* are defined based on the relations of particular supply options and demand groups, whereas some of them are based on the relation of supply and demand aspects to the market (*Average Consumer Price*) or to the infrastructure (*Transport Capacity Utilization Rate*). Therefore, a framework that involves the balancing of gas supply and demand via the market and infrastructure is adopted.

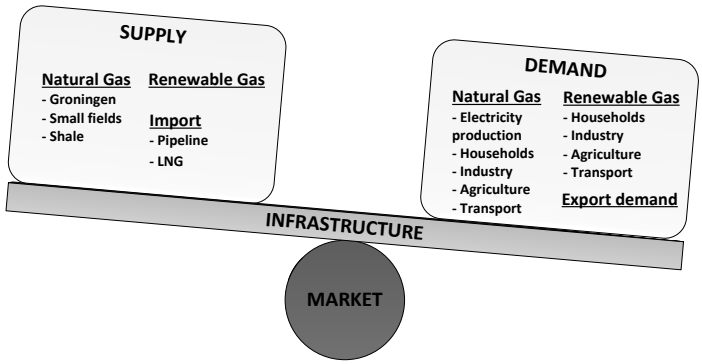


Figure 2.3: The system of interest from a supply-demand perspective

From this supply-demand balance perspective, Figure 2.3 illustrates the system of interest considered in this study, with the major components being supply, demand, infrastructure and market. The metaphor of a lever with a rolling fulcrum is used to depict the system of interest, because the infrastructure is seen as the stable entity providing a ground for the supply and

21B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

demand to be in balance, whereas the market conditions change depending on the balance of supply and demand similar to a rolling cylinder, and further affect the supply and demand balance. This system view is based on a high aggregation level, in which the system elements are considered on a national and long-term basis. The four major components of the system, with their elements and boundaries, will be discussed in detail below.

Demand

The Dutch natural gas consumption originates from 5 sectors, households (in general, buildings), agriculture (greenhouses), transport, industry and power generation. The first three of these sectors are grouped as small consumers who purchase the gas from utility companies, whereas the last two are large consumers who have direct access to the wholesale market. As shown in Figure 2.4, the household consumption was 14 bcm in 2010, whereas the agriculture and transport sectors consumed 4 and less than 1 bcm, respectively. The total consumption of large consumers in 2010 was far higher than the small consumers, with 19 bcm in the industry and 9 bcm in the power generation sector. The decomposition data is not available for the years after 2010, yet a small increase is observed in the consumption of small consumers while the large consumers reduced their consumption between 2010 and 2013.

In households, and public and commercial buildings, natural gas is used mainly for heating and cooking. In these sectors, the consumption level is dependent on the appliance preferences of people (e.g. electrical heating and cooking, or using micro-CHP) and the climatic factors. Winter temperatures strongly influence the natural gas consumption in buildings, and create a high seasonality effect.

The model includes an aggregate annual change rate for the households (in general residential and commercial buildings), which is assumed to encompass the uncertainty in consumption and energy efficiency trends. Although the seasonality effect is important for operational issues such as grid balancing, and storage and capacity planning, in this study which focuses on the long-term strategic issues, the annual total consumption and the annual change rates are taken into account, without the effect of seasonality within a year.

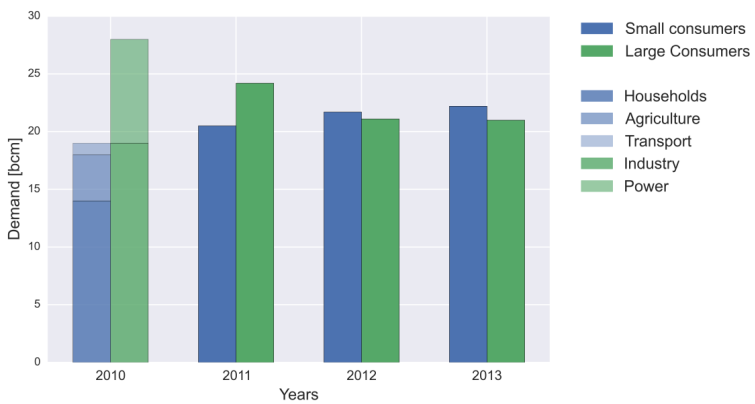


Figure 2.4: Natural gas consumption in the Netherlands for each consumer group
Data source: (EFNL, 2012) and (CBS, 2015a)

22A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The agriculture sector is an important natural gas consumer in the Netherlands, due to the widespread development of greenhouses, despite the relatively small consumption volumes. It is the only sector currently, which is subject to a reduced Value-Added-Tax rate, namely 6% instead of 21% as in other sectors. The growth of the sector and technological innovations are the main factors affecting the consumption in this sector, as well as the climatic factors.

The use of natural gas in the transport sector is currently very low and mainly used in public transport, i.e. city buses. However, the authorities consider the use of natural gas in the transport sector as a promising means to reduce CO_2 emissions. In future, manufacturer selection, availability of fuel stations, price competitiveness and governmental incentives are expected to be the factors affecting consumption for passenger mobility, whereas technological developments, i.e. LNG-fueled trucks can affect the natural gas consumption in long distance transport.

In industry, natural gas is used not only as an energy source, but also as a feedstock in chemical production. Industrial users of natural gas are charged with the normal VAT rate but a reduced energy tax, so that they can have low production costs and a competitive position compared to other countries. The total consumption of the sector is expectedly dependent on the economic growth and the efficiency of production processes, which may change with technological innovation.

A common factor that affects the gas demand of the four sectors mentioned above is definitely the price. In the case of a price change, consumers cannot immediately adjust their natural gas consumption or shift to another source due to the necessity of consumption and high switching costs, hence the short term price elasticity of natural gas demand is low. Yet, in the long term all consumer groups respond to the price changes by changing their demand, although the degree of this response may differ among the groups.

Besides the demand for natural gas, renewable gas demand of the abovementioned four sectors is taken into account separately in this system description. The sectors which currently consume renewable gas, or can consume in the future, are the same as those demanding natural gas, except the power generation sector. The reason for this exception is that renewable gas (biomethane) equivalent to natural gas is not used for electricity production due to inefficiency. (Yet, biogas, which is also the raw material of renewable gas, is used for electricity production.)

A certification system has recently been established in the Netherlands to sell renewable gas to end consumers. According to this system, producers are certified to be able to inject renewable gas into the grid, and consumers can opt for the ‘green’ option instead of natural gas if they are willing to pay extra. Therefore, natural gas demand can be substituted by renewable gas demand, and vice versa, depending on the relative price and other factors such as whether natural gas is perceived as an environmental friendly fuel or not.

22B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

In this study, the system model includes the abovementioned distinction between the natural and renewable gas demand, and the bilateral shifts between them based on price and societal acceptance differences. The four demand sectors are also separately included within the system boundaries, as well as the price-dependent changes of each. However, the factors affecting the gas demand, such as climatic change, economic growth etc. are not explicitly taken into account in the system model, but included as external factors.

Table 2.2: The shares of primary energy sources in electricity production[4]
Source: (CBS, 2015b)

Primary source	2010	2013
Natural gas	62.3%	53.6%
Hard coal	18.5%	24.3%
Other fossil fuels	3.6%	4.1%
Solar energy	0.1%	0.5%
Wind energy	3.4%	5.6%
Biomass	6%	5.9%
Nuclear energy	3.4%	2.9%
Other energy commodities	2.8%	3.1%

The electricity generation sector is a major consumer of natural gas in the Netherlands, with around 10 bcm annual consumption. In 2010, natural gas was the input for 62.3% of the total electricity produced, whereas the installed natural gas-based power generation capacity was 67% of the total capacity (CBS, 2015b). The share of natural gas in the electricity production has declined to 53.6% in 2013, as Table 2.2 shows, yet the power sector is still highly dependent on natural gas.

Table 2.2 also shows an increase in the share of renewable electricity, such as solar and wind, as well of that of coal, being a more CO_2 emitting but cheaper source. Hence, the dominant position of natural gas in the electricity sector can change in future, depending on the energy transition towards renewable sources, or the competition with coal and other cheaper sources.

The system boundaries of this study encompass the competition in the electricity sector between various sources, based on economic and social factors, in order to estimate the natural gas demand of the electricity sector.

The last demand sector, namely the export demand, refers to the foreign natural gas demand from the Netherlands. The total export volume of natural gas was 56.4 and 63.4 bcm in 2010 and 2013, respectively (CBS, 2015a), having Germany as the biggest buyer with 23.6 bcm in 2010, followed by UK, Belgium, Italy and France (GTS, 2013; IEA, 2012).

[4] Although it is one of the technologies included in this study, biogas-based electricity generation is not shown in this table, because it is included in the biomass and 'other energy commodities' categories, depending on the original biomass source used.

23A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The total foreign demand is considered within the system of interest as an external factor, meaning that the factors affecting the amount of demand from these countries are not included in this study.

Supply

The supply side of Figure 2.3 includes three main components, being domestic natural gas production, domestic renewable gas production, and the imports of natural gas. Domestic natural gas production supplies Dutch and foreign consumers (exports), whereas imported natural gas is used for domestic natural gas demand and for transit to neighboring countries, and the renewable gas production matches the renewable gas demand. Figure 2.5 illustrates the contribution of these options to the gas supply between 2010 and 2013. As seen in this figure, the Groningen field supplies approximately half of the domestic natural gas production, while the other half is supplied by the on- and offshore small fields. Shale gas, which is a natural gas supply option with large prospective resources, is not extracted currently but fiercely debated. Annual import volume varies between 20 and 25 bcm, and the share of LNG imports in these volumes is still very low.

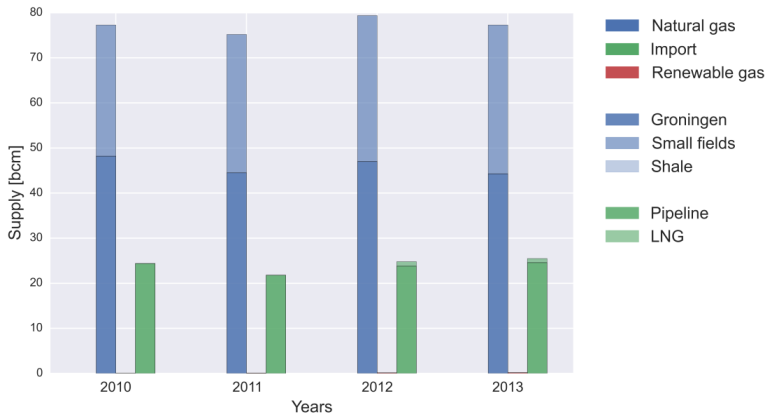


Figure 2.5: Gas supply in the Netherlands for each supply option
Data source: (NLOG, 2014; CBS, 2015a)

This study considers the three types of natural gas sources, namely the Groningen field, small fields and shale gas, separately, because of different production profiles, investments and policies applied to them. Regardless of the source type, the availability of reserves, and investments made in exploration and development of natural gas fields are included within the system boundaries as the factors determining the supply amount. However, geographic characteristics of the fields, i.e. their locations and connections to the grid, are not taken into consideration, because the high aggregation level of this study and focus on national level total production. Regarding the imports, the system boundaries are assumed to include the imports of only natural gas, yet it is possible to import renewable gas in future from biomass-rich countries such as Sweden. Besides, the 'imports' in this study are considered to represent

23B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

net imports, i.e. the volume of gas consumed in the Netherlands after entering the Dutch grid. The volume of gas entering the Dutch grid to be exported to other countries is called 'transit'.

Renewable gas that can be injected into the natural gas grid is also known as biomethane or 'green gas' in the Netherlands. Although the current contribution of renewable gas to the gas supply is very low compared to natural gas, as mentioned in the previous section, it is seen as a promising alternative to replace natural gas. The current resources of renewable gas production are biomass and excess electricity. The technology of producing biomethane from excess electricity is called 'power-to-gas' which is not mature yet (Patel, 2012). As for biomass, it is currently the main source for biomethane, and there are two production technologies: digestion and gasification. At present, digestion dominates the market, but gasification of biomass has a higher yield, and its product named "synthetic" or "substitute natural gas" is a promising alternative (Foreest, 2012). Geographical factors, i.e. the production location and where to inject it into the grid are important for the deployment of renewable gas technology.

The system boundaries in this study involve biomass-based renewable gas production, excluding the power-to-gas technology. The two biomass-based technologies, namely digestion and gasification, are included separately, due to their different technological and financial characteristics, as well as different policy measures implemented on them. Geographical factors are not examined in this study, due to the reasons similar to the case of natural gas. Although it is not consumed via the natural gas grid, biogas production and consumption on a local scale for heating is also included in this study.

The last supply option is the natural gas imported via pipelines from Russia and Norway, and as Liquefied Natural Gas (LNG) from various countries to the Gate Terminal in the Port of Rotterdam. As Figure 2.5 shows, in 2013, gaseous imports via pipelines were recorded as 24.6 bcm, while LNG imports were only 0.94 bcm (CBS, 2015a). Currently, imported gas enters the wholesale market when the domestic production cannot meet the demand in winter time, and when the price of imported gas is competitive with the price of locally produced gas.

In this study, the requirement (demand) and relative price are the major factors determining the import volumes included within the system boundaries. However, the availability of gas on the international market and political dynamics, e.g. political events affecting the amount of importable gas, are assumed to be external factors.

These supply options described above contribute to a common goal, which is meeting the gas demand, on the one hand, but on the other hand they compete with each other to increase or maintain their market share. This competition mechanism and how the supply options affect each other will be discussed in more detail in the 'Market' section below.

Infrastructure

The infrastructure is the technical subsystem that connects supply and demand in the Dutch gas sector. The Netherlands has an advanced infrastructure owing to the long history of

24A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

natural gas in the country and resulting from large investments made over time. This infrastructure is spread from the Groningen field and the North Sea to the 96% of households (IEA, 2012) in the country, and to the neighboring countries such as Germany, UK and Belgium.

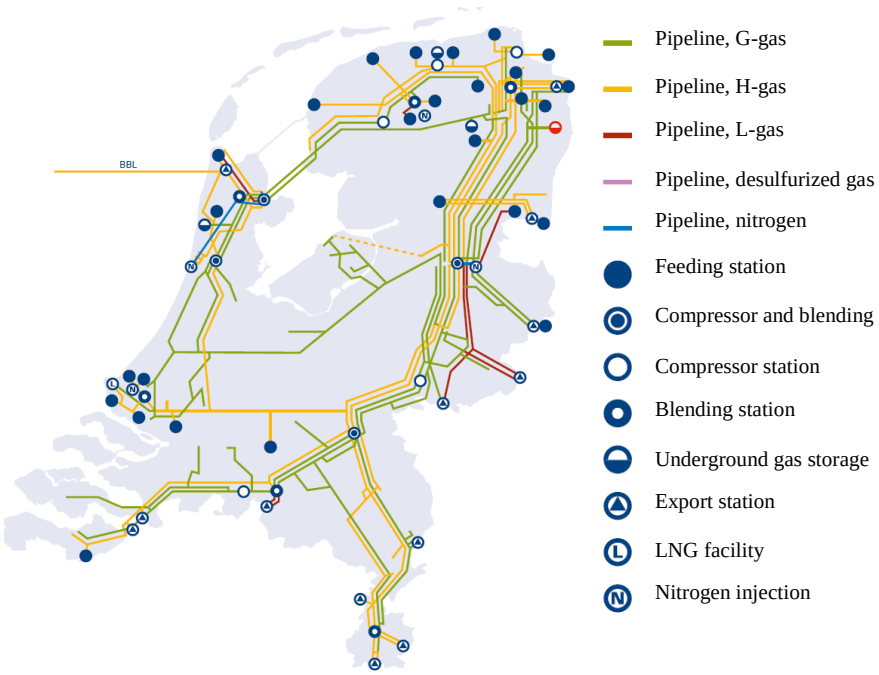


Figure 2.6 : Gas transmission infrastructure in the Netherlands
Source: (Energiezaak, 2011)

The natural gas infrastructure in the Netherlands is well-developed not only in terms of the production facilities, but also transmission and distribution networks and related structure, such as delivery points, compressor, metering and blending stations. The low pressure distribution network has a very high density and amounts to 120,000 km in total, delivering low calorific gas to small consumers (Energiezaak, 2011). The high pressure transmission infrastructure shown in Figure 2.6 is composed of two major parts, the network for high calorific gas (H-gas) produced from small fields or imported, and for Groningen gas with a lower calorific value (G-gas) produced from the Groningen field. It must be noted that a small portion of the network shown in Figure 2.6 is allocated for L-gas, which is the gas with low calorific value, and to be exported. In total, the transmission network accounts to 12,050 km (IEA, 2012). The presence of different qualities of natural gas and corresponding networks requires conversion between them, usually by adding nitrogen to H-gas. 19 blending stations that enable this conversion and 2 nitrogen production units are present in the Dutch gas network (Gasunie, 2015a). Besides, the infrastructure includes 1100 delivery stations, 22 compressor stations, 93 metering stations, 4 underground storage facilities with a total capacity of 5.2 bcm and an LNG terminal with a throughput capacity of 12 bcm/year (IEA, 2012; Gasunie, 2015a). 25 interconnection points linked to the Dutch network add up to an

24B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

entry (import) capacity of 165 million m^3 per day, and an exit capacity of 348 million m^3 per day (IEA, 2012).

The infrastructure may be modified in future, due to connections to new consumers and producers, unifying the quality standards (e.g. only H-gas), or decentralized production. Especially the capacity of international trade, namely the import and export capacity of the Netherlands, is a growing concern due to declining domestic production and the goal of the government to become a gas hub.

In this study, the infrastructure components taken into account are the natural and renewable gas production facilities, and the international trade capacity. The capacity of production facilities is assumed to grow depending on demand, resource availability and market condition, which are the factors included in the system of interest. Similar to the production capacity, the capacity of import and export infrastructure is assumed to depend on demand (e.g. the import need of the Netherlands), resource availability (e.g. a surplus of Dutch gas not used domestically), and market conditions (e.g. the price of gas in the Dutch market relative to the international market).

The factors that can change the characteristics of the network, especially the geographic ones, are not taken into account in this study, due to the focus on the eventual volume-wise balance of supply and demand. In other words, it is assumed that all natural or renewable gas produced in or imported to the Netherlands is delivered to the consumers.

Market

The wholesale market is the fourth major component of the gas system, as seen in Figure 2.3, where gas is purchased from producers and sold to utility companies or large consumers by traders. Being the commercial mechanism behind the inflow and outflow of gas through the infrastructure, the market balances the supply and demand of gas, too, via the dynamics of price.

As illustrated in Figure 2.2, the Dutch market has two components, being the spot market named TTF (Title Transfer Facility) where gas is traded virtually on a short term basis, and the bilateral market where gas is traded via long-term, confidential contracts between the producers, traders and buyers. In 2014, the virtual volume of gas traded in the spot market increased to 1400 bcm, from 848 bcm in 2013, while the actual volume slightly decreased from 46 to 44 bcm (GasTerra, 2014, 2015b). Compared to the volumes traded in the bilateral market by GasTerra, which are 60 and 52 bcm in 2013 and 2014, respectively (GasTerra, 2014, 2015b), the share of spot market trading in the total actual gas trade increased to 45% from 43.5%, besides the high growth of the virtual trade. In the spot market, the price may change instantaneously depending on supply and demand quantities, whereas in the bilateral market the price is specific for each contract, such as oil-indexed, fixed, spot-market-linked or in another customized way (GasTerra, 2015a).

In this study, due to the growing importance of TTF in determining the gas prices, it is assumed that the market price changes as in a spot market mechanism, based on the supply

25A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

and demand dynamics, and not directly linked to oil prices or another external factor. Still, the influence of oil prices or global natural gas price is included in the price of imported gas, which is assumed to be an external factor.

Similar to the other system components, the market is conceptualized using a long-term, aggregate view. Namely, a single market price value is assumed to indicate the overall price of different supply sources in the market. Besides, instead of instantaneous changes in supply-demand balance depending on the trade between individual spot-market participants, the balance of total annual gas supply and demand is taken into account as a factor affecting the market price.

The causal loop diagram in Figure 2.7 illustrates the relations between price, supply options and demand in a simplified way. In this diagram, an arrow denotes a causal link between two variables, and the polarity of that causal link is shown by the sign next to it. A positive polarity means that a change in the first variable causes the second variable to change in the same direction, whereas a negative polarity implies an opposite change. As seen in the diagram, an increase in the three supply options, namely the natural gas, renewable gas and imports, decreases the price, or vice versa, and a decreasing price reduces the supply in return. However, a decreasing price increases the demand, which leads to a positive effect on the price as opposed to the effect of supply. Moreover, an increase in the supply quantity of any of the options reduces the price, and this implies a reduced supply by other options. This mechanism is the basis of competition for a higher market share between the supply options.

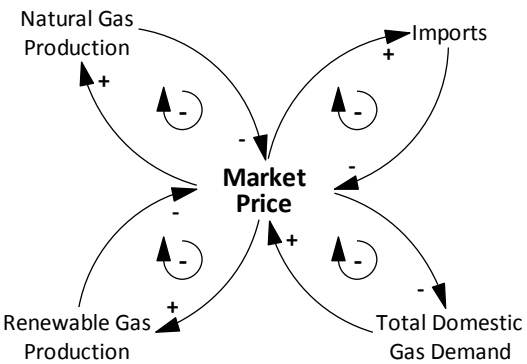


Figure 2.7: Causal loop diagram of the market subsystem

This section described the view on the gas sector adopted in this study, based on an aggregate supply-demand perspective, with the main components, mechanisms and boundaries of this system. This system description helps understand how the gas system works, and outlines the basis of the quantitative system model explained in Chapter 4. In the following section, the main actors corresponding to the substantive system elements discussed in this section will be presented, and their views on the government's policy objectives defined in Section 2.2 will be discussed.

25B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

2.4. ACTORS AND PERSPECTIVES ON THE FUTURE

In the policy analysis context, an *actor* is defined as "a person or group of persons, that has an interest in the system being analyzed and has the power to make changes to that system" (de Haan, 2007, 11), whereas a *stakeholder* is an actor "affected by the problem situation or by some of the solutions considered" (Hermans and Cunningham, 2013, 187) but cannot influence the system significantly (de Haan, 2007, 13). This chapter firstly discusses the main actors influential on the system of interest discussed in the previous section. Then, a distinctive set of stakeholder perspectives about the future of the Dutch gas sector is presented.

2.4.1. Main Actors in the Dutch Gas Sector

This section aims to present the main actors involved in the supply, demand, infrastructure and market components of the system. In addition to the information provided about their roles in the system, and the discussion about their views on the government's policy objectives, the paragraphs below clarify whether the actions of these actors are explicitly taken into account in the system model or not. Table 2.3 provides a list of actors discussed in this section, corresponding to components of the system of interest discussed in the previous section.

Table 2.3: Main actors in the Dutch gas sector corresponding to the system components

Supply	Demand
• Natural gas producers (e.g. NAM) • Energie Beheer Nederland (EBN) • Renewable gas producers • Importers	• Small consumers • Large consumers • Foreign consumers
Infrastructure	
• GasUnie • GTS • DSO's	
Market	
• Traders (e.g. GasTerra)	• Competition Authority (NMa)

Demand

As mentioned before, the demand for natural gas arises from two main groups of consumers, namely large and small consumers, the former being the industrial users and electricity producers, the latter being the households (including public and commercial buildings), agriculture sector and transport sector. These five demand sectors are treated separately in this study. However, each sector is assumed to be a unity, with an overall action mechanism for demand response to price, to the image of an energy source (i.e. societal acceptance), and to other external factors such as climate, although the degree of response varies among the sectors. Hence, for all consumer groups except the electricity sector, the actions taken into account in this study are their demand response to price changes, and societal acceptance of natural gas.

For the electricity production sector, the producers of, and investors in, not only the gas fueled electricity, but all technologies (e.g. biomass, coal, wind…) are included within the system boundaries, because the gas demand of the electricity sector results from the competition

26A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

between these technologies. Hence, as in the case of gas producers, these actors take part in the system with their decisions on how much to produce and how much new capacity to install.

Foreign consumers, i.e. the countries who import natural gas from the Netherlands, is another group of actors at the demand side. Being mainly concerned with the satisfaction of their demand, these consumers have neither high interest in the policy goals of the government nor a high influence on the Dutch sector. Hence, their demand is included in this system definition as an external factor, rather than taking their actions into account explicitly. The utility companies are included in this study as the buyers of gas in the wholesale market, but the retail market interactions, where they sell gas to small consumers, are not taken into account in this study. Related to the retail market, only the affordability of gas by consumers is taken into account.

Supply

The major group of actors at the supply side is formed by the natural gas producers. Many global and local exploration and production (E&P) companies operate on the Dutch on- and offshore small fields, such as Chevron, GDF Suez, Oranje-Nassau and TAQA. Yet, the biggest production company in the Netherlands is NAM (Nederlandse Aardolie Maatschappij BV), providing 70-80% of the total natural gas production. Currently, NAM is a joint venture of Royal Dutch Shell (50%) and Exxon Mobil (50%), and holds the production license for the Groningen field, besides several small fields (NAM, 2015). NAM is primarily interested in maximizing the natural gas production from the Dutch fields, minimizing the production costs so that they reduce the impact of price uncertainty on the company profits, and establishing public acceptance of natural gas (van der Meer, 2012).

Given these goals shared by other E&P companies, it can be said that the natural gas producers are in line with the government in terms of the security of supply (*Coverage of Domestic Demand* and *Import Dependency*) and gas hub goals (*Transport Capacity Utilization Rate*), but they prefer the locally produced natural gas to be the main means in reaching these goals. In terms of the price and state revenues, the interests of the government and producers are in principle conflicting, since high prices are in favor of producers, and a high state profit share reduces the profit share of producers. Yet, it must be noted that in reality the producers and government are in agreement with the current 50% state profit share, and the consumer prices are also affected by other factors such as taxes, rather than the wholesale price which concerns producers. *Societal Acceptance* is another outcome indicator about which the government and producers have a common view, i.e. to find a compromise between the natural gas production and public distress. Lastly, Dutch natural gas producers do not raise any objection to the renewable energy transition, either in the power or in the gas sector. They aim to position natural gas as a fuel assisting the transition, e.g. a backup of the intermittent renewable sources, hence to maintain the role of gas in the energy system.

Another actor with a strong influence on the Dutch natural gas production is EBN (Energy Beheer Nederland). EBN is an E&P company totally owned by the Ministry of Economic Affairs, active in the sector not as an operator, but by cooperating with exploration, production and transport companies to initiate business and to safeguard the government's

26B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

values (EBN, 2015). EBN can be considered as the acting body for implementing several government policies in the Dutch gas sector, for instance by financially participating in the E&P projects, or by facilitating innovation and knowledge dissemination.

The second group of actors at the supply side is the renewable gas producers, who are individual farmers using their biomass resulting from agricultural activities, or institutions such as municipalities or industries (e.g. dairy industry) using their residues for gas production. These producers are driven to produce renewable gas by factors such as waste utilization, contribution to sustainability, or profit making. Regardless of their main driver, the profitability of production is important for them, which is not the case currently due to the high costs compared to the natural gas price. This is where the interest of producers conflicts with the affordability goal of the government, and why the government provides subsidies for renewable gas production. Even in the case of subsidization, the desire of producers for high profitability and long-term revenue certainty is opposed to the interest of the government in low subsidization costs.

Foreign producers who sell gas to Dutch traders, e.g. Russian or Norwegian producers, constitute another group of supply side actors. They have no direct interest in the policy objectives of the government, but the volume they sell to the Netherlands, and the price they ask influences the security of supply, affordability and gas hub goals of the government.

These three producer groups are explicitly taken into account in the system model. The actions and decisions belonging to the natural and renewable gas producers and included in the model are how much to produce, and how much to invest in new capacity, mainly in response to the consumer demand and price changes. As for the foreign producers, their response to the price changes in the Dutch market is taken into account, whereas political factors that affect the volume sold are assumed as external factors outside the system boundaries.

Infrastructure

As mentioned in Chapter 1, following the liberalization in the 2000's, transport and commercial activities of network operators were unbundled in 2005. Hence, Gasunie, which had been the owner and operator of the gas network, as well as the trader, has become only the owner, while operating and trading responsibilities have been transferred to Gas Transport Services (GTS) and GasTerra, respectively.

Currently, Gasunie is the owner of the Dutch transmission network, both H-gas and L-gas, and the peripheral infrastructure such as metering stations, delivery points, and the Gate LNG terminal. All shares of Gasunie are held by the Dutch state, specifically the Ministry of Finance (GasUnie, 2015b). Gasunie's vision is in line with the policy goals of the government in terms of *Transport Capacity Utilization Rate* and *Renewable Gas Percentage*, whereas it has no high stake in other policy goals. The most important action of Gasunie included in the system boundaries is whether to invest in more import and export capacity, whereas its involvement in renewable gas production projects is included implicitly (not as the sole investor but as a participant).

27A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Being a subsidiary of Gasunie, GTS is the Transmission System Operator (TSO) of the Dutch gas network, mainly responsible for providing sufficient transport capacity, balancing the grid, and creating and maintaining connections to other grids (GTS, 2015). GTS has a crucial role for the functionality of the gas system and the implementation of policies, yet it is not considered as an influential actor in policy decisions, hence not explicitly included in the system.

Distribution system operators (DSO) constitute another important group of actors in the Dutch gas sector. There are 9 DSO's in the Netherlands, the largest ones being Enexis, Liander and Stedin, owning and operating the distribution grids in different regions of the country. DSO's are usually owned by the provincial and municipal authorities of the regions they are operating in, and they are responsible for constructing, maintaining, controlling and securing the grid installations (Energiezaak, 2011). Currently, DSO's consider renewable gas as a promising option to maintain the use of their assets, and to recover their investments, hence they are in line with government to increase the *Renewable Gas Percentage.* There is a potential clash between the government's view and that of DSO's on the *Average Consumer Gas Price*, because the networks costs are an important portion of the energy bill. Since the distribution network and the retail market are not in the focus of this study as mentioned in Section 2.3, the actions and decisions of DSO's are not included in the system boundaries.

Market

The primary actors in the market subsystem are traders, who buy gas from the producers and sell it to the large consumers and utility companies, or other traders. GasTerra is the major trading company, holding a 70-80% share in the Dutch market and also active internationally. GasTerra is currently owned by the Dutch state (10%) and state-owned EBN (40%), and the two E&P companies which also own NAM, namely Shell (25%) and Exxon Mobil (25%) (GasTerra, 2015c).

Apart from meeting the duties stated in the Gas Act, for example implementing the small fields policy, GasTerra's vision focuses on maximizing the value of Dutch gas reserves, reinforcing the liberal market by strengthening the position of TTF as the reference point for prices, and minimizing emissions while maximizing energy efficiency, although the last two are not considered as hard goals. Given this vision, GasTerra is in line with all the government's policy objectives stated in Section 2.2, especially the economic and environmental ones.

Traders in general decide on how much gas to buy, but due to the duties of GasTerra defined by law to buy all gas produced in the Dutch territory, the decision of traders on how much to buy from domestic producers is not included in the system of interest. Yet, the decision of traders about how much to buy from international producers, i.e. how much to import, is included within the system boundaries. The price setting in the market and the traders' influence on this are where their actions are also taken into account within the system boundaries.

The Netherlands Competition Authority (NMa) is another important actor in the market, not as a trader but as a protector of competition and consumer values. NMa is a part of the central

27B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

government, but is not connected to any ministry and holds an independent authority. Besides monitoring the market, NMa sets the rules for new developments, such as the integration of renewable gas into the market. This study assumes full compliance to NMa's rules and regulations by the market players, and hence, does not include NMa as an active actor in the system of interest.

2.4.2. Stakeholder Perspectives on the Future

One of the projects within the 'Next 50 Years' project of the EDGaR program, to which this project belongs as well, was on a stakeholder dialog in the Dutch gas sector. The researchers of the stakeholder project have identified different perspectives of stakeholders on the future of the Dutch gas sector, based on Q-methodology, and elaborated with two stakeholder workshops held in September and October 2014. This section presents their findings, to obtain an understanding of distinctive perspectives about future developments in the sector, in addition to the interests and actions of actors presented in the previous section. These findings are used in the later stages of the study, for an analysis of the future scenarios envisioned by the stakeholder group corresponding to each of these perspectives.

With the aim of analyzing the variety of perspectives in a population rather than describing that population, Q-methodology is based on the scoring of a set of statements by individual stakeholders, and statistical analysis of the results of this scoring (Brown, 1993). Following this methodology, the stakeholder dialog project has identified 6 distinct stakeholder perspectives, based on 40 statements covering several topics about the future of the Dutch gas sector, and 57 interviewees representing various stakeholders in the Dutch gas sector, such as the industry, academia, local authorities and non-governmental organizations. These 6 perspectives are summarized below, based on the findings of Figueroa *et al.* (2013) and Cuppen and Di Ruggero (2014).

Perspective 1: In gas we trust

This perspective is centered on the expectation that the Dutch gas industry is strong and prepared to deal with uncertainties in future, so natural gas will remain important in the energy system. The main drivers for this perspective are the belief that natural gas is crucial for security of supply, and that a transition to renewable sources is unaffordable by consumers. This perspective disagrees with the adverse effects of fossil fuels on climate change, and the urgency to act for climate change. Even if there will be some renewable energy production in future, this perspective sees natural gas as complementary to renewable electricity, to back-up the intermittent production.

Perspective 2: In renewables we trust

As opposed to the first perspective, this perspective considers the reduction of fossil fuel consumption crucial to prevent the consequences of climate change, which results in a minor role of gas in the energy system. Local initiatives and consumer demand for sustainable energy will be the main driver of transition to renewables, according to this perspective. Despite the minor role of natural gas as an energy source, due to its vast knowledge, this perspective sees the gas industry as a prospective provider of offshore renewable energy sources, such as wind, tidal and wave.

28A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Perspective 3: Adaptive gas sector in an uncertain future

This perspective includes a combination of several aspects of the first two perspectives, with a distinctive belief in the uncertainty of future. Like the first one, this perspective expects the gas sector to be resilient, and remain important in future. Similar to the second perspective, this perspective accepts the harmful effects of fossil fuels on climate change, and the concerns of citizens. Even though a switch to a more electric society will occur especially at the household level, this perspective expects gas to be important for industrial energy uses, and to have a considerable share in the energy system by adapting to circumstances.

Perspective 4: Gas in times of austerity

The distinctive characteristic of this perspective is the expectation that current living standards cannot be maintained in future, even if consumption is reduced and energy efficiency in increased by technological innovations. The concerns about climate change and the effects of fossil fuels on it are admitted by this perspective, yet the austerity conditions are expected to prevent investments in renewable technologies, hence to prefer natural gas as a cheap and relatively clean source. This perspective also foresees more consumer power in future, but focused on low energy costs rather than sustainability as expected by the second perspective.

Perspective 5: We need all energy sources!

According to Perspective 5, all energy sources will be utilized in future, due to energy being the fundamental element of economy and quality of life. This perspective expects natural gas to maintain an important role in the energy system in future, not only as a primary source but as a backup of renewables. Policies on the gas hub and decentralized, renewable gas production are seen as key drivers of a system with multiple sources. Besides, this perspective also expects more consumer power and local initiatives for sustainable technologies in future.

Perspective 6: Entrepreneurs serve the market better

This perspective expects an increasing importance of entrepreneurs and local energy companies in the energy system. However, the driver of these initiatives is not expected to be the urge to deal with climate change, but to steer innovation and to reduce the costs. According to this perspective, consumer power is going to increase, but consumers will not be willing to pay for the high costs of sustainable energy. Despite the decreasing role of natural gas in the country's economy and energy system, and the decreasing societal support, natural gas consumption will not be phased out, but it will be used as a cheap fuel that can provide flexible energy production.

These 6 perspectives not only describe 6 alternative futures with their general characteristics, but also indicate the interests and desired futures of the stakeholders in these perspectives. Although several common points are present, they differ from each other in fundamental aspects. With reference to the system diagram components, these differences are especially about uncertainties, outcome indicators and their future values. Chapter 5 will discuss these alternative futures described by the 6 perspectives in more detail.

28B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

2.5. POLICY ALTERNATIVES AFFECTING THE DUTCH GAS SECTOR

Although the liberalization in 2000 has terminated the direct influence of the government on the gas market, as the national level policy maker, the central government still holds many instruments to intervene in the supply and demand side of the gas sector. This section explores such interventions that have been done in the past, or are presently implemented in the Netherlands, as well as in some other countries which are in a similar situation as the Netherlands. Besides enhancing the understanding about the system, the primary purpose of this investigation is to derive a list of promising policy alternatives to be tested in the later stages of this study in terms of their effectiveness on the policy goals and in dealing with uncertainty.

2.5.1. Past and Present Policies Implemented in the Netherlands

In this section, the past and present policies implemented in the Netherlands are identified, based on a review of literature sources and the interviews mentioned in Section 2.1. The sources include policy documents and reports such as the Gas Act (MEZ, 2000), or National Renewable Energy Action Plan (MEZ, 2013), the country database of the International Energy Agency (IEA, 2015), and other policy scanning studies (Donat *et al.*, 2014). These policies demonstrate a variety of policy instruments, complying with the policy design framework of Howlett (2010), which contains four types of policy implementation tools. These tools are organizational (using government institutions and personnel), authoritative (setting regulations and administration), financial (transferring treasure sources for encouragement of an activity) and information-based (soft policies based on communication of information and knowledge) (Howlett, 2010). Since organizational tools are used to enable and facilitate the implementation of other types of policies in the Dutch gas sector, a simpler framework with the latter three types of tools is used in this study. In other words, policy instruments are categorized into three groups, being regulative (authoritative), financial and communicative (information -based).

Table 2.4 presents an overview of the policies identified, categorized according to the nature of the policy instrument, i.e. regulative, financial and communicative, and according to the intervention area, i.e. natural gas supply, renewable energy production, and demand. The renewable energy policies affect the gas sector in two ways: With their effects on renewable gas production at the supply side, and with their effects on natural gas demand from the power sector, at the demand side. It is important to note that the empty bullets in Table 2.4 mark the policies which have ended.

There are two major regulative policies implemented in the Netherlands, targeting the natural gas production. Firstly, a maximum limit on the production from the Groningen field is a regulative policy which has long been used by the Dutch government, in order to preserve the balancing capability of the field for a longer duration, and to stimulate production from small fields in the meantime. The previous form of this policy was a 425 bcm cap on the total production from the Groningen field for the period 2010-2020 (MEZ, 2012). However, in 2014, especially due to the societal unrest caused by earthquakes related to the natural gas production, the government set annual caps which further reduce the production (MEZ, 2014).

29A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The second regulative natural gas production policy is the *small fields policy*, which ensures that all gas produced from on- and offshore Dutch small fields will be purchased by GasTerra. Creating a favorable certainty for producers, this policy stimulates production from the small fields and reduces the demand from the Groningen field, hence complementing the cap policy.

Table 2.4: Past and present policies implemented in the Netherlands, related to the gas sector

	Regulative	Financial	Communicative
Natural Gas Production	• Production cap on the Groningen field • Small fields policy	• Natural gas production tax (State Profit Share) • Participating in exploration and development activities	-
Renewable Energy Production	• Government Coordination Scheme • Environmental Management Act • Priority for sustainable energy	• SDE+ • Energy Investment Allowance (EIA) • Green Funds ○ Environmental Quality of Electricity Production (MEP) ○ Subsidy Scheme for Fermentation Implementations (OVMEP)	• Biomethane production goal • Climate and Energy Agreement between the Government and Provinces • Green Deals • Energy Agreement for Sustainable Growth (SER)
Demand	• Energy Performance Standards for Buildings	• Value Added Tax (VAT) • Energy levy ○ Sustainable Mobility Scheme ○ Regulatory Energy Tax (REB)	• Green Deals • SER ○ Climate and Energy Agreement with Municipalities ○ Spring Agreement on Energy Conservation in New Buildings & More with Less

The primary financial Dutch policy regarding the natural gas production is the *State Profit Share (SPS)*, the tax collected from the producers' profit. Currently, combined with the corporate income tax, SPS amounts to 50% of the total profit of the producers (Den Dulk, 2009). The other financial intervention of the government in the gas production is for facilitating exploration and production activities, with up to 40% participation of EBN in investments (EBN, 2009).

The regulatory renewable energy policies primarily aim to facilitate the installation process of the production plants. The *Government Coordination Scheme* targets the large-scale production facilities, whereas the *Environmental Management Act* (Wet milieubeheer) focuses on the small plants, including the renewable gas production facilities. Existing since 2010, the *Priority for Sustainable Energy* ensures that the renewable electricity sources have priority to access the grid in the case of a congestion.

The *SDE+* (Stimuleering Duurzame Energie) is the primary financial incentive, which aims at stimulating the production of renewable energy. Revised in 2011 from the SDE scheme, SDE+ imposes the subsidization of several renewable energy technologies, including the renewable gas production from landfill/waste, biomass fermentation, biomass gasification. Although a different subsidy price is determined for each technology, the Dutch government uses a single subsidization scheme for all technologies, known as the 'spot market gap model'. In this scheme, a 'basic amount' is set every year, according to the investment and operation costs, and the subsidy price paid to a producer is the difference between the market

29B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

price and the 'basic amount' set in the year the producer has subscribed. This scheme does not provide a high financial certainty for the producers, but prevents the government from paying high amounts if the market price increases. The SDE+ scheme cannot be combined with MEP (Environmental Quality of Electricity Production) or OVMEP (Subsidy Scheme for Fermentation Implementations), which are the subsidization schemes offered before SDE, ceased in 2006 but effective until 2016 due to the ongoing projects funded.

In addition to the *SDE+*, renewable energy technologies are supported with other financial incentives such as tax exemptions for investments in renewable energy projects (*Energy Investment Allowance*) and lower interest rates offered by banks for loans to be used in renewable energy projects (*Green Funds*).

The first communicative, or soft, policy listed in Table 2.4 regarding the renewable energy production is the *biomethane production goal* of the government. For the contribution of renewable gas to the gas supply, the government specified a goal, which is 3 bcm by 2020 (Scheepers, 2013). To reach this goal, several agreements are made with the industry and utility companies to foster the installation of biomethane production facilities. The *Climate and Energy Agreement between the Government and Provinces* is one such agreement signed earlier in 2009, establishing that provinces should support renewable energy projects in the areas of spatial planning and authorization, as a role model and a stakeholder. Another 'soft' measure is the *Green Deals* by which the government provides information support and eliminates administrative difficulties for the sustainability initiatives. Another recent and comprehensive agreement is the *Energy Agreement for Sustainable Growth* signed with the Social and Economic Council of the Netherlands (SER) in 2013 for the industry to use more renewable energy, increase energy savings, provide more jobs, and for the government to provide tax breaks for local green energy initiatives. As seen in this example, such agreements include promoting both the production and consumption of renewable energy.

The policies affecting the demand side start with the *Energy Performance Standards for Buildings*, which impose certain insulation and energy efficiency measures on the new buildings, and affect the gas (or heating) demand of households. The financial policies affecting the demand of any sector are primarily the *Value-Added Tax (VAT)* and the *Energy Levy*. The VAT for natural or renewable gas use was increased to 21% from 19% in 2012, for all sectors (households, industry, transport) except agriculture. This percentage is similar to the rates in other Northwest European countries, although the rates within EU range from 6% (e.g. Luxembourg) to 25% (e.g. Sweden). *Energy Levy* is the tax paid by the consumers per unit of energy consumed (EUROSTAT, 2014). It varies between consumption groups, but in general, the 2015 tariff set for small consumers (households) of natural gas is 0.1911 EUR/m^3, whereas that for large consumers is 0.0118 EUR/m^3. All taxes and levies account for approximately 42% of the natural gas price for households in the Netherlands, whereas the European average is around 25% (EUROSTAT, 2014). The communicative interventions of the government affecting the demand side are the SER agreements and Green Deals, mentioned before.

30A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Despite the variety in their implementation ways and primary targets, the common characteristic of the abovementioned policies is their focus on a single policy objective. In other words, these policies are designed to improve the situation in a single area, e.g. only the renewable energy share, since it is not straightforward to find a single solution that can meet multiple, potentially conflicting, objectives. However, it is important to evaluate the impact of a policy not only on the objectives it primarily targets, but also on other policy objectives, in order to ensure a coherent energy policy strategy.

2.5.2. Policies Implemented in Other Countries

This section presents a selection of policies implemented in the United Kingdom, Germany and Sweden, regarding the natural gas production, renewable energy production and natural or renewable gas demand. The reasoning behind the selection of these three countries is as follows: The United Kingdom has a similar gas market to the Netherlands because of indigenous production of natural gas, and the similar effect of European renewable energy and emission goals. Germany is the pioneer European country in the renewable energy deployment, making its policies promising for other countries, and Sweden is the leader in the renewable gas production based on biomass. The policies discussed below, and summarized in Table 2.5, are selected mainly because of their differences from the Dutch policies.

Regarding the natural gas production, the UK government has implemented several measures to stimulate extraction especially in the North Sea. A 90% reduction in the annual rental rate (exploration and production licensing costs), and exemption from requirements to prove technical, environmental and financial competency in the first 2 years of activity are two striking incentives given to the natural gas producers (DECC, 2013). Besides, shale gas exploration is already allowed in UK, although there is no significant activity yet.

Table 2.5: Selected policies related to the natural gas production, renewable energy and gas demand, in the UK, Germany and Sweden

	United Kingdom	Germany	Sweden
Natural Gas Production	• Reduction in the annual rental rate • Shale gas exploration is allowed	-	-
Renewable Energy Production	• Renewables obligation • Bio-energy Capital Grants Scheme	• Fixed feed-in tariffs • Sharing of investment costs for grid connection	• Investment grants to municipalities and farms for renewable gas
Demand	• 90% exemption of energy-intensive industries from the energy levy	• Full exemption of energy-intensive industries from the energy levy • Renewable heat quota • Energy tax exemption of biomethane use	• Carbon dioxide tax and energy tax exemption of all biomethane utilization • Promotion in the transport sector

For the deployment of large-scale renewable electricity production, the UK government introduced a Renewables Obligation in 2002, obliging the energy suppliers to source a

30B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

percentage of the amount they supply to consumers from renewable sources (DECC, 2012). A financial measure the UK government uses to stimulate renewable energy production is the Bio-energy Capital Grants Scheme, by which capital grants are offered to the industrial, commercial and communal producers of biomass-fueled energy for installation of plants (IEA, 2015), instead of tax reductions as in the Netherlands.

On the demand side, the exemption of energy-intensive industries from the energy levy (Climate Change Levy) up to 90% (DECC, 2014) is similar between the UK and Netherlands, yet the full exemption in Germany (IEA, 2015) is distinctive. Regarding the renewable gas utilization at the demand side, Germany enforces renewable heat quotas similar to the renewables obligation in the UK, and fully exempts renewable gas consumption from the energy tax (Strauch *et al.*, 2013). As for the renewable energy production, Germany provides fixed feed-in tariffs which decline in regular intervals, hence guarantees a certain income for producers for a long time, while promoting innovation for cost reduction at the same time. This subsidization scheme which is substantially different from the scheme in the Netherlands also applies to renewable gas. Another distinctive German financial incentive for renewable gas production is the participation of the government in investments for grid connection (Strauch et al., 2013).

Sweden's policies for renewable gas production focus on providing investment grants especially to the farms and municipalities for facility installation, instead of tax reductions provided in the Netherlands. On the demand side, similar to Germany, renewable gas consumption is fully exempted from both energy and CO_2 tax, and the utilization of renewable gas for transport is promoted with several measures such as tax exemptions, green car premiums, and support for filling stations (Strauch et al., 2013).

2.5.3. Policy Alternatives Considered in This Study

The previous two sections discussed several regulative, financial and communicative policy options that are or that can be implemented by the Dutch government, to intervene in the supply or demand side of the gas sector. In the policy testing phase of this study, 8 of these policy options and the 'no policy/business as usual' case are taken into account, and will be analyzed in terms of their performance against uncertainties and on all of the abovementioned 8 outcome indicators. That is, this analysis aims at investigating the performance of each option not only in terms of the indicators that it directly affects, e.g. the cap policy on the natural gas production, but also all policy objectives the government has.

The policy options are considered in two groups in this analysis. The first group, which is listed in the first column of Figure 2.8, is composed of the 8 policies targeting natural gas, demand and renewable energy sectors. Some of these policies have multiple implementation options and these options constitute the second group. For instance, the *Groningen Cap* policy has 4 options including the 'no policy/business as usual' case, which is in the form of the cap policy implemented until 2014, or removing the cap, implementing it until 2050, or setting annual caps as done since 2014. Such implementation options that can replace each other are called 'exchangeable options', and the *Biomethane Subsidization* policy also has 10 such options. The second column of Figure 2.8 shows these exchangeable options, linked to each

31A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

policy they correspond to. Comparing the policies in the first group to each other requires selecting one of the exchangeable options for the ones which have these. Therefore, the analysis for the options in the second group is framed as a choice problem, as it will be discussed later.

The corresponding analysis sections of the Chapters 7 and 8 explain these policies, and assumptions made for their model-implementation.

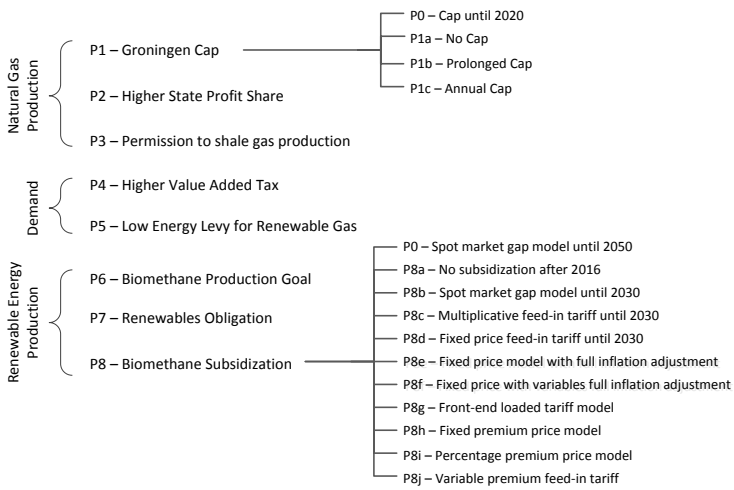


Figure 2.8: Hierarchical list of the policy options

2.6. UNCERTAINTIES REGARDING THE DUTCH GAS SECTOR

The last element of the policy analysis framework shown in Figure 2. consists of the *External factors (X)*, which are not under the control of policy makers or actors, but may affect the system, hence the outcome indicators, significantly. The concept of external factors can be broadened to uncertainties, as the factors which are not only uncontrollable but also limitedly known. The importance of uncertainties in policy analysis, and the approaches used to deal with them are discussed by (Walker *et al.*, 2013), and they will be examined in Chapter 3 of this thesis, too. This section, instead, focuses on providing an overview of uncertainties in the Dutch gas sector, to complete problem diagnosis and the scope of this study.

Defined as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" (Walker *et al.*, 2003, 1), what is perceived as an uncertainty varies between actors (Meijer, 2008, 33). For instance, one of the main uncertainties commonly mentioned by the interviewees was about future policies and regulations, which is not an uncertainty but a decision problem in the government's view. In addition to different uncertainty perceptions of the actors, uncertainties in an analyst's view may be different as well, including the uncertainties regarding methodology, assumptions, analytical outcomes, and conclusions. Although such uncertainties are important, and taken into account throughout this study, this section discusses the uncertainties related to the gas sector in a systemic view, as a collection of those perceived by actors. This discussion is carried out

31B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

based on a framework that classifies uncertainties with respect to three dimensions, for the purpose of better understanding and communicating them. Therefore, Section 2.6.1 below describes this framework, prior to the discussion of major uncertainties in the Dutch gas sector in Section 2.6.2.

2.6.1. A Framework for Identifying and Communicating Uncertainties

Several studies on uncertainty include a preliminary categorization of uncertainties, such as Funtowicz and Ravetz (1990) who distinguish between the *sorts* and the *sources* of uncertainty, or Morgan and Henrion (1992) who mention *nature* and *sources* of uncertainty. Integrating such previous research, Walker et al. (2003) developed a framework for classification and analysis of uncertainties, in the context of model-based decision support. Walker et al. (2003) argue that such a framework can provide better communication among policy analysts, policy makers and stakeholders, and better understanding which enhances decision support, as well as a prioritization of uncertainties. This framework, also named W&H framework, is composed of three dimensions of uncertainty: *location*, *level* and *nature*. Figure 2.9 illustrates these three dimensions of uncertainty and alternative forms for each dimension in a matrix.

Location		Level			Nature	
		Statistical uncertainty	Scenario uncertainty	Recognised ignorance	Epistemic uncertainty	Variability uncertainty
Context	Natural, technological economic, social and political, representation					
Model	Model structure					
	Technical model					
Inputs	Driving forces					
	System data					
Parameters						
Model Outcomes						

Figure 2.9: Uncertainty matrix
Source: (Walker et al., 2003)

The *level* of uncertainty shows how severe it is on a scale ranging from deterministic knowledge to total ignorance. Statistical uncertainty is the lowest level of uncertainty, implying that the deviation from the true value can be expressed in statistical terms. Scenario level uncertainty includes the situations where a set of outcomes can be derived, but since the functional relations leading to these outcomes are not well known, it is not possible to define the probabilities of these outcomes. Recognized ignorance is the state of knowing what is unknown, when the available knowledge is not sufficient to develop scenarios. Total ignorance is the deepest level of uncertainty, where we do not know even what is unknown.

The second dimension, *nature* refers to the main reason for uncertainty, being imperfection of knowledge (epistemic) or the inherent variability in the system, such as inherent randomness or anything which can be expressed with certain variation from the true value. In the model-

32A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

based policy analysis context of the study of Walker et al. (2003), *location* refers to where the uncertainty reveals itself in the model complex, e.g. in which components of the systems analysis framework.

Several modifications and extensions have been made to the W&H framework, mainly on the location and level dimensions, as summarized and synthesized by Kwakkel *et al*. (2010). In this research, for the level and nature dimensions, the approach of Kwakkel et al. (2010) is adopted. This approach adds *ambiguity* to the nature dimension, to represent uncertainty due to multiple frames of reference, i.e. different interpretations of the same data or phenomenon by different actors, depending on their worldview and values. Regarding the level dimension, Kwakkel et al. (2010) divides scenario level uncertainty into two, as *medium* and *deep uncertainty*. Medium level refers to the ability to list alternatives of an uncertain phenomenon, and to rank these alternatives in terms of likelihood, without being able to assign specific probabilities. A level further, deep uncertainty is the situation where only a number of alternatives can be enumerated, with neither a specific likelihood nor a rank-order.

At this stage of this study, we discuss the uncertainties prevalent in the Dutch gas sector, without taking a (quantitative) model-based view yet. Hence, we replace the location dimension with 'source', having the external factors (X), 'system model' (R) and 'value system' (W) components of the system diagram as the major sources of uncertainty. The following section provides a discussion about where in the system components, i.e. supply, demand, infrastructure and market, and in the value system uncertainties are manifest, and what their positions are in the nature and level dimensions.

2.6.2. Uncertainties in the Dutch Gas Sector

As mentioned before, this section discusses the uncertainties in the Dutch gas sector, corresponding to the system components as their sources, and in terms of their nature and level. These uncertainties are identified based on the answers of interviewees to a question on uncertainties that their organization encounters, and the following discussion on reasons and severity of this uncertainty, as well as based on a literature study of institutional reports and academic studies. Table 2.6 summarizes these uncertainties, which will be discussed in more detail below.

Table 2.6: Major uncertainties in the Dutch gas sector

Source		Uncertainty	Level	Nature
EXTERNAL FACTORS	Supply	Natural gas reserves	Statistical	Epistemic
		Biomass availability	Deep	Epistemic
		Efficiency and cost characteristics of new technologies	Deep	Epistemic
		Import availability and price	Deep	Epistemic
	Demand	The change rate of natural gas demand	Deep	Epistemic
		Price elasticity of gas demand	Deep	Epistemic
	Infra	Installation cost and lifetime of renewable gas plants	Deep	Epistemic
SYSTEM	Infra	Investment behavior of producers	Deep	Epistemic
	Market	The factors that affect the market price of gas	Deep	Ambiguity
		The effect of costs on price	Deep	Epistemic
		The effect of scarcity on price	Deep	Epistemic
VALUE SYSTEM		Prioritization of the policy goals	Deep	Ambiguity

32B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

On the supply side of the system, regarding natural gas, prospects and recoverability of both conventional and unconventional resources is a major uncertainty. Although extensive exploration activities have reduced the chance of new conventional natural gas discoveries, there is still a possibility to discover new fields. As for the unconventional resources, e.g. shale gas, the amount and recoverability of prospects are more uncertain, since there hasn't been any exploration in the Netherlands. Regarding the renewable gas production, as a new technology, how the efficiency and production costs will evolve in future, as well as the availability of biomass to be used for gas production, are the major uncertainties. As for the imports, the availability of gas on the international market to be imported to the Netherlands, including the political uncertainty affecting this import availability, and the price of that gas are the main uncertainties regarding the supply.

Gas demand is considered as one of the key uncertainties in the sector, emphasized by almost all actors. The rate it will change at in the coming decades, for instance depending on climate, insulation, economic growth etc., and the response of consumers to price changes are the two specific uncertainties regarding the gas demand.

Related to the development of infrastructure, two uncertainties arise as important. Firstly, the installation cost and lifetime of the production plants are the main economic and technical uncertainties. Secondly, how producers decide to invest in and install this infrastructure is a significant uncertainty affecting the deployment of renewable gas.

The market price of gas is a primary uncertainty affecting, and mentioned by, almost all actors. More precisely, the factors that determine price, and what kind of impacts they have are uncertain. In terms of their sources, these uncertainties are categorized as regarding the system model (*R*), rather than the factors external to the system (*X*). For instance, production costs and scarcity are the two factors known to affect the market price, but the exact relations between these factors and price, i.e. how price changes with respect to a change in these two factors, are not known.

Apart from the relations between system components and external factors, the value system is another element of the systems analysis framework where important uncertainties may be present. In Section 2.2, the policy goals of the government have been identified, and they are assumed to be represented by a particular list of 8 outcome indicators. However, no prioritization of these outcome indicators, i.e. which ones are more important than the others, is provided, because there is an important uncertainty about the preferences of the government and other actors, and prioritization of these outcome indicators. Hence, the uncertainty about the outcome indicators' prioritization is included in this study, too.

Among the uncertainties discussed above, only the ones related to the natural gas reserves are expressed with specific probability distributions. For instance, the prospects of shale gas are reported to have a triangular distribution with worst, most likely and best estimates as 48000, 110000, 230000 bcm (Muntendam-Bos et al., 2009). Therefore, this is considered as an uncertainty at the statistical level. However, despite the availability of a number of alternatives, neither a probability distribution, nor an order based on likelihood can be assigned to other uncertainties. For instance, Energiezaak estimates an average of 0.97%

33A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

annual increase in the total gas demand in the Netherlands between 2010 and 2030 (Energiezaak, 2011), whereas according to GTS this increase is only 0.56% per year between 2014 and 2033 (GTS, 2013). There is no information about which of these alternatives is more likely. Hence, the change rate of gas demand is a deep uncertainty, as the other uncertainties listed above, due to the possibility to enumerate a number of alternatives, but with neither a specific likelihood nor a rank-order.

As for the nature dimension, none of the uncertainties listed above has a stochastic nature due to an ontological variability. Instead, all uncertainties except 'the factors that affect the market price' and 'prioritization of the policy goals' are characterized as epistemic uncertainty, indicating that these uncertainties stem from a lack or absence of knowledge about the current or future state. The two exceptional uncertainties are considered to be caused by ambiguity, because there are multiple interpretations, or mental models about how the market price changes, as well as multiple prioritization schemes of policy goals.

The uncertainties discussed above are the major factors that cause the future of the Dutch gas sector to be uncertain. As mentioned, whether statistical or deep uncertainty, these uncertainties can be realized in many different ways in future. Hence, affecting the system components and being propagated towards the outcome indicators, these uncertainties imply many different futures. The presence of different possible futures hinders the assessment of policy options, since their effects on the outcome indicators may vary between alternative futures.

2.7. CONCLUSIONS

With a systems analytic approach, starting from the system diagram in Figure 2.1, the preceding five sections discussed, in line with the research questions 1.1-1.5: (i) the policy goals of the government and the outcome indicators representing them, (ii) a system representation of the Dutch gas sector, (iii) the actors related to this system, and stakeholder perspectives, (iv) the past and present policies implemented, as well as future policy alternatives, and lastly (v) the uncertainties associated with the system of interest, and the policy goals. Figure 2.10 illustrates these elements again in a system diagram form, similar to Figure 2.1, and summarizes the content of this chapter. (Note that uncertainties are positioned in three different location in this diagram, different than Figure 2.1.)

Referring to Figure 2.10 in the next page, the problem investigated in this study is the assessment of policy options exemplified at the top of the diagram, in terms of the states of 8 outcome indicators listed at the right side, in the alternative futures created by the uncertainties listed at the left side. Related to this assessment procedure, several methodological issues arise, such as how to develop a system model and how to deal with the multiplicity of the decision criteria (outcome indicators) and possible futures, as also addressed by the research questions 2.1 and 2.2. The following chapter discusses such methodological issues, namely which approaches and methods are chosen, and why.

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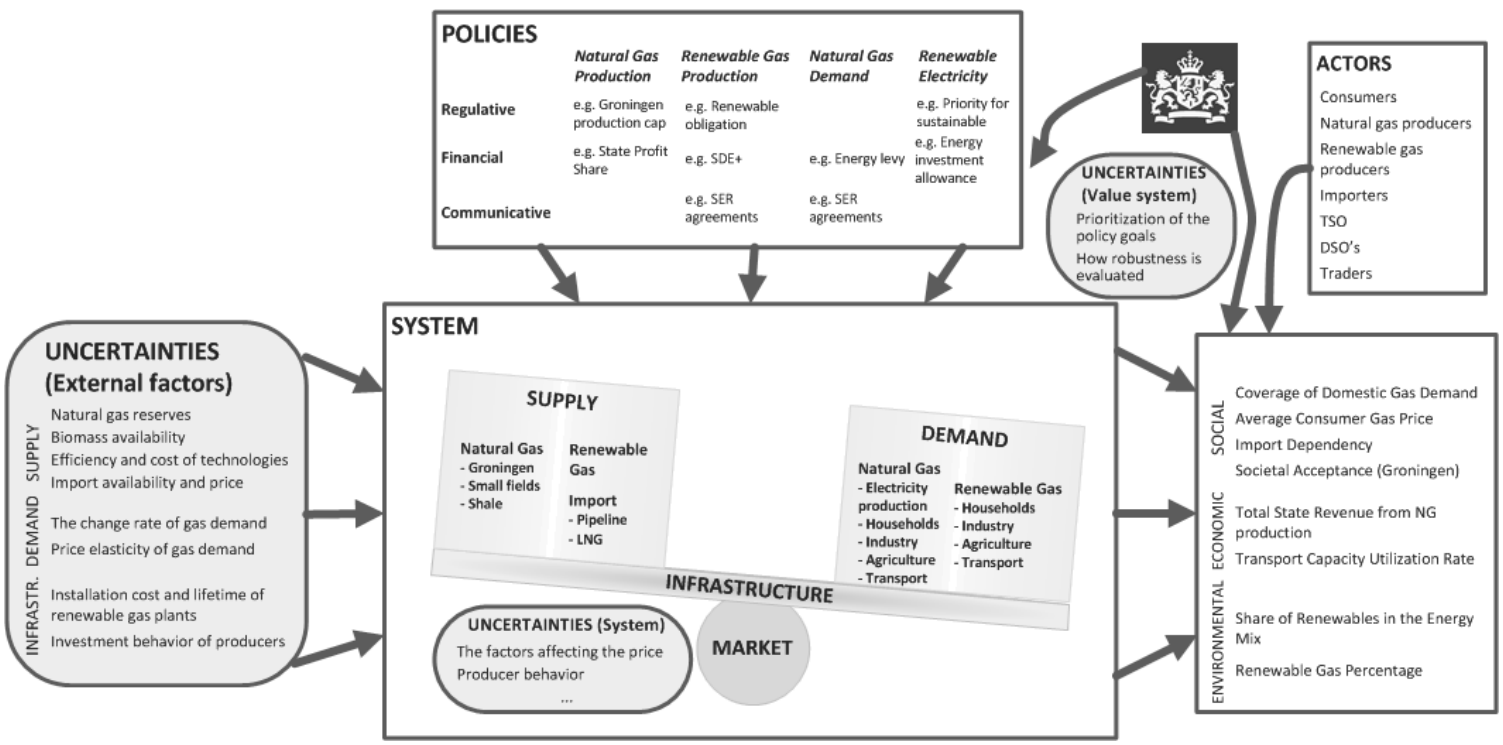


Figure 2.10: The system diagram for the problem of interest in Dutch gas sector

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34B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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35A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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Though this be madness, yet there is method in't.
W. Shakespeare, *Hamlet (2.2)*

3

RESEARCH METHODOLOGY

Chapter 1 briefly introduced a policy problem in the Dutch gas sector, as a combination of conflicting interests and future uncertainties, and stated the objective of this study as providing policy recommendations to deal with this problem. Besides, 'model-based policy analysis' and 'Exploratory Modeling and Analysis' were mentioned as two approaches to be followed to reach this objective. The policy problem introduced in Chapter 1 was defined more thoroughly in Chapter 2, based on a systems analytic approach. Chapter 2 also stressed the necessity of adopting a policy analysis approach which takes uncertainties explicitly and extensively into account. However, the abovementioned approaches were not described, and the reason for their selection has not been explained yet. Therefore, the aim of this chapter is to present the methods used in this study, and to explain why they are chosen for this particular case.

With this aim, this chapter first introduces the policy analysis discipline in Section 3.1 and discusses why a rational, model-based approach is chosen. Different approaches used to deal with uncertainty in policy analysis studies are also discussed in this section. Section 3.2 provides a review of studies using quantitative models for energy policy analysis, with the purpose of investigating their benefits and shortcomings especially in terms of dealing with uncertainty. Then, Section 3.3 introduces Exploratory Modeling and Analysis as an approach to deal with uncertainty, and explains why it is chosen. Lastly, Section 3.4 discusses the simulation modeling methodology integrated with the Exploratory Modeling and Analysis approach, which is system dynamics, and explains the reason behind this choice.

3.1. POLICY ANALYSIS

This study has been specified as a 'policy analysis' study in Chapter 1, aiming to provide policy recommendations to the Dutch government and to the key actors in the Dutch gas sector. Chapter 1 already mentioned the policy analysis approach adopted in this study as a rational style, model-based one, prior to the specification of research questions, and the problem diagnosis in Chapter 2 followed this approach. In this section, we outline this policy

36A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

analysis approach in more detail, i.e. how this study is positioned within the policy analysis discipline, and discuss the methodological choices related to the application of this approach.

The policy analysis discipline evolved from operations research and systems analysis in the 1960s. In the early years, it was defined as "a form of applied research carried out to acquire a deeper understanding of sociotechnical issues and to bring about better solutions" (Quade, 1982, p. 5). This definition of Quade refers to multiple methods of analysis, such as not only examining a policy alternative by decomposition but also designing and synthesizing new alternatives. Based on this multiplicity of possible methods, Dunn (1994, p. 84) provides a more specific definition, as "an applied social science discipline that uses multiple methods of inquiry in contexts of argumentation and public debate, to create, critically assess, and communicate policy-relevant knowledge". Despite acknowledging multiple methods, as Thissen and Walker (2013, p. 2) state, these definitions, and the policy analysis frameworks their authors suggest, currently reflect the traditional approach to policy analysis. This traditional approach is based on modeling the system and/or choosing among policy alternatives, besides the newer approaches such as argumentative (Fischer *et al.*, 2007) and participative ones (Geurts and Joldersma, 2001) or policy and process-oriented ones (Howlett, 2010; Bardach, 2011).

Recognizing this multiplicity of approaches and methods, Mayer *et al.* (2004) proposes a framework to understand various practices of policy analysis as a discipline, as well as to support selection of methods and tools for a new policy analysis study. This framework is based on six different activities of policy analysis, matching with six different styles and their underlying values. Figure 3.1 shows these 6 activities, being *research and analyze, design and recommend, advise strategically, clarify values and arguments, mediate,* and *democratize,* and the styles balancing two of these activities, such as *rational style, client advice style, argumentative style, participatory, process and interactive styles*. (The reader is referred to the original article for definitions of these activities and styles.)

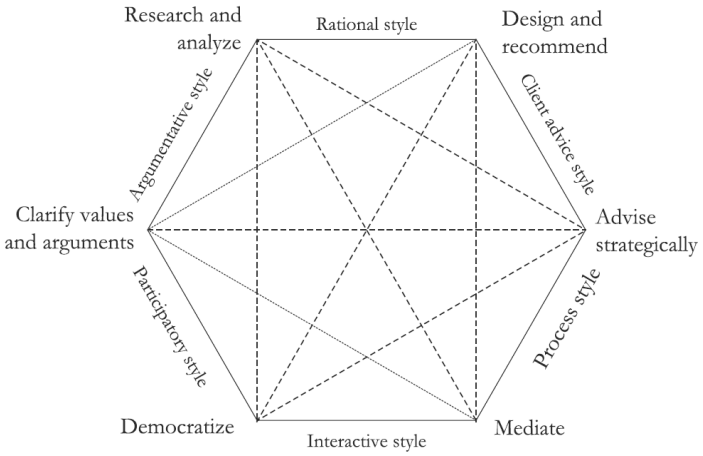


Figure 3.1: Policy analysis styles linked to activities, Source: (Mayer et al., 2004)

36B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

In Chapter 1, the objective of this study is specified as providing recommendations about which policies are effective in dealing with conflicting interests of actors and robust against uncertainties. This objective is then translated into a series of research questions, outlining a series of 'research and analyze' and 'design and recommend' activities, corresponding to the 'rational' and 'client advice' styles described by Mayer *et al.* (2004). These styles refer to finding policy alternatives, testing them, and providing advice based on such an analysis, in line with the traditional approach mentioned by Thissen and Walker (2013). The reason for adopting this approach was to conduct an explicit and systematic study by using the available knowledge, and to provide evidence-based recommendations, which are often desired by decision makers but cannot be easily obtained in the presence of uncertainty. It must be noted that the output of such a rational-style study can also serve as an input to other policy analysis activities, such as mediating and democratizing.

3.1.1. Model-Based Policy Analysis

Models have long been used in policy analysis to capture the complexity of policy problems. They assist analysts in dealing with such complexity, and enable them to conduct quantitative or qualitative experiments on the policy domain which are impossible or too costly to do in real life. Certainly, there are many types of models used in policy analysis, depending on their purpose, development method, use etc. Thissen and Walker (2013, p.151-155) divide these models into two as system and actor models. In this categorization, system models are linked to the activities like *research and analysis, design, strategic advice,* which focus on the physical system, whereas the actor models are used in other three policy analysis activities such as *mediating, democratizing or clarifying values,* which focus on the actors and process of policy making. Yücel and van Daalen (2009) take this division one step further, and investigate the types and examples of models that correspond to each policy analysis activity.

System models are often quantitative (or computer) models. Compared to mental models or mental analysis, computer models provide five major advantages, such as rigor and precision in conceptualizations, comprehensiveness of interrelationships, logic in processing a series of relationships, explicitness of the assumptions to be accessed by others, and flexibility in changing the assumptions and conditions (Meadows and Robinson, 1985, p.6). Given these advantages, they serve various purposes such as estimating phenomena that cannot be observed or measured directly, diagnosing the factors important in obtaining a particular outcome, forecasting the future trends, or providing an understanding of how the system works or may work in the future (Walker and van Daalen, 2013, p.157). The role of such models in policy analysis, referring to the systems analysis framework presented in Chapter 2, is to serve as a platform first to investigate how a system operates at the current time, then to explore different future states of this system and policy changes in these states (Walker and van Daalen, 2013, p.159).

In this study, as we specified earlier, we mainly carry out the policy analysis activities placed on the top of the hexagon in Figure 3., associated with system models. Therefore, to aid these activities and benefit from the abovementioned advantages, we choose to employ a quantitative system model. This model is to represent the system of interest described in Chapter 2, so that the future states of the outcome indicators can be investigated based on this

37A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

model, and the impact of uncertainties and policy interventions on the outcome indicators can be analyzed.

3.1.2. Policy Analysis under Uncertainty

Policy problems are characterized by high complexity of interactions between system elements and actor interests, and by high levels of uncertainty. Models aim to address the complexity aspect as discussed in the previous section, yet uncertainty is often disregarded. The reason for this disregard is seen as the dilemma between what is expected from science in policy making and the inherent uncertainty in policy problems. As Funtowicz and Ravetz (1990) discuss, policy makers expect high quality of scientific information, usually in the form of point estimates of what will happen if they choose a particular action. Yet, such information referred as 'incredible certitude' by Manski (2013) is often based on strict assumptions which ignore uncertainties in the current and future states of real life. Therefore, this attempt to provide high quality scientific information actually reduces the quality and credibility of it. Still, the attention paid to uncertainty is increasing not only among decision making scientists, but also in the policy arena. In several domains, researchers acknowledge the importance of taking uncertainty into account and propose methods to deal with it, such as in engineering design (De Neufville and Scholtes, 2011), economics (Manski, 2013), management (Aven, 2013), and policy analysis (Walker *et al.*, 2003; Lempert *et al.*, 2003; Walker, Marchau, *et al.*, 2013).

In the policy arena, uncertainty is well-recognized in the climate change debate. Since 1999, the Intergovernmental Panel on Climate Change (IPCC) sets requirements and guidelines for the treatment and communication of uncertainty in its reports (Schneider and Moss, 1999; IPCC, 2005; Mastrandrea *et al.*, 2010), although the implementation of these guidelines in the Assessment Reports is highly questioned. (This debate is mostly around the quantification of uncertainty, use of probabilistic statements and the procedure and purpose of the assessment (Katz *et al.*, 2013; Adler and Hirsch Hadorn, 2014; Budescu *et al.*, 2014).) The importance given to uncertainty is also increasing in the policy making process of European Commission. The Joint Research Center (JRC) is the main organization providing EU policies with scientific and technical support throughout the policy cycle, and it follows a set of guidelines known as 'sensitivity auditing' to ensure the quality and transparency of Impact Assessment models and analysis used for policy advice (JRC, 2014).

In the national-level policy arena of the Netherlands, uncertainty has long been accounted for, especially in the model-based decision support domain. What mainly led to this attention was a public criticism in 1999 by a senior statistician at the National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu, RIVM) about too much reliance on computer models (Petersen, 2012, p.1). Following a harsh public debate, the institute established a 'guidance' to assist its employees in their daily practice of performing research to advise policy-makers and the public, placing special focus on the assessment and communication of uncertainties (Janssen *et al.*, 2005; van der Sluijs *et al.*, 2008). Despite this recognition of uncertainty by the main policy research body in the last decades, the earlier history of Dutch natural gas presents an example of failing to account for uncertainty in policy making. As mentioned in Chapter 1, in the period following the discovery of natural gas, the

37B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

government estimated the future energy system to be nuclear-based, and wanted to maximize the benefit from natural gas before nuclear energy dominated the market. However, the ambitious export strategy which aimed to sell gas before it would become redundant resulted in an economic recession, while nuclear energy has never become the dominant energy source (Correljé *et al*., 2003).

As for the policy approaches to uncertainty, with a metaphor of monsters, van der Sluijs (2005) discusses four different styles used for dealing with uncertainty in the science-policy interface. The first style, *monster-exorcism*, reflects the idea of reducing uncertainty by more objective research. *Monster-adaptation* is the strategy where all uncertainties are attempted to be quantified so that they can be transformed into more easily manageable issues. For instance, Bayesian methods and using subjective probabilities are methods fitting with this approach. *Monster-embracement* is framed as acknowledging uncertainty, but mostly for manipulating uncertainties to deny them, i.e. denying environmental risks due to all the associated uncertainties. Lastly, *monster-assimilation* is the strategy that aims to adapt uncertainty to the environment in which it is assessed, and vice versa. In other words, uncertainty is given a central and explicit position instead of looking for a single truth.

Agusdinata (2008, p.7-9) also differentiates between different policy approaches to uncertainty, yet he focuses on the policy design phase from an analytical perspective and lists five approaches. These approaches differ from each other in the sense of making static, one-time decisions or dynamic decisions that can change over time. The *do-nothing* and *delay policy approach* are in the static and dynamic categories, respectively. *Optimal* and *static robust policy approaches* are both associated with one-time decisions, but in the former decisions are made according to a single, most likely prediction of the future, while in the latter a decision that performs well across plausible scenarios of the future is selected. The *adaptive policy approach* is also a robust policy approach, where the decision is dynamically modified according to the new information obtained.

In this study, the presence of deep uncertainties in the Dutch gas sector, and the importance of taking these into account in policy analysis has already been acknowledged. The stance we adopt in this study in terms of the scientific input given to the policy debate matches with the *monster-assimilation* approach of van der Sluijs (2005): Uncertainty is given a central role, and strict assumptions implying a single truth are avoided either in the input or in the output of this analysis. As for the policy design approach to deal with uncertainty, we limit ourselves to the *static robust policy* approach in this study, considering that adaptive policies can be investigated in future based on this research. Hence, we seek for policies to be implemented now but robust across future scenarios. However, it must be noted that the definition of some policy options (see Chapter 2) indicate an adaptation of the business-as-usual policy in future.

Having opted for a model-based policy analysis study taking uncertainties explicitly and extensively into account to seek for robust policies, the next section reviews existing model-based studies for energy policy problems and how they deal with uncertainty. The sections following this review will describe the methods chosen to conduct a model-based, robustness-oriented analysis, and the reasons for these choices.

38A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

3.2. MODEL-BASED ANALYSIS FOR ENERGY POLICIES

The energy sector has a long tradition of using systems modeling to support decision making. The emergence of this tradition dates back to the 1970's, when the oil crisis made policy makers aware of the importance of long-term planning, and the popularity of linear programming, which was developed during the Second World War, drew the attention of the energy sector, too (Pfenninger *et al.*, 2014). In the 1990's, the concerns about climate change and the liberalization of the energy markets again stimulated the intense and methodologically diverse use of quantitative modeling in the energy sector (Bunn and Larsen, 1997, p. 1). Following these two developments, the integration of renewable energy technologies into energy systems became another significant issue in the energy sector in the 2000's, and constituted the focus of many modeling studies since then (Connolly *et al.*, 2010).

To understand how energy systems modeling helped decision making in the past, and what shortcomings and challenges these studies had, this section presents a review of the modeling studies used for energy policy. This review starts with a short overview of the most well-known energy systems models in Section 3.2.1, and then focuses on the models built particularly for gas markets in Section 3.2.2. The key features paid attention in this review are the purpose and scope of the model, the methodology adopted and the approach to dealing with uncertainty.

3.2.1. Energy System Models

The first examples of energy system models were built with a linear programming approach in the late 1970's, and have evolved over time into widely used model families. The first such model was MARKAL (Market Allocation) developed by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (Fishbone and Abilock, 1981). MARKAL is a data-intensive model that focuses on the interaction of economy and environment, excluding the social factors. It mainly yields the optimal (least-cost) supply mix of energy that meets the demand over a horizon of 40-50 years, and can be used at the national, regional or local level. Combined with the Energy Flow Optimization Model (EFOM), MARKAL has evolved to be TIMES (The Integrated MARKAL-EFOM System), which is further developed into TIAM (Times Integrated Assessment Model) at the global scale (Loulou and Labriet, 2008). A nonlinear version of MARKAL exists, named MARKAL-MACRO and includes feedback loops between economic growth and energy demand (Manne and Wene, 1992). To deal with uncertainty, stochastic versions of MARKAL have been developed, and Monte Carlo simulations are used (Seebregts *et al.*, 2002). In addition to being adopted by the International Energy Agency (IEA) and the Energy Information Administration of the US (EIA), MARKAL has been used for hundreds of applications all over the world.

The second model family developed with the linear programming approach in the late 1970's is MESSAGE, which stands for "Model for Energy Supply System Alternatives and their General Environmental Impacts" (Schrattenholzer, 1981). Owned by the International Institute for Applied Systems Analysis (IIASA), MESSAGE has been constructed on a global scale, but used for national level analyses, too. As MARKAL, MESSAGE takes economy-

38B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

environment relations into account and generates key output about the utilization of domestic resources, energy imports and exports, investment requirements, the types of technology substitution and pollutant emissions. A stochastic version of the model exists, named "MESSAGE Robust Decision Framework", and this version is used for long-term scenario analysis to deal with uncertainty (Krey and Riahi, 2009). In addition to its use for assisting several national governments, MESSAGE has been used to inform several international organizations such as the Intergovernmental Panel on Climate Change (IPCC), the World Energy Council (WEC) and European Commission (IIASA, 2013).

The US Energy Information Administration (EIA) initiated the development of National Energy Modeling System (NEMS) about 1990 (Kydes and Shaw, 1997) which is still in use in analyses for the Annual Energy Outlook reports, and special requests from other governmental institutions (EIA, 2009). Following the previous models used by EIA, NEMS is a multi-modular nonlinear equilibrium model, which yields equilibrium prices and quantities used of each energy supply option by iteratively solving a sequence of linear and nonlinear equations (Gabriel *et al.*, 2001). The runtime of NEMS has been significantly reduced over time, but still, due to intense software requirements, it is used only by EIA, and a few other research institutions and universities. To deal with uncertainty, uncertainties in the model are quantified and Latin Hypercube Sampling is used to generate alternative outcomes (Baghelai *et al.*, 1995a, 1995b).

In Europe, the PRIMES model developed by the Energy-Economy-Environment Modelling Laboratory of the National Technical University of Athens has been the major tool used by the European Commission since 1998 to analyze the potential energy policies (E3MLab, 2014), and to prepare the 2050 roadmap (EC, 2011). In terms of being a multi-modular model, PRIMES is similar to NEMS. Yet, unlike NEMS, PRIMES is an agent-based model, where each agent's objective is defined independent of the others, and a concatenation of mixed complementarity problems is solved to obtain energy supply, energy system costs, prices and investment expenditure, emissions, and policy assessment indicators such as import dependency and renewable energy ratios (Capros, 2011). These outcome variables are generated for each country in the EU, candidate members and neighbors such as Norway, Switzerland and Turkey, from 2000 to 2050 for 5 year periods. No uncertainty analysis on the model has been reported so far, except the studies that use the model for generation of a limited number of different scenarios (Capros *et al.*, 2012; Capros *et al.*, 2014a, 2014b).

The models such as MARKAL and MESSAGE and their derivatives are huge model platforms that require intensive data collection for new applications and a long time to interpret the results. Admitting this difficulty, the developers offer training courses to the users all over the world. Monte Carlo simulations on the probabilistic versions of these models are reported to have long run times and extensive data requirements, impeding a common practice of uncertainty analysis. Similarly, NEMS and PRIMES have extensive software requirements; they lack transparency, hence replicability, and user-friendliness. Aiming to deal with such shortcomings of the well-known energy system models, several other optimization models have been developed, some of which are listed below.

39A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

LEAP (Long Range Energy Alternatives Planning System) was created in 1980 and onwards by the Stockholm Environment Institute (SEI, 2012) for easy and widespread use. LEAP is a platform to create models, rather than a model itself, combining account modeling, macroeconomic modeling, and optimization modeling with least cost capacity expansion and dispatch, under various constraints such as limits of CO_2 or local air pollution. It can be used at any scale, i.e. national, regional, local or sector, to track energy consumption, production and resource extraction as well as greenhouse gas emissions (SEI, 2014). LEAP has various applications all over the world, and allows users to construct and compare different scenarios (Cai *et al.*, 2007; Kumar *et al.*, 2003; Roinioti *et al.*, 2012; Shin *et al.*, 2005).

The optimization model integrated into LEAP is known as OSeMOSYS, the Open Source Energy Modeling System, which has recently been developed as a user-friendly alternative to huge optimization models such as MARKAL and MESSAGE (Howells et al., 2011). ERIS (Energy Research and Investment Strategy) and its successor ECLIPSE (Energy and Climate Policy and Scenario Evaluation) are the two other recent optimization models, developed at the global level with more detailed production functions in order to better represent the substitution of supply alternatives (Turton, 2008; Turton and Barreto, 2006). In the UK, the ESME model (Energy System Modelling Environment) developed by the Energy Technology Institute at the national level is spatially more disaggregated than MARKAL and similar models. It is also designed as a Monte Carlo model with probabilistic inputs to take uncertainty particularly in future energy prices, costs and performances of energy technologies into account (Heaton, 2014). Another optimization model recently developed in the UK is CGEN (Combined Gas and Electricity Network) expansion model (Chaudry et al., 2014), which yields least-cost investment decisions for expanding the networks in a time horizon till 2030. A Monte Carlo version of the model has been used to explore the effects of uncertainties related to wind generation and gas supplies from various sources such as LNG and pipeline imports (Chaudry *et al.*, 2013). To deal with the difficulty of replicating and performing uncertainty analysis on the existing complicated models, TEMOA (Tools for Energy Model Optimization and Analysis) has been introduced as an open source framework with a 'modeling to generate alternatives' approach (Hunter et al., 2013). TEMOA is a linear programming model with the objective to minimize the system costs, and it allows Monte Carlo simulations with parametric uncertainties and stochastic optimization.

Regardless of whether they are used to generate a few or numerous solutions, optimization models result in normative scenarios, where the prescribed future (mostly least-cost) does not necessarily reflect the visions and goals of all stakeholders. Therefore, using such models for policy analysis requires maintaining a probing and critical attitude. Alternatively, simulation models that do not search for optimal solutions but rather generate estimations of the future based on a system representation result in descriptive or exploratory scenarios, and allow testing and comparing decision alternatives under a variety of future scenarios.

The World Energy Model (WEM) of the International Energy Agency is an example of such models, used to generate annual World Energy Outlook scenarios which are internationally recognized and debated. Using a wide range of software tools, WEM is based on meeting the primary energy demand, which is calculated in a detailed way by considering the drivers in

39B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the industry, transport, household, agriculture and service sectors, and matched with a wide variety of supply options (IEA, 2013).

Table 3.1: Summary of the energy system models reviewed

Name	Reference	Methodology	Scope	Uncertainty treatment
MARKAL	(Fishbone and Abilock, 1981)	• Optimization model with dynamic linear programming with different versions • Led to TIMES/TIAM	• 40-50 years; national, regional, state or province, or community level • Economy-environment interaction, no social aspects • Yields the optimal (least-cost) supply mix of energy that meets the demand, data on emission profiles, energy chains and system costs	• Stochastic optimization
MESSAGE	(Schrattenholzer, 1981)	• Optimization model with dynamic linear programming, with different versions	• Developed at the global scale, but used for national policies, too • Output: Optimal (least-cost) utilization of domestic resources, energy imports, exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions and inter-fuel substitution processes	• Long-term scenario generation • "MESSAGE Robust Decision Framework" as a stochastic version
EFOM	(Loulou and Labriet, 2008)	• Optimization model with linear programming	• National, regional or sectoral (e.g. electricity) level • Describing the energy system as a network of annual energy flows with capacity limits • The objective is the minimization of the costs of the energy flows at each 5 years and the costs of the investments since the last milestone year.	• Sensitivity analysis • Scenario generation
NEMS	(Kydes *et al.*, 1995)	• Multi-modular linear/nonlinear optimization model	• Projecting the production, imports, conversion, consumption, and prices of energy • The factors considered: macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, demographics	• Sensitivity analysis with LHS
PRIMES	(E3MLab, 2014)	• Integrated agent-based model where decisions are implemented as mixed complementarity problems	• Time horizon: 2000-2050, 5 year time-step; EU countries and neighbors • Output: energy supply, energy system costs, prices and investment expenditure, emissions, policy assessment indicators such as import dependency and RES ratios	• Scenario generation
LEAP	(SEI, 2012)	• A combination of account modeling, macroeconomic modeling and optimization	• National, regional, local or sectoral • Least-cost capacity expansion and dispatch, under various constraints such as limits of CO2 or local air pollution • Output: energy consumption, production and resource extraction and greenhouse gas emissions	• Scenario generation
OSeMOSYS	(Howells *et al.*, 2011)	• Open source optimization model	• Can be used at any level, also sectoral • Based on cost minimization, emission accounting and capacity constraints	• Not reported
ERIS/ ECLIPSE	(Turton, 2008)	• Optimization model • Linear/nonlinear	• Time horizon till 2100, with 10 year time steps; global level with 11 regions • Cost minimization • Demand is inelastic in ERIS, whereas it is dependent on price in ECLIPSE • Output: Energy system costs, regional consumer utility, regional GDP, personal mobility and environmental impact	• Not reported
ESME	(Heaton, 2014)	• Linear optimization model	• Developed only for the UK energy system • Cost minimization model, used for the assessment of low carbon technologies	• Monte Carlo simulations

40A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Name	Reference	Methodology	Scope	Uncertainty treatment
CGEN	(Chaudry *et al.*, 2014)	• Optimization model	• Only for the UK • Least-cost capacity expansion for networks (both gas and electricity, local and imports) • Lacking environmental aspects	• Monte Carlo simulations
TEMOA	(Hunter *et al.*, 2013)	• Open source linear optimization model	• Can be used at any level over a user-specified time horizon • Minimizes the system-wide cost of energy supply by optimizing the deployment and utilization of energy technologies	• Monte Carlo simulations • Sensitivity analysis
WEM	(IEA, 2013)	• Simulation model in a variety of software including Vensim	• Global supply-demand match including demand sectors and supply options in a detailed way	• Scenario generation
IDEAS	(Wood and Geinzer, 1997)	• System dynamics simulation model • Evolved from FOSSIL2, led to Energy Transition Model and FREE	• The scope includes economic factors such as GNP growth, housing stock; four demand sectors and four supply sectors • Simulating market-clearing and price-setting mechanisms for the supply options, keeping the supply and demand balanced	• Not reported
Threshold21	(Bassi and Shilling, 2010)	• System dynamics simulation model	• Only for the USA • Energy, economy, environment, society modules, each with its components and feedback loops to the energy module • Main outputs: demand, production, technology, prices and costs of different energy sources, emissions, investment expenditure, carbon cycle	• Sensitivity analysis • Scenario generation

Another model developed by the US Department of Energy is (DoE) is the Integrated Dynamic Energy Analysis Simulation (IDEAS) model (Wood and Geinzer, 1997). IDEAS is a system dynamics simulation model which is based on the FOSSIL2 model developed earlier at DoE (Naill, 1992) and evolved from the master thesis of Roger Naill on natural gas production at MIT (Naill, 1974). The scope of the model included economic factors such as GNP growth and housing stock; four demand sectors, namely residential, commercial, industrial and transport; and four supply sectors being oil, gas, coal and electricity. The model simulates market-clearing and price-setting mechanisms for these four supply options, keeping the supply and demand of energy balanced. For over 15 years until the mid 1990's, the model was successfully used by DoE to assist the government in preparation of climate change policies (Wood and Geinzer, 1997). There is no publicly available study found about how the uncertainties are treated in the model. Originating from the development process of IDEAS, the Energy Transition Model of Sterman (1982) and Feedback-Rich Energy Economy model (FREE) of Fiddaman (1997) are the two SD models with improved feedback mechanisms between energy, economy and environment.

A recent example of energy systems modeling with system dynamics has been presented by Bassi and Shilling (2010). The Threshold21 model developed by the authors at the Millennium Institute aims at capturing market behavior and energy interaction feedback loops which were absent in IDEAS. Covering four modules on energy, economy, environment and society, and the feedbacks between them, the main outputs of the model are demand, production, technology, prices and costs of different energy sources, emissions, investment expenditure, and the carbon cycle. The extent of taking uncertainty into account can be said to

40B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

be low, since sensitivity analyses are reported only for oil resources and a limited number of scenarios are generated.

Table 3.1 shows a summary of the models presented in this section. It is important to note that only the most well-known and commonly used energy system models and recent studies that aim to deal with their shortcomings are included in this section. More extensive reviews of the energy system models can be found in (Pfenninger et al., 2014), (Bunn and Larsen, 1997), (Connolly et al., 2010) and (DeCarolis *et al.*, 2012).

3.2.2. Models of Gas Production and Market

In addition to the above-mentioned models which target to represent the whole energy system at the national or global level, there are several studies which focus on modeling the gas production and market. These studies also vary in terms of the modelling methodology they use, their scope and their views on uncertainty, as they are summarized in Table 3.2.

The first group of models are optimization models, which focus on the global or European natural gas trade. These models cover a 30-40 year span, except the GASMOD model of (Holz *et al.*, 2008) which statically compare three alternative models for the European market structure. Among these models, EUGAS centers around a market-clearing mechanism between European traders and suppliers at minimum cost (Perner and Seeliger, 2004), whereas the GASTALE model of the Energy Research Center of the Netherlands (ECN) generates optimal investment values in network and storage capacity for security of supply (Lise *et al.*, 2008). The NATGAS model of the Dutch Central Planning Bureau (CPB) focuses on production rather than trade, and investigates the relation between resource constraints and market power of the producers (Zwart and Mulder, 2006). Similar models are used at the global level, generating how the global gas trade will evolve in future, based on profit maximization decisions of the producers and traders (Hartley and Medlock, 1970; Egging *et al.*, 2010).

In addition to these optimization models, there is a group of studies which approach natural gas production and market with different simulation modeling methodologies such as system dynamics, discrete-event simulation and agent-based modeling. Early system dynamics models focus on the supply side, and aim to estimate the production dynamics of natural gas as a non-renewable source (Naill, 1974; Richardson *et al.*, 1988; Davidsen *et al.*, 1990). Originating from these, later system dynamics models investigate the market dynamics and the impact of policies on the long-term natural gas supply in a particular country, such as Colombia (Olaya and Dyner, 2005, 2008), the UK (Chi *et al.*, 2009) and Argentina (Ponzo *et al.*, 2011). Villada and Olaya (2013) focus on the distinction between the long-term contracts and the spot market of natural gas, and combine discrete-event simulation and agent-based modeling to examine the future dynamics of the Colombian gas market.

Agent-based modeling is also employed for operational problems in the gas market, such as capacity management and balancing of the natural gas network (Bucura *et al.*, 2011; Verhoog *et al.*, 2015). Another agent-based model is the ACEGES model of Voudouris *et al.* (2014), which investigates the future global oil and gas trade. Different from the previous studies, this study suggests to use this model for generating a large number of scenarios to deal with

41A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

uncertainty. Similarly, the study of Popper *et al.* (2009) seeks for robust strategies against deep uncertainty in Israel's natural gas and energy sector, by focusing more on the role of natural gas in the electricity production. This study combines three models, namely a model that generates electricity demand, a model that provides optimal (least-cost) dispatch of this demand on power generation capacity (of various technologies) and the LEAP platform that provides demand and supply interactions between these two models. These three models are combined in the Computer Assisted Reasoning System (CARS) developed by RAND Corporation for scenario generation and robustness testing of policies.

Besides the abundance of model-based studies regarding the natural gas production and markets, there are a few such studies for the newly-emerged renewable gas. The process of biomethane production is analyzed at an operational level production chain framework in only a few studies. These studies mostly have a financial approach, and either analyze the net present value of the production and injection projects (Gebrezgabher *et al.*, 2012; Balussou *et al.*, 2012) or use static calculation models (Bekkering *et al.*, 2010; Butenko *et al.*, 2012). An extensive modeling study regarding renewable gas is conducted by Weidenaar (2014), who focuses on the economic and spatial aspects of the biomethane supply chain and the gas distribution grid in the Netherlands. This model consists of biomass locations, gas grids, and gas consumers, as well as production capacity of biogas and biomethane. The output of the model consists of candidate solutions for a certain region about where to install the production capacity and where to inject the resulting biomethane into the gas grid.

Table 3.2: Summary of the natural gas models reviewed

Name	Reference	Methodology	Scope	Uncertainty treatment
EUGAS	(Perner and Seeliger, 2004)	• Linear optimization model	• 2005-2030, Europe and its suppliers • Market-clearing at minimum cost, perfect competition	• Not reported
GASTALE	(Lise et al., 2008)	• Game-theoretic optimization model	• 2010-2030, Europe and suppliers • To analyze the long term markets and economic impacts of new investments in natural gas corridors, namely pipeline, LNG, and storage facilities with a focus on supply security.	• Uncertainty in the preference of stakeholders is mentioned, but nothing reported about how it is dealt with.
NATGAS	(Zwart and Mulder, 2006)	• Mixed complementarity (optimization) model	• 2007-2032, Europe • To analyze the relations between market power, resource depletion and LNG imports	• Not reported
GASMOD	(Holz et al., 2008)	• Game-theoretic optimization model	• Static, Europe • Exports to Europe and wholesale trade • Three possible market structures, finding that Cournot competition is the most accurate representation, where suppliers generate a mark-up at the expense of the final customer	• Sensitivity analyses for price elasticities
World Gas Trade	(Hartley and Medlock, 1970)	• Linear optimization model	• 2002-2040, global trade • Perfect equilibrium	• Scenario analyses
World Gas Model	(Egging et al., 2010)	• Mixed complementarity (optimization) model	• 2005-2040, global (80 countries) • To explore the world gas trade based on profit maximization of actors such as producers, traders, pipeline operators etc.	• A stochastic version of the model is suggested to deal with uncertainty.
	(Naill, 1974)	• System dynamics	• 1900-2050, US • To represent and examine the implications of the factors controlling the supply of non-renewable resources, and to examine the effectiveness of various policies in alleviating the problem	• Not reported.
	(Richardson	• System dynamics	• 1870-2050, US	• Possibilities of scenario

41B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Name	Reference	Methodology	Scope	Uncertainty treatment
	et al., 1988; Davidsen et al., 1990)		• Evaluating resource estimation techniques; two estimation techniques analyzed are Hubbert lifecycle and USGS geologic analogy methods.	analyses are mentioned.
	(Olaya and Dyner, 2005)	• System dynamics + optimization	• 1995-2030, Colombia • To show the need for modelling support for policy assessment for the sustainability of industry • Natural gas market as an SD model, network operation as an optimization model	• Scenario analysis
	(Olaya and Dyner, 2008)	• System dynamics	• 1990-2050, Colombia • To study the dynamic relationships between markets, exploration and stochastic natural gas discoveries.	• Includes randomness to deal with uncertainty in discoveries, but nothing reported about other uncertainties.
	(Chi et al., 2009)	• System dynamics	• 1987-2030, UK • To investigate the factors influencing the long-term supply and demand of the UK indigenous natural gas and to determine the nature of the system behavior as well as examining the effectiveness of various policies	• Scenario analysis
	(Ponzo et al., 2011)	• System dynamics	• 2005-2025, Argentina • To analyze the effects of the market regulation and intervention on the security of supply	• Scenario analysis
	(Villada and Olaya, 2013)	• Discrete-event simulation combined with agent-based modelling	• 2012-2019 on a daily basis in Colombia • Primary market (long-term contracts) as a discrete-event simulation, spot market as an agent-based model	• Not reported
ACEGES	(Voudouris et al., 2014)	• Agent-based simulation model	• 2009-2035, global level • For oil and gas trade focusing on market structure, without environmental and social factors	• Monte Carlo simulations
RAND's natural gas model	(Popper et al., 2009)	• Simulation + optimization	• 2008-2030, Israel • Combining three models in CARS for robust decision making	• Focus on uncertainty with large number of scenarios used in robust decision making

In this section, the review of energy systems models and then the models specific for the gas sector have revealed two major issues. Firstly, these models lack a systematic consideration of uncertainty, regardless of the modeling methodology used or the time span taken into account. Many studies considered in this review do not report how the model or the analysis deals with uncertainty. There are certainly studies which consider uncertainty, and use one of the techniques discussed in Section 3.3.2, such as sensitivity analysis, scenario analysis or Monte Carlo simulations. However, the extent of these analyses is limited either to a few uncertain parameters (such as elasticities), or a limited number of scenarios. Only a few of these studies suggest exploring the future possibilities and testing the robustness of decision options across these possibilities (Popper et al., 2009; Voudouris et al., 2014), instead of basing decisions on point-estimates. This lack of uncertainty-orientation in energy models is discussed also by Pfenninger et al. (2014) and Pye *et al.* (2015) who emphasize the importance of taking uncertainty into account for a higher credibility of such studies and better advice to decision making.

The second issue is about the scope of these models. They are mostly energy-economy models which take only the technical and economic factors into account, or economy-environment models which still leave social factors out. Besides, many of the whole energy

42A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

system models focus on the competition in the power generation sector. Even though they consider other consumption sectors and different energy sources in these sectors, new technologies emerging in the gas sector such as renewable gas are not in their boundaries yet. Similarly, the gas models reviewed in Section 3.2.2 mostly consider natural gas only. A model that takes different types of gas, such as natural and renewable, and their competition in the market has not been developed and published yet, to our knowledge. Therefore, it can be said that there is no existing model that matches the system boundaries and elements defined in Chapter 2 for the Dutch gas sector.

Thus, based on these two points raised by the review of models used for energy policy problems, it is concluded that a new model is necessary, to match the system description in Chapter 2 and to address uncertainties extensively. Chapter 4 describes the simulation model developed for these purposes. This model is not an adaptation of an existing model mentioned in this section, yet it contains elements from many of these models. Before the model description, the following two sections discuss the approach adopted for this model-based study to deal with uncertainty and the modelling methodology chosen, respectively.

3.3. EXPLORATORY MODELING AND ANALYSIS

In Section 3.1, this study was specified as a model-based policy analysis study taking uncertainties into account systematically and seeking for robust policies. Exploratory Modeling and Analysis is the research methodology selected to combine these two aspects of the required analysis. This section explains what Exploratory Modeling and Analysis is, and why it is chosen.

3.3.1. What is Exploratory Modeling and Analysis?

Exploratory Modeling and Analysis (EMA) is broadly defined as "a research methodology that uses computational experiments to analyze complex and uncertain systems" (Bankes *et al.*, 2013, p. 532). EMA has emerged in response to 'consolidative' models which attempt to represent every aspect of a system by combining known facts so that the future can be projected most thoroughly (Bankes, 1993). This pursuit of completeness and a 'best estimate' future results in broad and detailed models which often drain the resources of a modeling study and fail to address unexpected events in their recommendations. In contrast, exploratory models tend to be simpler and inclusive of uncertain elements rather than of only known facts, and are suggested to be used for exploring the future possibilities rather than generating a 'best estimate' scenario. Based on a large number of computational experiments on a quantitative model, this exploration is suggested as a useful way to deal with long-term policy problems facing deep uncertainty (Lempert et al., 2003). Namely, these computational experiments help to relax model assumptions by taking an alternative representation of model parameters or structures into account in each experiment, and prevent relying on certitude of an assumption. By exploring future possibilities, EMA constitutes a basis for robust decisions, i.e. making static decisions robust against future uncertainty, and for adaptive policy design, i.e. making decisions that can be dynamically changed over time (Lempert et al., 2003; Walker, Haasnoot, *et al.*, 2013).

42B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Whether it is named EMA or Robust Decision Making (RDM), this approach of seeking robust decisions to deal with deep uncertainty by analyzing a large ensemble of future scenarios has been developed through and used in a variety of studies. For instance, Davis (2003) discusses the implications of model resolution, i.e. the detail level of a model, in decision analysis, and the use of simple models for exploring future scenarios. Lempert *et al.* (2006) demonstrate the use of this approach for generating robust pollution-control strategies in an iterative way, i.e. by determining candidate strategies and then improving them based on their vulnerabilities, which are the uncertainties that cause these policies to underperform. Agusdinata (2008) investigates and demonstrates the use of EMA on three cases from the energy and transport domains, in combination with several other methods such as real options analysis, multi-criteria decision analysis and simulation modeling. Kwakkel and Pruyt (2013) study the usability of EMA in future-oriented technology analysis by demonstrating its implementation in three cases, i.e. with three simulation models based on three methodologies, namely a system dynamics model, a hybrid model and an agent-based model.

Currently, applications and development studies of EMA focus on two major techniques: scenario discovery and multi-objective robust optimization. These techniques are either used for analyzing static robust policies or designing adaptive policies eventually. The first technique, namely scenario discovery aims to identify uncertainties responsible for generating a particular set of outcomes by using data mining algorithms. Classification and Regression Trees (CART) and Patient Rule Induction Method (PRIM) are two algorithms that can be effectively used for scenario discovery as concluded by Lempert *et al.* (2008), of which PRIM has become the most commonly used one. Groves and Lempert (2007) and Bryant and Lempert (2010) have introduced and established the use of the PRIM algorithm for scenario discovery. Kwakkel *et al.* (2013) demonstrate the use of this algorithm with time-series patterns as the outcomes of interest, while Dalal *et al.* (2013) investigate different versions of the algorithm for more accuracy in the results. In terms of its applications, this scenario discovery technique is used for identifying uncertain conditions that lead to a particular set of scenarios (McJeon *et al.*, 2011; Rozenberg *et al.*, 2014) and vulnerabilities of a policy (Lempert and Groves, 2010; Lempert, 2013; Eker and van Daalen, 2015), or it is embedded in adaptive policy design to detect signposts in the system that require adaptation of a policy (Hamarat *et al.*, 2013).

The second technique, namely multi-objective robust optimization, is mainly used to identify tradeoffs between multiple objectives under uncertainty (Kasprzyk *et al.*, 2009) and to determine (static) robust policies (Kasprzyk *et al.*, 2013; Eker and van Daalen, 2015). Besides, multi-objective robust optimization is used in adaptive policy design for identifying adaptation conditions, i.e. when to adapt a policy (Hamarat *et al.*, 2014) and for selecting robust adaptation pathways (Kwakkel *et al.*, 2014). However, there are many metrics that can be used to quantify robustness in a robust optimization analysis (Herman *et al.*, 2015). Kwakkel and Haasnoot (2015) compare several of these metrics, yet finding robustness metrics that can capture various aspects of performance of a policy against uncertainties and that can be computationally applicable remains as a challenge.

43A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

3.3.2. Why Exploratory Modeling and Analysis?

To deal with uncertainty in model-based decision support, EMA is certainly not the only methodology. Many analytical methods have long been used in the literature, and reviews of these methods can be seen in (Morgan *et al.*, 1992, p. 172-216; van der Sluijs *et al.*, 2004; Agusdinata, 2008, p. 10). Based on these reviews, five main methods can be named, being sensitivity analysis, uncertainty propagation, statistical methods, decision analysis and scenario analysis.

Sensitivity analysis is "the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli *et al.*, 2008, p. 1), aiming to determine importance of inputs with respect to the uncertainty in the output. Yet, sensitivity analysis practices usually take narrow ranges of uncertainty into account, and maintain the assumption of a best-estimate future. *Uncertainty propagation* is the analysis of uncertainty in the outputs of a model, induced by the uncertainty in the inputs (Morgan et al., 1992, p. 172). For example, Monte Carlo simulations on a model determine the uncertainty ranges of outputs based on the uncertainty of inputs. This approach constitutes a strong basis for investigating the effects of uncertainty, yet it requires further analysis to transform the knowledge of output uncertainty into insights for decision support. *Statistical and stochastic methods* apply probability theory to interpret the quantitative data and generate statistical indicators of uncertainty in the outcomes, such as mean value, variance, confidence intervals or probability distributions (Agusdinata, 2008). These methods, and also stochastic optimization, assign particular probability distributions to the inputs, which may not be elicited with certainty in the case of complex socio-technical systems and policy problems. *Decision analysis* aims to find the best decision based on an expected value, given the likelihood of future events their impacts with a Bayesian approach (Raiffa, 1968; Keeney 1982), e.g. with decision trees (Sage and Armstrong, 2000, p. 388). Real options analysis is a similar method commonly used in infrastructure design and investment decision, focusing only on two probable events such as the success or failure of a decision and two decisions alternatives such as act or do nothing (Mun, 2002). Despite the systematic representation of a decision problem, decision analysis is not adequate in the cases where likelihoods are not known and possible events are many. Lastly, *scenario analysis* is the method of describing a set of logical and internally consistent events to investigate how the future might, could or should unfold (van der Sluijs et al., 2004). In addition to an understanding about the effects of uncertainties on the system, this method enables using 'decision making under uncertainty' tools such as MaxiMin, MaxiMax, Hurwicz or Savage criterion (Sage and Armstrong, 2000, p. 384-387) to determine a good decision without prior information on uncertainties. The drawback of this method is the focus of common practice on a limited number of scenarios, such as the best or worst case scenarios, and on a limited number of factors included in the scope of such scenarios.

As the review in Section 3.2 shows, these methods are used in many modeling studies for the energy system and natural gas problems. For instance, stochastic versions of optimization models have been developed (e.g. MARKAL and World Gas Model), sensitivity analyses are conducted either to test the robustness of the model or to determine significant uncertainties

43B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

(e.g. GASMOD, EFOM), Monte Carlo simulations are used to propagate the effect of uncertainties on the outcomes (e.g. ESME, TEMOA) or the models are used for scenario generation and analyses (e.g. PRIMES, Threshold21). However, these implementations tend not to address uncertainty in a systematic manner as pointed out by Pye et al. (2015), and they inherit the shortcomings of each method, such as assigning certain probability distributions, incorporating only a limited number of alternative futures or lack of insights about decision making.

EMA addresses uncertainty in a systematic way and combines several of the above-mentioned methods. That is, in EMA uncertainties are systematically propagated on the model outcomes as the first step, and the important uncertainties are identified, if necessary, with scenario discovery techniques. Then, the decision alternatives are evaluated based on the set of scenarios generated with several possible techniques, as in traditional scenario analysis but by using computational power. Therefore, EMA is advantageous compared to these methods, as demonstrated and discussed by Agusdinata (2008, p.238-243): Compared to sensitivity analysis which usually provides a ranking of uncertainties, EMA provides complementary insight about at what value or in what range of values an uncertainty is important. Besides, not only parametric but also functional, structural and methodological uncertainties are taken into account in EMA, whereas sensitivity analysis practices and Monte Carlo simulations focus only on parametric ones. Compared to probabilistic methods and decision analysis, EMA is less dependent on probability distributions, of which specifications are usually uncertain, too. This reduced dependence is due to it being a scenario-based approach, i.e. treating the model outcomes as a result of what-if assumptions rather than events with a particular likelihood. In other words, EMA evaluates policy robustness without specifying probability distributions, hence eliminates questioning the plausibility of these distributions. Lastly, compared to traditional scenario analysis, EMA is a more extensive practice, due to the computational power that enables generating a much larger set of scenarios and facilitates identifying elements of surprise.

Thus, based on the abovementioned advantages of EMA over existing analytical methods to deal with uncertainty and the need to address uncertainties more systematically in model-based studies for energy policy problems, EMA is chosen as the primary research methodology in this study. This choice requires using a computational model to generate scenarios and a framework to assess policies across these scenarios. In this study, a new computational model is developed instead of using an existing model, due to the absence of a model that matches the system boundaries as discussed in Section 3.2.2. The methodology chosen for developing this model will be discussed in the next section, whereas the model itself will be described in Chapter 4 and the analysis framework will be introduced in Chapter 6.

3.4. SYSTEM DYNAMICS

System dynamics is chosen as the modeling methodology to develop a quantitative system model to represent the policy domain described in Chapter 2 and to generate scenarios by application of EMA. This section briefly describes the systems dynamics methodology, and explains why it is chosen.

44A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

3.4.1. What is System Dynamics?

System Dynamics (SD) is a modelling methodology used to analyze and understand the behavior of dynamic complex systems based on causal relations and feedback loops. It emerged in the late 1950s, originating from Jay Forrester's work on combining concepts and tools from control engineering, cybernetics, organizational theory and information technology and applying them to long-term, dynamic socio-economic problems (Meadows, 1980). These initial studies resulted in prominent and renowned projects and models in the system dynamics field, such as Industrial Dynamics (Forrester, 1961), Urban Dynamics (Forrester, 1969) and World Dynamics (Forrester, 1971; Meadows *et al.*, 1971). Mathematically speaking, the system dynamics methodology is based on integral equations, where variables that accumulate over time are represented by 'stocks' and the rates of change of these variables are represented by 'flows'. Following this, simulating a model is equivalent to integrating the equations which represent flow variables. A comprehensive review and explanation of system dynamics modelling can be seen in (Randers, 1980), (Coyle, 1996), (Sterman, 2000) and (Barlas, 2007).

The two main characteristics, i.e. main assumptions, of the system dynamics methodology are the causal feedback loop thinking and a high aggregation level. With causal feedback loop thinking, the system elements are conceptualized based on causal relations between them, and closed chains of these relations are assumed to create the complexity and nonlinear dynamics of the system. In other words, dynamic changes in the system are assumed to be caused by these closed chains, i.e. feedback loops, and the system behavior is explained by internal factors. Modeling a system in such a way that is based on causal relations and feedback is also an attempt to understand it, without trying to predict its behavior or to prescribe solutions for obtaining desired dynamics. In this regard, system dynamics models differ from econometric models which try to forecast system behavior based on statistical correlations or economic theories, and from optimization models which describe how a system should behave. Thus, system dynamics models are categorized as descriptive models, alternative to predictive and prescriptive models.

The second main assumption in system dynamics modelling is a high aggregation of entities and events. This high aggregation results in homogeneity of actors and decisions in a system dynamics model, unless the modeler considers a distinction between them. To express this high aggregation level, Schieritz and Milling (2003) use an analogy between SD modelling and modelling a forest, instead of modelling the trees in that forest. According to Schieritz and Milling (2003), this high aggregation and the top-down view stems from the importance given to the model structure and relations between the elements, rather than the actions and rules. Yücel (2010, p.47) also differentiates between relation-driven and action-driven simulation modeling methodologies, and places system dynamics in the relation-driven group. Still, the level of aggregation in a system dynamics model is a choice the modeler makes for each problem. Regarding this, Yücel (2010, p.49) distinguishes between two types of aggregation, such as macro-level and micro-level, and most system dynamics models fall into the first group. The micro-level models, according to Yücel (2010), focus on individual elements more, such as the supply chain models of Sterman (2000, p.709-757) which

44B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

differentiate between wholesalers and retailers, and individual vehicle choice in Struben's models (Struben, 2006). Recently, more SD models tend to take an agent-perspective and demonstrate different ways of incorporating individuals or heterogeneity in SD models, either by developing hybrid system dynamics and agent-based models (Martinez-Moyano *et al.*, 2007; Duggan, 2007), or having an agent-perspective in system dynamics models (Feola *et al.*, 2012; Fallah-Fini *et al.*, 2013).

In practice, system dynamics modeling includes five major steps as problem identification, conceptualization, formulation/specification, model testing and model use (Sterman, 2000; Randers, 1980). The first step refers to articulation of the problem with the main components of the system and model boundaries, as presented in Chapter 2 in this thesis. Model conceptualization involves building a qualitative backbone of the model, such as the causal relations and loops in the model and formulation of a dynamic hypothesis. The specification step is where the model equations are formulated quantitatively, and the numeric values of model parameters and tabular functions are set. Model testing includes subjecting the model to a series of verification and validation tests, to assess if the resulting model fits the initial purpose and provides a useful representation of reality. Following these tests, the last step refers to using the model for the purpose of the study, such as understanding the system, policy evaluation or scenario generation. In addition to these five steps, communication of the model itself or the results plays an important role in the modeling cycle.

3.4.2. Why System Dynamics?

In this study, the system model introduced in Chapter 2 is transformed into a simulation model by adopting the system dynamics methodology. This choice is motivated by three main reasons. First, the descriptive nature of system dynamics models is considered appropriate for the main purpose of the simulation model in this study, which is generating scenarios to explore the future. Second, the focus on relations between the elements and feedback loops is seen useful to capture the complexity of the problem in the gas sector, and to seek robust polices based on long-term dynamics. Last, the relatively limited computational power required to simulate system dynamics models is viewed as beneficial when conducting a large number of simulations to explore the future and analyze policies.

Regarding the fit between the descriptive nature of system dynamics and Exploratory Modeling and Analysis, our argument is based on the preference to create descriptive scenarios for the exploration of the future. In scenario analysis, scenarios are often distinguished as descriptive and normative ones, where the former refer to possible, non-intervention futures, and the latter refer to preferable futures (Van Notten *et al.*, 2003). Technically, it is possible to implement EMA with a prescriptive model that generates normative scenarios, yet the exploration in this case is expected to be bounded by the worldview embedded in that model, e.g. cost minimization, that describes how the future should be. Therefore, a system dynamics model is considered to have a better capability to capture uncertainties and generate a variety of future scenarios without imposing a certain view about how the future should develop.

45A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The second reason for selecting to build an SD model is its relation-driven structure and dynamic behavior being suitable for seeking robust policies. Long-term policy analysis focuses on the future states of the system over a time-span. SD models create continuous dynamic behavior in such a time span, and the resulting transient scenarios provide a basis to evaluate robustness of policies. As discussed before, the relation-driven nature of SD models result in a high aggregation level, which is a disadvantage when the problem of interest arises because of the relation between individual actors or events. However, this study seeks to find robust policies by considering the main components of the gas system at a strategic level. In this case, a high abstraction level suffices to generate long-term scenarios, without necessitating the heterogeneity of system elements and actors, especially when the computational advantage of an SD model is considered, which is the third reason to opt for such a model.

Using SD models in EMA is discussed in more detail by Kwakkel and Pruyt (2015) who compare the core ideas of the approaches. They stress that the major implication of EMA in SD practice is the need to emphasize multiple perspectives and multiple models, instead of a single model and a single dynamic hypothesis. As for the applications, SD models are used in EMA studies to obtain internally consistent and plausible scenarios in various domains, such as energy transitions (Pruyt *et al.*, 2011; Loonen *et al.*, 2013), resource scarcity (Auping *et al.*, 2012; Eker and van Daalen, 2013), epidemics (Pruyt and Hamarat, 2010; Eker *et al.*, 2014; Pruyt *et al.*, 2015) and radicalization (Pruyt and Kwakkel, 2014).

3.5. CONCLUSIONS

This chapter outlines the methodology of this thesis work by narrowing it down step-by-step from the overarching discipline to operational choices. Positioned in the policy analysis discipline with a rational and client-advice style, this study is firstly specified as a (quantitative) model-based analysis which focuses on uncertainties and seeks robust policies. Then, in order to guide the development and use of a system model and to generate scenarios to be used for the search of robust policies, Exploratory Modeling and Analysis is chosen as the computational research methodology. The main reason for this choice is the ability of EMA to treat deep uncertainties systematically with a large set of future scenarios leading to policy insights, and without requiring specific probability distributions. Following this, the choice of system dynamics as the modeling method to be combined with EMA further specified the methodology of this thesis work. As for the main motivation behind this choice, it was the descriptive nature and long-term, high abstraction level of scenarios generated by a system dynamics model to be suitable for exploring future possibilities extensively and for developing robust strategies.

As an intermediary step, this chapter included a review of the existing system models used for energy policy problems. From this review, it is concluded that existing model-based studies lack a systematic consideration of uncertainty in their models, analyses and resulting policy recommendations. Besides, none of these models could capture the scope of the policy problem defined in Chapter 2, i.e. the competition specifically in the gas market between natural and renewable gas options with technological, economic and social factors. Therefore, it has been decided to develop a model that matches the previously defined system boundaries

45B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

of this study, and that takes uncertainties into account comprehensively. The following chapter will describe this system model with its main assumptions and detailed formulations.

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48A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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48B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm



"This is not a pipe."

The Treachery of Images

René Magritte, 1929
Los Angeles County Museum of Art, Los Angeles, CA

49A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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4

A SUPPLY-DEMAND MODEL FOR THE DUTCH GAS SECTOR

Chapter 2 described the system of interest within the gas sector, with its main components and boundaries, as well as the outcome indicators derived from the interests of actors, potential policy alternatives and uncertainties. As explained in Chapter 3, the effects of these policy alternatives and uncertainties on the outcome indicators will be analyzed based on an ensemble of scenarios. Therefore, a platform is needed to generate internally consistent and plausible scenarios within the boundaries of the system of interest. This chapter presents such a platform, a system dynamics simulation model, developed for the purpose of representing the system of interest and generating future scenarios.

In the first section of this chapter, an overview of the simulation model is presented, and main assumptions about the scope are discussed. The following three sections describe three main segments of the model, namely the supply, demand and market subsystems, respectively. The description of each sub-model in these sections explains both the main assumptions of this sub-model generally, and the formulations of its equations in detail. (Therefore, the list of equations can be skipped by readers who are not interested in formulations.) Lastly, Section 4.5 concludes this chapter with a brief discussion on the model, and with a reflection on its main assumptions.

4.1. OVERVIEW OF THE MODEL

In Chapter 2, it is stated that the system model conceptualizes the Dutch gas sector in a supply-demand view. Complying with an energy-economy model, this view focuses on the consumer demand on the one hand, the supply sources on the other, and the infrastructure and market balancing these two in the middle. By an analogy with a lever on a rolling fulcrum, this view was depicted in Figure 2.3, which constitutes the conceptual basis of the simulation model to be described in this chapter. The simulation model includes the three main segments of this figure, being the supply, demand and market, excluding the infrastructure because the

50A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

production infrastructure is included in the corresponding supply sub-model, and the transport infrastructure is not in the scope of this study as explained in Chapter 2.

Figure 4.1 illustrates an overview of the simulation model with the three major sub-models and with the connections between them. These connections are the model variables determined in one of the sub-models, and used in another one. As the figure shows, the supply sub-model produces the production rates and costs of each supply source, which are used in the market sub-model to determine the price. Price-setting in the market reflects the competition between supply sources, as the eventual price value is used in the supply sub-model to determine profitability, and hence further production and the market share of these sources. The price variable is also used in the demand sub-model since consumer demand changes as price changes. The demand volumes determined in this sub-model are used in the market sub-model for price-setting in return, to indicate the effect of the supply/demand balance. Between the supply and demand sub-models, the demand volumes determined in the latter are major factors used in the supply sub-model to determine production rates or import volumes. From the supply sub-model to the demand, the link is the societal acceptance of natural gas production, which determines the demand flow between natural and renewable gas via consumer preference.

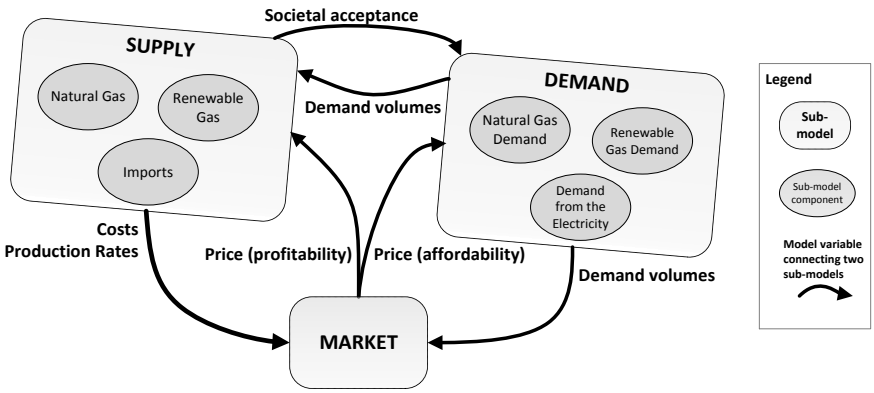


Figure 4.1: Overview of the simulation model

Being a system dynamics model and considering the national gas sector, this model concentrates on the total or average values of system variables at a high aggregation level. For instance, the production rate of natural gas does not represent the production from a single natural gas field based on a decision of a single producer, but the total production rate from all such fields, based on a decision of the totality of producers, assumed to be a homogenous group. With this homogeneity assumption, this model includes the actions and decisions of several actor groups in addition to the above-mentioned system components, as the drivers of change in the system. Table 4.1 lists these actors and their actions included in the model. It must be noted that the government is not included in this list, since its actions will be analyzed in later chapter.

50B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Table 4.1: Actors and their actions and decisions included in the simulation model

Actor	Actions/Decision variables
Natural gas producers	Investment in exploration and development Production profile Desired natural gas price
Renewable gas producers	Capacity installation Desired renewable gas price
Traders	Expected market price Import volumes
International traders	Import price
TSO	Import capacity installation
Gas consumers	Natural and renewable gas demand Switching to electricity
Electricity producers	Capacity installation and utilization

The following three sections describe the supply, demand and market segments of the model, respectively, with their sub-models including the actions and decisions of the above-mentioned actors.

4.2. SUPPLY SIDE

As mentioned before, three main supply sources are taken into account in this study, being the domestically produced natural gas, renewable gas, and imported natural gas. Equation 1 shows the *Total Supply (TS)* in the Dutch gas market as the sum of contributions from these three sources, namely *Total Production Rate of Natural Gas (TPR_{NG}), Total Production Rate of Renewable Gas (TPR_{RG}),* and *Total Import Volume (TIV)*. The sections below will describe the model structures corresponding to each of these supply options.

$$TS(t) = TPR_{NG}(t) + TPR_{RG}(t) + TIV(t) \quad (1)$$

4.2.1. Natural Gas Production[5]

As mentioned in Section 3.2.2, several system dynamics models that investigate natural gas or petroleum resources exploration and production have been described in the literature (Davidsen *et al.*, 1990; Dyner *et al.*, 1998; Olaya and Dyner, 2008; Chi *et al.*, 2009), which originate from an early model of Naill (1974). The model developed in this study is similar to these models, in terms of the relation between the exploration and production activities and the corresponding investments, and the factors that affect investments such as price and demand. However, this model is different than those in terms of three main aspects: First, a more detailed lifecycle structure of natural gas fields is implemented in this model, as will be explained further below, in order to test policies specific to the Netherlands and to different steps of the extraction process. Secondly, this model includes the societal acceptance of natural gas production and its effects on investments, due to the recent developments in the Netherlands and in the world regarding this issue. Lastly, having the general purpose of focusing on uncertainties to generate a large number of future scenarios, this model includes several parametric and structural uncertainties, i.e. the model formulations representing different assumptions that could be made for the same phenomenon.

[5] Earlier versions of this model are published in (Eker and van Daalen, 2012), (Eker and van Daalen, 2013a) and (Eker and van Daalen, 2013b).

51A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Natural gas is extracted from the large Groningen field, and on- and offshore small fields in the Netherlands. These two types of natural gas production are taken into account separately in the model, in order to represent different regulations for these and to be able to test policies specific to each of these. Being a natural gas type with different technological characteristics and cost values, shale gas production is assumed to have the same model representation as the other two types of natural gas, once it is allowed to be produced. The *Production Rates* (*PR*) of these three types of natural gas constitute the *Total Natural Gas Production Rate (*TPR_{NG}*)*, as Equation 2 shows. Technically, these three types of natural gas are denoted with the subscripting feature of Vensim DSS on the same model structure, and they are not explained separately in the sections below, unless necessary. Namely, the equations describing the model do not contain any indices corresponding to these three types, as long as there is no difference between their equations.

$$TPR_{NG}(t) = \sum_{i} PR_i(t) \quad ; \text{ i = Groningen, small fields, shale} \tag{2}$$

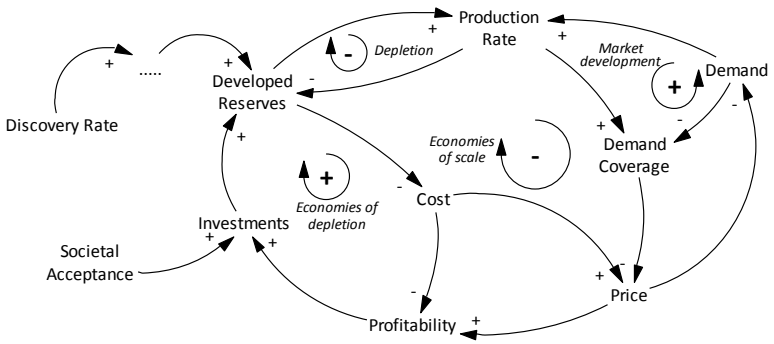


Figure 4.2: A simplified causal loop diagram of the natural gas production

Figure 4.2 summarizes the main causal relations and loops governing the natural gas production mechanism in the model. In this diagram, an arrow denotes a causal link between two variables, and the sign next to it signifies the polarity of that causal link. If a change in the first variable changes the second variable in the same direction, then the polarity is positive, otherwise it is negative. The Depletion Loop is the main loop in the field lifecycle, implying that increased production depletes the reserves, which reduces further production. Regarding the investment of producers to stimulate production (and new discoveries), the Economies of Depletion is a reinforcing loop, which means that depletion due to increasing *Production Rate* increases the unit cost, leading to a price increase which makes the investments in production more attractive. The Economies of Scale loop, however, is a balancing loop which describes the increased production reducing price, which further reduces the investments, and hence the production rate. Lastly, the Market Development loop summarizes the supply-demand relation in the market, where high production decreases the price, and hence increases the demand, which further increases the production. This aspect of the model is further explained in Section 4.4. The next three sections will describe the natural gas sub-model in three parts, namely the field lifecycle describing the technical system, the economics section explaining the decision making of producers about investments and other economic aspects, and the

51B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

societal acceptance section describing how this social phenomenon is incorporated into the model.

Field lifecycle of natural gas production

The technical subsystem of natural gas production is modelled based on the field lifecycle which is composed of exploration, appraisal, development and production phases (Jahn *et al.*, 2008), and in correspondence with the resource and reserve terminology of the Society of Petroleum Evaluation Engineers (SPEE, 2002) and the Dutch exploration and production company EBN (EBN, 2013). This terminology includes four categories of resource base, namely *Prospective Resources*, *Contingent Resources*, *Undeveloped Reserves* and *Developed Reserves*, unlike the previous system dynamics models that have only two categories as discovered and undiscovered resources. The reason for this distinction was the delays from discovery to production that can strongly affect the producible volume, and the actions that should be taken at different stages to keep this volume high. These four categories of the resource base are represented by a chain of stock variables as shown in Figure 4.3, since they accumulate over time as new discoveries and developments flow in or out.

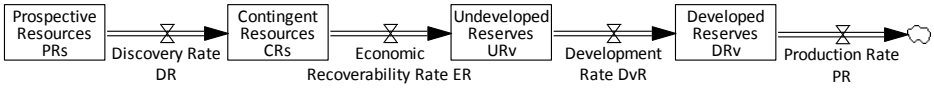


Figure 4.3: Stock-flow structure of the natural gas production sub-model

As explained in Section 3.4, stock variables in the systems dynamics methodology are mathematically the integrals of the summation of the flows that affect them. Equation 3 demonstrates this formulation for the *Developed Reserves (DRv)*, where the inflow of this stock variable is *Development Rate (DvR)* and the outflow is *Production Rate (PR)*. The rest of this section focuses on the formulations of the flow variables. Besides, the volume unit used in these formulations is billion cubic meters (bcm), where 1 bcm gas has the equivalent calorific value of 1 bcm Groningen gas.

$$DRv(t) = DRv(0) + \int_{t_0}^{t} \left(DvR(\tau) - PR(\tau) \right) d\tau \tag{3}$$

The *Discovery Rate (DR)* is the flow variable representing new natural gas discoveries as a result of exploration activities. As seen in Equation 4, it is formulated as the ratio of *Effective Investment in Exploration (*INV^*_{exp}*)*, which is on the scale of billion euros per year, to the *Unit Cost of Exploration (*C_{exp}*)*, which is on the scale of euros per m^3 of gas discovered. The unit cost is a variable that increases over time with respect to the ratio of *Prospective Resources (PRs)* to its initial value (total undiscovered resources) as shown in Equation 5. This increase in the cost reflects the 'creaming effect', which means that as the amount of undiscovered resources declines with discoveries, it becomes more difficult, hence more costly to find new fields. Due to this limitation, the cumulative number of discoveries follows a logarithmic growth pattern, also named 'creaming curve' in the petroleum engineering terminology (EBN, 2012). Therefore, since the change rate of logarithmic growth linearly decreases, the unit cost is assumed to be linearly dependent on the ratio of initial *Prospective Resources (PRs)* to its current value.

52A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$DR(t) = \frac{INV^*_{\exp}}{C_{\exp}(t)} \tag{4}$$

$$C_{\exp}(t) = C_{\exp}(0)\frac{PRs(0)}{PRs(t)} \tag{5}$$

Economic Recoverability Rate (ER) is formulated as a fraction of the *Contingent Resources (CRs)*, which represent the stock of discovered but economically not viable resources. This fraction is a variable depending on the *Profit Percentage of Natural Gas (PP_{NG})* and formulated as the multiplication of a base value of this fraction (ρ_{ER}) and the *Effect of Price on Economic Recoverability ($f_{p,ER}$)* which is an increasing graphical function. Equation 6 denotes these formulations.

$$ER(t) = CRs(t) * \rho_{ER} * f_{p,ER}(PP_{NG}) \tag{6}$$

With economic recoverability, *Contingent Resources (CRs)* become *Undeveloped Reserves (URv)*, which is the group of resources economically viable to extract, but has not been developed yet for production, i.e. there is no infrastructure installed in the field. The *Development Rate (DvR)* represents the rate of conversion from undeveloped to developed reserves with such infrastructure installation and similar activities. It is formulated similar to the *Discovery Rate (DR)*, as the ratio of *Actual Investment in Development (INV^*_{dev})* to the *Unit Development Cost (C_{dev})* (Equation 7). Unlike the exploration cost, the development cost is assumed to be constant over time, since the factors that change it, such as rig availability, field location etc., are not included in the scope of this study.

$$DvR(t) = \frac{INV^*_{dev}(t)}{C_{dev}} \tag{7}$$

Production Rate (PR) is formulated differently for the Groningen and small fields production, because the Groningen field is given a 'swing producer' position, which implies that the demand is first satisfied by the small fields production, then the Groningen field is used to meet the remaining demand. As seen in Equation 8, *Production Rate of Small Fields (PR_{Sf})* is stimulated by the *Total Natural Gas Demand (TD_{NG})*, which is the sum of domestic (Dutch) natural gas demand and international demand for the Dutch gas. However, with a 'min' formulation, it is limited by the production profile, which is formulated as the ratio of *Developed Reserves* to the *Average Lifetime of Small Fields (T_{Sf})*. This lifetime parameter actually represents a preference of producers about how long they want to maintain the reserves. *Production Rate of the Groningen Field (PR_{Gr})* is formulated similarly in Equation 9 , except that the demand from the Groningen field is the difference between the total demand (TD_{NG}) and the supply from small fields (PR_{Sf}).

$$PR_{Sf}(t) = \min\left(TD_{NG}(t),\ DRv_{Sf}(t)/T_{Sf}\right) \tag{8}$$

$$PR_{Gr}(t) = \min\left(TD_{NG}(t) - PR_{Sf}(t),\ DRv_{Gr}(t)/T_{Gr}\right) \tag{9}$$

Economics of natural gas production

As mentioned before, investments in exploration and development are what stimulates the production of natural gas. As shown in Figure 4.2, profitability and societal acceptance are the two factors that affect the investments. Additionally, the expected future demand and the

52B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

availability of resources targeted by the investments, such as the volume of estimated *Prospective Resources*, are two other factors important in the investment decision of producers. This section explains how the effect of these four factors and the eventual investment decisions are formulated, first for the exploration investments, then for the development.

Annual investments both in exploration and production are quantified in billion euros per year. *Intended Investment in Exploration ($IINV_{exp}$)* is the multiplication of a reference amount of investment, namely *Normal Intended Investment in Exploration (INV^0_{exp})* and the effects of three factors being the *Effect of Prospects on Exploration ($f_{exp,PRs}$), Effect of Profitability on Investments (f_{pr}),* and *Effect of Societal Acceptance on Investments (f_{SA})* (Equation 10). All of these three effects have a positive impact on the investments, and they are formulated with increasing graphical functions. The inputs of these functions are normalized *Estimated Demand Coverage of Prospective Resources (C_{PRs}), Profit Percentage of Natural Gas Production (PP_{NG}),* and *Societal Acceptance (SA)*, respectively, as shown in Equations 11-13. While the last two of these inputs will be explained later, *Estimated Demand Coverage of Prospective Resources (C_{PRs})* is formulated as in Equation 14, indicating for how long the current value of *Prospective Resources* meet the domestic natural gas demand (D_{NG}), if it remains the same. Although the three graphical functions are approximately determined for the base case and they are highly uncertain, Figure 4.4 shows their initial (base case) forms.

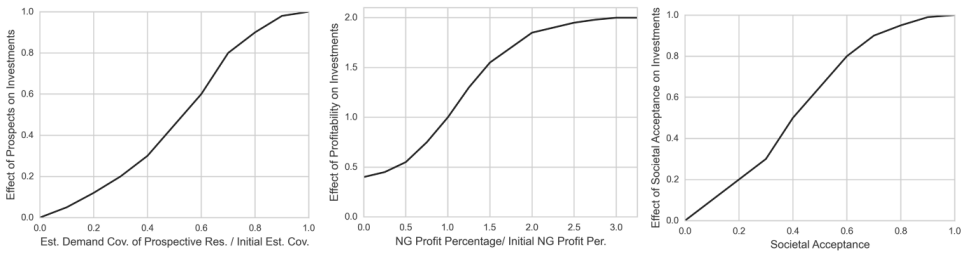
$$IINV_{\exp}(t) = INV^0_{\exp} * f_{\exp,PRs}(t) * f_{pr}(t) * f_{SA}(t) \quad (10)$$

$$f_{\exp,PRs}(t) = f_{\exp,PRs}\left(C_{PRs}(t)/C_{PRs}(0)\right) \quad (11)$$

$$f_{pr}(t) = f_{pr}\left(PP_{NG}(t)/PP^0_{NG}\right) \quad (12)$$

$$f_{SA}(t) = f_{SA}\left(SA(t)\right) \quad (13)$$

$$C_{PRs}(t) = PRs(t)/D_{NG}(t) \quad (14)$$



(a) *Prospects* **(b)** *Profitability* **(c)** *Societal Acceptance*

Figure 4.4: Graphical functions showing the effects of three factors on Exploration Investments

In addition to the above formulation for intended investment, *Actual Investment in Exploration* (*$AINV_{exp}$*) reflects the effect of requirement for exploration (to be able to meet future demand) on the investments. For this effect, producers are assumed to follow a stock-control approach. In other words, it is assumed that producers try to maintain a certain volume of *Contingent Resources*, hence make their decisions based on a required exploration rate. To define the required exploration rate, the stock management structure of Sterman (2000, p. 668) is adopted. In this structure, *Required Discovery Rate (DR_{req})* is modeled as the sum of

53A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

an adjustment for the stock variable (*Contingent Resources*) and an expected loss rate in this stock, as denoted by Equation 15. The first part of this element shows the stock adjustment, as the first order delay of the nonnegative difference between the initial and current *Contingent Resources*, where d_{Adj} is the *Adjustment Delay*. The second part is the expected loss rate of this stock, which a first order information delay of its outflow, namely the *Economic Recoverability Rate (ER)*. Vensim's SMOOTH function is used to represent this information delay (Ventana, 2009).

$$DR_{req}(t) = \frac{\max\left(CRs(0) - CRs(t),\ 0\right)}{d_{Adj}} + \text{SMOOTH}\left(ER(t),\ d_{Adj}\right) \tag{15}$$

The effect of required discoveries on investment is determined with respect to the ratio of required to intended discovery rate. *Intended Discovery Rate* is the division of *Intended Investment in Exploration ($IINV_{exp}$)* by the *Unit Cost of Exploration (C_{exp})* as in Equation 16. As shown in Equation 17, *Actual Investment in Exploration ($AINV_{exp}$)* is the multiplication of *Intended Investment in Exploration ($IINV_{exp}$)* by an increasing function of which the input is the normalized ratio of required to intended discovery rate. The base run shape of this function is shown in Figure 4.5. Since the discoveries take time, there is a delay between the actual investments, and the effective investments that determines the discovery rate. Therefore, *Effective Investment in Exploration (INV^*_{exp})* used in Equation 4 is formulated with a first order material delay, i.e. *Actual Investment in Exploration ($AINV_{exp}$)* divided by the discovery delay (d_{dis}).

$$DR_{int}(t) = IINV_{exp}(t) / C_{exp}(t) \tag{16}$$

$$AINV_{exp}(t) = IINV_{exp}(t) * f_{req}\left(DR_{req}(t) / DR_{int}(t)\right) \tag{17}$$

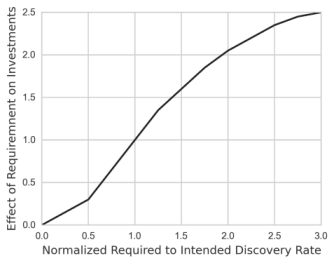


Figure 4.5: Graphical function showing the effect of requirement on exploration investments

This model structure for the decision making of producers on exploration investments is used also for the development investments with a few differences. The first difference is the absence of the effect of prospects, hence *Intended Investment in Development* covers only the effect of profitability and societal acceptance on the normal investment level. However, since producers do not invest if there are no reserves in the 'undeveloped' category, *Actual Investment in Development* includes the effect of available *Undeveloped Reserves.* The third difference is the formulation of *Required Development Rate.* This variable is also formulated with a stock management approach, as in the case of *Required Discovery Rate*, yet the desired level of the stock variable for adjustment is determined differently. This desired level was the initial value of *Contingent Resources* for discoveries, assuming that producers aim to maintain this level, but for development, it is assumed to be the multiplication of the current production

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rate by the desired lifetime of the reserves. This assumption is based on the assumption that producers aim to maintain the current production rates for a particular duration of time.

Regarding the economics of natural gas production, in addition to investments, two other model mechanisms are the calculation of costs and how producers determine their desired price to be influential in the market price-setting. These two components of the model will be described below briefly.

The *Total Unit Cost (TUC_{NG})* of natural gas production has three components, being the exploration cost, development cost and production cost. For the exploration and development cost of one unit og gas extracted immediately from the *Developed Reserves,* it must be noted that these are not equal to the unit costs of exploration and development *(C_{exp} and C_{dev})* because of the delays between exploration and production. The effect of these delays is modeled with a co-flow structure explained in Appendix 4.1, and the average development cost and average exploration cost of one unit of developed reserves is added to the *Unit Production Cost (C_{prod})* as shown in Equation 18. As for the production cost, it is based on a well-known phenomenon in the natural gas production, which is the increase in the production costs as the reserves deplete, due to decreasing reservoir pressure and production becoming more difficult. This increase in the cost is formulated in the model with respect to the ratio of *Developed Reserves* to its initial value, and with an increasing function as shown in Equation 19 and Figure 4.6, where C^*_{prod} is the reference production cost. This formulation is based on two assumptions: According to the ideal gas law, under constant (reservoir) volume and temperature, a change in the amount of gas inversely affects the pressure, hence the rate of decline in the amount of gas is equal to the rate of decline in reservoir pressure, and the rate of cost increase to replace this pressure. However, producers do not continuously invest in increasing this pressure when the amount of remaining gas is very low (Jahn et al., 2008, p.123). Therefore, the function in Figure 4.6 saturates as the ratio of initial gas to the remaining one increases.

$$TUC_{NG}(t) = C_{prod}(t) + C_{dev,DRv}(t) + C_{exp,DRv}(t) \quad (18)$$

$$C_{prod}(t) = C^*_{prod} * f_{prod,DRv}\left(DRv(0)/DRv(t)\right) \quad (19)$$

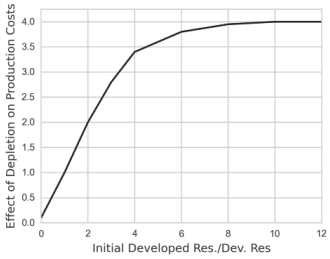


Figure 4.6: Graphical function showing the effect of depletion on the production costs

Once the *Total Unit Cost* is determined in the abovementioned way, the *Profit Percentage of Natural Gas Production (PP_{NG})* is the ratio of net unit profit to the unit costs, as denoted in Equation 20 where p_{market} is the market price of natural gas, and TUT_{NG} is the tax paid by the producers per unit of natural gas sold. This unit tax is a percentage of the unit profit as seen in Equation 21, where τ_{NG} is the total tax percentage for natural gas production, including the corporate income tax and the State Profit Share (SPS). Based on this unit tax, *Total State*

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Revenue from Natural Gas Production (Rev_{NG}) is computed as the sum of tax amounts collected for each gas type, namely the multiplication of unit tax and the corresponding production rate (Equation 22).

$$PP_{NG}(t) = \frac{p_{market}(t) - TUC_{NG}(t) - TUT_{NG}(t)}{TUC_{NG}(t)} \tag{20}$$

$$TUT_{NG}(t) = \tau_{NG}\left(p_{market}(t) - TUC_{NG}(t)\right) \tag{21}$$

$$\text{Rev}_{NG}(t) = \sum_i TUT_{NG,i}(t) * PR_i(t); \quad i = \text{Groningen, small fields, shale} \tag{22}$$

Natural gas producers set a desired markup on the *Total Unit Cost*, which influence the price-setting in the market between the traders and producers, with the effect of demand coverage as will be explained later in Section 4.4. The formulation of this *Desired NG Price (DP_{NG})* (Equation 23) is an example of structural uncertainty, because three alternatives can be thought of about how the producers decide on the profit markup, but there is no evidence about which one represents the reality better. These three options are incorporated to the model with a switch structure, namely the *Producer Price Structure Switch (PPSS)*. The first option (*PPSS*=0) is a constant markup value (PM^*_{NG}), which sets the desired price to the multiplication of the unit costs and a markup value which does not change over time, as in Equation 24. The second option (*PPSS*=0.5) assumes that producers are eager to obtain more profit as the market price increases, and set increasing markup values as the price expectations increase. Equation 24 shows that this increase in the profit markup is formulated with a graphical function, of which the input is the normalized ratio of expected market price to the total unit cost ($R^*_{p,c}$). Lastly, the third option (*PPSS*=1) assumes that producers are careful and reduce their desired profit markup as the market price declines, to prevent a reduction in demand. This formulation is also shown in Equation 24, with a different graphical function but the same input variable. The base case shapes of these two graphical functions can be seen in Figure 4.7.

$$DP_{NG}(t) = TUC_{NG}(t) * \left(1 + PM_{NG}(t)\right) \tag{23}$$

$$PM_{NG}(t) = \begin{cases} PM^*_{NG} & ; \ PPSS = 0 \\ PM^*_{NG} * f_{PM,inc}\left(R^*_{p,c}(t)\right); & PPSS = 0.5 \\ PM^*_{NG} * f_{PM,dec}\left(R^*_{p,c}(t)\right); & PPSS = 1 \end{cases} \tag{24}$$

$$R^*_{p,c}(t) = \frac{p^*_{NG}(t) / TUC_{NG}(t)}{PM^*_{NG}} \tag{25}$$

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(a) $f_{PM,inc}$



(b) $f_{PM,dec}$

Figure 4.7: Graphical functions showing the two alternative effects of price on the profit markup

Societal acceptance of natural gas production

Societal acceptance is included in the model with a simple structure that can function as an indicator of public opinion about natural gas production (of each type). Therefore, the *Societal Acceptance* variable, which is assumed to take values between 0 and 1, does not directly refer to an actual measurable notion, such as the percentage of population that is in favor of natural gas etc. For the formulation of *Societal Acceptance (SA)*, it is assumed that public opinion is formed as a cumulative effect of related events, and an information delay formulation is used, where *SA* is a stock variable. In this formulation seen in Equation 26, the net flow is assumed to be the difference between the *Expected SA (SA*)* and the current *SA*, divided by the *Reaction Delay* (d_{SA}). To ensure that *SA* remains between 0 and 1, the *Expected SA* is limited with min and max functions as in Equation 27. *Indicative Expected SA* (ISA^*) is the variable which reflects the effect of three factors on *SA* in a multiplicative formulation with nonlinear graphical functions, as shown in Equation 28. These three effects are the *Effect of Demand Coverage on SA* ($f_{Dc,SA}$), *Effect of Prices on SA* ($f_{Pr,SA}$) and *Effect of Disturbance on SA* ($f_{Dist,SA}$).

$$SA_i(t) = SA_i(0) + \int_{t_0}^{t} \frac{SA^*(\tau) - SA(\tau)}{d_{SA}}\, d\tau \tag{26}$$

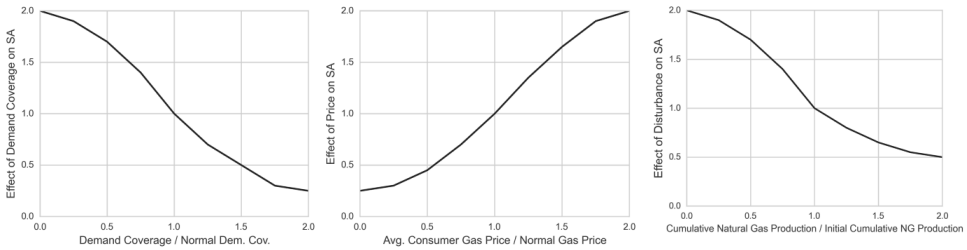
$$SA^*(t) = \min\left(\max\left(ISA^*(t),\, 0\right),\, 1\right) \tag{27}$$

$$ISA^*(t) = SA(t) * f_{Dc,SA}(t) * f_{Pr,SA}(t) * f_{Dist,SA}(t) \tag{28}$$

Effect of Demand Coverage on SA is a decreasing function of (perceived) demand coverage of natural gas, i.e. the ratio of total gas supply in the Netherlands to the total gas demand. Low demand coverage implies a scarcity of gas, and it is assumed to increase the acceptance of natural gas because the energy need should be satisfied. *Effect of Prices on SA* is an increasing function of a normalized value of *Average Consumer Gas Price.* It is based on the assumption that more consumers develop a positive opinion about more natural gas production, as the prices increase and their purchase power of gas decreases. The third effect, which is that of 'disturbance' on SA, represents the decline in societal acceptance as production causes incidents such as earthquakes, environmental or landscape damage. Therefore, *Effect of Disturbance on SA* is formulated as a decreasing function of a normalized value of *Cumulative Natural Gas Production*, which is the accumulation of annual production rates. This assumption was based on the finding that earthquakes in Groningen are dependent on cumulative production (Muntendam-Bos and De Waal, 2013). Being based on

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approximations, these effect functions are highly uncertain, yet their base run forms are shown in Figure 4.8 below as an example.



(a) *Demand Coverage* **(b)** *Price* **(c)** *Disturbance*

Figure 4.8: Graphical functions showing the effects of three factors on *Societal Acceptance*

4.2.2. Renewable Gas Production[6]

This sub-model's core structure is the production chain from biomass to biomethane at the national level. In this chain shown in Figure 4.9, both biomass supply is shared between heating, electricity generation and biogas production. Similarly, biogas supply is shared between electricity production, heating and upgrading sectors. This is how the local biomass is utilized in the Netherlands; therefore the production of biofuels for transport is excluded from the model. The biomass types used or that can be used for biomethane production in the Netherlands are manure and other agricultural waste products, sewage sludge, landfill gas, industrial waste water and household waste (vegetables, fruit and garden waste). These are grouped into two, as wet and dry biomass with average gas yield and heating values for each group, and matched with biogas production or other end-use technologies accordingly.

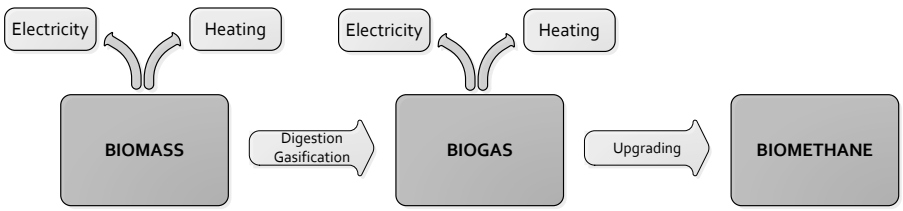


Figure 4.9: Production chain of biomethane

As mentioned in Chapter 2, there are two technologies for producing biogas from biomass, namely *digestion* that uses wet biomass, and *gasification* that uses dry biomass. As in the case of different natural gas types, these two technologies of biogas, and then biomethane, production are taken into account separately in the model, with similar market and capacity construction mechanisms but different parameter values for costs, biogas yields and subsidies, by using the subscripting feature of Vensim DSS. Therefore, *Total Production Rate of Renewable Gas (*TPR_{RG}*)* is composed of two *Production Rates* shown in Equation 29, corresponding to two technologies.

$$TPR_{RG}(t) = \sum_{j} PR_{RG,j}(t) \quad ; \text{ j = digestion, gasification} \tag{29}$$

[6] This section is published as a part of (Eker and van Daalen, 2015).

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Biomethane is produced in a decentralized manner, and this feature raises the question of where to inject it into the gas grid. It can be injected into the distribution or transmission grid, right after production or after being collected in a hub, or it can be stored. Depending on the selected options, the gas grid may be reshaped in future, for example in a decentralized way. However, this model focuses on production and excludes spatial dynamics of the infrastructure. In other words, in the model it is assumed that all biomethane produced can be used for a useful final purpose.

The production chain structure is derived from a generic commodity market model (Sterman, 2000, p. 798-824) where production is dependent on resource availability, installed capacity and demand, and capacity installation is dependent on expected resource availability, expected demand and price. These relations will be detailed in the next two sub-sections that describe biogas and biomethane production mechanisms.

Biogas production

The causal loop diagram in Figure 4.10 illustrates the relationships between the main elements of the biogas production model and the feedback loops formed by these relationships. In the model, *Biogas Production Rate*, which is the volume of gas produced each year, is dependent on two factors: *Biogas Demand* and *Biomass Allocated for Biogas*, which is the resource availability constraint on production. *Biogas Production Rate* is also restricted by the *Biogas Production Capacity*, but since *Biomass Allocated for Biogas* is not more than the capacity can accommodate, this restriction is already included in the resource availability. The variables *Biogas Production Rate*, *Biogas Production Capacity* and *Biomass Allocated for Biogas* are subscripted by two technologies, namely digestion and gasification, to represent the individual values of these variables for each technology.

The Market Development loop is formed by the fundamental relations between supply, demand and price. As *Biogas Production Rate* increases, a large supply with respect to demand reduces the price, and a lowered price increases the demand. Expected demand for biogas determines the desired production capacity, which triggers further capacity installation if it is higher than the current installed capacity. Installed *Biogas Production Capacity*, together with *Biogas Demand*, determines *Biomass Allocated for Biogas*. Additionally, biomass is pulled into the biogas market as its availability stimulates production, which increases demand and results in higher installed capacity that demands more biomass. This positive loop formed via *Biogas Demand* is called Pull Loop. However, as increased supply due to biomass availability for biogas increases *Biogas Production Rate* and reduces price, the biogas sector becomes less attractive for biomass use compared to heating and electricity, and less biomass is allocated for biogas production. These relations form the negative feedback loop called Shooting Yourself. Although they are not shown in the diagram, other negative feedback loops included in the model are due to the obsolescence mechanism of the production capacity and the increased price in response to increased demand.

56A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

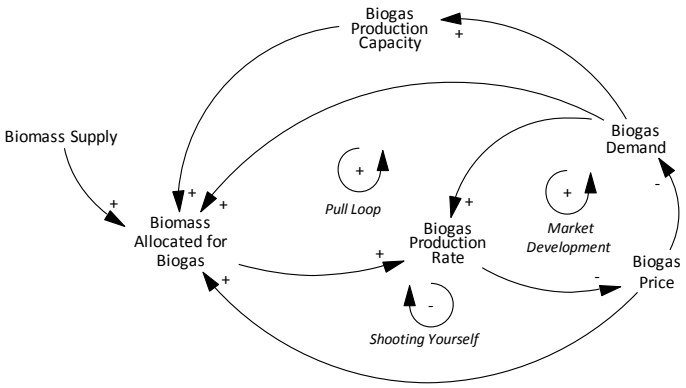


Figure 4.10: Causal loop diagram for biogas production

Wet biomass is allocated between biogas production via digestion and electricity generation in Combined Heat and Power (CHP) units. Dry biomass is allocated between biogas production via gasification, heating, and electricity generation by co-firing in coal power plants and in CHP units. The basis of the allocation mechanism is the biomass demand and financial attractiveness of these sectors, and it is translated into equations as follows: In Equation 30, *Initial Wet Biomass Allocated for Biogas (*$IBMS_{W,BG}$*)* is the minimum of *Wet Biomass Demand of the Biogas* sector ($BMSD_{W,BG}$) and a fraction of *Wet Biomass Supply (*BMS_W*).* This fraction ($\theta_{W,BG}$) which symbolizes the attractiveness value is determined by the ratio of *Wet Biomass Value for Biogas (*p_{BG}^{wbms}*)* to the sum of this and *Wet Biomass Value for Electricity (*p_E^{wbms}*)*, as in Equation 31. *Wet Biomass Value for Biogas (*p_{BG}^{wbms}*)* is the price ultimately obtained in the biogas sector for each unit of biomass, and formulated as the multiplication of *Biogas Price (*p_{bg}^**)* and *Average Biogas Yield of Wet Biomass (*y_w*)* as seen in Equation 32.

$$IBMS_{W,BG}(t) = MIN\left(BMSD_{W,BG}(t),\ BMS_W(t)\theta_{W,BG}(t)\right) \tag{30}$$

$$\theta_{W,BG}(t) = \frac{p_{BG}^{wbms}(t)}{p_{BG}^{wbms}(t) + p_E^{wbms}(t)} \tag{31}$$

$$p_{BG}^{bms}(t) = p_{bg}^*(t)\, y_w \tag{32}$$

Biomass Demand of Biogas (both wet and dry), as well as that of the electricity sector, is assumed to be dependent on the installed capacity. *Biomass Demand of Heating* is assumed to change fractionally for simplicity, and this fraction is assumed to be a step function in time. The heat generated in biomass-based CHP's is assumed to replace heat generated by biomass, and reduced from *Biomass Demand of Heating.* Similar to the *Biomass Demand, Biogas Demand* is the sum of demand from heating, upgrading and electricity sectors, which are modeled similarly.

Biogas Production Capacity (BG_C*)* is the accumulation of annual installation activities and loss due to obsolescence, both for digestion and gasification, as formulated in Equation 33. Since installation delay is short, accumulation of capacity under construction is not taken into account in this model. The *Installation Rate (*IBG_C*)* in Equation 34 is assumed to be a

56B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

percentage of *Desired Installation Rate* (IBG_C^*), where this percentage is denoted by *Investment Response to Profitability* (IRP_{BG}). IRP_{BG} (Equation 35) is formulated as an increasing function (f_{BG}^I) of *Profit Percentage of Biogas* (PP_{BG}). *Desired Installation Rate* (IBG_C^*) is the nonnegative discrepancy between the *Desired Biogas Capacity* (BG_C*) and current *Biogas Production Capacity* (BG_C) divided by the *Installation Delay* (d_I), as seen in Equation 36; and BG_C* is assumed to be equal to the *Expected Total Biogas Demand* (ED_{BG}), which is the sum of biogas demand from electricity, heating and biomethane production sectors. *Obsolescence Rate* (OBG_c) is determined by a single negative feedback loop mechanism, and its formula shown in Equation 37 is BG_C divided by the *Average Lifetime of Biogas Plants* (d_T^{BG}).

$$BG_C(t) = BG_C(0) + \int_{t_0}^{t} \left(IBG_C(\tau) - OBG_C(\tau) \right) d\tau \tag{33}$$

$$IBG_C(t) = IBG_C^*(t)\, IRP_{BG}(t) \tag{34}$$

$$IRP_{BG}(t) = f_{BG}^I\left(PP_{BG}\right) \tag{35}$$

$$IBG_C^*(t) = \frac{MAX\left(0,\, BG_C^*(t) - BG_C(t)\right)}{d_I} \;;\; BG_C^*(t) = ED_{BG}(t) \tag{36}$$

$$OBG_C(t) = \frac{BG_C(t)}{d_T^{BG}} \tag{37}$$

Being a new technology, the production costs of biogas via both digestion and gasification are expected to decline over time due to the *Learning Effect*(L_{bg}) as *Cumulative Production*(C_{bg}) increases. This learning effect is formulated as in Equation 38, following Sterman (2000, p.507). Therefore, *Variable Unit Cost of Biogas Production* (VUC_{bg}) is calculated as in Equation 39, as the sum of production costs (PC_{bg}) reduced by a learning effect (L_{bg}) and fuel costs (FC_{bg}), which is the price of biomass per unit of gas. *Unit Investment Cost of Biogas* (IUC_{bg}) is calculated by spreading the investment cost of a capacity unit (IC_{bg}) over the potential production throughout the lifetime (d_T^{BG}) with the equivalent annual cost (EAC) formula based on the *Interest Rate (r)*, as seen in Equation 40.

$$L_{bg}(t) = \left(\frac{C_{bg}(t)}{C_{bg}(0)} \right)^{-l_{bg}} \tag{38}$$

$$VUC_{bg}(t) = FC_{bg}(t) + PC_{bg} L_{bg}(t) \tag{39}$$

$$IUC_{bg} = \frac{IC_{bg}\, r\, (1+r)^{d_T^{BG}}}{\left((1+r)^{d_T^{BG}} - 1 \right)} \tag{40}$$

Biogas Price (p_{bg}), which actually does not exist since there is no market for biogas where it is traded in this form, is a variable in the model used to represent the effect of profitability on investments and the fuel costs of technologies that use biogas. The value of biogas is determined by its producers and consumers, as the multiplication of *Desired Biogas Price* (DP_{bg}) by the *Effect of Demand Coverage on Biogas Price* (f_{bg}^D) in Equation 41. (Note that

57A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

this effect function is similar to the one used for the natural gas price, as it will be explained later in Section 4.4.) A profit mark-up (PM_{bg}) dependent on the ratio of biomethane price to the unit cost of biogas is added to the total unit cost of biogas production (TUC_{bg}) to represent the desired price of producers (DP_{bg}) as seen in Equation 42. (It must be noted that the total unit cost is the sum of variable and investment costs shown in Equations 39 and 40)

$$p_{bg}(t) = DP_{bg}(t)\, f_{bg}^{D}(t) \tag{41}$$

$$DP_{bg}(t) = TUC_{bg}(t)\left(1 + PM_{bg}(t)\right) \tag{42}$$

Biomethane production

Biomethane production is modeled almost the same as biogas production, except that the resource for production, which was biomass for biogas, is replaced by biogas for biomethane, and the demand is replaced by the renewable gas demand of consumers (households, industry, agriculture, transport). Figure 4.11 shows how biogas supply stimulates the biomethane market and further demand for biogas, which also illustrates how Figure 4.10 and Figure 4.12 are connected through *Biogas Production Rate* and *Biomethane Production Capacity* variables.

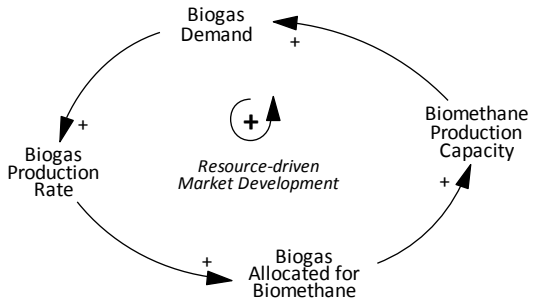


Figure 4.11: Resource-driven Market Development Loop for Biomethane

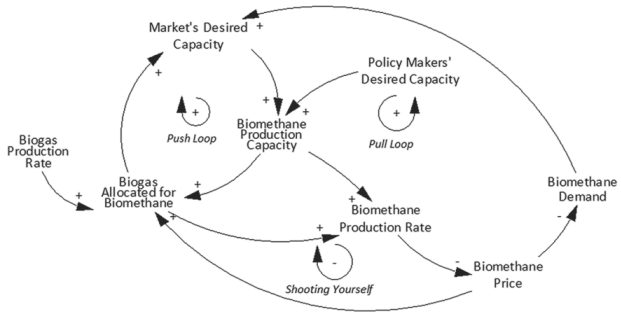


Figure 4.12: Causal Loop Diagram for Biomethane Production

As Figure 4.12 illustrates, *Biomethane Production Rate (PR_{RG})* is determined by two factors, and it is formulated as the minimum of these (Equation 43), namely the *Biomethane Production Capacity* and *Producible Biomethane*, which depends on *Biogas Allocated for Biomethane* (BG_{bm}) and the upgrading efficiency (u_{bm}).

57B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$PR_{RG}(t) = \min\left(BM_C(t),\ BG_{bm}(t) * u_{bm}\right) \tag{43}$$

The causal loop diagram of the biomethane production model in Figure 4.12 is almost the same as that of Figure 4.10, because the same framework of resource, capacity, production and demand interaction has been applied. However, the major difference is the effect of policy on capacity construction. The Dutch government has an ambition to inject 3 billion cubic meters (bcm) biomethane per year into the gas grid by 2020, as shown in Figure 4.13. Therefore, besides providing subsidies, government agencies and related distribution and transmission system operators (DSO's and TSO's) actively support producers in capacity installation projects to realize this goal. Attributed to this policy-driven mechanism of capacity installation, two types of desired capacity are defined in the model, and the actual installation rate is assumed to be the minimum of the two desired installation rates determined by these two desired capacity levels. *Market's Desired Capacity* (MBM_C^*) is assumed to be the minimum of *Expected Producible Biomethane* (EBM_R) which indicates the expected resource availability, and *Expected Total Renewable Gas Demand* (ED_{RG}) which is dependent on the renewable gas demand determined in the demand sub-mopdel. *Market's Desired Installation Rate* of biomethane production capacity ($MIBM_C^*$) is formulated as the nonnegative difference between the market's desired and current *Biomethane Production Capacity* (BM_C) divided by the *Installation Delay* (d_I). Equations 44 and 45 belong to these two formulations.

$$MBM_C^*(t) = MIN\left(EBM_R(t), ED_{RG}(t)\right) \tag{44}$$

$$MIBM_C^*(t) = \frac{MAX\left(MBM_C^*(t) - BM_C(t), 0\right)}{d_I} \tag{45}$$

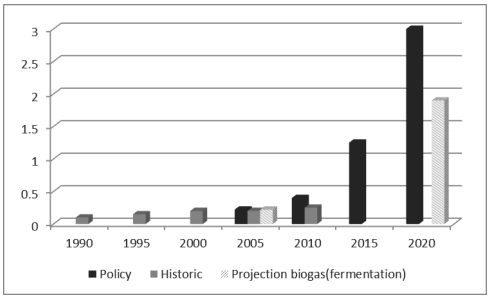


Figure 4.13: Biomethane targets - Source: (Scheepers, 2013)

Policy Makers' Desired Capacity is assumed to be an increasing function approximated to the goals specified in Figure 4.13, starting from nearly zero in 2000 and increasing to 3 bcm in 2020 with an annual increase fraction of 27%. After 2020, it is assumed that policy makers adjust this goal depending on the level of achievement. Therefore, a floating goal mechanism (Sterman, 2000, p. 532-535) is implemented as seen in Figure 4.14 and Equations 46 and 47, in which the *Desired Capacity of Policy Makers* (PBM_C^*) is formed by the accumulation of difference between *Goal Change Rate* (GCR_{BM}^{2020}) which increases the desired capacity until 2020 and *Adjustment Rate of Biomethane Capacity Goal* (AR_{BM}) which is effective after 2020. AR_{BM} is formulated as the discrepancy between the desired (PBM_C^*) and actual (BM_C)

58A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

biomethane upgrading capacity, divided by the Goal Adjustment Time (d_{AR}), so that the values of the actual capacity lower than the desired capacity result in a reduction in the goal and vice versa.

$$PBM_C^*(t) = PBM_C^*(0) + \int_{t_0}^{t} \left(GCR_{BM}^{2020}(\tau) - AR_{BM}(\tau) \right) d\tau \tag{46}$$

$$AR_{BM}(t) = \frac{PBM_C^*(t) - BM_C(t)}{d_{AR}} \tag{47}$$

Producers' decision making

Eventually, the desired installation rate of the biomethane production capacity is the maximum of the market's and policy makers' desired installation rates; whereas the actual installation rate is a fraction of this eventual desired installation rate, as shown in Equation 48. This fraction is called the biomethane producers' *Investment Response to Profitability (IRP$_{BM}$)*, and it represents how producers make a decision for capacity installation. The formulation developed for this decision making exemplifies a structural uncertainty, because two alternative formulations are possible, and taken into account. Depending on the value of *Producers' Decision Structure Switch (PIDS)* as shown in Equation 49, IRP_{BM} is determined by an assessment of producers either based on a net present value (NPV) calculation, hence a long-term view, or based on the current profitability of biomethane production, hence a short-term view.

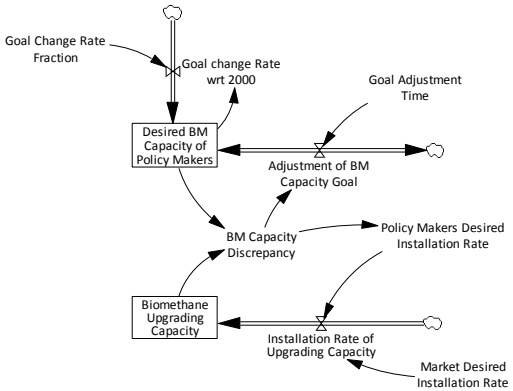


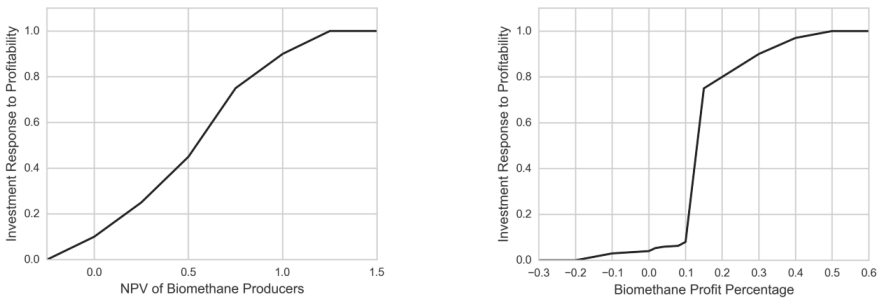
Figure 4.14: Floating Goal of the Policy Makers for Biomethane Upgrading Capacity

$$IBM_C(t) = IBM_C^*(t)\, IRP_{BM}(t) \tag{48}$$

$$IRP_{BM}(t) = \begin{cases} f_{IRP}^{npv}\left(NPV_{BM}(t) \right); & PIDS = 0 \\ f_{IRP}^{prf}\left(PP_{BM}(t) \right); & PIDS = 1 \end{cases} \tag{49}$$

Both of these alternative formulations involve a graphical function, namely f_{IRP}^{npv} and f_{IRP}^{prf}, which are both increasing functions since the installation increases as the profitability increases. Although the form and values of these functions are highly uncertain, their base run shapes are shown in Figure 4.15.

58B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm



(a) *Based on NPV* **(b)** *Based on Profit Percentage*

Figure 4.15: Graphical Function for the Investment Response to Profitability of Biomethane Production

As for the two different indicators of profitability, the *Profit Percentage of Biomethane (PP$_{BM}$)* shown in Equation 50 is the ratio of the unit profit of biomethane production, i.e. the difference between the current price (p_{bm}) and the total unit cost (TUC_{bm}), to the unit cost. It must be reminded that both *TUC* and p_{bm} are formulated similar to those of biogas, except that p_{bm} includes a subsidy, if applicable. While this formulation only considers the profitability at the time of decision making about installation, the NPV-based one takes the profitability of next 12 years. Although it is shorter than the lifetime of a biomethane plant, this duration is selected because the government's subsidy calculations are based on a 12-year project lifetime. The NPV of unit biomethane produced is calculated as in Equation 51 with r_{bm} being the rate of return, and ENI_i being the *Expected Net Income* of producers in *i* years ahead. The projection of future values is kept in an array by using the subscripting feature of Vensim DSS, hence the summation as in the actual NPV calculation rather than an approximation was possible.

$$PP_{BM}(t) = \frac{p_{bm}(t) - TUC_{bm}(t)}{TUC_{bm}(t)} \tag{50}$$

$$NPV_{BM}(t) = \sum_{i=1}^{i=12} \frac{ENI_i(t)}{(1+r_{bm})^i} \tag{51}$$

Expected Net Income of each year in the 12-year lifetime is the difference between *Expected Producer Price* and *Net Costs* as seen in Equation 52.

$$ENI_i(t) = EPP_i(t) - NC_i(t) \tag{52}$$

Expected Producer Price is dependent on the subsidy scheme provided by the government. In the no-policy case, it is assumed that the current subsidization scheme continues, and *EPP* is formulated as the maximum of *Expected Market Price (EMP$_{bm,i}$)* in *i* years ahead and the *Basis Price (BP$_{bm}$)* determined by the government, which is the price producers receive if their cost is higher than the market price but remains the same for 12 years (Equation 53). *Expected Market Price* is formulated with the FORECAST function which extrapolates the *Biomethane Market Price (p_{bm}) i* years ahead based on the data of last 5 years (Equation 54).

$$EPP_i(t) = \max\left(EMP_{bm,i}(t),\, BP_{bm}(t)\right) \tag{53}$$

$$EMP_{bm,i}(t) = \mathrm{FORECAST}\left(p_{bm}(t), 5,\ i\right) \tag{54}$$

59A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Net Costs (NC_i) is formulated as in the calculations made by the Netherlands Energy Research Center (ECN, 2014) for advising the government on subsidization. The components of this cost value are the operations and management cost, tax amount and an annual equivalent of the investment cost. The exact formulation of this variable can be found in Appendix 4.2.

4.2.3. Imports

The last supply option included in the model is the imported natural gas. This section explains the model structure representing the import decision of traders. There are three main assumptions that require mentioning before a description. Firstly, as mentioned in Chapter 2, natural gas is imported to the Netherlands in two ways: In the gaseous form via pipelines from Russia and Norway, and as Liquefied Natural Gas (LNG) from various countries (e.g. Algeria) to the Gate Terminal in the Port of Rotterdam. The model includes these two types of imports separately, with the same structure but subscripted variables as in the case of different gas types in the previous sections. The description below will focus on the common structure and not include these subscripts, unless necessary.

The second main assumption is that the import volumes in this model represent the net imports, because it is assumed that natural gas is imported only when the total domestic gas production is not adequate to cover the total annual demand. In other words, only the imports of natural gas used domestically are taken into account in this study as 'import'. Also, only the domestically produced natural gas is assumed to be exported, as long as there is surplus not used in the domestic market. The volume of gas enters the Dutch grid and transported to the neighboring countries is called 'transit'. Figure 4.16 depicts these gas flows, whereas Table 4.2 summarizes the definition of two key variables, namely the *Import Volume* and *Total Import Volume*.

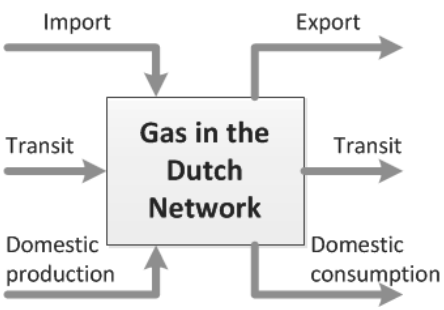


Figure 4.16: Main gas flows in the Dutch gas grid

Table 4.2: Definition of the key model variables in the import sub-model

Variable	Definition
Total Import Volume	The total volume of natural gas imported as LNG and via pipelines, to cover the difference between the domestic production and the domestic demand
Import Volume (= net imports)	The volume of gas imported via one of the import means, i.e. LNG or pipelines. It is a fraction of the Total Import Volume.

The third assumption relates to the volume measure, and as in the case of small fields or renewable gas, the volume of imported gas is measured in Groningen-equivalent billion cubic meters.

Import Volume (IV) is the key variable in this sub-model and it represents the annual volume of imported natural gas. The three factors that affect this volume are depicted in Figure 4.17, as the availability of gas on the international market (*Import Availability*), the entry capacity of the border infrastructure (*Import Capacity*) and the *Import Demand*, which includes the

59B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

effect of supply discrepancy and the price on imports. These relations will be detailed in the formulations below.

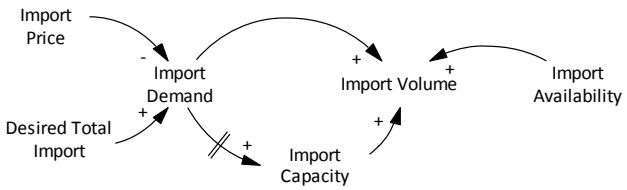


Figure 4.17: The main factors affecting the *Import Volume*

Equation 55 shows the formulation of *Import Volume*, assumed to be the minimum of *Import Demand* (*ID*) and *Possible Import Volume(*IV_{pbl}*)*. *Import Demand* represents the annual volume demanded by each import mean (gaseous or LNG), and it is formulated as a fraction of the *Desired Total Import (*TIV^**)* as in Equation 56. TIV^* is the nonnegative discrepancy between the *Total Domestic Gas Production (TPR)*, which is the sum of total natural and renewable gas production, and *Total Domestic Gas Demand* (*TD*) as shown in Equation 57. As for the fraction, it is named *Smoothed Fraction of Import Mean (*ρ^*_{imp}*)* and its formulation can be seen in Equation 58. The reason for using a smooth function with the delay time d_{mp} is the information delay between the price change and the effect of this on the import demand. The actual fraction is determined based on the relative price of importing gas by each import mean. In other words, the fraction of gaseous import in covering the *Desired Import Volume* is the ratio of the price of importing gas via LNG ($p_{imp,LNG}$) to the sum of prices of each import mean. Note that this inversion between the fraction and price is because high prices of an import mean makes it less attractive, as high prices of gaseous import creates a higher market share for LNG.

$$IV(t) = \min\left(ID(t),\ IV_{pbl}(t)\right) \tag{55}$$

$$ID_i(t) = TIV^*(t) * \rho^*_{imp,i}(t)\ ;\quad \text{i = gaseous, LNG} \tag{56}$$

$$TIV^*(t) = \max\left(TPR(t) - TD(t),\ 0\right) \tag{57}$$

$$\rho^*_{imp,i}(t) = \text{SMOOTH}\left(\frac{p_{imp,i^-}(t)}{\left(p_{imp,i^-}(t) + p_{imp,i}(t)\right)},\ d_{mp}\right) \tag{58}$$

Import Price ($p_{imp,i}$*)* represents the price paid to foreign suppliers in the international market. Certainly, this international trading is subject to the basic market rules, and the price increases if demand increases. (Increase in supply due to a price increase in the Dutch market will be discussed later, regarding the *Import Availability*.) Although the dynamics of the international market is beyond the scope of this study, the change in the *Import Price* with respect to a change in the import demand of the Netherlands is taken into account. However, this market mechanism is subject to many uncertainties, and hence, a simple model structure, which can represent the uncertainties parametrically, is preferred. Appendix 4.3 explains this structure, i.e. the formulation of *Import Price* in detail.

Possible Import Volume(IV_{pbl}*)* represents two limitations on the imports, such as *Import Availability* (*IA*) (the gas available for the Netherlands on the international market) and *Import*

60A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Capacity (Imp_C). Hence, it is formulated as the minimum of these two factors, as Equation 59 shows. *Import Availability* is assumed to be a fraction of the total gas available on the international market that the Netherlands can potentially import, which is called *Import Potential (IP)*. The *Import Potential* parameter is not the total production amount of the producers from which the Netherlands can import, but it is an indicator of what the Netherlands can maximally import given the demand of others. This maximum amount is reduced by the *Political Restriction Fraction* ($\rho_{imp,pol}$) and the *Fraction of Potential Imports for the Netherlands* ($\rho_{imp,pr}$) which shows the attractiveness of the Dutch market for the internationally available gas. While the former is assumed to be a constant, the latter fraction is formulated with a negative exponential function, which is a common choice for simple resource allocation structures (Sterman, 2000, p. 545). Since a fraction cannot be greater than 1, the exponential function is converted to be a logarithmic function as seen in Equation 61, meaning that the fraction of potential gas that can be imported to the Netherlands saturates around 1, as the market price in the Netherlands becomes too high compared to the international market price. This *Relative Market Price (RMP)* is denoted in Equation 62 as the ratio of *Import Price* in the Dutch market to the *Average Price in the International Market (p_{intl})*, which is assumed to be a constant in this study.

$$IV_{pbl}(t) = \min\left(Imp_C(t),\, IA(t)\right) \tag{59}$$

$$IA(t) = IP * \left(1 - \rho_{imp,pol}\right) * \rho_{imp,pr}(t) \tag{60}$$

$$\rho_{imp,pr}(t) = 1 - e^{-RMP(t)} \tag{61}$$

$$RMP(t) = p_{imp}(t) / p_{intl} \tag{62}$$

The last part of the import sub-model to be explained is the capacity installation. *Import Capacity (Imp_C)* is a stock variable in the model which represents the total entry capacity of the Dutch gas grid (not only for the 'imports' as defined in this study, but also for exports and transit). This variable increases with *Import Capacity Installation Rate (IR_{imp})* and decreases with *Import Capacity Obsolescence Rate (OR_{imp})*, as Equation 63 shows. For simplicity, the installation procedure is not detailed with more stock variables including capacity planned, commissioned, under construction etc. Instead, the delays caused by these steps are summed in *Import Capacity Commissioning Delay (d_{imp})* in the formulation of installation rate. Equation 64shows this formulation, as a fraction ($\rho_{com,i}$) of *Total Desired New Capacity ($TImp^*_C$)* for each import mean, divided by the commissioning delay. As for the *Obsolescence Rate*, it is the division of the installed capacity by the *Average Lifetime of Import Capacity*.

$$Imp_C(t) = Imp_C(0) + \int_{t_0}^{t} \left(IR_{Imp}(\tau) - OR_{Imp}(\tau)\right) d\tau \tag{63}$$

$$IR_{Imp,i}(t) = \frac{\rho_{com,i}(t) * TImp^*_C(t)}{d_{imp,i}}; \qquad \text{i=gaseous,LNG} \tag{64}$$

Total Desired New Capacity is the nonnegative difference between the total installed capacity and *Expected Import Demand (EID)* (Equation 65), where expected demand is formulated as smoothed annual *Import Demand*.

$$TImp^*_C(t) = \max\left(EID(t) - \sum_i Imp_{C,i}(t),\, 0\right) \tag{65}$$

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As for the fraction of each import mean in installation of new capacity to cover this discrepancy, it is formulated as the relative attractiveness of each mean, where this attractiveness depends on the costs and potentially available import amount of each. Namely, Equation 66 presents this fraction ($\rho_{com,i}$) as the ratio of the attractiveness measure of each import mean ($\delta_{com,i}$) to the sum of these measures. (Note that this formulation is a general resource allocation formulation also used in the renewable gas model for the allocation of biomass and biogas resources.) The attractiveness measure has a multiplicative formulation combining the *Effect of Costs on Installation* ($f_{imp,cost}$) and the *Effect of Availability on Installation* ($f_{imp,av}$), as shown in Equation 67. As in Equation 61, a negative exponential formulation is chosen for this effect function. Since the causality between the costs and installation is negative, a decreasing function is used for this formulation, whereas an increasing logarithmic function is preferred for the positive effect of availability on installation. Equation 68 and 69 show these formulations, having the *Total Unit Cost of Imports (TUC$_{imp}$)* and *Expected Import Availability* (*EIA*) as the inputs, respectively. *Total Unit Cost of Imports* is the sum of the *Import Price* (of which formulation is shown in Appendix 4.3), and a fixed cost representing the infrastructure costs. *Expected Import Availability* is a forecast of the *Import Availability* discussed in Equation 60, formulated with the FORECAST function of Vensim. These two variables are normalized with respect to a reference value for each (TUC^*_{imp} and EIA^*) to be used as an exponent.

$$\rho_{com,i}(t) = \delta_{com,i}(t) \Big/ \sum_i \delta_{com,i}(t) \tag{66}$$

$$\delta_{com}(t) = f_{imp,cost}(t) * f_{imp,av}(t) \tag{67}$$

$$f_{imp,cost}(t) = e^{-TUC_{imp}(t)/TUC^*_{imp}} \tag{68}$$

$$f_{imp,av}(t) = 1 - e^{-EIA(t)/EIA^*} \tag{69}$$

4.3. DEMAND SIDE

As mentioned in Chapter 2, there are five major groups of gas consumers in the Netherlands, being households (including commercial and public buildings), agriculture, industry, transport and the electricity generation sector. The first four of these can use both natural and renewable gas provided by the natural gas grid, whereas the electricity sector uses biogas, not renewable gas (biomethane), for power generation. In other words, natural gas is demanded by five sectors including the electricity sector, whereas renewable gas is demanded by only the four of these sectors. Therefore, the *Total Domestic Gas Demand* (*TD*) in the Netherlands is the sum of *Total Natural Gas Demand except Electricity (TD$_{NG,ee}$), Natural Gas Demand from the Electricity Sector (D$_{NG,e}$)* including a reduction due to cogeneration of heat and power, and *Total Renewable Gas Demand (TD$_{RG}$)*, as seen in Equation 70.

$$TD(t) = TD_{NG,ee}(t) + D_{NG,e}(t) + TD_{RG}(t) \tag{70}$$

The electricity sector lies at the core of the energy transition, and the future role of natural gas in this sector is highly uncertain, hence the gas demand from this sector is highly uncertain. Therefore, the electricity sector is modeled in more detail in this study, with the competition between several technologies yielding the share of natural gas in the power mix, whereas the

61A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

demand from other sectors is modeled with a simpler structure, which is the same for all consumer groups. The two sections below explain these sub-models, first for the electricity sector, then for the other sectors.

4.3.1. Natural Gas Demand of the Electricity Sector[7]

In the Netherlands, the electricity sector is currently dominated by gas-fired generation because natural gas has been an abundant and reliable source for decades, leading to an accumulation of natural gas power plants. However, while the transition to a renewable energy system is expected to moderate the share of the natural gas in the power sector on the one hand, the intermittent nature of renewable energy production requires a flexible backup source on the other hand. Natural gas is considered as a strong candidate to be the substitute of intermittent renewable electricity due to its relatively low CO_2 emissions and flexible operation, which may give a different role to gas in the future. Yet, coal-fired and nuclear power technologies are still important competitors of gas, due to lower fuel prices and almost zero CO_2 emissions, respectively. Thus, due to such developments in the power sector which are important for the future of gas demand and supply, electricity generation is explicitly modeled in this study.

The total power generation capacity installed in the Netherlands in 2010 is reported as 25.4 GW, which yielded 123.8 TWh electricity in that year (Energiezaak, 2011). This current capacity contains a wide variety of technologies and resources, although their shares in the power mix significantly differ. Table 4.3 lists the technologies included in the model and their installed capacity, and capacity under construction values in 2010.

Table 4.3: Electricity Generation Capacity in the Netherlands in 2010

Type	Installed Capacity	Capacity under construction
Biogas	0.216 GW (Panoutsou and Uslu, 2011)	0
Biomass	1.214 GW (Panoutsou and Uslu, 2011)	0
Coal	3.6 GW (EFNL, 2011)	4.5 GW (EFNL, 2011)
Coal with CCS	0 GW	0
Natural gas	10.5 GW (Enipedia, 2010; CBS, 2012)	5 GW (EFNL, 2011)
Decentral natural gas	5.55 GW (CBS, 2012)	0
Natural gas with CCS	0 GW	0
Nuclear	0.5 GW (EFNL, 2011)	1.6 GW (EFNL, 2011)
Solar	0.088 GW (CBS, 2013)	0
Wind	2.24 GW (CBS, 2013)	2 GW (EFNL, 2011)

All these 10 power generation sources are assumed to have the same capacity installation, market and operation structure with different parameter values, and the model is based on the two negative feedback loops demonstrated in Figure 4.18. The *Capacity installation decision* loop represents the decision making of producers about commissioning new capacity, according to the discrepancy between current supply level and the expected demand, and the *Technology Score*, which is calculated based on the profitability of each technology under the current market conditions and the societal acceptance level. The second loop, *Annual production decision*, represents the adjustment of the capacity utilization factor according to the share in the power mix and profitability, which determines the desired production of each

[7] This section is partially published in (Eker and van Daalen, 2013a).

61B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

technology based on the expected demand value. The model structure behind these two loops will be described in more detail below, in the corresponding two sections.

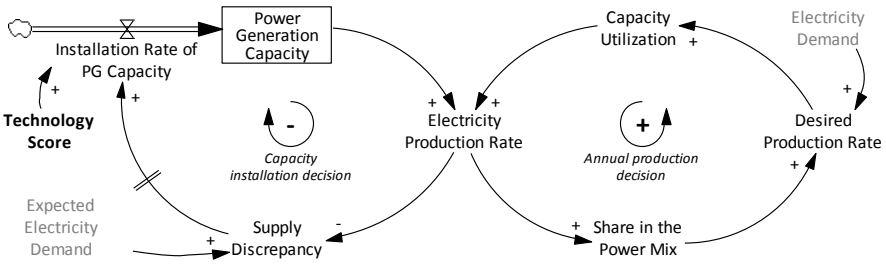


Figure 4.18: Overview of the electricity generation model

Capacity installation

As shown in Figure 4.18, *Power Generation Capacity* is represented by a stock variable that increases with new installations and decreases by obsolescence (not shown in the figure for simplicity). *Installation Rate* of each technology is dependent on the *Supply Discrepancy* and *Installation Fraction* which is a fraction that distributes the expected supply discrepancy among the technology options for capacity installation. *Supply Discrepancy* is the nonnegative difference between the total electricity production (sum of all technologies) and the expected electricity demand. *Installation Fraction* (ρ_E) is the ratio of the *Technology Score (S)* of each electricity generation technology to the sum of all such scores (Equation 71).

$$\rho_{E,i}(t) = \frac{S_i(t)}{\sum_k S_k(t)}; \quad \text{k = biogas, biomass, coal, natural gas, ...} \tag{71}$$

The score of each technology (*S*), is assumed to be the weighted average of the profitability and societal acceptance of this technology, with uncertain weights depending on the preferences of decision makers. This formulation can be seen in Equation 72. (Note that the weights sum up to 1.)

$$S(t) = w_{pr} P_E(t) + w_{SA} SA_E(t) \tag{72}$$

The *Profitability* of an electricity generation technology (P_E) is determined by the costs and the market price of this technology, with two alternative structures discussed for the investment decision of biomethane producers (Section 4.2.2) and shown in Equation 49. These alternative structures involved the same graphical functions both for the NPV-based alternative and the one based on profit percentage, and the NPV and profit percentage of each electricity technology is calculated similarly as explained in Section 4.2.2. However, the cost calculation of electricity technologies differs from the costs of biomethane, because the CO_2 price is taken into account, as well as the natural gas and biogas prices which are internal variable elements of this model. These factors affect the *Total Variable Cost* (TVC_E) of electricity, which is one of the components of *Total Unit Cost*, or 'simple levelized cost' of electricity.

62A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

As Equation 73 shows, *TVC* is the sum of *Variable Operation and Maintenance Costs* (VC_{OM}), *CO_2 Cost* (VC_{CO2}) and *Fuel Cost* (VC_{fuel}). *O&M Costs* (Equation 74) include the reducing effect of learning depending on the cumulative production, which is formulated similar to that of biogas costs as in Equation 38, hence create a reinforcing loop between production and costs. *CO_2 Cost* is the carbon price paid for each ton of CO_2 emitted during the production of one unit of electricity by a generation technology. Therefore, its formulation which can be seen in Equation 75 is the multiplication of the *CO_2 Price* (p_{CO2}) and *Average CO_2 Emission* (e_{CO2}), which is a different value for each technology. *CO_2 Price* is assumed to be a constant over time. As for the *Fuel Cost*, it is assumed to be an uncertain constant for technologies such as biomass, coal and nuclear as seen in Equation 76, and zero for wind and solar energy, yet a variable value for biogas and natural gas, whose prices are determined in the other segments of this model. This fuel price (p_{fuel}) is the conversion of the price value determined per volume unit to a value per energy unit. In Equation 77, this is exemplified for natural gas, where the consumer price of natural gas for electricity sector ($p_{consumer,E}$, see Equation 106) is divided by the calorific value of natural gas (W_{NG}) and the fuel efficiency (eff_{NG}) to yield the price electricity producers pay for unit electricity produced.

$$TVC_E(t) = VC_{OM}(t) + VC_{CO_2}(t) + VC_{fuel}(t) \tag{73}$$

$$VC_{OM}(t) = VC_{OM}^{*} * L_E(t) \tag{74}$$

$$VC_{CO_2}(t) = p_{CO_2} * e_{CO_2} \tag{75}$$

$$VC_{fuel}(t) = \begin{cases} c_{fuel,k} & ;\ \text{k = biomass, coal, coalCCS, nuclear} \\ 0 & ;\ \text{k = wind, solar} \\ p_{fuel,k}(t) & ;\ \text{k = biogas, natural gas, decentral gas, gasCCS} \end{cases} \tag{76}$$

$$p_{fuel,NG}(t) = p_{consumer,E}(t) / (W_{NG} * eff_{NG}) \tag{77}$$

The second factor in determining the score of each technology (*S*) is *Societal Acceptance*. As in the case of natural gas, the public opinion about controversial technologies such as coal, nuclear and Carbon Capture and Storage (CCS) is assumed to affect the investments in capacity installation. *Societal Acceptance* of electricity (SA_E) is modeled similar to that of natural gas explained in Section 4.2.1, except that the *Effect of CO_2 Emissions on SA* ($f_{CO2,SA}$) is added to the multiplicative formulation in Equation 28. For this formulation, it is assumed that not being able to meet the CO_2 targets set by the EU and adopted by the Dutch government reduces the societal acceptance of CO_2-intense technologies such as coal and natural gas. Therefore, this effect is formulated with a decreasing S-shaped graphical function, of which input is the ratio of total CO_2 emissions due to electricity production to the target emission levels.

Annual Electricity Production

Having explained the decision making mechanism of electricity producers on capacity installation, this section explains the shorter-term decision on annual electricity production, i.e. the capacity utilization decision of producers, based on the reinforcing loop shown in Figure 4.18. As this figure shows, the two factors affecting the *Electricity Production Rate* (PR_E) are the installed capacity and *Capacity Utilization (CU)*, and the production rate is the multiplication of these two, as shown in Equation 78. However, it must be noted that for the

62B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

biogas and biomass technologies, the production amount is restricted by the amount of these resources allocated for electricity production as explained in Section 4.2.2. *Fuel Availability (A_{fuel})* used to represent this restriction in Equation 78 is the conversion of biomass and biogas amounts to electricity units with the calorific value and fuel efficiency of each.

$$PR_{E,k}(t) = \begin{cases} \min\left(CU_k(t) * PGC_k(t),\ A_{fuel,k}(t)\right) & ;\ \text{if k = biogas, biomass} \\ CU_k(t) * PGC_k(t) & ;\ \text{otherwise} \end{cases} \quad (78)$$

Capacity Utilization (CU) depends on the *Desired Production Rate (PR^*_E)* of each technology, and is formulated with an increasing graphical function of which the input is the ratio of desired to possible production rate, i.e. *Power Generation Capacity (PGC)*. In this formulation shown in Equation 79, the graphical function (f_{CU}) is mostly linear, implying that all desired production is actually produced, but it saturates and converges to one since *Desired Production Rates* higher than the capacity cannot be fully accommodated. As for the *Desired Production Rate*, it is formulated as a fraction of total *Electricity Demand*, where this fraction is the *Expected Share in the Power Mix (s^*)* of each technology, as shown in Equation 80. This variable represents the expectations of producers on their share in the market in the coming year, and is assumed to be a smoothed value of the current *Share in the power Mix (s)*. Equation 81 formulates the *Share in the power Mix* as the ratio of *Production Rate* of a technology to the total electricity production rate.

$$CU(t) = f_{CU}\left(PR^*_E(t)/PGC(t)\right) \quad (79)$$

$$PR^*_E(t) = s^*(t) * D_E(t) \quad (80)$$

$$s_k(t) = \frac{PR_{E,k}(t)}{\sum_k PR_{E,k}(t)} \quad (81)$$

Natural gas demand

The main purpose of this electricity generation model was to derive the natural gas demand of the power sector. This demand value ($D_{NG,e}$) shown in Equation 82 is the difference between the *Natural Gas Demand for Electricity Production ($D^{pr}_{NG,e}$)* and *Demand met by Cogeneration (D_{cog})* in Combined Heat and Power units, because this heat production utilized in homes or district heating systems substitutes natural gas that would have been demanded otherwise. The volume of gas demanded for electricity production ($D^{pr}_{NG,e}$) is formulated as in Equation 83. In this equation, the *Production Rate* of each technology that uses natural gas is divided by the corresponding fuel efficiency (*eff*) to obtain the electricity-equivalent of natural gas consumption, and then the sum of these is divided by the calorific value of natural gas (W_{NG}) to obtain the natural gas demand in volume unit. It must be noted that since all natural gas demand of the electricity sector is assumed to be satisfied, the consumption and demand values are used interchangeably. As for the *Demand met by Cogeneration*, heat generated per unit of electricity in CHP units by the combustion of natural gas (h_E), which is assumed to be constant, is multiplied by the *Production Rate*. This electricity-equivalent of the heat generated is divided by the calorific value of natural gas to obtain the volume of natural gas saved (Equation 84).

63A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$D_{NG,e}(t) = D^{pr}_{NG,e}(t) - D_{cog}(t) \tag{82}$$

$$D^{pr}_{NG,e}(t) = \left(\frac{PR_{E,gas}(t)}{eff_{gas}} + \frac{PR_{E,gasDecentral}(t)}{eff_{gasDecentral}} + \frac{PR_{E,gasCCS}(t)}{eff_{gasCCS}} \right) \frac{1}{W_{NG}} \tag{83}$$

$$D_{cog}(t) = \frac{h_e * PR_{E,gasDecentral}(t)}{W_{NG}} \tag{84}$$

4.3.2. Natural and Renewable Gas Demand except the Electricity Sector[8]

As explained in Chapter 2 and reminded at the beginning of Section 4.3, the natural and renewable gas consumers, excluding the electricity generation sector, are grouped into four in this study. These groups refer to the consumption of gas in the households (including the commercial and public buildings), and by the industry, agriculture and transport sectors. Therefore, the simulation model includes 4 separate sectors for both natural and renewable gas demand, corresponding to these 4 consumer groups. These four sectors are represented by the same structural elements but different parameter values, by using the subscript feature of Vensim DSS, as in the previously described sub-models.

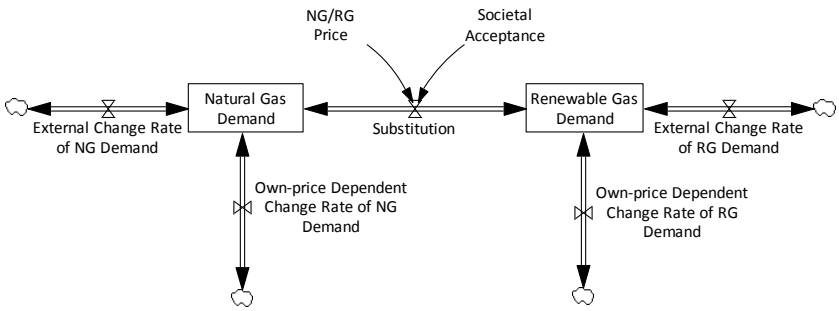


Figure 4.19: Simplified stock-flow diagram of the demand segment of the model

The two key stock variables of this sub-model are *Natural Gas Demand (D_{NG})* and *Renewable Gas Demand (D_{RG})*, which represent the annual demand for these two types of gas in terms of billion cubic meters of Groningen equivalent gas per year. The summation of these variables over the four demand groups yield the *Total Natural Gas Demand except Electricity ($TD_{NG,ee}$)* and *Total Renewable Gas Demand (TD_{RG})*. Each of the stock variables for natural and renewable gas demand are assumed to be determined by two flow variables representing the net annual change rate due to price changes and external factors such as consumption trends, in addition to the substitution between them. An overview of this model structure is depicted in the simplified stock-flow diagram in Figure 4.19. The three flow variables representing the three important factors affecting the annual demand will be discussed in the paragraphs below.

Own-price Dependent Change Rate

The *Own-price Dependent Change Rate (ODCR)* indicates the change in the consumption behavior of consumers due to a price change, and it is formulated based on the concept of

[8] This section is partially published in (Eker and van Daalen, 2015).

63B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

price elasticity of demand. Equation 85 shows the formulation of *ODCR* for renewable gas, where D_{RG} is the *Renewable Gas Demand*, and $\rho_{OD,RG}$ is the annual percentage change in *Renewable Gas Demand* due to a price change. This percentage change is formulated as the multiplication of the *Price Elasticity of Renewable Gas Demand* (e_{RG}) and the annual change in the *Biomethane Price* (p_{bmt}), but since consumers do not change their behaviour immediately, the actual change rate is formulated with an information delay. The 'smooth' function of Vensim DSS is used to represent this information delay, where the delay time is *Own-Price Demand Adjustment Delay* (d_{ODCR}) as shown in Equation 86. The same formulation is used for natural gas, with corresponding variables and the elasticity parameter. Appendix 4.4 explains how this formulation is derived from the elasticity definition.

$$ODCR_{RG}(t) = D_{RG}(t)\,\rho_{OD,RG} \tag{85}$$

$$\rho_{OD,RG} = SMOOTH\left(e_{RG}\,\frac{p_{bmt}(t) - p_{bmt}(t-1)}{p_{bmt}(t-1)},\ \ d_{ODCR}\right) \tag{86}$$

The concept of elasticity is well-studied in the economics literature, and a constant elasticity value is seen improper in many cases, since the response of consumers to a price change may be dependent on where this price change occurs on a spectrum of affordable price values. Besides, from a system dynamics point of view, it can be argued that this formulation aggregates many factors such as the availability of substitutes or the purchasing power of consumers into a single parameter value, and does not thoroughly represent the real mechanism of demand response to price change. However, this simple formulation with an elasticity parameter is preferred in this study, due to the importance given to simplicity in exploratory modeling and the ability to capture various scenarios with different values of this uncertain parameter.

The response to price changes, hence the value of the elasticity parameter, varies among the demand sectors. For instance, the households are assumed to have a higher elasticity value than the industry, because small consumers can easily save some heat in the residential consumption or switch to electricity, whereas large consumers require a certain amount of energy to maintain their economic activities such as manufacturing.

Lastly, it must be noted that since *ODCR* represents the annual change rate in demand, the change in price is also determined on an annual basis. Hence, the percentage change in price at time *t* is calculated with respect to the price value of one year ago.

External Change Rate

External factors affecting the demand change, such as income effect or energy need, are aggregated as an 'external' change rate of both natural and renewable gas demand. A formulation similar to those own-price dependent change rate is used, where the annual *External Change Rate* ($EXCR_{RG}$) is a fraction of the demand, as shown in Equation 87. This fraction ($\rho_{EX,RG}$) is a highly uncertain parameter, and it is assumed to change its value in three periods of the simulation horizon. Namely, it is formulated as a step function, where the parameter value changes in 2012 (after the past data is used between 2000 and 2012), 2025 and 2035, as exemplified in Figure 4.20. In the model, this is represented by four different

64A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

parameters, and the last three ones representing the change rates after 2012 are uncertain. This demand change fraction could as well be assumed to be an uncertain constant without a stepwise formulation. However, this step-wise formulation is thought to better represent the uncertainty in such a long horizon as 50 years by incorporating the potential changes over time.

$$EXCR_{RG}(t) = D_{RG}(t)\,\rho_{EX,RG} \tag{87}$$

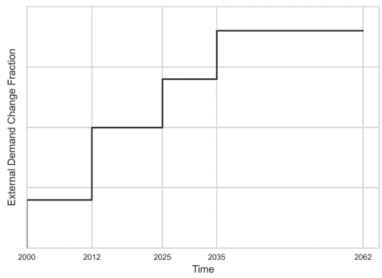


Figure 4.20: An example step function for *External Demand Change Fraction* ($\rho_{EX,RG}$)

Substitution Rate

Currently in the Netherlands, renewable gas (biomethane) is sold to end consumers based on a certification system. Producers are certified to be able to inject biomethane into the grid, and consumers can subscribe to the 'green' option instead of natural gas if they are willing to pay extra. Following this, the substitution of natural gas by biomethane is, or expected to be, a key factor in determining both natural and renewable gas demand. This substitution is assumed to depend on the relative price of the two options and the societal acceptance of natural gas.

The formulation of the substitution rate between natural gas (NG) and renewable gas (RG) demands is an example of model structure uncertainty, since there are two alternative formulations which are based on two microeconomic concepts that can be used for this phenomenon. The first one is based on the "cross-price elasticity", defined as the percentage change in the demand of a good with respect to 1% change in the price of another good (Png, 2013, p.72). Derived from this definition, *Substitution Rate of NG due to RG Price Change ($SR_{NG,RG}$)* is defined as in Equation 88, whereas Equation 89 shows the change in the RG demand due to NG price change. In these equations, $e_{NG,RG}$ and $e_{RG,NG}$ are cross-price elasticities of natural to renewable gas, and renewable to natural gas, respectively, and p_{NG} and p_{bmt} denote the natural and renewable gas prices. *Substitution Rate due to the Societal Acceptance of NG (SR_{SA})* is formulated similarly, as in Equation 90, and the total substitution rate (*SR*), which is assumed to be the shift from RG to NG, is obtained from the summation in Equation 91.

$$SR_{NG,RG}(t) = D_{NG}(t)\,e_{NG,RG}\,\frac{p_{bmt}(t) - p_{bmt}(t-1)}{p_{bmt}(t-1)} \tag{88}$$

$$SR_{RG,NG}(t) = D_{RG}(t)\,e_{RG,NG}\,\frac{p_{NG}(t) - p_{NG}(t-1)}{p_{NG}(t-1)} \tag{89}$$

$$SR_{SA}(t) = D_{NG}(t)\,e_{NG,SA}\,\frac{SA(t) - SA(t-1)}{SA(t-1)} \tag{90}$$

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$$SR(t) = SR_{NG,RG}(t) - SR_{RG,NG}(t) + SR_{SA}(t) \tag{91}$$

The second alternative is based on the concept of "elasticity of substitution (EoS)" which represents "a proportionate change in the ratio of two factors corresponding to a proportionate change in their marginal rate of substitution or in their price ratio" (Mundlak, 1968, p.1). The substitution rate resulting from this definition is formulated as in Equation 92, where e_{sub} is the parameter representing EoS and u is a simple additive utility function shown in Equation 93 with weights w_p and w_{SA} given to the relative price and societal acceptance, respectively. Appendix 4.5 explains how Equation 92 is derived from the definition of EoS.

$$SR(t) = \frac{D_{NG}(t)\, D_{RG}(t)}{D_{NG}(t) + D_{RG}(t)} e_{sub} \frac{u(t) - u(t-1)}{u(t-1)} \tag{92}$$

$$u(t) = w_p \frac{p_{bmt}(t)}{p_{NG}(t)} + w_{SA}\, SA(t) \tag{93}$$

4.4. MARKET

As mentioned in Chapter 2, the wholesale market is the fourth major component of the system model, where gas is purchased from producers and sold to utility companies or large consumers by traders. In addition to balancing the supply and demand via the dynamics of price, the market is where the competition between the supply options takes place. Namely, an increase in the supply quantity or a decrease in the costs of any of the options causes the market price to converge to the price of this supply option, e.g. as a reduction, and this implies a reduced supply by other options which cannot compete with low prices.

Currently in the Netherlands, there is no actual common market for natural and renewable gas, although domestically produced and imported natural gas are traded on the same market. However, since the prices of both are expected to influence each other, a common market mechanism is supposed, and the competition is modeled accordingly.

The market model includes the roles of traders, producers and consumers in price setting as in many energy system models. These models, usually optimization models, assume one of these market players to be the price-setter (e.g. producers), the other to be the price-taker (e.g. consumers), and determine an optimal price based on the objective function. In this model, none of the actors is assumed to be the price-setter. Instead, the influence of each of them is included in the model. Still, different assumptions can be made about the extent of each actor's influence, and different model structures can be developed. This structural uncertainty led to three alternative price-setting mechanisms to be incorporated into the model, representing different forms of involvement of each actor in the market. Technically speaking, a switch structure is used to represent these different price-setting mechanisms as in Equation 94, where *PSS* stands for *Price Structure Switch*. The paragraphs below explain these three structures.

$$p_{market}(t) = \begin{cases} p_{1,market}(t), & PSS = 0 \\ p_{2,market}(t), & PSS = 0.5 \\ p_{3,market}(t), & PSS = 1 \end{cases} \tag{94}$$

65A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Option 1: Sterman's commodity market price setting

This option is based on the price-setting mechanism of the generic commodity market model of Sterman (2000, p. 813). In this alternative structure depicted in Figure 4.21, three groups of market actors are represented equally, and the *Market Price* of gas (p_{market}) is assumed to be dependent on the *Traders' Expected Price* (*TEP*), producers' desired price represented by the *Effect of Costs on Price (EC)*, and consumers' demand coverage represented by the *Effect of Demand Coverage on Price (EDC)*, as shown in Equation 95.

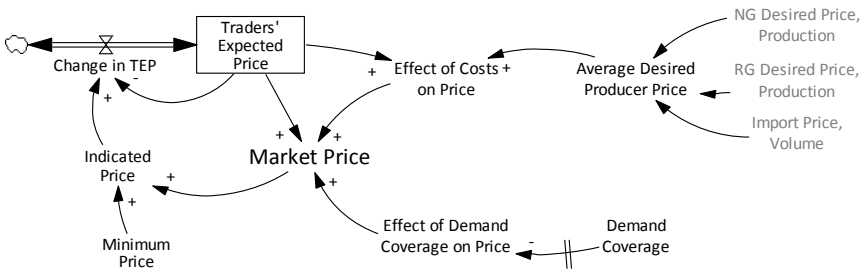


Figure 4.21: Overview of the first price-setting option

$$p_{1,market}(t) = TEP(t) * EC(t) * EDC(t) \tag{95}$$

Traders' Expected Price is formulated as a stock variable since it is constantly adjusted to the market price with a first order information delay. Traders adapt their expectations continuously having the *Indicated Price (InP)* as a reference, as in the form of a first order information delay. This *Indicated Price* value is assumed to be the maximum of the current market price and a *Minimum Price (p_{min})* as in Equation 96, which is equal to an average of the 'variable' cost of each supply option, based on the assumption that producers would ask at least their variable cost.

$$InP(t) = \max\left(p_{market}(t),\ p_{min}(t)\right) \tag{96}$$

As for the *Effect of Costs on Price*, it is formulated as in Equation 97 following Sterman (2000). In this equation, k_c is a key parameter representing the *Sensitivity of Price to Costs*. The implicit assumption in this equation is that the market price converges to the desired price of producers if demand coverage has no effect, since the equal value of *DPP* and *TEP* make this function's value equal to 1 when the price is fully sensitive to the costs ($k_c=1$). *DPP* is the *Average Desired Price of Producers*, which is assumed to be a weighted average of the price values (*DP*) expected by each producer group. The weights in this formulation shown in Equation 98 are the market share of each option, i.e. the ratio of its *Production Rate (PR)* or *Import Volume (IV)* to the total supply in the market. This formulation ensures that if one of the supply options is dominant, the market price is closer to its cost value.

$$EC(t) = 1 + k_C\left(\frac{DPP(t)}{TEP(t)} - 1\right) \tag{97}$$

$$DPP(t) = \frac{PR_{NG}(t) * DP_{NG}(t) + PR_{RG}(t)\,DP_{RG}(t) + IV(t) * p_{imp}(t)}{PR_{NG}(t) + PR_{RG}(t) + IV(t)} \tag{98}$$

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Lastly, the *Effect of Demand Coverage on Price (EDC)* is also formulated as in the Commodity Market Model, depending on *Demand Coverage* with a negative exponent as shown in Equation 99. This negative exponent, k_{DC} represents the *Sensitivity of Price to Demand Coverage*, and the base of it is the ratio of *Perceived Demand Coverage (PDC)* to the *Reference Demand Coverage (RDC)*, which is the initial demand coverage value in 2012. *Perceived Demand Coverage* takes the delay in the perception of consumers about whether their demand is met or not into account, and formulated with a first order information delay. The actual *Demand Coverage (DC)* is the ratio of total supply in the Dutch market (Equation 1) to the total gas demand of the Dutch consumers (Equation 70), as seen in Equation 100.

$$EDC(t) = \left(\frac{PDC(t)}{RDC} \right)^{-k_{DC}} \tag{99}$$

$$DC(t) = \frac{TS(t)}{TD(t)} \tag{100}$$

Option 2: Price setting based on producer price and demand coverage

The second alternative price setting mechanism excludes the influence of traders, and formulates the market price depending only on the desired price of producers and the effect of demand coverage. This formulation shown in Equation 101 also omits the 'sensitivity' factor used in the previous alternative, and in a simpler way, sets the market price to the multiplication of *Average Desired Price of Producers (DPP)* and *Effect of Demand Coverage on Price*, where the latter is formulated with a graphical function in this case. The input of this graphical function is *Perceived Demand Coverage*, and its form can be seen in Figure 4.22.

$$p_{2,market}(t) = DPP(t) * f_{dem,price}(PDC(t)) \tag{101}$$

Option 3: Price setting based on accepted consumer price

The third alternative model structure for the market price-setting includes all three actors again, yet with a different role of each. This alternative is also based on a structure found in the system dynamics literature (Barlas *et al.*, 2007) and highlights the role of traders since the profit margin on the costs is assumed to be dependent on acceptance by traders. Different from the original model structure which assumes a constant accepted margin, in this model, the accepted profit margin is assumed to be a variable depending on price. Besides, the role of consumers, i.e. *Effect of Demand Coverage on Price*, is represented by the same formulation as in Option 2.

More precisely, the *Market Price* of gas is modeled with a first order information delay mechanism shown in Equation 102, where the delay time is *Market Price Adjustment Time* (d_{market}) and the actual price value is *Traders' Expected Price* (TEP^3). TEP^3 is the multiplication of the *Effect of Demand Coverage* and the *Accepted Price (AP)* as shown in Equation 103. As for the *Accepted Price* presented in Equation 104, it is the multiplication of *Average Cost of Gas* in the market (*ACG*), which is the weighted average of total unit costs of the supply options instead of the desired prices of producers, and *Traders' Accepted Margin (TAM)*. This margin has a multiplicative formula seen in Equation 105, where a reference profit margin (TAM^*) is multiplied by the E*ffect of Relative Price on Accepted Margin*

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($f_{price,margin}$). This effect is represented by a decreasing graphical function (since high prices make traders reluctant to pay more), as well, which can be seen in Figure 4.23.

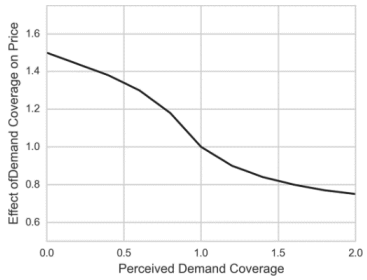


Figure 4.22: Graphical function showing the *Effect of Demand Coverage on Price*

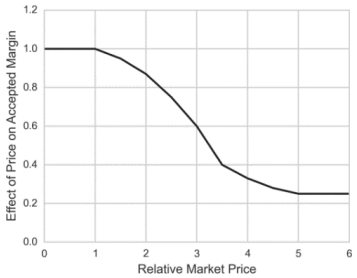


Figure 4.23: Graphical function showing the *Effect of Price on Accepted Margin*

$$p_{3,market}(t) = p_{market}(0) + \int_{t_0}^{t} \left(\frac{TEP^3(\tau) - p^3_{market}(\tau)}{d_{market}} \right) d\tau \quad (102)$$

$$TEP^3(t) = AP(t) * f_{dem,price}(PDC(t)) \quad (103)$$

$$AP(t) = ACG(t) * TAM(t) \quad (104)$$

$$TAM(t) = TAM^* * f_{price,margin}\left(p^3_{market}(t) / p_{market}(0) \right) \quad (105)$$

The market price determined with any of these three options affects the profitability in the subsystems of supply options. As for the demand changes, they are determined with respect to the consumer price, which is calculated based on the market price, with the addition of transportation costs and taxes. Equation 106 shows this consumer price formulation, with the main components of an energy bill in the Netherlands being the *Transport Cost* (C_{tr}), *Energy Levy* (C_{levy}) and *Value-added Tax* (C_{VAT}). Among these three components, the first two are set as absolute values, whereas VAT is collected as a percentage-based tax. Since the consumer price is different for each sector, an average value of these different prices, i.e. the weighted average based on the demand of each sector, is used as an indicator of consumer prices in testing the effectiveness of policies.

$$p_{consumer}(t) = \left(p_{market}(t) + C_{tr} + C_{levy} \right) * (1 + C_{VAT}) \quad (106)$$

4.5. CONCLUSIONS

This chapter presented the simulation model developed in this study to quantify the conceptual system model and to generate scenarios for policies to be tested on. The three segments of the model, namely the supply options, demand sectors and the market, are explained with their main assumptions and detailed formulations. Focusing on the representation of uncertainties, this model included several parametric and structural uncertainties, i.e. multiple alternatives of a model structure if it is subject to uncertainty due to several possible modelling assumptions.

This model is the result of an iterative modelling process. Some steps of this process involved extensions to the breadth and depth of the model to improve its validity, while some of them

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made simplifications to obtain a 'good enough' but a 'small and simple' model. Despite such efforts, the eventual model cannot be claimed to be small and simple, but it is considered good enough to capture the complexity of the problem, which itself covers a broad area in the energy sector. Besides the extent of the problem, the aim to use some components of the model in separate studies is the second factor that caused a growth in size. As referred throughout the chapter, especially the natural gas and renewable gas components of the model are used in studies that focus on the production dynamics of these two types of gas particularly.

The efforts to find simple model structures that can represent uncertainties sufficiently and be used for scenario generation resulted in some formulations which are not fully compatible with the fundamental concepts of system dynamics. For instance, the formulations borrowed from econometrics such as price elasticities of demand or supply-demand curves to derive the changes in import prices would not be found in system dynamics models that aim to describe the actual mechanisms in the system independent from the economic theories. As mentioned, these were conscious choices to have simple structures that can encompass the related uncertainties. Standing as an example of how the features of other modeling methodologies can be utilized to fit model to its purpose, this issue also stresses the question of what features should an exploratory system dynamics model should have.

This model included several actions made by the main actors in the system, such as the investment decisions of natural gas producers or price influence of traders. The structural uncertainties included in the model were mostly related to these decision making mechanisms, resulting from ambiguities due to multiple possible approaches adopted by the actors in the same group. This heterogeneity in the actions of actors, as opposed to the homogeneity assumption in this model, can be accommodated in an agent-based model more thoroughly if the purpose is to investigate the effects of such differences of actors on future dynamics of the system.

Following this description of the model, the next chapter will discuss the validity of this model in more detail and present the formal validation tests conducted. The base-run behavior of the model and a large ensemble of scenarios generated by the model will also be discussed in the next chapter.

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Thus, it was established thousands of years ago that the Universe as a whole, in its full complexity, cannot be represented by any simulation smaller than itself. In other words, you can't get any picture of the Universe as a whole except by studying all the Universe.

Isaac Asimov, *Prelude to Foundation*

5

ANALYZING THE MODEL BEHAVIOR

Chapter 4 described the simulation model developed to represent the system of interest, i.e. the policy domain relevant for the Dutch gas sector. As explained in Chapter 3, the purpose of this model is, with reference to the systems analysis framework introduced in Chapter 2, (i) to examine future values of outcome indicators, (ii) to investigate the effects of uncertainties on outcome indicators in a large number of scenarios, and (iii) to analyze the effects of policies on outcome indicators given the presence of uncertainties. This chapter addresses the first two of these goals, i.e. examining the future dynamics of outcome indicators in a reference simulation, and exploring the uncertainty space of outcome indicators by propagating the effects of uncertainties on them through the system model. Additionally, the scenario space generated by the model is analyzed according to the 6 stakeholder perspectives described in Chapter 2.

This chapter is structured as follows: Section 5.1 explains the model behavior in the reference simulation without taking uncertainties into account, including a comparison of model output to the historical data. Section 5.2 presents the results of exploration, which is the set of scenarios generated by the model and uncertainty spaces of outcome indicators in these scenarios. Section 5.3 discusses how stakeholder perspectives are incorporated into this model-based study and how they differ from each other in the scenario space. Section 5.4 concludes this section with a brief discussion on the results.

5.1. REFERENCE SIMULATION

In this section, the base case model behavior (reference simulation results) will be analyzed in two time frames. Firstly, the simulation results will be compared to the historical data. Having

68A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the primary aim of this comparison as validation of the model, implications of this comparison and further remarks on the validity of the models will be discussed in Section 5.1.2. Secondly, future dynamics of the model in the reference simulation will be explained in Section 5.1.3. This reference simulation is not intended to be presented as the most-likely or the main behavior pattern of the model. It is rather used to understand and explain the behavior of the model. Before these explanations of the simulation output, Section 5.1.1 describes the specification of the input data and the settings of the reference simulation.

5.1.1. Model Specification and Simulation Settings

The model is developed by using the system dynamics simulation software Vensim DSS (Ventana, 2009). The simulation horizon is set as the time period between 2000 and 2062. The portion of this time horizon between 2000 and 2012 is used for a comparison to real life data, whereas the 50-year period between 2012 and 2062 is the future simulation horizon. (Note that the current time is assumed to be 2012, since this modeling study started in 2012.) The time unit is one year, meaning that annual changes in the system variables are taken into account, whereas the computations are made at each 1/16 year. That is, the time step of the model is set as 0.0625. The differential equations constituting the model are solved with the Euler integration method.

As for the data inputted to the model in the form of parameter values and graphical functions, it is collected from various sources. The databases of Netherlands Oil and Gas Platform (NLOG, 2014), Central Statistics Bureau (CBS) of the Netherlands (CBS, 2014a, 2014b, 2014c) and Enipedia (Enipedia, 2010) and European Comission statistics (EUROSTAT, 2014) were the primary sources of numerical data, as well as the publications of the natural gas company EBN, Energy Research Center Netherlands (ECN) and other industrial and academic publications. The data from these various sources was not consistent in many cases. In such cases, an average value is assumed to be the reference value of a parameter, yet this ambiguity is observed as an important source of uncertainty in a model-based study for the Dutch gas sector. Available data was needed to be processed in some cases, to obtain the values that match with what model parameters represent. For instance, regarding the electricity and heat produced in Combined Heat and Power (CHP) units, annual total production volumes of both electricity and heat are available for the period 2000-2012. Based on these, the parameter *Heat generated per unit of electricity in CHP units* by natural gas combustion *(h_E)* is obtained as the average of annual ratio of the heat to the electricity production.

The parameter values which could not be derived from available data, for instance the *Sensitivity of Gas Price to Cost*, are calibrated based on the historical data of output variables. For this purpose, the optimization tool of Vensim DSS is used, and the parameter values that minimize the difference between the data and the model output are searched for.

Formed in the abovementioned ways, the input data used to simulate the model is shown in Appendix 5.1. This data includes the base-run values of the model parameters, initial states of stock variables (in 2000), and the parameter (switch) values indicating which alternative model structure is used. The base-run shapes of graphical functions are already shown in

68B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Chapter 4. Additionally, it is assumed that no additional policy is implemented or no policy is changed in the reference simulation. This implies that the current policies are included in the reference simulation as the business-as-usual (BAU) case, with the specifications below:

- a 10-year cap of 425 bcm on the Groningen field until 2020,
- the tax percentage for natural gas production (State Profit Share, SPS) equal to 50%,
- no permission to shale gas exploration and production,
- 21% VAT in the consumer price of gas, for all demand sectors except agriculture,
- the current energy levy values in the consumer gas price,
- a 3 bcm goal by 2020 for biomethane production,
- no obligation to utility companies to provide a portion of their supply from renewables
- biomethane subsidization with the current subsidization scheme (spot market gap model) until 2050.

5.1.2. Comparison of Model Behavior to Historical Data

In simulation studies, a behavior reproduction test is a common validation technique regardless of the methodology (Forrester and Senge, 1980; Barlas, 1996; Balci, 1994). This test suggests comparing the model output to the real life data, and check if the model can sufficiently replicate the real life behavior. The similarity between the model output and data is often measured with statistical methods, e.g. autocorrelation tests (Barlas, 1990) and Theil's inequality statistics (Sterman, 2000, p.874-880). Considering uncertainties, the reliability of this method can be questioned, because a model cannot be argued to be capable of properly estimating the future even if it correctly reproduced the past data. Still, the plausibility of the system's historical behavior is not debatable, and with this comparison, we aim to check if the model can generate this plausible behavior with particular instances of uncertain model parameters, functions and structures.

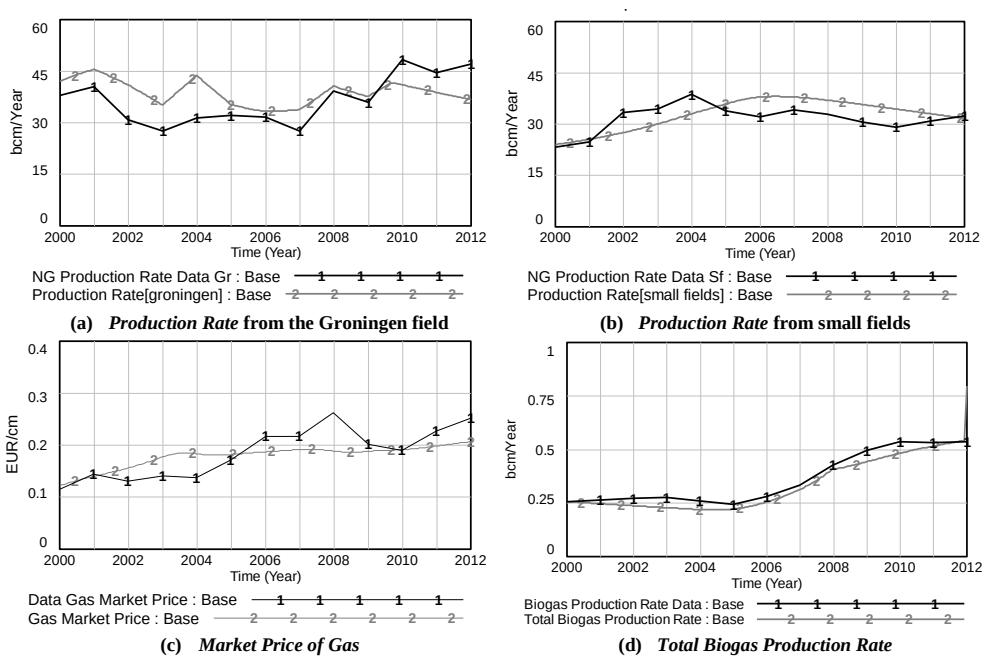
For many model variables, the available data does not cover a long time horizon, especially because many technologies included in the model are new, such as renewable gas or wind and solar energy. Therefore, as the reference past behavior of the system, we take the period between 2000 and 2012, for which data is available on NLOG and CBS platforms. Besides, a visual comparison is considered adequate in this study, without a numeric comparison of the model output and real data, since a thorough replication of the real-life dynamics is not aimed at, as explained before.

Figure 5.1a-d show the results of this comparison for the *Production Rate* of natural gas (separately for the Groningen field and small fields), *Market Price of Gas*, and *Total Biogas Production Rate*. In plots (a) and (b), the data (lines 1) for production from the Groningen field and small fields are seen to inversely follow each other, that is, increasing small fields production leads to decreasing Groningen production, and vice versa. The model behavior is observed to follow this pattern with a short delay. It must be noted that the production volumes of the Groningen field do not follow a smooth pattern in the model output. This piece-wise pattern is because of the inclusion of *Annual Export Demand*, which is an external factor in the model, as a time-dependent variable in this period corresponding to the real life data. Hence, summed with the total domestic natural gas demand, which is an internal

69A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

variable in the model, this variable causes such a discrete output for the Groningen production.

As for the *Market Price of Gas*, the real-life data (line 2 in plot c) shows a gradual increase from 2000 to 2012, and the model output (line 1) demonstrates a similar behavior but without sharp changes. In the real life data, a more rapid increase is observed from 2004 to 2008, and this is attributed to increasing global oil prices in this period, and their effects on the gas markets (IEA, 2009), which are not in the scope of this model. Lastly, Figure 5.1d shows the comparison of model output (line 2) to the data (line 1) for *Total Biogas Production Rate*. The model generates a similar behavior to the data, in the form of an initial stagnation and then a logarithmic increase. In this period when biogas was not yet used for conversion to biomethane, the main drivers of biogas production were its use in heating and electricity generation, and the model output demonstrates these effects, too, as seen in the behavior of variables *Biogas Allocated for Heating* and *Biogas Allocated for Electricity* in Appendix 5.2.



(a) ***Production Rate*** **from the Groningen field** **(b)** ***Production Rate*** **from small fields**

(c) ***Market Price of Gas*** **(d)** ***Total Biogas Production Rate***

Figure 5.1: Comparison of model output to the data in the period 2000-2012

In addition to these four examples of comparing the model output to the historical real-life data, such comparisons of more variables can be seen in Appendix 5.2.

Further remarks on validation

Behavior reproduction is certainly not the only test that can be employed for validation, and only one type of test is not considered adequate. In the system dynamics domain, Barlas (1996) divides the validation tests into two as structure and behavior pattern tests. Structure tests aim to check the model structure (i) directly, such as inspecting formulations, parameters and dimensions by reviews and walkthroughs with experts, (ii) based on the behavior, such as

69B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

with extreme-condition tests (stress-testing) and sensitivity analyses. Behavior pattern tests, which aim to establish the accuracy of model behavior by comparing it to real behavior, are suggested to be conducted once sufficient confidence in the model structure is obtained by structure tests.

In this study, we opted for direct structure tests to evaluate the appropriateness of model structure, and then for behavior pattern tests. We first checked the dimensional consistency and meaningfulness of model equations, and discussed the main assumptions of the natural gas and renewable gas sub-models with experts in these fields. Namely, we consulted a professor of petroleum engineering at Delft University of Technology and a senior bio-energy and biomethane consultant at the Netherlands Enterprise Agency (RVO). This discussion led to the conclusion that the corresponding components of the model, namely the natural gas and renewable gas production sub-models, are suitable to represent the real system, given the purpose of this study to generate long-term plausible dynamics.

The two commonly used structure-oriented behavior tests are the extreme condition tests and sensitivity analyses. In this study, these tests are not conducted in a univariate manner, i.e. by changing the inputs of the model one by one. Instead, a revised approach is adopted and the model formulations that cause an error are investigated, once an error is detected in a large set of simulations.

These simulations were generated in an automated manner as in the exploration phase of EMA. The input ranges of these simulations covered a wide uncertainty range, and the extreme conditions for many of the inputs. Yet, interpreting the results was not as straightforward as in the case of a manual univariate extreme conditions test or sensitivity analysis. In the resultant simulation set, erroneous runs such as disrupted or explosive (sudden exponential increase or decline) simulations, or simulations that result in negative values for a variable that has to have positive values, indicated an error in the model. Such simulations were found out by analyzing the output data and retrieving the single simulation that resulted in an unexpected output. Then, considering the input values in this particular simulation, the model formulations which cause the error were traced back and revised. Detecting the errors and revising the model formulations in this manner was an iterative process as in usual validation testing.

Following these, the behavior pattern tests presented in this section are conducted to check if the model behavior represents the real system behavior in the period between 2000 and 2012.

As Barlas (1996) argues, the validity of a model is assessed according to the type and purpose of this model. System dynamics models aim to explain how the model behavior is generated and to propose potential ways to change this behavior, if necessary. The abovementioned framework of validation tests is composed for models of this type. However, in addition to enhancing the understanding about structure-behavior relations, exploratory models aim to generate a large number of scenarios and a variety of behavior patterns to investigate what may happen in future. In this regard, not all of the established validation tests in system dynamics are considered suitable for exploratory models, because they are expected to iteratively result in a single, ‘good’ model structure whereas exploratory models acknowledge

70A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the presence of multiple possible model structures. Therefore, it is considered worthwhile to investigate theoretical and practical aspects of validating exploratory models in future research, based on the validations tests already established in the literature and the purposes of exploratory models.

5.1.3. Model Behavior in the Reference Scenario

In this section, the behavior of the outcome indicators in the reference simulation will be explained. In addition to the figures presented here, many complementary behavior plots can be seen in Appendix 5.2.

In Figure 5.2, the base-run dynamics of *Coverage of Domestic Gas Demand* can be seen. This variable represents the ratio of the total supply in the domestic market (domestic production and net imports) to the total domestic gas demand. The model output shows that in the period between 2012 and 2062, the total gas demand is mostly stable and total production declines gradually and below the demand levels after 2025 (see Figure A5.1 in Appendix 5.2). In this period, the demand from industry and agriculture declines, whereas the household demand increases, and the total demand volumes remain stable, as seen in Figure A5.2. The demand changes are mostly due to the price changes and external factors, and the switch rate from natural to renewable gas remains very low. As for the production volumes, sharp fluctuations also seen in *Coverage of Demand* before 2012 are due to the export demand, as explained before (see the historical data comparison for the Groningen production in page 107), and the increasing trend in this period is due to the increasing production from small fields. However, starting from ~2010s, the production from both Groningen and small fields declines gradually (Figure A5.3). The first reason of this decline is the preference of producers to maintain *Developed Reserves* longer, as they decline. The second reason is the reduced exploration investments due to the decline in prospects, although *Prospective Resources* are not all discovered and the market price and societal acceptance do not inhibit investments.

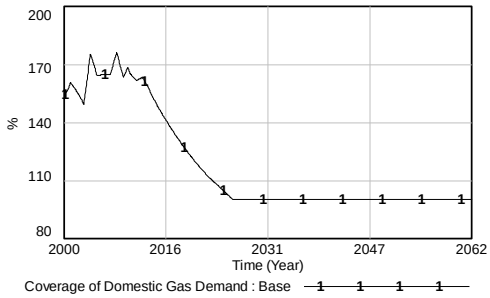


Figure 5.2: Behavior of *Coverage of Domestic Gas Demand* in the reference simulation

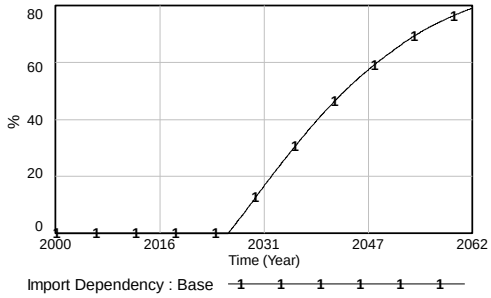


Figure 5.3: Behavior of *Import Dependency* in the reference simulation

Besides natural gas production, the contribution of renewable gas remains comparably very low in the model results for the period of 2012-2062. The production rates of biomethane increases until 2030s, as can be seen in Figure A5.4, yet the volumes are still very low, and the following decline is due to the allocation of limited biogas resources mostly to heating and electricity production. Increasing gas and electricity prices make these two options more

70B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

attractive to utilize biogas, whereas the cease of subsidies reduces the profitability of conversion to biomethane, since biomethane costs are still high at that time compared to natural gas. Due to declining domestic production, imports become inevitable, and the *Import Dependency* increases starting from the time when production drops below the demand, as seen in Figure 5.3. Since the net imports are taken into account in this study, and the import demand is assumed to be the discrepancy between domestic supply and demand, *Coverage of Domestic Demand* remains stable at 100% as *Import Dependency* increases with a decreasing rate till 80% by 2062. Despite such a high dependence on imports, it can be said that the demand is covered fully in the reference simulation, without any supply shortages in the domestic market.

Since the total consumption is mostly stable, *Renewable Gas Percentage* in Figure 5.4 follows the pattern of renewable gas production, i.e. an increase until around 2030 and then decline as explained above. In this simulation, renewable gas supplies maximum ~3% of the total gas consumption. As for the *Share of Renewables in the Energy Mix*, namely the percentage of renewables in the total gas and electricity production, it shows a steady increase until 2050 and reaches 20% in Figure 5.5, then rapidly drops. This sudden drop in 2050 is due to the cease of subsidization, and the production of solar energy going down, which is not profitable yet at that time without subsidies (see Figure A5.5 in Appendix 5.2). Still, the production of wind energy keeps increasing by 2062, and provides an increase again in the share of renewables, although the electricity production from biogas and biomass are almost stable by the end of simulation.

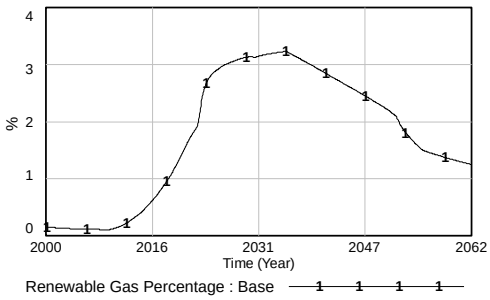


Figure 5.4: Behavior of *Renewable Gas Percentage* in the reference simulation

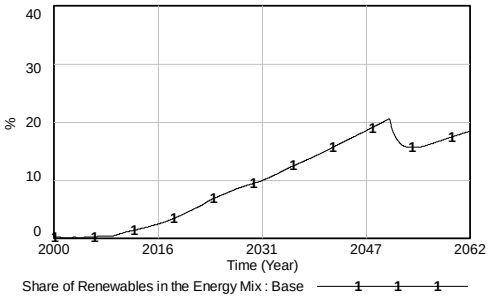


Figure 5.5: Behavior of *Share of Renewables in the Energy Mix* in the reference simulation

Figure 5.6 shows the model results for *Market Price of Gas* and *State Revenues from Natural Gas Production*. Price demonstrates an increasing pattern, with higher increase rates than the first decade after ~2015, yet the rate of increase declines after around 2030, leading to an approximate s-shaped growth in the simulation horizon. The reason of this increase in price is mostly the effect of demand coverage, which follows a decreasing pattern but stabilizes when demand coverage drops to 100% (as in Figure 5.2), indicating a sufficient level of imports to cover the domestic supply shortage. Desired producer price of gas also increases in the simulation horizon, not only because of increasing natural gas production costs but also because of increasing import prices due to the increasing demand for imported gas. Still, the effect of cost on the market price is mostly a decreasing one, because the effect of demand coverage is much higher and the desired producer price remains below it. Due to the

71A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

increasing market prices, *State Revenues* maintain an increasing pattern despite the decreasing production volumes of natural gas. However, this increase stops around 2030 and the revenues collected from natural gas production steadily decrease afterwards.

In the reference simulation, *Societal Acceptance* of natural gas production from the Groningen field and from shale resources demonstrate the behavior patterns seen in Figure 5.7. Following minor fluctuations due to demand coverage, *Societal Acceptance* of the Groningen production declines until ~2015. This is due to the effect of disturbance which decreases societal acceptance as production continues, and the relative stability in the effects of prices and demand coverage. Yet, after this time, increasing prices and decreasing demand coverage lead to an increase in societal acceptance, besides the still decreasing effect of disturbance (as can be seen in Figure A5.6). As for the shale gas, its acceptance also increases due to the effects of price and demand coverage. Yet, a very rapid increase is observed given the reference run conditions, since shale gas is not actually produced, and the influence of actual disturbance is not observed. Hence, the increasing effect of price and scarcity are more influential on the societal acceptance of shale gas.

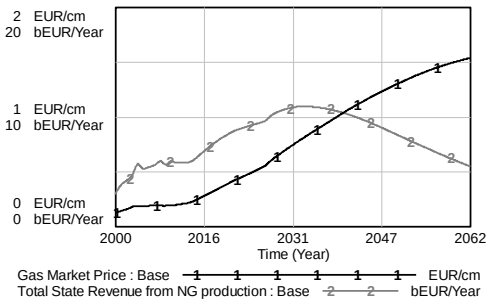


Figure 5.6: Behavior of *Market Price of Gas* and *State Revenues from Natural Gas Production* in the reference simulation

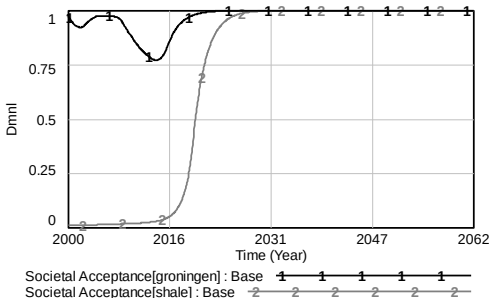


Figure 5.7: Behavior of *Societal Acceptance* in the reference simulation

5.2. EXPLORATION OF FUTURE DYNAMICS

Having the reference simulation results investigated, this section presents the uncertainty spaces of outcome indicators in the scenarios obtained by propagating uncertainties through the model on them. Below, Section 5.2.1 explains the technical aspects of this scenario generation, whereas Section 5.2.2 presents and discusses the results.

5.2.1. Analysis Specification and Simulation Settings

For exploring the effects of uncertainties on outcome indicators, 5000 simulations of the model are conducted, each corresponding to a different scenario, with different combinations of the instances of model uncertainties. This large number of simulations is handled using EMA Workbench (Kwakkel, 2015), which is a free software created with Python programming language, to control Vensim through its Dynamic Link Library (and a few other simulation environments, too) and to analyze the resulting data.

71B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The input values to these simulations are provided by sampling from the alternative ranges or sets of uncertain model elements with Latin Hypercube Sampling (LHS). Unless specified, these uncertainties are assumed to have a uniform distribution, since this distribution does not impose different likelihoods for different alternatives and better represent deep uncertainty in exploratory analysis. In this study, only the prospects of shale gas resources are assumed to have a triangular distribution as it is specified in geological studies (Muntendam-Bos *et al.*, 2009). Sampling is done from continuous ranges for parametric uncertainties and from a set of discrete alternatives for categorical uncertainties, e.g. the switch parameters that determine which model structure is to be used. As for the graphical functions, for creating alternative shapes in an automated manner, the parameterization method discussed by Eker *et al.* (2014) is used (with triangular functions). The uncertainty ranges and sets used in this sampling can be seen in Appendix 5.1.

As in the reference simulation, the exploration of scenarios are done based on the business-as-usual policy case described in Section 5.1.1. For policy testing presented in the following chapters, the scenario sets corresponding to policy options are formed in the same way, i.e. simulating the model 5000 times with LHS from the uncertainty ranges and sets.

5.2.2. Future Scenarios

In this section, resulting scenario sets are depicted by envelopes of uncertainty ranges of the outcome indicators. An envelope illustrates the bandwidth between the minimum and maximum value of an outcome indicator in these scenarios at each time point between 2012 and 2062. At the top of each figure below, the envelope of 5000 simulations is seen, with a few examples of individual simulation results encompassed in that envelope. At the bottom, the Gaussian kernel density estimates (KDE) (Jones *et al.*, 2014) of the 2020, 2030, 2050 and the end state values can be seen. The density graphs illustrate the distributions of the output data obtained from 5000 simulations at these time points. It must be noted that the bottom figures share the y-axis with the top figure (possibly in a different scale), whereas their x-axes indicate the density estimate of each value on the y-axis.

In Figure 5.8, the envelope of *Coverage of Domestic Gas Demand* is seen. In the first two decades, the range of possibilities is wide, for instance showing many scenarios with higher than 200% demand coverage in 2020, i.e. with domestic production volumes as high as more than twice the domestic demand. The uncertainty range of *Coverage of Domestic Gas Demand* is even wider later, yet with only a few scenarios resulting in very high values, since the KDE of 2030 shows that the majority of scenarios are around 100%. As seen in the next two KDE's, almost all the scenarios converge to 100% demand coverage in the later decades, which was the case in the reference run, too, due to imports covering the domestic supply shortage. Still, the model results show a few scenarios when demand coverage is still more than 100%, and more scenarios where it is less than 100%. The demand coverage values below 100% imply that imports are not sufficient to cover the domestic demand and there are supply shortages, e.g. because of the unavailability of gas in the international market or very high import prices.

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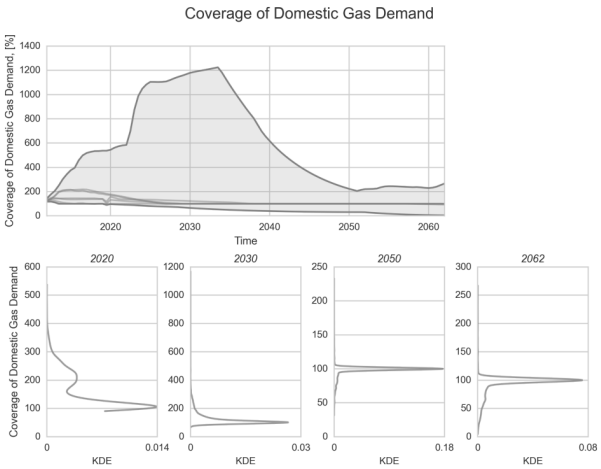


Figure 5.8: Envelope of *Coverage of Domestic Gas Demand* and the KDE's in 2020, 2030, 2050 and 2062

The uncertainty range of *Renewable Gas Percentage* behavior is depicted in Figure 5.9, where the model results show much higher results than the reference case in many scenarios. However, despite up to 40% renewable gas percentage in the total consumption, such cases are very few, and in the majority of scenarios the share of renewable gas is still very low. Such low percentages are more apparent in the last decades as the KDE's of 2050 and 2062 show very high densities below ~3%. This decrease can be attributed either to the cease of subsidization or biomass scarcity, as it will be analyzed in the following chapters. Also, by analyzing the scenarios where *Renewable Gas Percentage* has very high values with the scenario discovery tools, the opportunities for maintaining or further stimulating high biomethane production can be grasped.

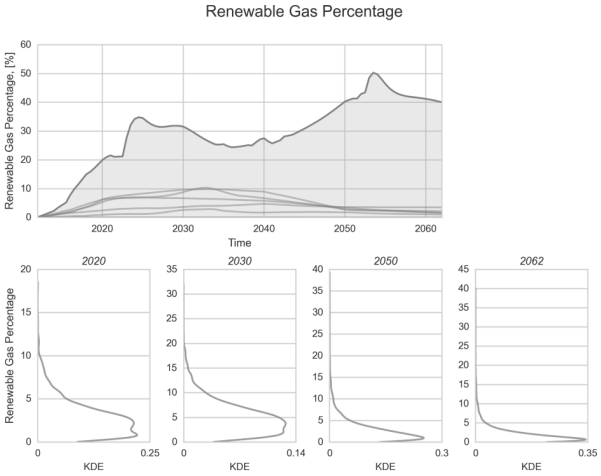


Figure 5.9: Envelope of *Renewable Gas Percentage* and the KDE's in 2020, 2030, 2050 and 2062

The envelope of *Import Dependency* also shows a wide uncertainty range in Figure 5.10. In some scenarios, positive net imports start earlier in contrast to the reference simulation where it starts around 2030. Such results accord with initially low domestic production e.g. due to market conditions that impede the extraction of domestic reserves, or very high production and demand coverage that depletes the domestic reserves earlier. Regardless of the reason, the

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majority of scenarios result in low import dependency in the early decades, whereas it is around or above 80% in most scenarios in the last decades as the KDE's of 2050 and 2062 show. Still, the presence of scenarios with a low or relatively low import dependency can be considered as an opportunity to find how this dependency can be kept low.

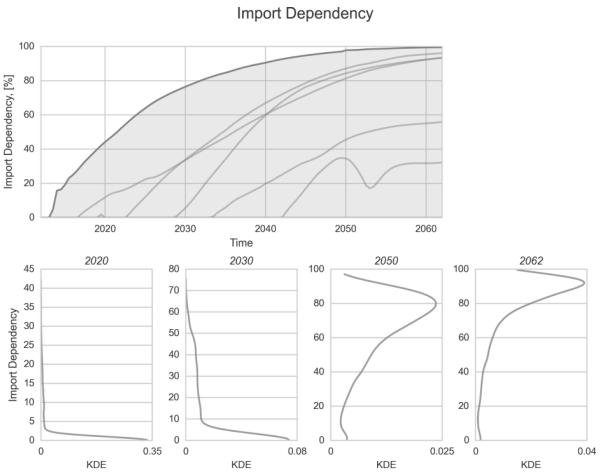


Figure 5.10: Envelope of *Import Dependency* and the KDE's in 2020, 2030, 2050 and 2062

As for the *Share of Renewables in the Energy Mix*, the results show in Figure 5.11 that not only the uncertainty range of scenarios but also the average value of them is increasing over time. According to these results, 14% renewable energy goal of the Netherlands by 2020 (see Chapter 1) is not achieved in any scenario, yet the density of scenarios moves upward in the following years. Even though there are individual scenarios in which the share of renewables declines in the last decades, the model results show up to 80% renewable energy share in the total consumption by the end of the simulation horizon.

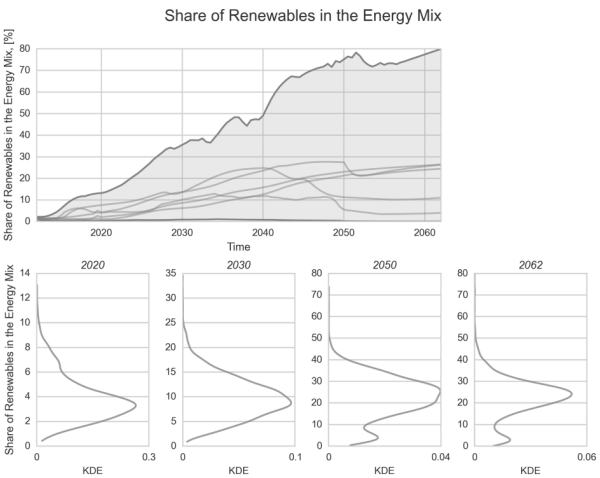


Figure 5.11: Envelope of *Share of Renewables in the Energy Mix* and the KDE's in 2020, 2030, 2050 and 2062

The envelopes and density graphs of the other four outcome indicators in these scenarios can be seen in Figures A5.7-10 in Appendix 5.2.

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5.3. FUTURE DYNAMICS FROM THE STAKEHOLDER PERSPECTIVES

In the previous section, the future scenarios are explored not from a particular view but by considering a common uncertainty space in the scope of the model. However, as discussed in Chapter 2, different stakeholders in the Dutch gas sector have different views on the future. In this section, the scenarios created by the model in the previous section are analyzed from each of these stakeholder perspectives, to investigate how these perspectives differ from each other. Below, Section 5.3.1 explains how these perspectives are expressed quantitatively in terms of the uncertainty ranges used in this model-based analysis. Section 5.3.2 first discusses the internal components of each perspective and the relations between them based on the analysis of scenarios corresponding to them, and then compares the scenario spaces of each perspective.

5.3.1. Model-based Representation of the Stakeholder Perspectives

Chapter 2 provided an overview of the six stakeholder perspectives identified in the 'Stakeholder Dialog' branch of the Next Fifty Years project. These perspectives listed in Table 5.1 were derived from an application of Q-methodology and were elaborated in two stakeholder workshops. Each of these perspectives describes how several aspects of the Dutch energy system are expected to look like in the future. Hence, each perspective can be considered as a qualitative scenario, or a set of such scenarios, although they have not been purposefully and elaborately developed as scenarios.

The perspective descriptions include not only positive statements about what is expected to happen in the future, but also normative statements about what should be done. In other words, they consist of both future views and wishes/expectations of the stakeholder groups, as well as their preferred prescriptions. However, this study has adopted a systems analytical view which clearly differentiates between such concepts as desired futures (policy objectives), future values of outcome indicators and preferred policies, as explained in Section 2.1. Therefore, to be consistent with this systems analytical view, it is assumed that these perspectives describe how various stakeholder groups envision the future, rather than describing their desired futures or suggested solutions. In other words, the perspective definitions are assumed to indicate descriptive scenarios.

Table 5.1: Summary of the 6 stakeholder perspectives

Perspective name	Key concept
Perspective 1 - In gas we trust	Natural gas will still be an important energy source.
Perspective 2 - In renewables we trust	Renewable technologies will prevail.
Perspective 3 - Adaptive gas sector in an uncertain future	The gas sector will be able to adapt to changing conditions.
Perspective 4 - Gas in times of austerity	Natural gas, as a cheap energy source, will prevail due to austerity conditions.
Perspective 5 - We need all energy sources!	A wide variety of energy technologies will be required and used to be able to satisfy demand.
Perspective 6 - Entrepreneurs serve the market better	To steer innovation and reduce costs, entrepreneurs and small companies will gain importance.

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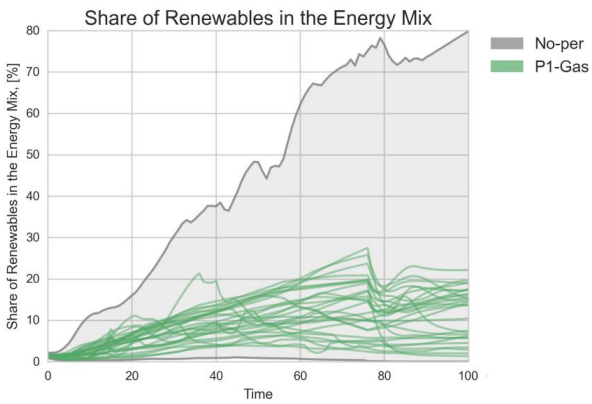


Figure 5.12: The subset of scenarios corresponding to *Perspective 1*, and the entire set of scenarios (*No-per*) for the *Share of Renewables in the Energy Mix*

Following this assumption, the descriptive and quantitative scenarios generated by the simulation model are classified in a way to match the perspective descriptions. Namely, a subset of model-generated scenarios is formed for each perspective to represent the common future view of stakeholders having this perspective. Figure 5.12 exemplifies such a subset for *Perspective 1*. In this figure, the grey shaded area depicts the envelope of business-as-usual scenarios generated by the model for the outcome indicator *Share of Renewables in the Energy Mix*, and the green lines correspond to the scenarios of which the outcomes are as expected in *Perspective 1*. The procedure followed for this model-based representation of the perspectives has three main steps explained below.

Firstly, detailed descriptions of the perspectives and their defining Q-statements were examined. Defining Q-statements of a perspective are the statements agreed or disagreed with most by the interviewees who are categorized in that perspective after the statistical analysis. Since each Q-statement is focused on a particular aspect of the energy sector, these statements can be matched with a model element, if it is included in the system boundaries. For instance, "Liquefied Natural Gas (LNG) imports will increase, contributing to security of supply." is a statement agreed with most in Perspective 1. This statement can be matched with the model variable *Annual Import Volume by LNG*. In this way, a comprehensive list of model elements is formed, including both uncertain inputs and dynamic output variables.

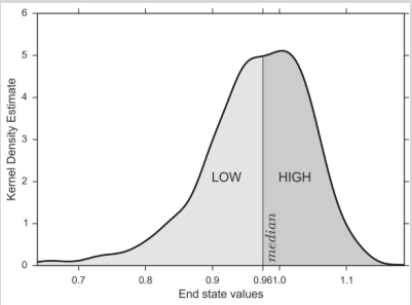
Secondly, this list of model elements was presented to the team of five researchers who worked on identification of the stakeholder perspectives and facilitated the stakeholder workshops. Each model element was discussed by the team in terms of its relevance to a perspective, and the representative elements are identified with a consensus. The research team also decided on whether a representative model element of a perspective takes high or low values in the future according to that perspective. It must be noted that none of the perspectives included quantitative indicators about the future values.

74A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

In the last step, the information collected in the previous steps was translated into a quantitative specification of perspectives in terms of model inputs and outputs. First, input conditions are set as modified uncertainty ranges. For instance, the importance of societal acceptance in the consumers' view (compared to price) for switching to renewable gas from natural gas is low according to Perspective 1. The parameter corresponding to this statement is the *Weight of Societal Acceptance* in the demand sub-model which affects the substitution rate of natural gas by renewable gas, and its uncertainty range is narrowed down to [0, 0.25] from [0, 1] as an input condition of Perspective 1. In general, if a parameter is determined to have a low value, its uncertainty range is reduced to the first quarter of the entire range, if a high value is specified, the upper quarter is used.

Box 5.1: The median value approach in representing the perspectives

Using the median value as a threshold to select perspective scenarios



The perspective statements do not specify a quantitative value for the future states of an outcome, but only mention if it is expected to be high or low. In this study, we opt to use the median value of the end states of each output variable mentioned in a perspective as a threshold for dividing the scenario space.

The major disadvantage of this median approach is a potential failure to realistically represent the perspectives, because the scenario subspace referred by a perspective definition may be wider or narrower than the median approach identifies. Further research may be helpful to elicit these thresholds from the stakeholders, yet it is expected to bring further complications because setting a quantitative value is difficult for stakeholders, as well as reaching a consensus on such a single value. Such complications are avoided with the median approach, which is capable of providing an estimate of the scenario subspace referred by the perspective.

Partitioning of the scenario space with other statistical measures is also possible. For instance, the scenarios above the 3rd quartile can be categorized as 'high', whereas the ones below the first quartile can be in the 'low' group. Compared to such examples, the median approach results in a larger set of selected scenarios for each output condition of a perspective, and increases the chance of having an intersection with the selected set of another output condition, when combinations of them are considered. Therefore, the median approach is chosen in this study as a simple and transparent way to represent scenario subspaces, although further research can lead to more customized definitions of these subspaces.

Following such revision of uncertainty ranges of inputs relevant for each perspective, ensembles of 10000[9] simulations are generated for each perspective. Then, the subspaces within these 10000 simulations which comply with the output conditions of the corresponding perspective are found. The quantitative specification of output conditions was based on the median value of the end states. In other words, if a variable is specified to have high values in a perspective, only the scenarios of which end states are above the median are included in the scenario subspace representing this perspective. For instance, *Coverage of Domestic Gas Demand* is high according to Perspective 1, thus, the scenario subspace of this perspective

[9] The number of scenarios, is set as 10000 in these experiments instead of 5000 as it was in the previous section. The reason for that was a very low number of perspective scenarios filtered from 5000 cases, as it will be explained in Section 5.3.2. Hence, 10000 scenarios enabled having a larger number of scenarios in the subset corresponding to each perspective.

74B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

includes only the scenarios in which the end state of this variable is higher than the median value. In Box 5.1, a more detailed discussion on the advantages and disadvantages of the median value approach is provided.

The input and output conditions for each perspective resulting from the first two steps of this procedure can be seen in Appendix 5.3. The scenario subspaces resulting from the application of this model-based representation procedure are discussed in Section 5.3.2 below.

5.3.2. Exploring Future Scenarios in Each Perspective

This section presents the scenarios generated by the simulation model corresponding to each perspective, discusses their characteristics and comparison to each other. As explained in the previous section, the scenario subspaces representing each perspective are filtered from an ensemble of 10000 simulations based on the output conditions. (Note that these 10000 scenarios are generated according to the input conditions of the corresponding perspective.) These subspaces show a variety in size, and each of them is a small portion of the entire set of 10000 scenarios as Table 5.2 shows.

Table 5.2: Number of scenarios found, representing each perspective

Perspective name	No of Scenarios in 10000
Perspective 1 - In gas we trust	28
Perspective 2 - In renewables we trust	341
Perspective 3 - Adaptive gas sector	69
Perspective 4 - Gas in times of austerity	63
Perspective 5 - We need all energy sources!	92
Perspective 6 - Entrepreneurs serve the market better	70

Such small numbers of selected scenarios are attributed neither to a small size of the entire scenario space nor to strict output conditions, because 10000 is a large sample size and selecting the scenarios above or below median results in approximately 5000 scenarios for each outcome variable. Hence, these small numbers are rather attributed to the difficulty of finding scenarios where all output conditions of a perspective are satisfied simultaneously, given the input conditions of this perspective which also affect the co-occurrence of certain output conditions. According to the causal assumptions in the model, some output conditions are indeed implausible to coexist in the scenario set generated by this model. In Section 5.3.2.1 below, such conflicts between the output conditions will be investigated. Then, Section 5.3.2.2 will present a comparison of perspectives to each other in terms of the characteristics of the scenario sets belonging to them.

5.3.2.1. Investigating the conflicting elements of the perspectives

We adopt a pairwise comparison approach to investigate which outcome conditions mainly cause the decrease in the size of scenario subspace representing a perspective. To determine the extent of conflict between each pair of outcome conditions, and to compare this to others, we first define a conflict measure. This measure is defined as the percentage decline in the number of scenarios when two outcome variables are taken into account simultaneously compared to the number of scenarios when one of them is considered alone. This measure

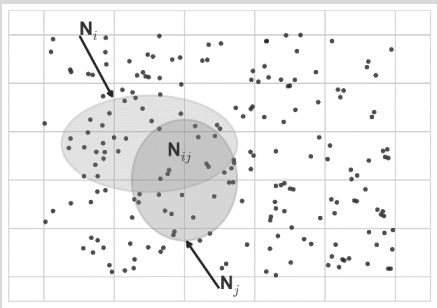
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discussed further in Box 5.2 enables an ordering of the outcome condition pairs in terms of how much they restrain the scenario space. Based on this measure and causal relations, the most influential factors in reducing the scenario space are discussed below for each perspective.

Below, the conflicting outcome variables of each perspective are visualized in a bubble graph. These graphs are based on a matrix of the outcome variables of the corresponding perspective. A circle is plotted on this matrix, if the conflict metric (described in Box 5.2) of the corresponding two outcome indicators is higher than a certain threshold. The circles are plotted in bigger size and darker color, as the conflict measure (reduction percentage of the number of scenarios) increases.

Box 5.2: Explanation of the conflict measure

Percentage reduction in the number of scenarios as a conflict measure



In this chapter, the percentage decline in the number of scenarios when two outcome variables are simultaneously considered is assumed to be an indicator of conflict between the two outcome conditions of a perspective. In other words, the conflict measure $C_{i,j}$ is denoted as follows:

$$C_{i,j} = \frac{N_i - N_{i,j}}{N_i}$$

In this equation, N_i is the number of scenarios found when only the output condition of variable i is considered, and $N_{i,j}$ is the number when variables *i* and *j* are considered simultaneously as depicted in the figure at left. These scenario counts are determined according to the median value obtained from 10000 end state values, as mentioned before. For instance, N_i is defined as the cardinality of the set containing scenarios of which the final value of the outcome indicator *i* is higher than the median, and N_{ij} is the cardinality of the intersection of this set with the counterpart for the outcome indicator j.

$$N_i = |S| \,;\, S = \left\{ s : O_{i,s}\left(t = t_{final}\right) \geq \underset{s=1\ldots10000}{q_{50}}\left(O_{i,s}\right) \right\}$$

$$N_{i,j} = |S| \,;\, S = \left\{ s : O_{i,s}\left(t = t_{final}\right) \geq \underset{s=1\ldots10000}{q_{50}}\left(O_{i,s}\right) \text{ and } O_{j,s}\left(t = t_{final}\right) \geq \underset{s=1\ldots10000}{q_{50}}\left(O_{j,s}\right) \right\}$$

Such a conflict measure could be defined in different ways, for instance by considering the increase in the number of scenarios when one of the outcome conditions are removed from the entire set of outcome conditions of a perspective. Different quantifications, such as the range of scenarios could as well be used instead of a cardinality measure. Yet, we select the above mentioned measure due to its simplicity, and its ability to represent the independent effect of an outcome condition on the scenario space.

The symmetric conflict measures $C_{i,j}$ and $C_{j,i}$ are very similar to each other, since N_i and N_j are similar to each other due to the division of the scenario space at the median value. Therefore, the figures shown in this section to depict the conflicts are highly symmetrical. Still, there are minor differences between $C_{i,j}$'s and $C_{j,i}$'s (for instance *Coverage of Domestic Gas Demand* vs. *Total Cumulative Substitution Rate* in Figure 5.13) due to the minor differences in the denominators (N_i and N_j) of these metrics.

Perspective 1 - In gas we trust

As shown in Appendix 5.3, Perspective 1 was represented by 10 output conditions. To calculate the conflict measure, firstly, the number of scenarios meeting each output condition (N_i) and the number of scenarios meeting each 2-combination of output conditions ($N_{i,j}$) are found, and they are shown in Appendix 5.4. Figure 5.13 visualizes the conflict measures higher than 50%, i.e. the combinations which cause more than 50% reduction in the number

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of scenarios, with an increasing size and darker color as the reduction percentage increases. According to this figure, it is most difficult to find scenarios in which both *Coverage of Domestic Gas Demand* and *Total Natural Gas Demand* are high. Since demand coverage is defined as the ratio of total supply in the Dutch gas market to the total demand, the inverse relation between these two variables explains the conflict. Besides, this finding implies that the supply levels are not sufficiently high to maintain high demand coverage values, as opposed to the expectation in Perspective 1.

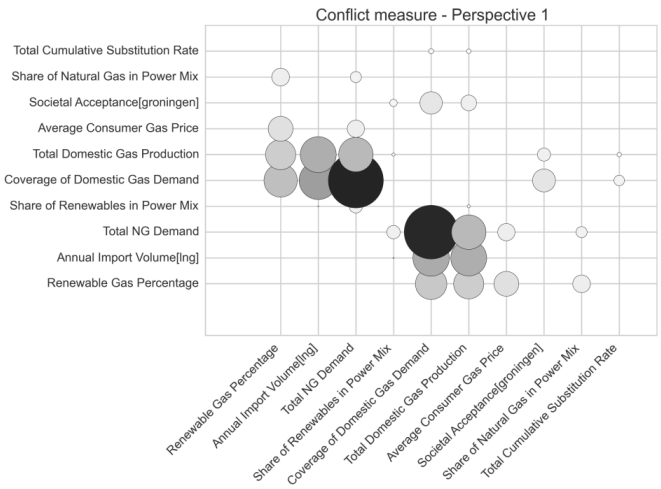


Figure 5.13: Conflicting outcome variables of Perspective 1

Table 5.3: Summary of conflicting outcome variables of Perspective 1

		Renewable Gas Percentage	**Annual Import Volume (LNG)**	**Total Natural Gas Demand**
		↓	↑	↑
Total Domestic Gas Production	↑	Total Domestic Gas Production includes both natural (NG) and renewable gas (RG). Due to depleting NG reserves, total production is high when RG production is high. Hence a low RG percentage and high total production are not observed together in many scenarios.	In the model, it is assumed that the purpose of imports is to cover the supply shortage. Hence, high imports and high production are not observed simultaneously in the model results.	Demand and production are related to each other with positive causality. Hence, depleting NG reserves reduce the scenarios with high production, and low production leads to low demand due to high price, in contrast to what is expected by the perspective. Therefore the number of scenarios in which both of these two variables are high is small.
Coverage of Domestic Gas Demand	↑	By definition, high demand coverage (*total supply/total consumption*) and low RG percentage in the total consumption have an inverse relationship. However, there are no many scenarios where this inverse relation is present, due to the high share of RG in the supply. In other words, since NG production is low, high demand coverage is observed usually when RG percentage is high, too.	In the model, it is assumed that the purpose of imports is to cover the supply shortage, i.e. to make the demand coverage 100%. Therefore, scenarios where demand coverage is more than 100%, are not observed together with high imports, but only with high domestic production.	The definition of demand coverage as *Total Supply/Total Demand* involves an inverse relation between Total Natural Gas Demand and demand coverage. Hence, the number of scenarios where they are both high (due to a very high *Total Supply*) is small.

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Furthermore, the relations of Total Domestic Gas Production and Coverage of Domestic Gas Demand to Renewable Gas Percentage, Annual Import Volume[LNG] and Total Natural Gas Demand are observed as the most conflicting factors, because they cause the maximum percentage reduction in the number of scenarios when the pairs of these variables are considered. Table 5.3 summarizes why the conditions expected in Perspective 1 for these outcome variables are contradictory to each other, based on the causal relations included in the model.

Perspective 2 – In renewables we trust

Figure 5.14 visualizes the most conflicting outcome indicators of Perspective 2, based on the scenario counts shown in Appendix 5.4. High *Renewable Gas Percentage* and low *Share of Natural Gas in the Power Mix* are the two conditions which cause the highest reduction in the number of scenarios when considered together. The incompatibility of these two conditions is attributed to the high electricity prices in the case of low natural gas share in the power mix, which attracts more biogas to the electricity sector and leaves less for the renewable gas production. Figure 5.15 supports this argument, showing the end state density distributions of both electricity price and biogas allocated for the power sector shifted upwards, in the scenarios where the two outcome conditions are met (red) compared to the rest of the scenarios (blue).

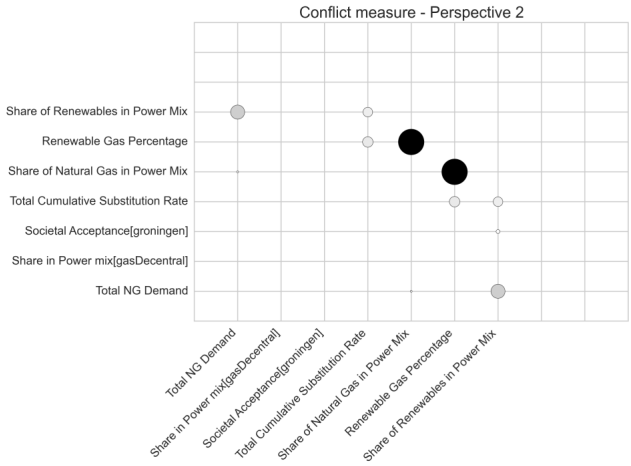
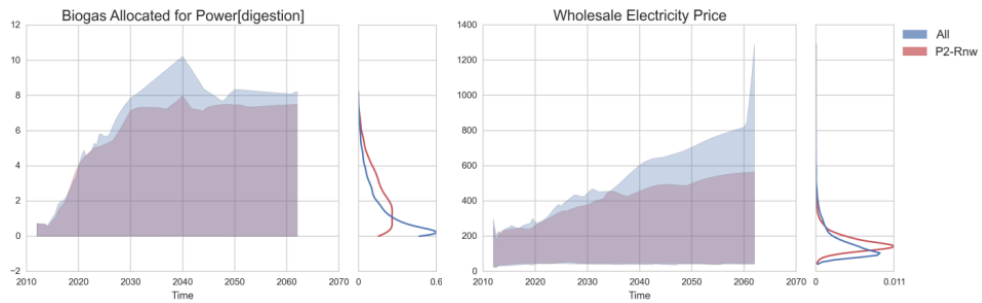


Figure 5.14: Conflicting outcome variables of Perspective 2



(a) **(b)**

Figure 5.15: Envelopes and End State Densities of *Biogas Allocated for Power* and *Wholesale Electricity Price*

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The following substantial conflict is observed between the *Share of Renewables in the Power Mix* and the *Total Natural Gas Demand*, since the former is expected to be high and the latter to be low in Perspective 2. The reason for this conflict is the following causal relations in the model: Low natural gas demand brings high demand coverage, which leads to lower prices. Low price of natural gas makes it more attractive in the power sector, increases its share and reduces the share of renewables. Hence, this sequence of relations is a barrier to the expectations of stakeholders regarding the renewable share in the power sector and the natural gas demand.

Perspective 3 – Adaptive gas sector

According to Perspective 3, the total natural gas demand excluding that of the industry sector is expected to be low, whereas the total demand including the industrial consumption of natural gas is expected to be high. This condition implies a high percentage of industrial demand in the total natural gas demand, and it is found to be the most difficult one to be satisfied in the scenario space, as Figure 5.16 shows. This finding can be interpreted as follows: Industrial demand does not have a dominant share in the total natural gas demand in future, and other sectors such as households maintain a high natural gas demand in the future scenarios where the total natural gas demand is high.

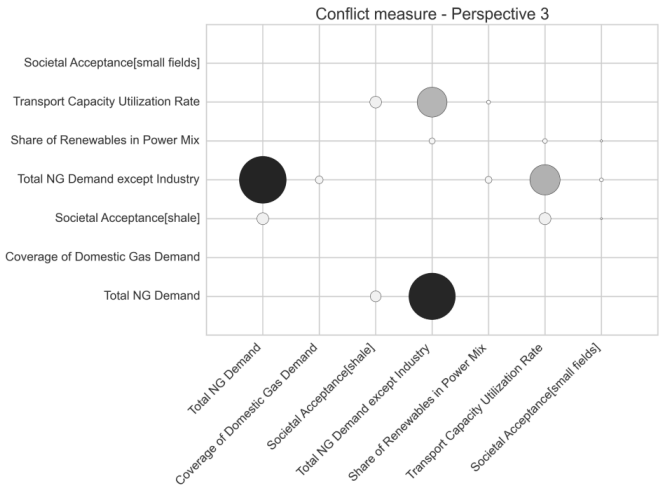


Figure 5.16: Conflicting outcome variables of Perspective 3

Perspective 3 also expects a high utilization of the international transport capacity. However, this expectation is contradictory with the low natural gas demand (excluding the industrial demand) expectation, as Figure 5.16 shows. Since the transport capacity is mainly used for importing rather than exporting as the domestic resources decrease, low natural gas demand which does not necessitate imports is an obstacle to high transport capacity utilization expected in this perspective.

Perspective 4 – Gas in times of austerity

Among the output conditions of Perspective 4, a low *Share of Renewables* and a low *Share of Decentral Gas-based Production in the Power Mix* are found to create the highest reduction in the number of scenarios when considered together, as seen in Figure 5.17. These

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technologies are expected to have a low share due to their relatively high costs in times of austerity, but by definition, one of them being low leads to the other being high, if there is no other technology that strongly dominates both of them. The results indicate the absence of such a dominant technology in a large scenario subspace, since the share of renewables and decentral gas-based production are simultaneously low only in a small number of scenarios.

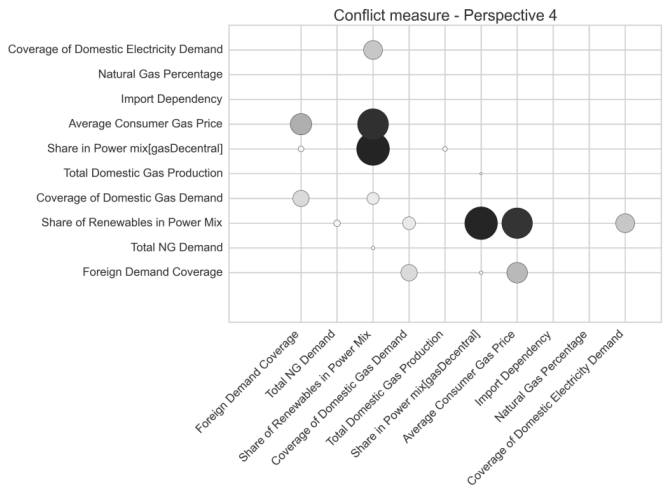


Figure 5.17: Conflicting outcome variables of Perspective 4

The second most conflicting pair of outcome indicators of Perspective 4 is found as a high Average Consumer Gas Price and a low Share of Renewables in the Power Mix. The underlying reason of this conflict is that renewable energy technologies can compete with natural gas when its prices are high, and increase their share in the power mix. Hence, it is rare to obtain scenarios where prices are high and the share of renewables is low, as expected in the austerity perspective.

Perspective 5 – We need all energy sources!

Perspective 5 expects a high contribution from all energy sources, yet the competition between them is a barrier to this. As Figure 5.18 shows, the combination of high *Total Domestic Gas Production* and high *Import Dependency* results in the lowest number of scenarios, because a high domestic production expected by this perspective keeps the import dependency low, as opposed to high import expectations.

The second most conflicting combination of outcome conditions is that of a high *Transport Capacity Utilization Rate* and a high *Coverage of Domestic Gas Demand*. The reason of this conflict is that *Transport Capacity Utilization* is high when imports are high, and imports aim to cover the supply shortage, i.e. making the demand coverage 100%, rather than making it higher than 100%. Therefore, the model rarely generates scenarios in which both transport capacity utilization and demand coverage are high.

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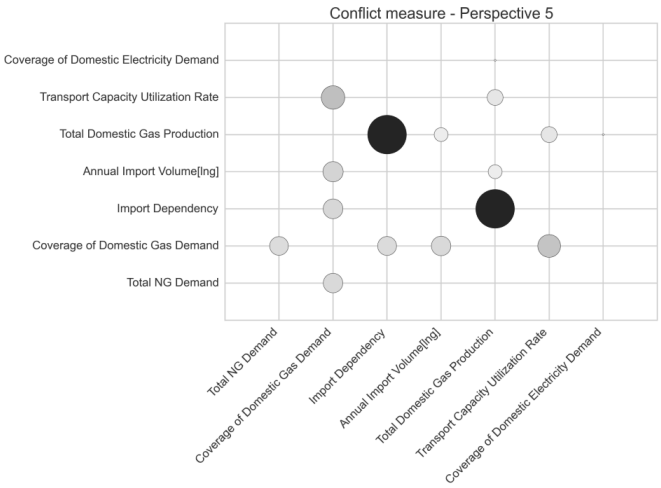


Figure 5.18: Conflicting outcome variables of Perspective 5

Perspective 6 – Entrepreneurs serve the market better

Perspective 6 expects more market orientation in the future, and low gas and electricity prices as well as high share of renewables in such a future. However, low prices reduce the competitiveness of renewable energy technologies, hence the combination of a high *Share of Renewables in Power Mix* and a low *Average Consumer Gas Price* results as the most conflicting outcome condition, as seen in Figure 5.19.

The second major reduction in the size of scenario subspace is found when the scenarios with high *Share of Renewables in the Power Mix* and low *Cumulative Biomethane Production via Gasification* are selected. This finding can be traced back to the effect of the natural gas price on these two factors, since a high share of renewables is stimulated by high gas prices, which also enables biomethane production via gasification, which is economically competitive only when gas prices are also high. Hence, low gas prices, which is a defining outcome condition of this perspective, enable low biomethane production but not a high share of renewables.

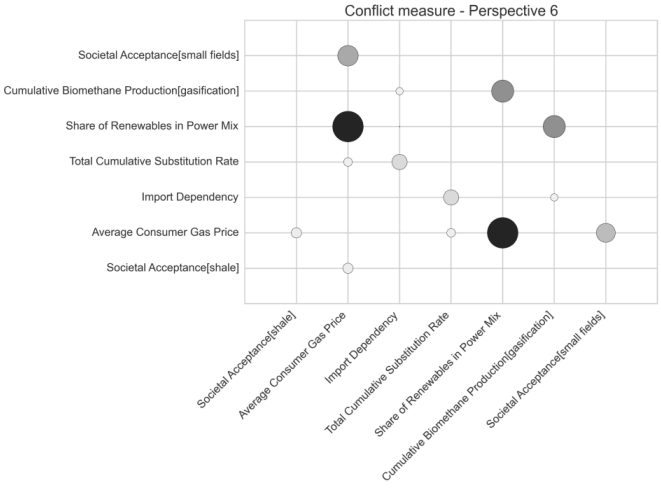


Figure 5.19: Conflicting outcome variables of Perspective 6

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Lastly, a small number is counted for the scenarios where the *Average Consumer Gas Price* and *Societal Acceptance* of the natural gas production from small fields are both low. In the model, a positive causality is assumed between the gas price and societal acceptance, hence these two variables are expected to be both low in a large number of scenarios. Still, the resultant number of scenarios in which they are both low is low, and this is attributed not to the model structure, but to the input condition of the perspective which expects the effect of prices on societal acceptance to be high. Due to such a high effect of price, low societal acceptance is not frequently observed in the scenarios with low price.

This section investigated why the scenarios meeting all the conditions of perspective definitions are small subsets of the entire scenario space. The major reasons were found to lie in the causal relations between the system elements. As mentioned before, these stakeholder perspectives are not intended and elaborated to be used as internally consistent scenarios. Therefore, it is not known whether the stakeholders of a perspective were aware of the conflicts between the future statements they have specified, and that these statements can be realized only in a small subset of future possibilities. If the stakeholders were not aware of these conflicts and their reasons, but expected their future views to unfold easily, then it can be said that these future views included inconsistent elements. In that case, the model-based representation enables matching each perspective with a small but internally consistent (according to the model assumptions) set of scenarios. If the stakeholders were aware of the conflicts and their reasons, and already expected their future vision to be realized difficultly, then the above analysis of conflicting elements can be said to reveal the most restricting conditions. In that case, the analysis can be extended to investigate if a perspective vision requires an alteration to increase the prospects of a future envisioned by that perspective, or to reach an agreement with other perspectives.

5.3.2.2. Comparing the perspectives to each other

This section presents a visual comparison of the perspective scenarios with respect to the 8 outcome indicators of the policy goals of the government. These 8 indicators include the major output variables of the perspectives, but not all. Still, they provide a common ground for the comparison of perspectives to each other, and to the entire set of scenarios generated and used in the previous chapters. This set of scenarios generated without any perspective restriction is named 'No-perspective' in the rest of this section. In the figures below, the scenario sets corresponding to each perspective, i.e. the subsets obtained from an ensemble of 10000 scenarios according to the output conditions, are visualized in envelopes and density graphs as in the previous section. The discussion below on the comparison of perspective scenarios utilizes both envelope and density figures.

Coverage of Domestic Gas Demand

For the demand coverage variable, the envelope of scenarios generated in the business as usual case without any perspective restriction ('No-perspective') demonstrates the widest range of envelopes in Figure 5.20. However, as the density estimates show in Figure 5.21, the number of scenarios with very high values in 2030 and later is very small. Perspective 2 and Perspective 6 result in higher values in the early decades, e.g. a wider range and with higher density around higher demand coverage values. For Perspective 2, this result can be explained

78B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

by the low natural gas demand expected in this perspective, whereas for Perspective 6 high demand coverage is a precondition of low prices, which is the primary expectation of this perspective.

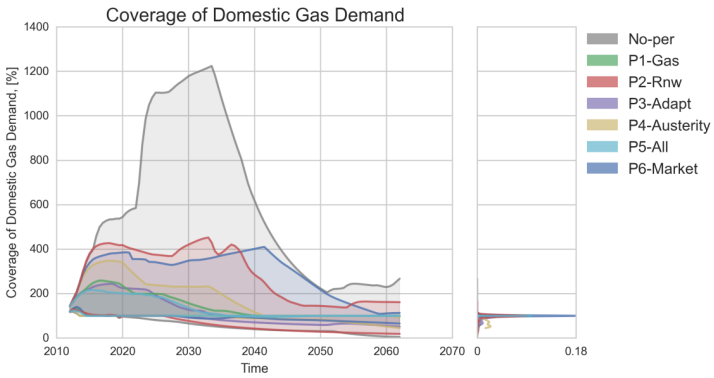


Figure 5.20: Envelopes of the *Coverage of Domestic Gas Demand* for each perspective and the end state KDE's

Perspectives such as 1, 3 and 5 which expect a powerful gas sector in the future result in scenarios with a smaller range of demand coverage values in the early decades, attributed to their high demand expectations. Yet, in terms of the final value, they do not result in as many scenarios with supply shortages (less than 100% demand coverage) as Perspective 2 results in, indicated by the longer left tail of the density estimate of Perspective 2 in 2062. Furthermore, the distinction of Perspective 4 from other perspectives can be clearly seen, since its end states results only in less than 100% demand coverage.

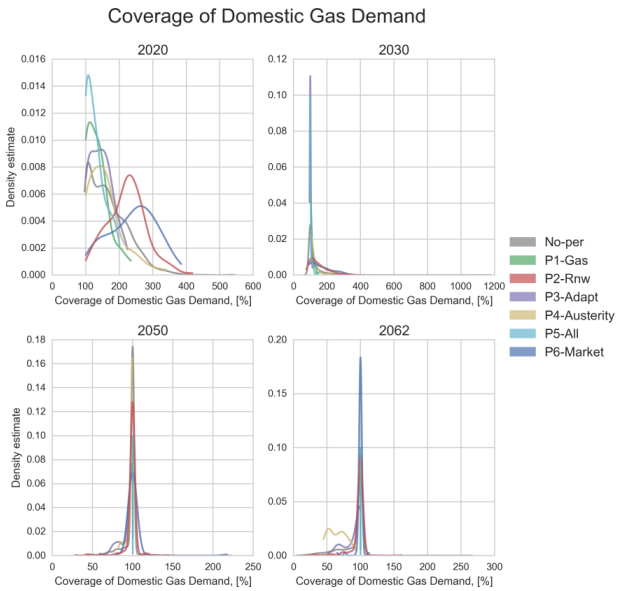


Figure 5.21: KDE's of *Coverage of Domestic Gas Demand* for each perspective in 2020, 2030, 2050 and 2062

Transport Capacity Utilization Rate

In terms of the second outcome indicator, namely *Transport Capacity Utilization Rate*, there are no major differences between the perspectives in the early decades, as shown by the

79A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

similarity of 2020 densities in Figure 5.22. However, in the later decades, a considerable divergence is observed. On the one hand, the perspectives with a more positive view on gas, namely Perspective 1, 3 and 5 group together, with similar and high values. This result is expected for Perspective 3 and 5 since their definitions include high values of transport capacity utilization, but for Perspective 1, this result is attributed to high imports. On the other hand, Perspective 2 and 6 group together with similar and low values. The reason for these ranges of lower values is the low natural gas demand expectation of Perspective 2, and low import dependency expectation of Perspective 6.

Besides these two distinct groups of perspectives, the range of Perspective 4 lies at the upper end of the possible values. According to this perspective, neither exports nor imports of gas are expected to be high due to austerity conditions, but the resulting high capacity utilization is due to low volumes of installed transport capacity, and the respective high ratio of imports to this. Similar to the demand coverage, the widest range of scenarios is observed in the case of No-perspective, where the scenario space is not restricted by perspective conditions.

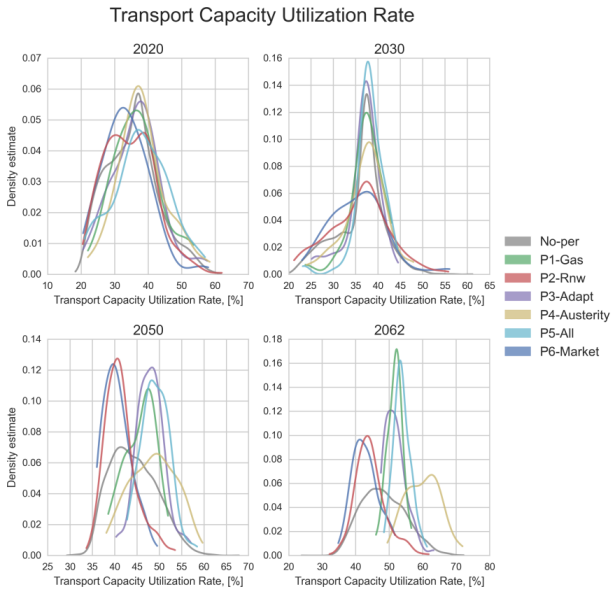


Figure 5.22: KDE's of the *Transport Capacity Utilization Rate* for each perspective in 2020, 2030, 2050 and 2062

Average Consumer Gas Price

As seen in Figure 5.23, the scenario subspaces of perspectives show a distinction also in terms of the gas price, yet with different perspectives grouped together. Perspective 1 shows the narrowest range over time, with a density distribution around low values eventually. Despite their relatively wider ranges, the end state densities of Perspective 5 and 6 are very similar to that of Perspective 1, again accumulating around low values such as 1-2 EUR/m^3. Perspective 3 shows a relatively narrow range, yet its final density distribution is very similar to that of the no-perspective case. These two density estimates have a low mean value similar to the previous group, but a wider range and more scenarios resulting in high values. In the third group, Perspective 2 and 4 have similar density estimates, with higher mean values and flatter

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distributions. The reason for such high prices is the austerity conditions specified in Perspective 4, and the scarcity of natural gas due to the lack of investments in Perspective 2.

Having low prices more desirable than high prices, these findings imply that Perspectives 1, 5 and 6 envision more favourable futures in terms of the *Average Consumer Gas Price.*

Note that in Figure 5.23, and in some other figures below for other outcome indicators, the envelope of a perspective goes slightly beyond the no-perspective envelope. This finding can be found puzzling, since the input and output ranges representing a particular perspective are defined as subsets of the input and output ranges in the no-perspective case, hence the perspective scenarios are expected to be encompassed by the no-perspective envelope. These deviations from the expectation, i.e. a perspective exceeding the no-perspective envelope, are attributed to different input values resulting from the same sampling procedure. In other words, although the input ranges of perspectives are subsets of the no-perspective input ranges, sampling from a small range and sampling from a wide range that covers it do not necessarily result in the same values. Therefore, these different input values cause differences in the individual scenarios, which can fall slightly out of the uncertainty space covered by the no-perspective case.

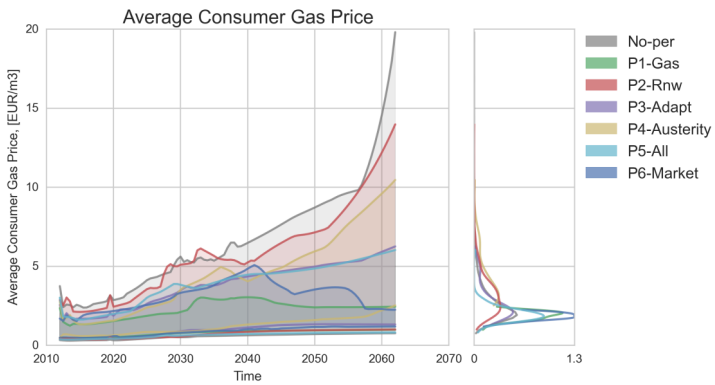


Figure 5.23: Envelopes of the *Average Consumer Gas Price* for each perspective and the end state KDE's

Renewable Gas Percentage

Figure 5.24 shows the envelopes of the Renewable Gas Percentage over time in the scenario subspaces corresponding to each perspective. Only the no-perspective, Perspective 2 and Perspective 6 scenarios result in a wide range with high values of *Renewable Gas Percentage*, although these high values are obtained only in a few scenarios. According to other perspectives, the share of renewable gas in the gas consumption is low with maximum values less than 10%. In terms of the final values in 2062, Perspective 1 and 4 have the lowest values, as stated in their defining conditions. Perspective 3 and 5 have fatter density distributions, as well as the no-perspective case, implying a higher expectation of higher renewable gas contribution. Perspective 2 and 6 can be said to be the most optimistic perspectives in terms of the renewable gas, since they have wider ranges with higher mean values.

80A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Given these results, it can be said that the high renewable gas percentage objective of the government is more in line with the futures envisioned by Perspective 2 and 6, while it is opposing to those envisioned by Perspective 1 and 4.

Total State Revenue from Natural Gas Production

When the range of possible government revenues collected from natural gas production is considered, Perspective 1 and 4 result in narrower ranges in the early decades, due to low production in the case of austerity and due to low prices in the case of Perspective 1 (Figure 5.25). In later decades, the ranges are observed to narrow down for all perspectives, due to declining production. If the end state density estimates are considered, the steep density curves of Perspectives 1, 4 and 5 with low mean values indicate very low state revenue expectations. For perspectives 2, 3 and 6, although the mean values are similarly low, a wider range of possibilities is observed, indicating a possibility of higher revenues.

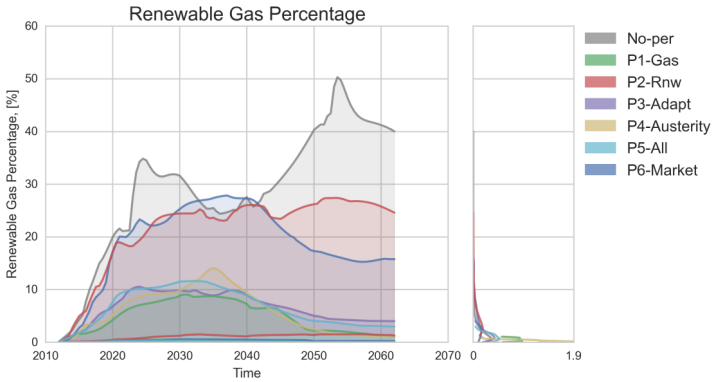


Figure 5.24: Envelopes of *Renewable Gas Percentage* for each perspective and the end state KDE's

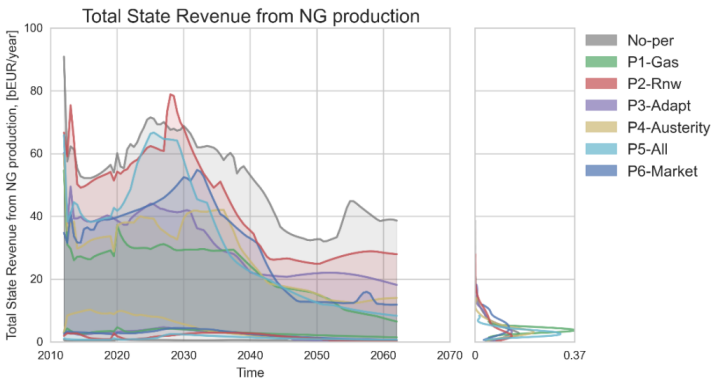


Figure 5.25: Envelopes of *Total State Revenue from NG production* for each perspective and the end state KDE's

Societal Acceptance (of natural gas production in Groningen)

Regarding the societal acceptance of natural gas production from the Groningen field, the future views of the perspectives show a wide variety as in Figure 5.26, except Perspective 1 according to which societal acceptance will be very high. The scenarios corresponding to other perspectives also accumulate around high values, e.g. more than 80%, in 2062, but they show varying degrees of steepness. For instance, Perspective 5 has more scenarios resulting in

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more than 80% societal acceptance, whereas Perspective 2 has fewer of high values and more of very low values.

Share of Renewables in the Energy Mix

The share of renewable energy in the total energy mix is a distinctive factor of the perspectives. Still all perspectives have a considerable intersection region of scenarios, as shown in Figure 5.27. As mentioned in their definitions, Perspective 2, 3 and 6 do not include very low values in the late decades, whereas the other perspectives do. In terms of the end state densities, Perspective 2 shows a wide range of relatively high values, whereas Perspective 3 shows a narrower range but still high values. Perspective 1 and 4 show the highest densities of low end state values for the share of renewables.

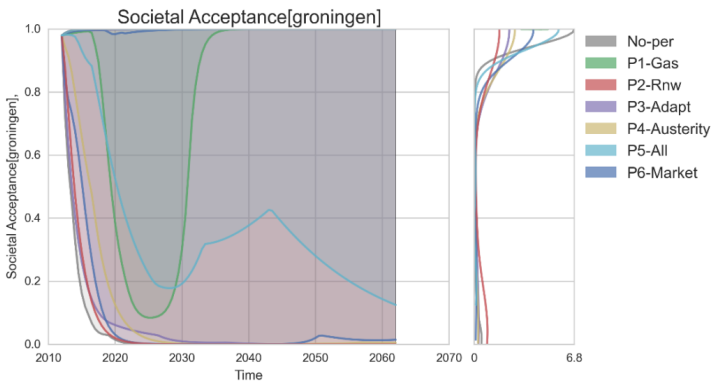


Figure 5.26: Envelopes of *Societal Acceptance* for each perspective and the end state KDE's

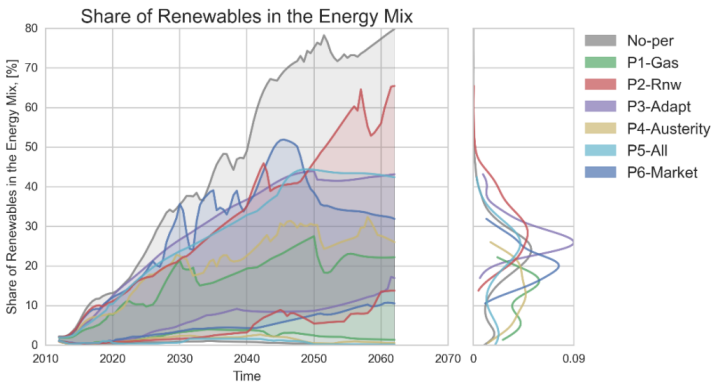


Figure 5.27: Envelopes of *Share of Renewables in the Energy Mix* for each perspective and the end state KDE's

Import Dependency

As Figure 5.28 shows, the density of scenarios with high import dependency increases over time, regardless of the perspective. Especially in the scenarios of Perspectives 1, 4 and 5, expected import dependency at the end of the simulation horizon is very high, as the steep density curves point out. These results are attributed to the specification of Perspectives 1 and 5, expecting high import volumes, and the lack of domestic production in the case of austerity (Perspective 4) although the perspective definition includes low import volumes. Such high value of import dependency expected by these perspectives is conceivably not in line with the

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low import dependency goal of the government. According to Perspective 3 which primarily expects an adaptive gas sector, the end state values are still in a high band, yet with a flatter distribution, indicating the possibility of a lower import dependency. The density estimates of Perspective 2 and 6 cover a wide range including very low values. While such low import dependency is specified in the definition of Perspective 6, for Perspective 2 it is attributed to low gas demand expectations.

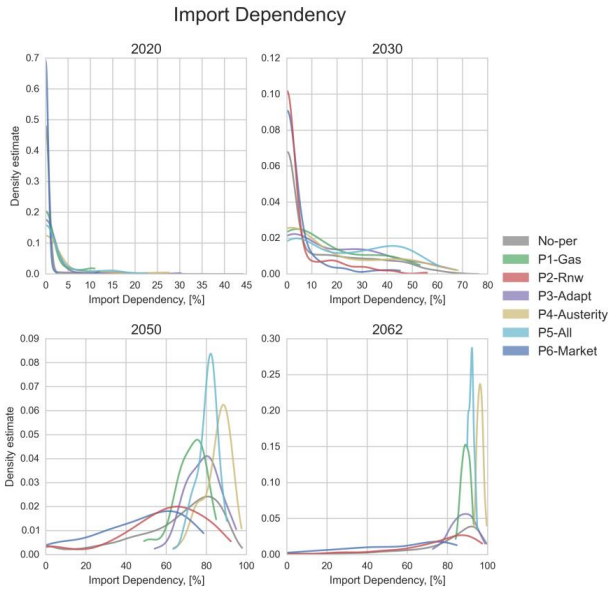


Figure 5.28: KDE's of the Transport Capacity Utilization Rate for each perspective in 2020, 2030, 2050 and 2062

This section presented the subsets of model-generated scenarios corresponding to the six stakeholder perspectives. Firstly, the internal plausibility of each perspective and the barriers to achieve such a future that is envisioned by each perspective were discussed. Secondly, the perspectives were compared to each other in terms of their scenario subspaces. This comparison has led to two general conclusions:

- The scenarios generated by the model without any perspective restriction have the widest range of possibilities, implying that the model can capture scenarios that are not envisioned by the perspectives, given the assumptions made to quantify them. Still, it is important to note that these scenarios specific to the no-perspective case do not constitute a majority, because the density of such scenarios is low as seen in the above figures.
- The perspectives show significant differences from each other in terms of the envisioned futures. For some outcome indicators, a common subset of the future possibilities envisioned by several perspectives could be found. However, for some outcome indicators, the scenario spaces corresponding to several perspectives are exclusive of each other, indicating that these perspectives do not include any common future possibilities. The scenario spaces of Perspective 1 and 4 in terms of *Average*

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Consumer Gas Price, or those of Perspectives 5 and 6 in terms of *Import Dependency*, exemplify this observation.

In conclusion, this section demonstrated how qualitatively defined future views of the stakeholders can be quantified, in order to compare them to each other and establish a basis for the assessment of policies. Yet, it must be reminded that the results presented in this section are based on a series of assumptions in the model and about the quantification of perspective definitions. For instance, Perspective 1 expects high import volumes in future, as well as high domestic production. This expectation is found to be one of the most conflicting factors in Perspective 1. However, it must be reminded that the import volumes in the model represent the net imports (import-export) and in the model it is assumed that natural gas is imported only when domestic production is not sufficient to cover the domestic demand. Therefore, such a conflict between the perspective elements may stem from model assumptions, besides an actual conflict in the perspective definition which was known or unknown to the stakeholders of this perspective. Discussing such assumptions about the quantitative representation of perspectives with stakeholders is valuable to establish the validity of these representations, despite its own challenges. Yet, such an additional study and testing the implications of different assumptions to represent the perspectives were beyond the time limits of this study, and suggested for future research.

5.4. CONCLUSIONS

This chapter presented the behavior of the simulation model described in Chapter 4, in a reference simulation to understand the model behavior and in a large number of scenarios to explore the future possibilities. The reference simulation results are also used for comparing the model output to the data of real behavior in the period 2000-2012. This comparison served for the validation of the model, in addition to expert consultations and formulation reviews carried out to test the suitability of the model structure. Following these tests, it was concluded that the model is a suitable representation of the reality in order to generate plausible scenarios.

Propagation of uncertainties through the model resulted in wide uncertainty ranges of the outcome indicators. In this chapter, the scenario space created by the model is presented visually, and density estimates at particular points in time visualized how the scenarios are dispersed in the uncertainty range of an outcome indicator. It must be noted that these density estimates provide information about where in the uncertainty range the model results accumulate, not which future states are more likely. The results of this exploration, i.e. the scenario spaces of outcome indicators, will be a basis for testing policies in the following chapters with respect to their robustness against uncertainties. The factors leading to particular scenarios in this space will also be analyzed in the following chapters, in order to better understand the effects of uncertainties and system elements on the outcome indicators based on the structure-behavior relationships of the model.

This chapter also presented an investigation of the scenarios created by the model according to the six stakeholder perspectives found in the Dutch gas sector. The first step of this analysis was the quantification of stakeholder perspectives, and dividing the scenario space into parts

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to represent each perspective. However, this step showed that there were many conflicts between the elements, or future views, of a perspective. In other words, given the causal relations in the model, many future conditions envisioned by a perspective are opposed to each other. In this study, we did not have a chance to validate if the stakeholders were aware of these conflicts and that these statements can be realized only in a small subset of future possibilities. Still this analysis yielded the most restricting conditions of a perspective, and helped to understand the conflicting objectives and system elements in the gas sector in general. Besides, this analysis of perspective scenarios can constitute a basis in future studies to search for policies that are acceptable by each of these perspectives.

Having the future values of outcome indicators investigated in a reference simulation and in a large number of alternative futures created by uncertainties, the following chapters will present analyzing the effects of policies on outcome indicators given the presence of uncertainties. Prior to the results of this analysis, Chapter 6 will introduce the framework developed to assess the performance of policies in terms of their effectiveness on outcome indicators and their robustness against uncertainties using the model-based scenarios generated.

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In the strict formulation of the law of causality—if we know the present, we can calculate the future—it is not the conclusion that is wrong but the premise.

Werner Heisenberg, (On an implication of the uncertainty principle)[10]

6

A FRAMEWORK FOR ANALYZING POLICY EFFECTIVENESS AND ROBUSTNESS

In Chapter 2, it was stated that there are multiple policy objectives of the government that should be taken into account in an analysis of policy alternatives, as well as a vast number of uncertainties. Having these multiple policy objectives as a measure of effectiveness on the one hand, on the other hand, the wide range of dynamic scenarios shown in Chapter 5 requires assessing the policy alternatives also in terms of their robustness against uncertainties. Besides, these dynamic scenarios raise the question of where in time, e.g. in an horizon of 50 years, the comparison of policies should be made. This chapter aims to combine these three aspects of analyzing policy alternatives under uncertainty, in a framework that will be used in the following two chapters.

In addition to the combination of these three aspects of decision analysis, this framework involves a multi-method view in order to take methodological uncertainty into account. In other words, multiple methodological options are explored for each of the three dimensions in the framework. The main purpose of this multi-method view is to investigate the robustness of policy options against different methodological choices, and generate insights about why the results differ for different method alternatives, if they indeed do so.

Below, Section 6.1 explains the analysis framework. The three dimensions of this framework, namely time, robustness against uncertainties and multi-criteria approach are described in detail, with the methodological choices made for each. Section 6.4 concludes this chapter with a brief discussion on this framework.

[10] Quoted in David C. Cassidy, 2009, *Beyond Uncertainty: Heisenberg, Quantum Physics, and the Bomb*, p.162.

83A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

6.1. METHODS USED TO ASSESS AND COMPARE THE POLICY ALTERNATIVES

This section explains the quantitative assessment and comparison framework which is used to analyze the policy alternatives listed in Section 2.5.3 in terms of both their robustness against uncertainties and effectiveness with respect to the 8 outcome indicators presented in Section 2.2. This methodological framework has three dimensions, namely the time, robustness and multi-criteria dimension. The time dimension aims at dealing with the transient nature of the scenarios created by the model. In other words, one should decide on how to aggregate the information about the states of the outcome indicators in a 50-year time horizon into a single (point) metric. The second dimension regarding the robustness of policy alternatives represents how the performance of a policy under deep uncertainty can be assessed. Similar to the time dimension, the robustness dimension requires aggregating the information obtained from an ensemble of scenarios (e.g. 5000 alternative futures) into a single metric. Thirdly, the multi-criteria dimension implies how the 8 outcome indicators are taken into account in the comparison of policy alternatives, either with a single metric or with a decision heuristic.

Since this analysis evaluates a countable number of policy options, our approach to the multi-criteria aspect of the policy problem is based on the Multi-Attribute Decision Analysis, which is a branch of Multi-Criteria Decision Analysis approaches. A multi-criteria, or multi-attribute, decision analysis may have several purposes, such as choosing, sorting or ranking (Vincke *et al.*, 1992). The purpose of our analysis is to choose one of the exchangeable options for each policy that has such options, then to provide a comparison of the 9 policy options presented in the first column of Figure 2.8. Therefore, we use the MCDA methods mostly for ranking.

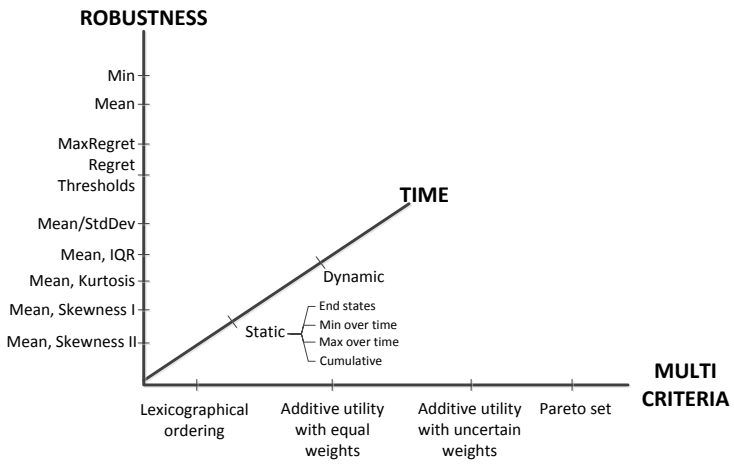


Figure 6.1: Three dimensions of the methodological framework with alternatives for each

Multi-attribute decision analysis methods are based on certain impacts of each policy option on each attribute (criterion). In this study, the robustness dimension requires adaptation of this impact concept. Therefore, instead of an absolute attribute value, the robustness value obtained from that attribute values across the range of alternative scenarios is used as the

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impact of each policy on each attribute. The purpose of this methodological choice is not to evaluate robustness equally as an attribute value, but to acquire a ground for combining the robustness performance and the multi-criteria effectiveness of a policy option.

The selection of a method for each of the three dimensions mentioned above is a metaproblem of deciding on how to evaluate, because several alternatives exist for each dimension. This multiplicity of alternatives indicates a method uncertainty, which may affect the assessment of policy options prominently. Therefore, several methodological alternatives are included in this framework, instead of selecting one, for each of these dimensions, as mentioned before. Figure 6.1 summarizes these alternatives for each of the three dimensions. A solution (ranking or sorting of policy options) is found for each combination of these alternatives, e.g. for a particular robustness metric, time metric and multi-criteria method. If a policy option receives the same rank, e.g. the first rank, with many of these methodological alternatives, then it is considered to be methodologically robust. Whether methodological robustness is observed or not, the results are used to generate insights about the implications of different methodological choices.

The three sections below will discuss and explain the alternatives for each of the three dimensions. Yet, before this explanation, the general nomenclature for the metric definitions is presented below:

i	:	The index for the outcome indicators, i=1…M
j	:	The index for the policy options, j=1…J
s	:	The index for the scenarios, i.e. s = 1…N
N	:	Number of scenarios (alternative futures)
t	:	Time, i.e. $t = t_0 ... t_{final}$
$O_{i,j,s}(t)$	:	The value of the outcome indicator *I*, with policy *j*, in scenario *s* and at time *t*
$O^*_{i,j,s}$	:	The time-metric of the outcome indicator *I*, with policy *j*, in scenario *s*
$R_{i,j}$	:	The robustness value of the i^{th} outcome indicator, with policy *j*
U_j	:	The performance indicator of the policy *j* used for the selection or ranking of policies

In this framework, the performance indicator U_j is calculated based on the robustness value of each outcome indicator, whereas the robustness value is calculated based on the values of the time metric, for each static time metric, or at each point in time in the case of a dynamic option. In technical terms, U_j is a function of $R_{i,j}$, which is a function of $O_{i,j,s}$. Hence, the general form of the calculations is

$$\begin{aligned} U_j &= f\left(R_{i,j}\right) \text{ or } U_j(t) = f\left(R_{i,j}(t)\right) \\ R_{i,j} &= f\left(O^*_{i,j,s}\right) \text{ or } R_{i,j}(t) = f\left(O_{i,j,s}(t)\right) \\ O^*_{i,j,s} &= f\left(O_{i,j,s}(t)\right) \end{aligned} \tag{107}$$

84A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

6.1.1. Time Dimension

As mentioned above, the time dimension of the analysis method of this chapter is related to the question of how to select a policy option now, given the information obtained from the model output about the coming fifty years. Two main options are considered regarding this dimension in this analysis. The first one is selecting a point metric to aggregate this 50-year data, which is named the 'static' option. The static option is computationally advantageous, yet it causes a loss of information about the rest of the time horizon. An alternative to deal with this disadvantage is to conduct the robustness calculation and policy assessment at each time point in the 50-year horizon instead of a single point. This alternative named 'dynamic' option, requires more computational power, but generates more information about the performance of policy options over time.

If the static option is adopted, one is confronted with several options such as the end states of the 50 year horizon (e.g. in year 2062) or the states in a particular year (e.g. 2020 or 2050 depending on the policy goals). In this study, four alternatives of a static time metric are considered:

i. *End states:* The first option is to consider the final value of the each outcome indicator in each scenario. This option provides simplicity but ignores the information about the path followed until the end state. The time metric is defined as

$$O^*_{i,j,s} = O_{i,j,s}\left(t_{final}\right) \tag{108}$$

ii. *Minimum over time:* This option adopts a pessimistic view (or an optimistic one for the outcome indicators to be minimized) and focuses on the minimum value taken by each outcome indicator in the fifty year horizon of each scenario. Hence, the metric is defined as

$$O^*_{i,j,s} = \min_{t=t_0 \ldots t_{final}} \left\{O_{i,j,s}\left(t\right)\right\} \tag{109}$$

iii. *Maximum over time:* In contrast to the *Minimum over time* option, one can adopt an optimistic view (or a pessimistic one for the outcome indicators to be minimized) and focus on the maximum values taken in the entire time horizon. In this case, the time metric is defined as

$$O^*_{i,j,s} = \max_{t=t_0 \ldots t_{final}} \left\{O_{i,j,s}\left(t\right)\right\} \tag{110}$$

iv. *Cumulative value:* The fourth option is to define the time metric as the cumulative sum of the values taken at each time point (e.g. each year) over the 50-year horizon. Despite the lack of a real life meaning, this metric enables taking the entire time horizon into account, instead of a single point in time. The formulation of the metric is

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$$O^*_{i,j,s} = \sum_{t=t_0}^{t=t_{final}} O_{i,j,s}(t) \tag{111}$$

When the dynamic option is chosen, without defining a time metric (O^*), the robustness value ($R_{i,j}$) and the performance indicator of each policy (U_j) is calculated at each time point, i.e.

$$\begin{aligned} R_{i,j}(t) &= f\left(O_{i,j,s}(t)\right) \\ U_j(t) &= f\left(R_{i,j}(t)\right) \end{aligned} \tag{112}$$

6.1.2. Robustness Metrics

The robustness of a policy option, i.e. how good it performs across a wide set of alternative futures, can be defined in several ways, as indicated by the plethora of the metrics used in the decision making literature. These metrics vary in the extent that they include the values of outcome indicators, and the variation in these outcome values across the scenarios. Besides, these metrics differ from each other in terms of how they represent uncertainty preferences, such as risk-aversion and risk-proneness. As for the approaches to quantify robustness across a range of scenarios, Lempert and Collins (2007) differentiate between the optimum expected utility, regret-based and satisficing approaches to quantify robustness. Herman et al. (2015) extend the analysis of robustness measures with various regret-based and satisficing metrics, and concludes that methodological choices lead to the selection of substantially different alternatives.

Two expectation-based metrics are included in this study, the first one being the expected value. Based on the Bayesian decision theory, the expected value approach suggests to weight the possible future states, i.e. to assign probabilities, and to select the policy option with the maximum weighted average welfare (Schoemaker, 1982). The shortcomings of this approach are disregarding the degree of variance in the outcome, and the requirement to assign probabilities, as stated in several studies (Rosenhead *et al.*, 1972; Lempert *et al.*, 2003, pg. 26; Lempert and Collins, 2007; Manski, 2013, pg. 122). Another classical approach to decision making under uncertainty is the *maximin* criterion of Wald (1950), suggesting to select the option that maximizes the minimum value across the alternative futures (if this value is to be maximized). In other words, this criterion selects the option with the best worst case scenario and represents a highly risk-averse uncertainty preference. This metric is considered as an expectation-based approach, because it is centered on the most pessimistic expectation, i.e. the worst case scenario, hence it is very conservative. Although there is another metric, namely the Hurwicz criterion (Hurwicz, 1951), that mitigates the pessimism of this approach with an 'optimism index'(Sage and Armstrong, 2000, pg. 385), we include the *maximin* criterion in this study, to represent this extremist view on decision making under uncertainty.

Regret-based approaches originate from Savage (1954, pg. 21), who proposes the concept of 'sure-thing principle' for assessing the decision options if an alternative future would have surely occurred. Following this concept, regret is defined as the difference between a policy option's performance in any alternative future and the performance of the zero-regret option in that alternative future. Based on this definition, the best policy option in each alternative

85A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

future scenario is determined, then the regret of each policy option in each alternative future is calculated. A robust policy option is specified as the one that minimizes the maximum regret across the alternative futures. Commonly used in robust decision making studies (Lempert *et al.*, 2006; Hallegatte *et al.*, 2012; Kasprzyk *et al.*, 2013; Herman et al., 2015), the advantage of regret-based approaches are mainly avoiding the use of subjective probabilities, and focusing on the future scenarios that distinguish between the policy options. In this study, two regret-based robustness metrics are taken into account, the first one being the *maxregret* metric of Savage (1954), which also represents a risk-averse view. The second metric is the fraction of scenarios in which the outcome exceeds a certain threshold of the zero-regret value, which is a combination of regret-based and satisficing approaches, as exemplified by Popper *et al.* (2009). This metric represents a relaxation to a purely risk-averse approach.

Satisficing approaches suggest, in general, to set thresholds for outcome indicators, hence to reduce the outcome space, and to define robustness based on the volume of the uncertainty space corresponding to this reduced outcome space. One of the most well-known examples of satisficing robustness metrics is the domain criterion (Starr, 1963; Schneller and Sphicas, 1983), i.e. the fraction of scenarios in which certain thresholds are met. Another well-known satisficing approach is the info-gap theory of (Ben-Haim, 2004; Hall *et al.*, 2012), where the robustness is defined as "the greatest level of knowledge-deficiency" (uncertainty) at which the threshold value of an outcome indicator is guaranteed. Despite their power to deal with uncertainty compared to optimality-based approaches and the tradeoff information they provide to the decision makers, satisficing approaches require information from the stakeholders about the performance thresholds, hence create another source of uncertainty for the analyst about the value system of stakeholders.

Alternatively, robustness can be defined based on statistical characteristics of the density distribution of future states, without any requirement to specify performance thresholds, as used in (Hamarat *et al.*, 2014; Kwakkel, Haasnoot, *et al.*, 2014; Kwakkel and Pruyt, 2014; Voudouris *et al.*, 2014). In this study, to avoid specification of performance thresholds, we include a group of statistical measures as the third category of robustness metrics, rather than satisficing measures of robustness.

Hence, this study takes three groups of robustness metrics into account, namely the expectation based, regret-based and statistical metrics. The metric formulations are explained in the corresponding three sections below.

6.1.2.1. Expectation-Based Metrics

Mean: Following the expected value approach with equal weight on each scenario, this metric is the mean value of the density distribution obtained for each time metric. In other words, it is the average of N outcome indicator values obtained for each time metric, as Equation 113 shows.

$$R_{i,j} = \mu\left(O^*_{i,j,s}\right) = \sum_{s=1}^{N} O^*_{i,j,s} \Big/ N \tag{113}$$

85B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Min: Representing the *maximin* criterion, this metric determines the worst case value for each policy option and outcome indicator. The notation of the metric is

$$R_{i,j} = \begin{cases} \min\limits_{s=1...N} \left\{ O^*_{i,j,s} \right\} \ ; \ \textit{if } O_i \text{ is to be maximized} \\ \max\limits_{s=1...N} \left\{ O^*_{i,j,s} \right\} \ ; \ \textit{if } O_i \text{ is to be minimized} \end{cases} \tag{114}$$

6.1.2.2. Regret-Based Metrics

MaxRegret: Following the abovementioned definition of regret, Equation 115 shows the formulation of the maximum regret for each policy option and outcome indicator. In this formulation, *G* is the regret of each scenario, and *Z* is the zero-regret of each scenario which is the best value obtained in this scenario with the optimal policy.

$$\begin{aligned} R_{i,j} &= \max_{s=1...N} \left\{ G_{i,j,s} \right\} \\ G_{i,j,s} &= \left| O^*_{i,j,s} - Z_{i,s} \right| \\ Z_{i,s} &= \begin{cases} \max\limits_{j=1...J} \left\{ O^*_{i,j,s} \right\} \ ; \ \textit{if } O_i \text{ is to be maximized} \\ \min\limits_{j=1...J} \left\{ O^*_{i,j,s} \right\} \ ; \ \textit{if } O_i \text{ is to be minimized} \end{cases} \end{aligned} \tag{115}$$

Regret Thresholds: As mentioned above, the use of *regret thresholds* to measure robustness is exemplified by Popper et al. (2009, pg. 77), who define the metric as the fraction of scenarios in which the maximum regret is less than a certain threshold of the zero-regret value. The set of such scenarios is denoted by $S^*_{i,j}$ in Equation 116 below, which shows the formula of the *regret thresholds* metric. The parameter ρ signifies the threshold, and set to 5%, implying that only the scenarios which differ from the zero-regret value by maximum 5% are included in $S^*_{i,j}$.

$$\begin{aligned} R_{i,j} &= \frac{n\left(S^*_{i,j}\right)}{N} \\ S^*_{i,j} &= \left\{ s : G_{i,j,s} \le \rho Z_{i,s} \right\} \end{aligned} \tag{116}$$

6.1.2.3. Statistical Metrics

The metrics in this group define robustness based on the statistical characteristics of the output data. Two types of characteristics, in other words, two aspects of the Kernel Density Estimate of this data is important in determining the robustness: An average value, e.g. the value which most of the scenarios accumulate around, and the dispersion around this value, e.g. a measure of the uncertainty bandwidth. The comparison of policy options can be done on the basis of a metric that combines these two aspects, or of both aspects simultaneously.

The average value is simply represented by the mean of the data set. As for the dispersion aspect, there are three concepts important for decision making under uncertainty, and several statistical measures to quantify these concepts. The first concept is the degree of dispersion, e.g. the uncertainty bandwidths of the outcome indicators. Variance (or standard deviation) is

86A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the basic and most well-known measure of dispersion, often used in robust optimization applications (Watkins and McKinney, 1997; Hamarat et al., 2014; Kwakkel and Pruyt, 2014). The second concept is related to what kind of dispersion is more desired, i.e. if the distribution is skewed towards more desirable values or not. Since skewness do not consider the extent of variation in the outcome, but how desired this variation is, it can be said to represent a risk-prone view on uncertainty. Peakedness, representing the sharpness of the density estimate around the mean value, hence if the majority of scenarios accumulate around the mean or not, is the last concept related to dispersion. This concept is based on the aim of narrowing down the uncertainty range, not necessarily the entire range but the range where a large majority of the scenarios fall, represents a risk-averse view. The alternative quantifications of these concepts and the metrics selected among these alternatives for this study are described below. Figure 6.2 illustrates the statistics used in the metric formulations on an example data set, in order to graphically assist the explanation of the metrics below.

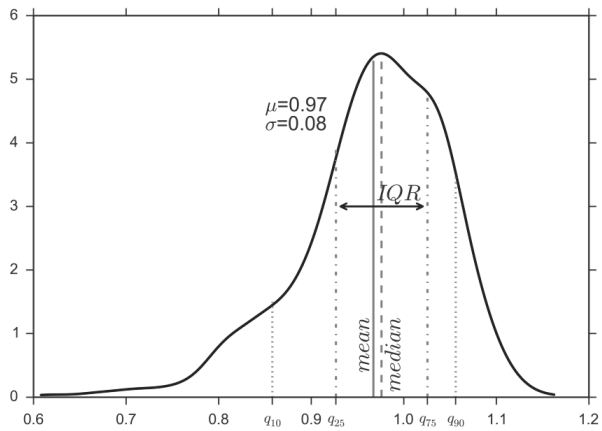


Figure 6.2: An illustration of the statistics used in the metric definitions

Mean-to-Standard Deviation: A simple way to couple *mean* and the degree of dispersion is inspired by the signal-to-noise ratio in control theory, and formulated as the ratio of mean to standard deviation if the outcome indicator is to be maximized, or the multiplication of these two measures if the outcome indicator is to be minimized. Maximizing the ratio or minimizing the multiplication means aiming for a more desired average value, while simultaneously keeping the dispersion low. Hamarat et al. (2014) and Kwakkel and Pruyt (2014) use this metric with addition of 1 to both measures, e.g. $\mu+1/\sigma+1$, to avoid division by zero in the case of standard deviation being zero. However, since zero variance is not expected in our case, we prefer to use this metric without addition of 1.

$$R_{i,j}=\begin{cases}\dfrac{\mu\left(O^*_{i,j,s}\right)}{\sigma\left(O^*_{i,j,s}\right)} & ;\text{ if } O_i \text{ is to be maximized; } s=1...N\\ \mu\left(O^*_{i,j,s}\right)\times\sigma\left(O^*_{i,j,s}\right) & ;\text{ if } O_i \text{ is to be minimized; } s=1...N\end{cases} \tag{117}$$

86B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

This coupling of mean and standard deviation is prone to not being monotonic (Ray *et al.*, 2014), and hinders the information about the tradeoff between the mean and dispersion value (Kwakkel and Pruyt, 2014). Therefore, following Kwakkel and Pruyt (2014), we consider the mean and following dispersion metrics simultaneously, e.g. in a disaggregate manner. In this way, not a ranking of the policy options but a Pareto set will be obtained, that is composed of the non-dominated options in terms of both the mean and the dispersion metric.

Mean & Skewness: Several measures can be used to quantify the favorable dispersion from the mean. Kwakkel and Pruyt (2014) uses the sum of squared differences from the mean. They minimize the sum of differences for data values higher than the mean, and maximize this sum for values smaller than the mean, for an outcome indicator to be minimized. This approach represents skewness with two measures, hence adds two metrics to the coupling of mean and a dispersion measure instead of one and increases the complexity of the problem. Therefore, for practical purposes, a single metric that denotes desired skewness, or asymmetry, is more preferable.

Among several expressions of skewness, we first choose a quantile-based definition following Voudouris et al. (2014), due to the potential unreliability of moment-based definitions if the density estimate is fat-tailed (Davidson, 2012), i.e. if there are many scenarios (data points) in the tail regions. For this metric shown in Equation 118, the 10^{th} and 90^{th} quantiles are taken into account, and the metric is defined as the difference of the mid-value between the 90^{th} and 10^{th} quantile from the median (m), divided by half of the difference between the 90^{th} and 10^{th} quantiles. The higher the absolute values of this metric, the more skewed the density estimate, towards the right (higher values) if the skewness is positive and towards the left (lower values) if it is negative. Therefore, for outcome indicators to be maximized, the policy options with higher skewness is preferred, whereas for outcome indicators to be minimized, lower skewness is more favorable.

$$
\begin{aligned}
&R_{i,j} = \left(\mu\left(O^*_{i,j}\right), Sk^1_{i,j}\right) \\
&Sk^1_{i,j} = \frac{\left(q_{90} + q_{10}\right)/2 - m}{\left(q_{90} - q_{10}\right)/2} \\
&q_{90} = q_{90}\left(O^*_{i,j,s}\right), \quad q_{10} = q_{10}\left(O^*_{i,j,s}\right), \; m = q_{50}\left(O^*_{i,j,s}\right); \; s = 1...N
\end{aligned}
\tag{118}
$$

As an alternative to the quantile-based skewness metric, we include a moment-based but pedagogically more understandable definition of skewness (Doane and Seward, 2011). This alternative is one third of the Pearson's second skewness coefficient (Pearson, 1895) and known as the nonparametric skew. As shown in Equation 119, this skewness metric is formulated as the difference between the mean and median, divided by the standard deviation. As the first skewness metric, positive values of this metric indicate right-skewness, whereas the negative ones indicate left-skewness, and the higher the metric value, the more skewed the density estimate is.

87A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$R_{i,j} = \left(\mu\left(O^*_{i,j}\right), Sk^2{}_{i,j}\right)$$
$$Sk^2{}_{i,j} = \frac{\mu\left(O^*_{i,j,s}\right) - m}{\sigma\left(O^*_{i,j,s}\right)}; \quad s = 1...N \tag{119}$$

Mean & Interquartile Range: To represent the peakedness of the density estimate, two alternative metrics are considered in this study. The first one is the interquartile range, which refers to the width of the peak region of the density estimate, and which is also used by Kwakkel, Haasnoot, et al. (2014) to measure robustness. As shown in Equation 120, the interquartile range is simply the difference between the 3rd and 1st quartiles (q_{75} and q_{25}, respectively) of the output data, and the lower values are preferred since it indicates a narrower uncertainty range around the mean.

$$R_{i,j} = \left(\mu\left(O^*_{i,j}\right), IQR_{i,j}\right)$$
$$IQR_{i,j} = q_{75}\left(O^*_{i,j,s}\right) - q_{25}\left(O^*_{i,j,s}\right); \; s = 1...N \tag{120}$$

Mean & Kurtosis: Kurtosis is a more well-known measure, established originally to describe peakedness. Among several formulations of kurtosis (Joanes and Gill, 1998), a quantile-based and simple metric shown in Equation 121 is adopted for this study, which is also used by Voudouris et al. (2014). The higher this metric, i.e. the smaller the IQR compared to the interval between 90th and 10th quantiles, the more peaked the density estimate around the mean. Unlike the previous metric, this formulation distinguishes between two options with the same IQR value, and enables choosing the option with lower tail values.

$$R_{i,j} = \left(\mu\left(O^*_{i,j}\right), K_{i,j}\right)$$
$$K_{i,j} = \frac{q_{90} - q_{10}}{q_{75} - q_{25}} \tag{121}$$

Separating the mean and the dispersion statistic as in the last four metrics creates more computational complexity besides the trade-off information it provides. For these separate (disaggregated) metrics, the solution procedure we established is as follows: First, the policy options are ranked with respect to each of the mean and the dispersion metric, and for each multi-criteria method. Then, the Pareto set is formed with the policy options which are not outranked by another option with respect to both the mean and dispersion metric. Hence, Equation 112 is modified as shown in Equation 122, where P is the Pareto set.

$$R_{i,j}(t) = \left(R^0_{i,j}(t), R^1_{i,j}(t)\right)$$
$$R^0_{i,j}(t) = \mu\left(O^*_{i,j,s}\right), \qquad R^1_{i,j}(t) = f\left(O^*_{i,j,s}\right); \; s = 1...N$$
$$U^0_j(t) = f\left(R^0_{i,j}(t)\right), \quad U^1_j(t) = f\left(R^1_{i,j}(t)\right) \tag{122}$$
$$r^0_j = \text{rank of policy } j \text{ wrt } U^0_j, \; r^1_j = \text{rank of policy } j \text{ wrt } U^1_j$$
$$P = \left\{ j: \; r^0_j \le r^0_k \text{ and } r^1_j \le r^1_k \;\; \forall k \in [1, J] - j \right\}$$

87B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

6.1.3. Multi-criteria methods

Four alternative methods are considered in this analysis in order to measure the effectiveness of a policy option on the multiple outcome indicators. In the selection of these methods, three factors are taken into account. These factors are:

i. The understandability and transparency of the method
ii. The extent of information required from the problem owner and stakeholders
iii. How the method deals with commensurability

The understandability and transparency of the method is important for communicating the solution procedure, especially to an audience which may not have a prior methodological knowledge such as policy makers and other policy analysts. Besides, simple and easily understandable methods are preferred for the exploratory purposes of this framework. Regarding the second factor, the methods which do not require high degrees of information (e.g. attribute thresholds, importance order, discordance thresholds etc.) are preferred, because the elicitation of such information from the problem owner and stakeholders is expected to pose more uncertainty. The last factor, namely the approach to commensurability is an important concept related to the inter-criteria relations in the domain of multi-criteria problems. It is defined as the suitability of criteria to be traded off against each other. The framework used in this study includes methods that represent two extreme approaches to deal with commensurability, as well as intermediary approaches.

6.1.3.1. Pareto Set

Constructing the Pareto set, i.e. finding the non-dominated solutions among the policy options, is the basic method that does not consider any inter-criteria tradability, hence that can fully deal with incommensurability. This method is based on a *dominance* relation. Policy *j* is said to *dominate* policy *k* if *j* is better than or equal to *k* in terms of all criteria, and strictly better than *k* in terms of some criteria (Keeney and Raiffa, 1993, pg. 69). In other words, policy *j* is at least as good as policy *k*. The Pareto set contains the solutions (policy options) which are *non-dominated* by any other solution. With the abovementioned general nomenclature, the Pareto set (P^*) is defined as

$$P^* = \left\{ j \;\middle|\; \begin{array}{l} R_{i,j} \geq R_{i,k} \;\forall i \\ R_{i,j} > R_{i,k} \;\exists i \end{array} \;;\; j,k = 1...J,\, j \neq k \right\} \tag{123}$$

The Pareto set approach is advantageous since it does not require commensurability between the criteria. Yet, it is disadvantageous when it results in too many non-dominated options and cannot facilitate a selection. Still, it can help in eliminating of a few policy options from the set of alternatives.

6.1.3.2. Lexicographic Ordering

Lexicographic ordering is a simple method that takes the importance order of the criteria into account. It is applied in an iterative manner, first looking for the best policy option in terms of the most important criterion, then for the best option in terms of the second most important criterion, and continuing similarly. On the one hand, the advantage of this method is that it does not require any inter-criteria trade-off information, but only an ordinal ranking of the

88A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

criteria. The disadvantage, on the other hand, stems from the strong preference over the policy options which are good only for the highly prioritized criterion (Keeney and Raiffa, 1993, pg. 77). To deal with this disadvantage, several adjustments can be made to the original method, e.g. setting performance thresholds. In this analysis, it is opted to select the policy options which are ranked high according to the basic lexicographic ordering, and which are not the worst option for any of the first four most important criteria. Hence, the selected option(s) according to this adjusted lexicographic ordering method are denoted as follows, where I is the index of the criterion picked from the lexicographic ordering set $O_1 \succ O_2 \succ O_3 \succ O_4 ...$ one by one:

$$\left\{ j \middle| \begin{matrix} R_{i,j} > R_{i,k} \\ R_{i,j} \not\preceq R_{i,k},\ \forall i = 1,2,3,4 \end{matrix} \ ;\ j,k = 1...J \right\} \tag{124}$$

The order of criteria used in this analysis is

- Share of Renewables in the Energy Mix
- Coverage of Domestic Gas Demand
- Import Dependency
- Total State Revenue from NG production
- Average Consumer Gas Price
- Renewable Gas Percentage
- Societal Acceptance (Groningen)
- Transport Capacity Utilization Rate

This order is derived from the objective ordering survey which is described in Chapter 2, and with which the stakeholders were asked to score the policy objectives. The first-rank frequency of each criterion (objective), i.e. for how many times it is selected as the most important criterion by the participants, is the main determining factor of the order above, together with the distribution of lower ranks for each criterion. For instance, 'Share of Renewables in the Energy Mix' is selected as the most important criterion by the highest number of participants (8 of 16), and it is placed at the second and third ranks by 2 participants.

This order cannot be argued to be a strong representative of the view of the government, which is considered to be the decision maker in this analysis. It is rather an approximation of the viewpoint of a biased set of stakeholders. Still, the results derived from this order can be interpreted accordingly, generating insights for this point of view.

6.1.3.3. Additive Utility Method with Equal Weights

In contrast to the Pareto set method, the additive utility method assumes full commensurability of the criteria, and represents the trade-offs with weights assigned to the criteria. Hence, the weighted sum of the normalized values of the criteria provides a utility indicator for each policy option. In this method based on Multi-Attribute Utility Theory, independence of the attributes (criteria) is the key precondition for an application. Sage and Armstrong (2000, pg. 418) define *attribute independence* with the following three statements:

i. "The relative importance of satisfying separate performance criteria does not depend on the degree to which each criterion has in fact been satisfied.

88B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

ii. The rate at which increased satisfaction of any given criterion contributes to the overall worth is independent of the levels of satisfaction already achieved on that and other criteria.
iii. The rate at which decision makers would be willing to trade off decreased satisfaction on one criterion for increased satisfaction in another is independent of the levels of satisfaction already achieved by the criteria."

These statements basically refer to the attribute weights, and indicate that they should be independent of the achievement level of the attribute they are assigned to, or those of the other attributes. In this study where attributes are actually the robustness values of the outcome indicators, it is assumed that the weight assigned to an attribute is constant regardless of the achievement level in that attribute or others. However, such dependence relation between the attributes should be investigated further by consulting the decision maker.

The traditional Multi-Attribute Utility Theory assumes the resulting weighted sum as an overall utility value. In this study, the aggregation of the robustness values with this weighted sum approach is used only as an indicator of the performance of a policy option.

A preliminary step of the additive utility method is the normalization of the data, since the outcome values differ in scale across the attributes and normalization makes them comparable. Table 6.1 shows an example impact table, with policy options in rows and attributes (criteria) in the columns. Normalization means that the data, x_{ij}'s, in each column are brought to a scale where they can be compared to the ones in other columns. There are several ways to conduct such a normalization, such as i) dividing each x_{ij} by the largest value in the column, ii) range normalization where the minimum and maximum values of the column are adjusted to 0 and 1 respectively, iii) statistical standardization, i.e. the ratio of the difference from the mean to the standard deviation (of the data in the column), and iv) dividing by the total (Tofallis, 2014). Among these options, the second and third distort proportionality, and the last one eliminates a meaningful interpretation of the normalized data. Therefore, we select the first option, namely the division of data by the largest value.

Table 6.1: An example impact table for a multi-criteria problem

	O_1	O_2	O_3	…
P_1	x_{11}	x_{12}	x_{13}	…
P_2	x_{21}	x_{22}	x_{23}	…
P_3	x_{31}	x_{32}	x_{33}	…

As the first option of implementing an additive utility method in this analysis, a set of equal weights is used, based on the assumption that the criteria are equally important. It is not argued that this equal importance reflects the real situation, but this is rather used as a test case to see what the results could be, if the criteria are treated equally. Equation 125 shows the computational implementation of this method, based on the general nomenclature used in this section.

89A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$U_j = \sum_{i=1}^{M} w_i R_{ij}^*$$

$$R_{ij}^* = \frac{R_{ij}}{\max_{j=1..J}\{R_{ij}\}} \ , \forall i \qquad (125)$$

$$w_i = \begin{cases} 1/M \ \ ; \ if\ O_i \text{ is to be maximized} \\ -1/M \ ; \ if\ O_i \text{ is to be minimized} \end{cases}$$

6.1.3.4. Additive Utility Method with Uncertain Weights

Using the additive utility method with equal weights is considered as a test case, despite the uncertainty in the weights, i.e. importance given to the criteria. Therefore, from a decision analysis point of view, it is more important to investigate how robust the selection (or sorting) of policy options is against the uncertainty in the weights. For such an investigation, 1000 Monte Carlo simulations are conducted on the weighted sum approach shown in Equation 125 , with 1000 different weight sets. These weight sets represent a wide variety of importance order and inter-criteria trade-off preferences.

For a selection problem, e.g. for the second layer policy options, the mean rank of a policy option resulting from these simulations, and the distribution of ranks it receives, is used to determine which policy is most preferred with each robustness metric. Besides, the matches between the weight sub-spaces and the preference of policy options are investigated. In other words, the policy options favored for different trade-off (preference) structures are found, to provide the decision makers and stakeholders with information about the favorable policy options under different prioritizations.

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The variety of solution methods in the MCDA domain is certainly not limited to the above four methods selected for this analysis. On the contrary, there is an abundant number of methods and variations of them, especially in the group of outranking methods. From this abundance, the selection of the above four methods is motivated primarily by the three reasons stated at the beginning of this section. The first two of these reasons, namely the understandability and transparency of the solution process, and the requirement of additional information from the decision maker, are also the main reasons for the exclusion of outranking methods (e.g. ELECTRE, PROMETHEE), and other methods such as Analytical Hierarchy Process and ARGUS from this analysis. Despite this exclusion of these methods from this framework, which is a preliminary attempt to combine multiple robust decision making and multi-criteria methods, future investigation of them in such a combination is expected to be worthwhile.

6.2. CONCLUSIONS

This chapter presented a quantitative assessment and comparison framework which is used to analyze policy alternatives in terms of both their robustness and effectiveness. This framework was composed of three dimensions to accommodate the time, robustness and multi-criteria aspects of a decision analysis process, and several options for each of these

89B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

dimensions. The primary purpose of including multiple methodological options was to investigate the robustness of policies not only against the uncertainties in the system but also to methodological choices, i.e. methodological uncertainty. Even if such methodologically robust policy options cannot be found, the analysis based on this framework enables generating insights about which policy options are preferred under which methodological choices, and why.

Due to the large number of combinations of method options at each dimension, the implementation of this framework is computationally intensive. For instance, when static time metrics are used with each multi-criteria method, a matrix of 9x4 solutions are generated. With uncertain weights, this matrix is based on 1000 solutions for each cell. As for the dynamic solutions, a solution is generated for each robustness metric in each year in the 50 year horizon, hence 9x50 solutions are obtained for each multi-criteria method.

The next two chapters explain and discuss the analysis of policy options listed in Section 6.2 based on this framework. Firstly, in Chapter 7 this framework is used for the selection of an option for policies that can be implemented in many different ways. Then, Chapter 8 presents the analysis (comparison and sorting) of "first layer" policies in Section 6.2 conducted by using this framework.

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90A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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You can't always get what you want
But if you try sometime, you just might find
You get what you need

Rolling Stones, *You can't always get what you want*

7

SELECTION OF EXCHANGEABLE POLICY OPTIONS

In Chapter 2, the policy alternatives that are included in this study were listed, and a framework to analyze them were introduced in Chapter 6. These policy alternatives were depicted in two layers, where the second layer alternatives represented the multiple ways in which the corresponding first layer policy can be implemented. For instance, 4 options were identified for implementing the cap policy on the Groningen field, or 11 options for the renewable energy subsidization. This chapter presents and discusses the selection of an option for each of these two policies from the corresponding group of options based on the framework presented in Chapter 6. The scenario space taken into account in this analysis includes all future possibilities created by the possible values of model uncertainties, as presented in Chapter 5. In other words, the policy options are tested in terms of their effect on the entire uncertainty space, rather than a portion of it.

In this chapter, Groningen cap policies and different subsidization schemes for renewable gas are analyzed and discussed in detail, in Sections 7.1 and 7.2, respectively. Each section includes a visual comparison of alternatives, numerical comparison based on static time metrics, and a dynamic comparison, as well as a discussion about selecting an option for further analysis. In Section 7.4 the conclusions of this chapter are discussed.

7.1. ANALYZING THE PRODUCTION CAP POLICIES

Limiting the natural gas production from the Groningen field is a policy which has long been used by the Dutch government, in order to preserve the balancing capability of the field for a longer duration, and to stimulate production from small fields in the meantime. Previously, the total production from the Groningen field was set to 425 bcm for the period 2010-2020

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(MEZ, 2012). In 2014, the earthquakes in the Groningen region due to natural gas production, and societal unrest caused by them, led the government to abandon the 10-year cap and to set annual caps which further reduce the production. Therefore, the limit was 42.5 bcm/year in 2014 and 2015, and set as 40 bcm/year in 2016. It is said that this limit can be reduced to 30 bcm/year if necessary (MEZ, 2014), and in the beginning of 2015, 16.5 bcm is determined as the quota for the first half of 2015 (Remie, 2015). We consider these two options, namely a 10-year cap until 2020 and stricter annual caps, for limiting the Groningen production, and prolonging the 10-year cap policy as well as a 'no policy' option. Table 7.1 lists and explains these four options to be evaluated with respect to 8 policy objectives of the government.

Table 7.1: Options for the Production Cap Policy

ID	*Name*	Explanation
P0-BAU	*10-year Cap*	In 2012, the initial time of the simulations, the 10-year cap was in use. Therefore, Business-as-Usual (BAU) option is the continuation of the 10-year cap until 2020, as set in 2010. In other words, the total (cumulative) production between 2012 and 2020 is set to 353 bcm, subtracting the actual production of 2010 and 2011 from 425 bcm.
P1a	*No Cap*	This is the 'no policy' case, in which there is no limit on the production from the Groningen field starting from year 2012.
P1b	*Prolonged Cap*	The third policy option is prolonging the 10-year cap (*P0*) until 2050, implemented as follows: After 2020, once in every 10 years, the cap for the total production of a 10-year period is assumed to be reset to 50% of the *Developed Reserves* available in this year.
P1c	*Annual Cap*	With this policy option, the Groningen production is limited by the values mentioned above, namely 42.5 and 40 bcm/year for 2014-2016. For the period 2016-2020, the annual cap is assumed to decrease by 5% each year to 32.5 bcm in 2020. There is no cap considered after 2020, and initially between 2012 and 2014, 10-year cap values are implemented.

7.1.1 Analyzing the Cap Policies with Static Metrics

7.1.1.1. Visual Comparison (Based on Kernel Density Estimates)

A Gaussian kernel density estimate (KDE) illustrates the relative density of the output data across the range of values in that data set. In this section, we use such density estimates for a visual comparison of the policy options. Figure 7.1-Figure 7.4 below show the Kernel Density Estimates of the data resulted from 5000 simulations, for three outcome indicators selected, where each simulation is executed with a different combination of the possible values of the model uncertainties. In these figures, each subplot illustrates the density distribution in the case of one of the four time-metrics introduced in Chapter 6, with a line colored differently for each policy option. Regardless of the time-metric used, the density estimates of the policy options are almost identical for many of the outcome indicators, such as *Renewable Gas Percentage*, *Societal Acceptance of Groningen Gas*, and *Average Consumer Gas Price*, as Figure 7.1 exemplifies.

When the four policy options are compared in terms of their effects on the *Coverage of Domestic Gas Demand* as in Figure 7.2, the density estimates they yield for the *End states* and for the *Minimum over time* are identical. It must be reminded that such insensitivity of the density estimates to different production cap options is not due to identical, or very similar,

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production values, but due to the contribution of imports to demand coverage, and demand levels adapting to supply. When the maximum values of the 50 year horizon are considered, P1a (No Cap) results in a better average value, and more scenarios around this average value. This can be attributed to the fact that No Cap policy allows very high natural gas production volumes if demanded. As for the cumulative results, P1b (Prolonged Cap) results in higher density around the mean value, although it does not yield very high values in any scenario. This means that the prolonged cap policy is better at generating good average demand coverage, when the entire 50-year horizon is considered.

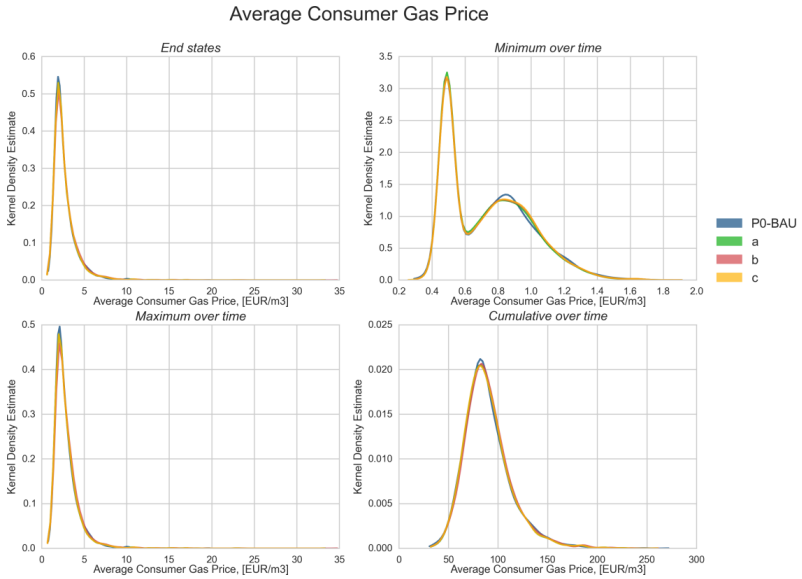


Figure 7.1: Density distributions of the 4 policy options for 4 time-metrics, for *Average Consumer Gas Price*

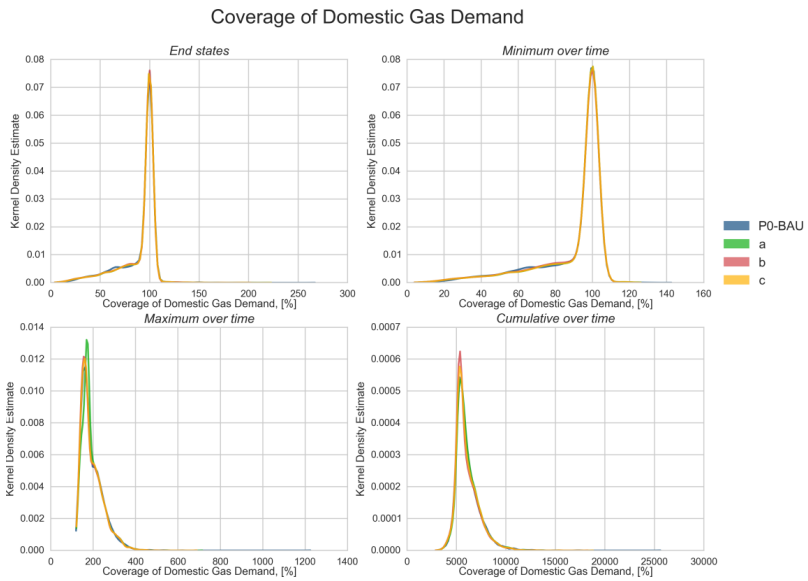


Figure 7.2: Density distributions of the 4 policy options for 4 time-metrics, for the *Coverage of Domestic Gas Demand*

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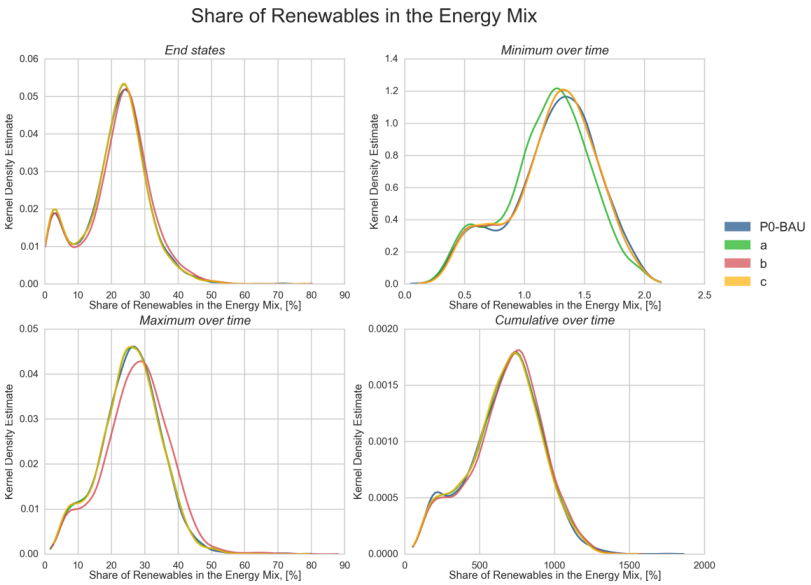


Figure 7.3: Density distributions of the 4 policy options for 4 time-metrics, for the *Share of Renewables in the Energy Mix*

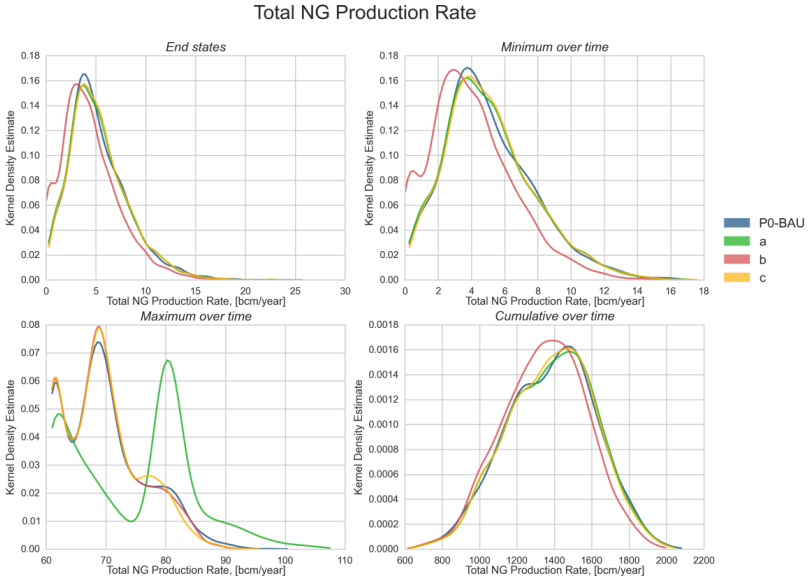


Figure 7.4: Density distributions of the 4 policy options for 4 time-metrics, for the *Total Natural Gas Production*

For the outcome indicator *Share of Renewables in the Energy Mix*, the differences between the policy options are more observable, as Figure 7.3 shows. Regardless of the time metric, P1b (Prolonged Cap) shifts the distribution towards higher values. For the *Minimum over time* metric, P1b is almost identical to P1c (Annual Cap until 2020), but for the other time-metrics, it stands alone. This difference of P1b can be related to two factors: Firstly, lower values of natural gas production, caused by P1b as shown in Figure 7.4, stimulates renewable energy production not only because of necessity but also because of increasing prices. Secondly, the

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share of renewables in the energy mix is defined as the share of renewables in the total domestic electricity and gas production. A prolonged cap reduces the total natural gas production as implied by Figure 7.4, hence increases the share of renewables in the total energy production.

7.1.1.2. Numerical Comparison

Table 7.2 shows the rank-order, or the selected set, of the 4 cap policy options for each time-metric, robustness metric and multi-criteria method. More precisely, the last four rows of this table (the two dimensional robustness metric), and the last four columns (Pareto Set as the multi-criteria method) show the set of selected policy options, whereas the rest of the cells contain a rank-order of the policy options from the most to least preferred.

The first striking observation obtained from Table 7.2 is that Pareto sets in the last four columns include all policy options (except *Min* robustness and *Cumulative* time metric). The meaning of this observation is that there is no policy option, which is better than all other options in terms of all criteria, regardless of the robustness metric. This finding emphasizes the conflicts between the criteria, and the difficulty of satisfying all of them with a single policy.

When lexicographic ordering of the criteria is used for comparison of the policy options, either there is no solution found, mostly for the *Minimum over time* metric, or there is a single, or a few options selected instead of a complete ranking for the first five robustness metrics. This is due to the strict rules of the heuristic used, i.e. an option being the best for the most important criterion and not being the worst for any of the first four most important criteria. Therefore, the conflicting nature of the first four criteria eliminates many options that are preferred for the *Share of Renewables in the Energy Mix* but not for the *Coverage of Domestic Gas Demand*, or *Import Dependency*. Besides, due to the small number of policy options compared to the number of outcome indicators, this method favored the options that are preferred for the first few most important criteria.

Option *P1a-No Cap* resulted as the dominant option with the lexicographic ordering method, for many robustness and time metrics. This preference of 'no cap' is attributed to its higher performance on the demand coverage, import dependency and state revenues, rather than the share of renewables, which is the most important criterion. However, when the overall long-term dynamics are considered with the *Cumulative* time metric, this dominance of *P1a* is changed, indicating the long-term benefits of a cap policy even though no cap is better in the short term or at particular points in time. From the robustness point of view, especially when the cumulative dynamics are taken into account, the pessimistic robustness metrics such as *Min* and *MaxRegret* favor option *P1c*, whereas the statistical metrics which focus on a favored distribution include *P0* and *P1c* as preferable options, too.

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Table 7.2: Static solutions for the cap policy options, (cells colored according to the 1st rank, or the only selected, option)

Multi-criteria method		Lexicographic				Additive, Equal Weights				Additive, Uncertain Weights				Pareto front			
Time		End	Min	Max	Cum	End	Min	Max	Cum	End	Min	Max	Cum	End	Min	Max	Cum
Robustness																	
Expected	**Min**	c			c>0	c>0>a>b	b>c>0>a	0>c>b>a	a>0>c>b	c>0>a>b	b>c>0>a	0>c>b>a	0>a>c>b	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b}
	Mean	a		a>0	0>a	c>0>a>b	b>c>0>a	a>0>c>b	0>c>a>b	c>0>a>b	b>c>0>a	a>0>b>c	0>a>c>b	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
Regret	**MaxRegret**	a		a>c	c	0>c>a>b	b>c>0>a	a>c>0>b	a>b>c>0	0>c>a>b	b>c>0>a	a>c>0>b	b>a>c>0	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
	Regret Thresholds	a		a>0	a	0>c>a>b	a>c>0>b	a>0>b>c	0>c>a>b	0>c>a>b	a>c>0>b	a>0>b>c	0>c>a>b	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
Statistical	**Mean/Std**	0		0		c>0>a>b	c>0>a>b	b>0>c>a	b>c>0>a	c>0>a>b	c>0>b>a	b>0>c>a	b>0>c>a	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
	Mean, Sk1	{a}		{a}	{0}	{c}	{a, b, c}	{a, b, c}	{0, b, c}	{c}	{a, b, c}	{a, b}	{0, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
	Mean, Sk2	{a}		{a}	{0, c}	{c}	{b, c}	{a, b}	{0, b, c}	{c}	{b, c}	{a, b}	{0, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
	Mean, IQR	{a, c}		{a, c}	{0, b}	{b, c}	{b}	{0, a, b, c}	{0, b, c}	{b, c}	{b}	{0, a, b}	{0, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}
	Mean, Kurtosis	{0, a}		{a}	{0, a, c}	{b, c}	{a, b}	{a, b}	{0, b, c}	{b, c}	{a, b}	{a, b}	{0, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}	{0, a, b, c}

0 a b c

Regarding the additive utility methods, the first striking observation is the similarity between the results of equal weighting and uncertain weighting of the criteria. For most of the robustness and time metrics, the rank-order and set of selected options obtained from equally weighted criteria and the rank order obtained from 1000 different importance orderings of the criteria are the same. The main reason for this indifference to criteria weighting is the selected option having a high or averagely good impact on most of the outcome indicators. For instance, *P1c*, which is the first-rank option when *Mean* robustness metric and *End* values are taken into account, is the best option for 3 out of 8 criteria (consumer price, state revenues and import dependency), and the second best for another 2 criteria (transport capacity and societal acceptance). Therefore, *P1c* can be considered as a robust option against different preferences of stakeholders. Similarly, *P1a* is the best option for 3 out of 8 criteria, and the second best for 2, with the *Mean* robustness metric and *End* values. Besides, the small differences between the policy options in terms of many criteria as shown in the previous section can be considered another reason leading to the indifference to criteria weightings.

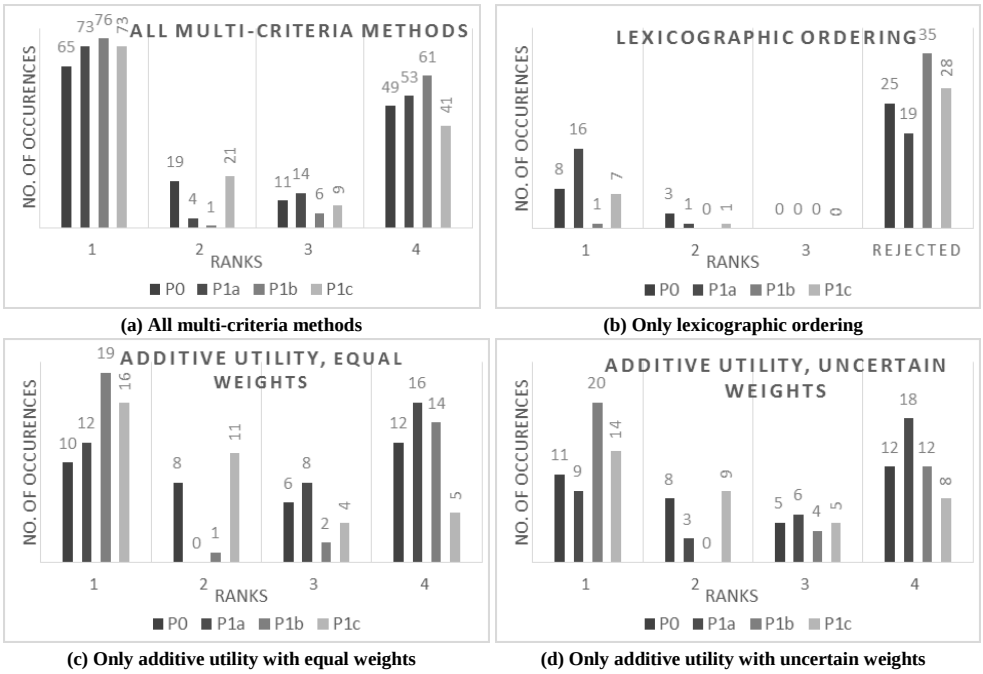
The results of the additive utility method also indicate that the preferred options are more dependent on the time metric, rather than the robustness metric. For instance, *P1c* is the first or second-rank option, or in the selected set for all robustness metrics, when the *End* states are taken into account, indicating that a stricter cap implemented only until 2020 yields favorable results at the end of the simulation horizon. Similarly, *P1b* is the most preferred option robust against the robustness metric selection with *Min* time-metric, so are *P1a* and *P0* for *Max* and *Cumulative* time metrics, respectively. High performance of *P1b* for the worst cases over time can be attributed to that a prolonged cap prevents very low natural gas production values obtained eventually if the cap is removed, causing the worst cases for criteria such as *Coverage of Domestic Gas Demand, Total State Revenues* and *Import Dependency*. In contrast, when the best cases over time is considered with the *Max* time metric, *P1a-No Cap* being the most preferred option is due to the peaked production in the early years, creating very high values for *Coverage of Domestic Gas Demand, Total State Revenues* etc. Lastly, *P0* (10-year cap) having high performance with the *Cumulative* time metric indicates that a short and not strict limitation of the production is better than other options when the entire simulation horizon and all criteria are considered.

Figure 7.5 illustrates the coloring of Table 7.2 in histogram form, namely the rank distribution across the policy options for each rank. These histograms are created by counting the occurrences of each rank for each policy option, including all multi-criteria methods[11] in Figure 7.5a, and for only one of the multi-criteria methods in other subfigures. If an option is in the Pareto set, its rank is counted as 1; if not, it is counted as 4. Higher number of occurrences for rank 1 and rank 4 compared to other ranks is attributed to this methodological choice. Moreover, for the lexicographic ordering method, the options which do not satisfy the heuristic criterion, hence do not receive any rank, are included in the 'rejected' group. These

[11] As a combination of 9 robustness metrics, 4 time metric and 4 multi-criteria methods, Table 7.2 included 144 solutions comprised of a rank order or a Pareto set. In the case of 11 combinations, e.g. lexicographic ordering and *Min* time metric, a solution could not be found, hence 133 solutions are taken into account. The histograms in Figure 7.5 show in how many of these 133 cases a policy option receives a particular rank. For instance, according to Figure 7.5a, *P0* has the first rank, or in the Pareto set, in 65 of these 133 cases.

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options are assumed to take the last (worst) rank when all methods are considered. When all multi-criteria methods are considered, P1b has the highest frequency of receiving the 1st rank, also the highest frequency of receiving the last rank, closely followed by P1a and P1c. For the two additive utility methods, the position of P1b does not change in the first rank, whereas for lexicographic ordering it is replaced by P1a.



(a) All multi-criteria methods **(b) Only lexicographic ordering**

(c) Only additive utility with equal weights **(d) Only additive utility with uncertain weights**

Figure 7.5: Rank Frequency of Cap Policy Options across the Performance Metrics

Uncertainty in the Criteria Weighting

As explained before, the additive utility method with uncertain weights ranks the policy options based on their mean rank obtained with 1000 different weight sets, and the distribution of ranks received by each policy. Appendix 7.1 shows the histograms of these rank distributions, for each robustness and time metric. These distributions confirm the rank-order of policies presented in Table 7.2, based only on mean-ranks. Namely, the steepness of the histogram of a policy around its rank based on mean-ranks, in other words high frequency at this rank value, bolster the ranking of policies as in Table 7.2.

Besides supporting the findings based on mean ranks, these histograms provide insights about the variation of ranks obtained by each policy, hence the robustness of them against different weighting of criteria. For instance, with the *Min* robustness and *End* time metric, there is no variation in the ranks of any policy option, indicating a strong robustness of *P1c-Prolonged Cap*, which is the first-rank option, to different weighting of criteria. However, when there is variation in rank frequency, for instance with *MaxRegret* robustness and *Cumulative* time metric, then it can be said that there are weighting schemes that change the preference of a policy. It is worthwhile to investigate these weighting schemes, to provide the decision maker and stakeholder with information about the trade-offs between criteria.

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For such an investigation, the 8 dimensional weight space covered by the Monte Carlo simulations is visualized in box and whisker plots for each policy option, and for each robustness and time metric. In other words, the weight values of each criterion that lead to a particular policy option being the most preferred one is displayed in a box plot. **Figure 7.6** is one of such plots, that show the results for the robustness metric *Min* and time metric *End*. With these metrics, P0 (10-year cap) and P1a (No cap) are the only options that are ranked first with a weight set. For both of these options, *Coverage of Domestic Gas Demand* and *Share of Renewables in the Energy Mix* are the most influential criteria, because only a small subspace of the weights for these criteria lead to the selection of the two policy options. Yet, these weight subspaces (for the two criteria) are opposite to each other for P0 and P1a. These findings imply that a cap policy (in that case, 10-year cap) is more preferred than no cap in a view that prioritizes the renewable energy rather than the security of supply for gas. In contrast, 'no cap' option is better in a view that prioritizes the security of gas supply over the share of renewable energy.

It is important to note that such a strong tradeoff between the *Coverage of Domestic Gas Demand* and *Share of Renewables in the Energy Mix* does not exist in the case of all other robustness and time metrics. For instance, Figure 7.7 shows the boxplots of the weight subspaces for the robustness metric *MaxRegret* and time metric *Cumulative*. P0 is the most preferred option with these metrics in the majority of the weight space, and there is no evident tradeoff between the *Coverage of Domestic Gas Demand* and *Share of Renewables in the Energy Mix*. Given this finding, it can be said that P0 is considerably robust against the prioritization of criteria. Yet, there is a small subspace that lead to P1a being the most preferred option. The most important characteristic of this subspace is low values for *Average Consumer Gas Price* and *Transport Capacity Utilization Rate*, and high values of *Import Dependency*. This means that, no cap is the most preferred option when high consumer prices, low utilization of the international trade capacity and high import dependency are accepted, considering the entire simulation horizon.

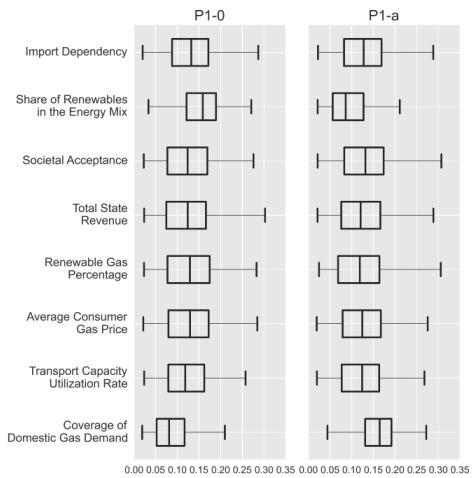


Figure 7.6: Weight subspaces leading to the most preferred policy options, when Min robustness metric and End states are considered

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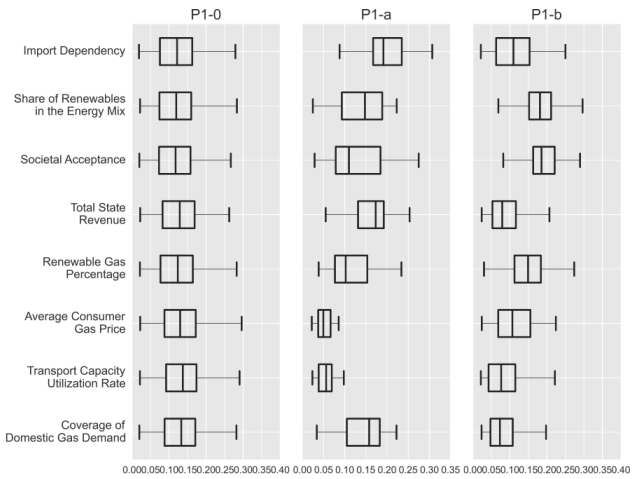


Figure 7.7: Weight subspaces leading to the most preferred policy options, when MaxRegret robustness metric and Cumulative values are considered

Besides the two examples discussed above, Appendix 7.2 presents the boxplots of weight subspaces leading to the most preferred policy option, for each robustness and time metric. The overall conclusion of this analysis is that the relation between the preference of a policy option and the prioritization of criteria is dependent on methodological choices. There are common observations, for instance, with many metrics, P1a-No Cap is the most preferred option when state revenues are valued low and renewable gas share is valued high, unlike the case of *MaxRegret* and *Cumulative* time metric shown in Figure 7.7. Yet, although a criterion results as influential in preferring a policy (implied by a narrow range of weights for this criterion) according to a particular robustness and time metric, it may be uninfluential according to other metrics (implied by a wide range of weights). Besides, a policy option supported by a particular weight subspace (e.g. a very low prioritization of a criterion) according to a particular metric may be supported by very different weight subspaces according to other metrics (e.g. a very high prioritization of that criterion). Therefore, one cannot strongly argue that a policy is good for a particular set of policy objectives, or in a particular worldview.

7.1.2 Analyzing the Cap Policies Dynamically

In this section, we investigate which policy option is more preferred over time, for each robustness metric and multi-criteria method. In other words, the analysis presented in the previous section for four time-metrics (*End states*, *Minimum over time*, *Maximum over time* and *Cumulative*) is conducted for each year in the 50 year horizon between 2012 and 2062. In each year, the data obtained from simulating 5000 scenarios is used to calculate the robustness metrics, and the values of the robustness metrics are used for ranking or selection of the policy options, by using a multi-criteria method. Below, the results are presented and discussed in three subsections, for each multi-criteria method.

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7.1.2.1. Lexicographic Ordering

Figure 7.8 shows the outcome of first 5 robustness metrics, namely *Min*, *MaxRegret*, *Regret Thresholds*, *Mean/Std.Dev. and Mean*, each represented by a different color and marker shape. The x-axis of this figure shows the time, whereas the y-axis shows the four policy options. The option ranked first at each time point is spotted with a marker in the left plot, whereas the option ranked last is marked in the right plot. Similar to the static solution, the first observation obtained from this figure is that there are no solutions found at many time points, especially with the *Min* robustness metric, due to the strict condition on the selection. In the cases where a solution is found, several options are marked as both the most and least preferred option with a robustness metric, indicating that this option is the only solution found at that time point. Both in the first and last decade, regret-based metrics favor P1a, whereas statistical metrics yield a preference for P0, and a disfavor for P1b (and P0 in the last decade). In the mid-decades, there is a wide variety of selection, based on both time and metric.

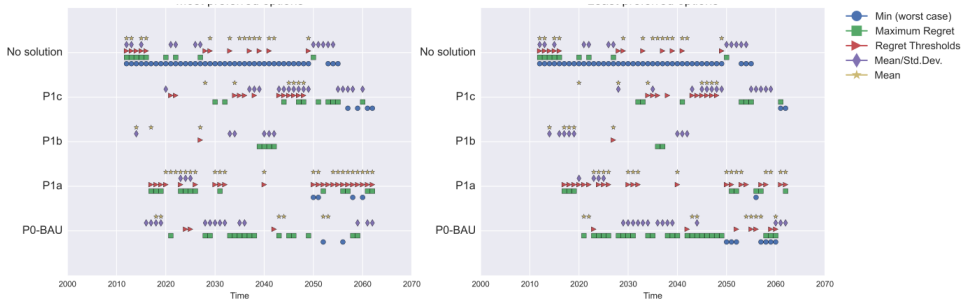


Figure 7.8: Preferred cap policy option over time, with 5 robustness metrics and for lexicographic ordering

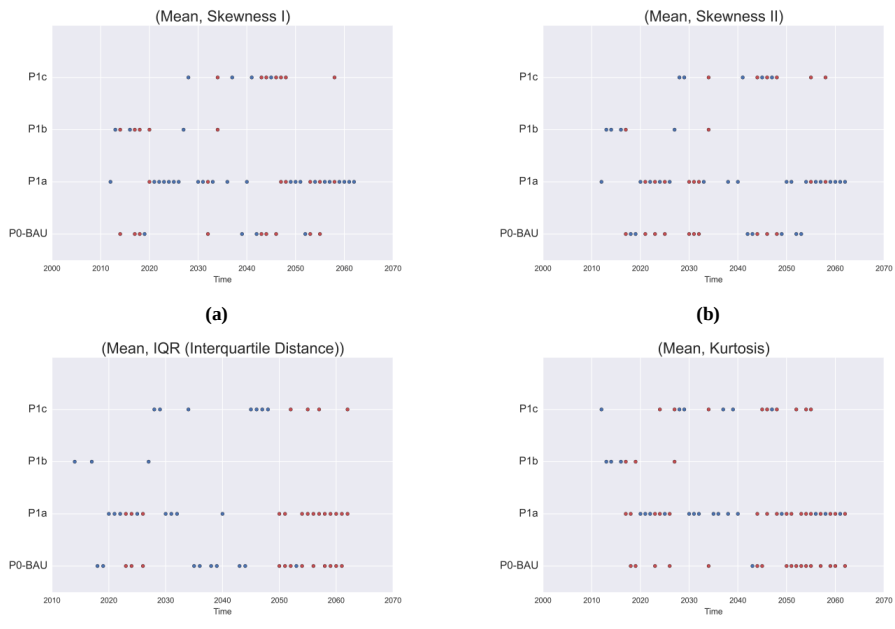


Figure 7.9: Preferred cap policy option over time, with the 2 dimensional metrics and for lexicographic ordering

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For the two dimensional robustness metrics, i.e. where mean and a statistical dispersion metric is coupled, the results is a set of selected options rather than a ranking, as mentioned before. These sets are marked in Figure 7.9a-d, for each time point. If a policy option is the only selected one, it is colored blue, and if there are multiple options in the selected set, they are colored red. Despite a relatively small degree of variety in the selections over time or according to the metric, P0 and P1a are the two options that are preferred most of the time, and with all four metrics.

7.1.2.2. Additive Utility Method with Equal Weights

When the additive utility method is used with equal weighting of the criteria, as pointed out also by the static solution, the preferred options are more dependent on time, rather than on the robustness metric. Before 2020, as seen in Figure 7.10, P1a results as the most preferred option with almost all metrics and in almost every year, while P1c is the least preferred one. These two findings indicate that limiting the Groningen production is not favored in the short term, due to its adverse effects on several criteria such as demand coverage, capacity utilization and consumer prices. Yet, after 2020 when the cap is ceased both in option P0 and P1c, P1c and P1b results as the most and least preferred options in the early years, respectively. Later, until the cap is removed in 2050, P1b is the most preferred option with most of the metrics, whereas P1a is the least preferred one. The results change again after 2050, leading to P1c being more preferred and to P1b being the least preferred. These findings firstly indicate the long-term orientation of the cap policy, since P1c (stricter cap) and P1b (longer cap) give better results than P0 and P1a in the long term. However, P1b has a low performance in the last years, attributed to prolonged adverse effects made on some policy objectives such as price and import dependency. This finding implies that the Groningen production should be limited beyond 2020, but at an optimal duration that does not create adverse effects in the longer term.



Figure 7.10: Preferred cap policy option over time, with 5 robustness metrics and for additive utility with equal weights

With the two dimensional metrics, the selected set includes multiple options as Figure 7.11a-d show, except the first decade where P1a is the most preferred option as in the case of previous metrics. The coupling of mean and the second skewness metric does not differentiate between the options, but with the other three metrics, P1b and P1c are dominantly the most preferred options most of the time.

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7.1.2.3. Additive Utility Method with Uncertain Weights

As in the case of static solutions, the results obtained by equal weighting of the criteria and uncertain weighting are almost identical. Therefore, Figure 7.12 and Figure 7.13 are almost the same as their counterparts in the previous section, leading to a similar discussion. It must be noted that the results below are based on the mean ranks of the options resulting from 1000 Monte Carlo simulations.

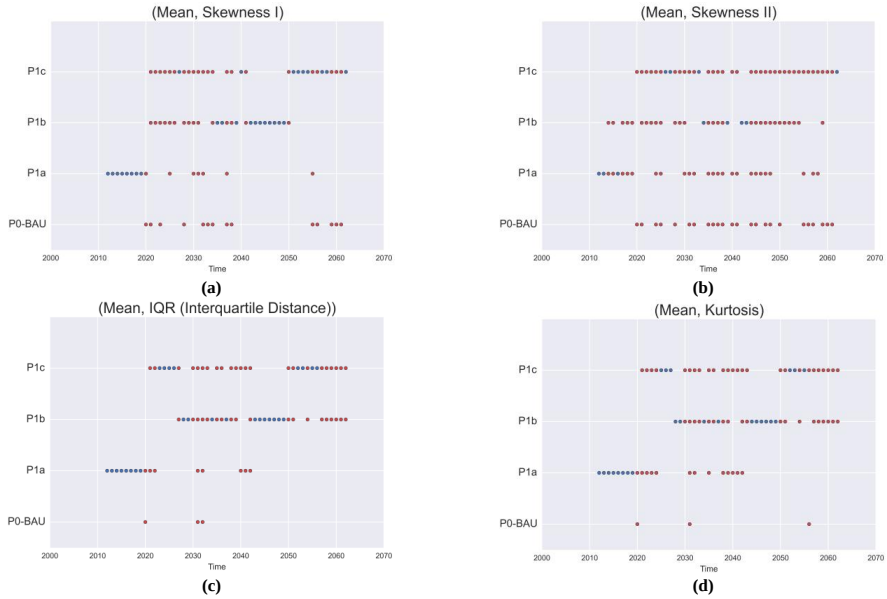


Figure 7.11: Preferred cap policy option over time, with the 2 dimensional metrics and for additive utility with equal weights

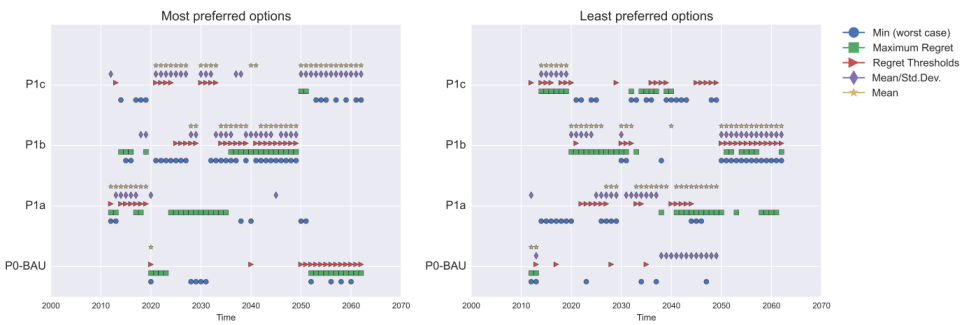


Figure 7.12: Preferred cap policy option over time, with 5 robustness metrics and for additive utility with uncertain weights

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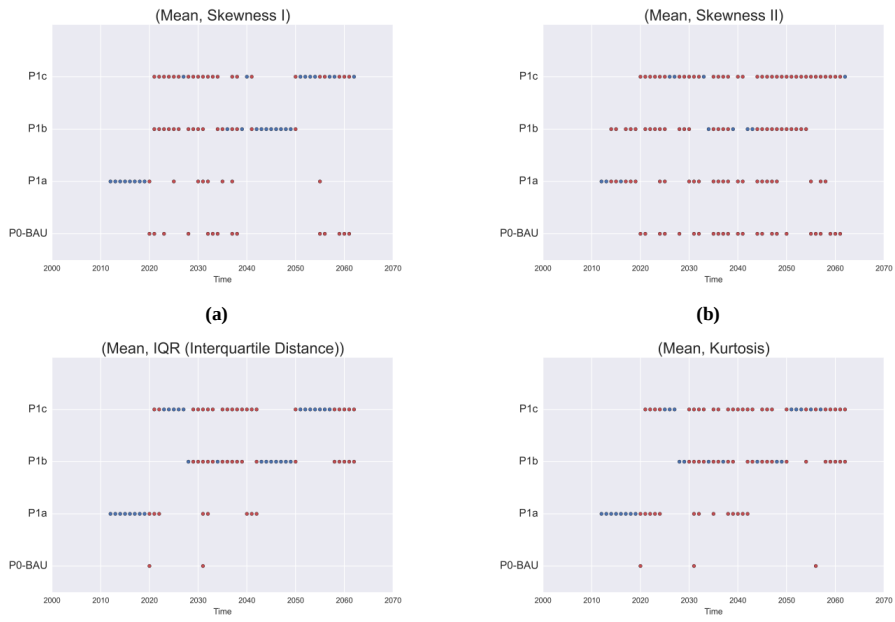


Figure 7.13: Preferred cap policy option over time, with the 2 dimensional metrics and for additive utility with uncertain weights

7.1.3 Selecting a Cap Policy for Further Analysis

Due to high dependence on methodological assumptions such as robustness metrics and multi-criteria methods and little difference in terms of many criteria as shown in the analysis above, it is not straightforward to select one of the cap policy options as the most preferred one. However, such a selection is necessary for further analysis, even though a strong rank-order of policies, e.g. an order robust against methodological choices, cannot be obtained due to the complexity of the problem. Therefore, **P1b-Prolonged Cap** is selected as the cap policy option, to be compared to other policies in the next chapter. This selection is based on the high frequency of P1b being the most preferred option across all robustness, time and multi-criteria methods, and in a longer duration, despite its low performance in the last years if additive methods are used. Still, the insights derived from the analysis above should be taken into account in a decision making process, rather than establishing a strong confidence in the prolonged cap option.

7.2. Analyzing the Biomethane Subsidization Schemes

To stimulate the deployment of renewable energy, subsidization has long been used in the Netherlands, as in several other countries. As mentioned in Chapter 2, SDE+ is the subsidization policy currently implemented in the Netherlands, based on the payment of the difference between a predetermined basis price and the market price to producers. Besides this form of subsidization named spot-market gap model, there are several alternative subsidization schemes, such as the fixed feed-in tariffs as provided by Germany or percentage

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premiums on the market price as provided by Spain in the past. Couture and Gagnon (2010) discuss the various subsidization schemes implemented in various countries, and their advantages and disadvantages for investors and society. In this study, the list of schemes provided by Couture and Gagnon (2010) and a few additions are used to be compared to each other in terms of robustness and performance on the outcome indicators. Since the cost of subsidization to the government is an important factor in measuring the success of these schemes, a 9th outcome indicator, namely the *Cumulative Cost of Biomethane Subsidization*, which indicates the total cost of subsidization during the period it is implemented, is added to the list of 8 outcome indicators identified before.

Table 7.3 summarizes the subsidization scheme options used in this analysis, and how producers and the government are financially affected if price changes in the case of each scheme. The paragraphs below explain these schemes in more detail, and Appendix 7.3 describes how they are implemented in the simulation model.

Table 7.3: Options for the Biomethane Subsidization Scheme

ID	Subsidization scheme	Market dependent	Producer		Government	
			Price ↑	Price ↓	Price ↑	Price ↓
P0	*Spot-market gap model until 2050*	χ	☺	😐	☺	☹
a	*No subsidization after 2016*	χ	☺	☹	😐	😐
b	*Spot-market gap model until 2030*	χ	☺	😐	☺	☹
c	*Fixed cost percentage until 2030*	χ	☺	😐	☺	☹
d	*Fixed feed-in tariff until 2030*	χ	☹	☺	☹	😐
e	*Fixed FIT with fixed inflation adjustment until 2030*	χ	☹	☺	☹	😐
f	*Fixed FIT with variable inflation adj. until 2030*	✓	☺	☹	☹	☺
g	*Front-end loaded tariff model until 2030*	χ	☹	😐	☹	😐
h	*Fixed premium on market price until 2030*	✓	☺	☹	☹	☺
i	*Percentage of market price until 2030*	✓	☺	☹	☹	☺
j	*Variable premium until 2030*	✓	☺	😐	☺	😐

In the *spot market gap model* of the Dutch government, a 'basis price' is set every year, according to the net present value of investment and operation costs of the production facilities, with a certain rate of return. The subsidy amount paid to a producer is the difference between the market price and the 'basis price' set in the year the producer has subscribed, as Figure 7.14 illustrates. Although the subsidy amount is dependent on the market price of gas, the spot market gap model is categorized as a market-independent scheme by Couture and Gagnon (2010) since the basis price is determined independent of the market price. This scheme does not provide a high financial certainty for producers, but prevents the government from paying high amounts if the market price increases. Besides, since this model imposes the market price on producers if it is above the basis price, both producers and the government can benefit from high market prices, the former due to increased revenues, the latter due to reduced subsidization costs. However, only the government takes the risk of low market prices, which increases the subsidizations costs for the government while ensuring the basis price for producers. In this study, the basis price is assumed to be set with a 15% rate of return

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and 2% inflation; the period a producer receives subsidy is set as 12 years as in the real case, and the duration of subsidization is 38, 4 and 18 years in options *P0*, *a* and *b*, respectively.

The *fixed cost percentage* model is similar to the spot market gap model, in the sense that the government pays the difference between the market price and a basis price to producers. However, this basis price is determined as a multiple of the unit production cost of renewable gas. The production cost is assumed to be the cost value in the year a producer subscribes to subsidization, and to remain constant during the subsidy period (12 years), without taking the learning effect on costs into account. Therefore, this scheme provides more incentives for producers to reduce the production costs, and stimulates innovation. In the model, the basis price is assumed to be 12% more than the unit production cost of renewable gas produced via both digestion and gasification.

In the *fixed feed-in tariff model* illustrated in Figure 7.15, a fixed price is paid to producers who inject their product to the grid. This model is purely market-independent since the feed-in tariff is determined regardless of the market price. Despite high certainty provided to producers, the costs of this model to the government is higher, since the entire feed-in tariff is paid by the government. This model is in favor of producers while keeping the government indifferent if prices drop. However, an increased price is a missed opportunity both for producers who could obtain higher revenues and for the government who could save the subsidization costs. This scheme is implemented in our model with a fixed feed-in tariff equal to 0.55 EUR/m^3 for digestion and 0.65 EUR/m^3 for gasification, which are the average feed-in tariffs (basis price in SDE) between 2012 and 2015.

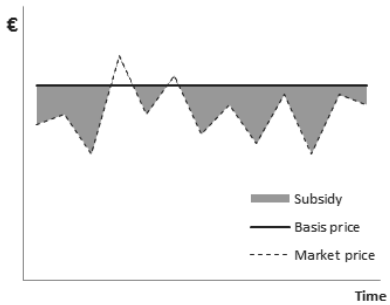


Figure 7.14: Spot market gap model
Adapted from Couture and Gagnon (2010)

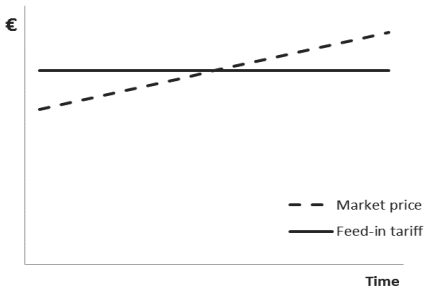


Figure 7.15: Fixed feed-in tariff model
Adapted from Couture and Gagnon (2010)

Due to the unattractiveness of a low fixed price to producers if the market price increases, the fixed feed-in tariff model is usually adjusted according to inflation. The first adjustment option is to modify the fixed feed-in tariff periodically with a fixed inflation percentage, independent of the market price, as exemplified in Figure 7.16. In this model named *fixed feed-in tariff model with fixed inflation adjustment*, the eventual feed-in tariff can be below or above the market price, but producers know that their income will increase. This adjustment reduces the missed opportunity of both producers and the government in the case of rising prices, however, it is not favored if the price increase is very high. With this model, a price decline is not financially harmful for producers, whereas the government is unaffected by it.

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In the model, this scheme is implemented with a 2% increase in the initial feed-in tariff once in every three years during the subsidy period, which is again 12 years.

The second adjustment option is to modify the fixed feed-in tariff periodically according to the changes in the market price, for instance as in Figure 7.17. This model makes the fixed feed-in tariff model market-dependent, and provides producers with higher income than the case of fixed percentage adjustment if the market price rises although the government has to pay higher subsidization costs. In the case of a price drop, this market-dependence implies low income for producers, and low costs for the government. Similar to the fixed inflation adjustment case, this scheme is implemented with an adjustment in every 3 years, while the adjustment percentage is determined based on the 3-year price difference.

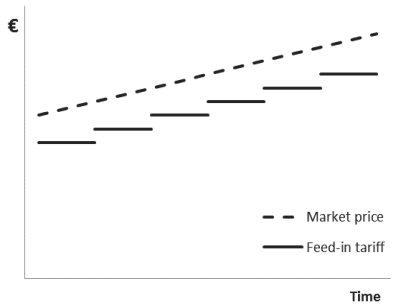


Figure 7.16: Fixed feed-in tariff model with fixed inflation adjustment, Adapted from Couture and Gagnon (2010)

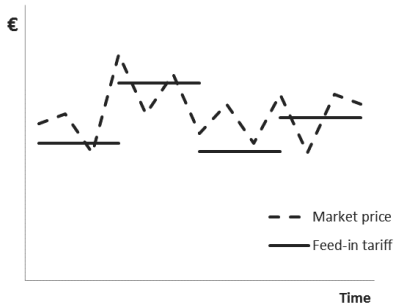


Figure 7.17: Fixed feed-in tariff model with variable inflation adjustment

The *front-end loaded tariff model* is another variation of the fixed price model, however, unlike the inflation adjustment, this model reduces the feed-in tariff in later stages of the project. As seen in Figure 7.18, the feed-in tariff offered by the government is high in the early stages, which is attractive for producers, but it is reduced later, which stimulates producers to reduce the production costs. This model protects both the government and producers from declining prices in the long-term, whereas the price levels above the feed-in tariff creates a missed opportunity for both parties. In the model implementation of this scheme, the initial feed-in tariff is assumed to be 25% more than the basis price of the fixed cost percentage model, and it assumed to be reduced by 10% in every 5 years during the 12 year subsidy period.

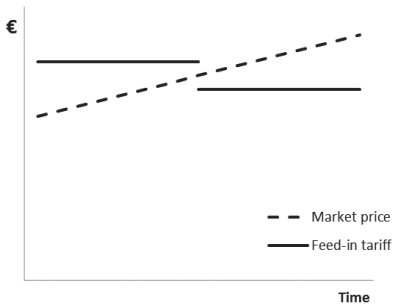


Figure 7.18: Front-end loaded tariff model
Adapted from Couture and Gagnon (2010)



Figure 7.19: Fixed premium on market price
Adapted from Couture and Gagnon (2010)

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A purely market-dependent scheme is the *fixed premium on market price*, where producers receive a constant premium in addition to the market price. In this scheme illustrated in Figure 7.19, the constant premium is determined either based on the production costs or environmental concerns. In this study, the premium is determined as the difference between the market price and the production cost in the year a producer subscribes to subsidy. Alternatively, the *percentage market price model* sets the feed-in tariff as a percentage of the market price, as seen in Figure 7.20. This model leaves producers more exposed to market volatilities, while the government has the chance of paying less than the fixed premium model. This scheme is implemented in the simulation model with a percentage value equal to the ratio of estimated market price in 6 years to the production cost value in the year subsidization is initiated. In both of these market-dependent options, the government and producer have opposite interests, since increasing prices are preferred by the latter but unwelcome by the former, and vice versa.

The last subsidization scheme is another market-dependent option, where an initial fixed premium is varied according to the market price changes. In this *variable premium model*, the premium paid to producers declines gradually as the market price increases until a certain level, where the premium becomes zero and producers receive the market price. Figure 7.21 depicts a two-stage example of this model. In this example, the premium declines until a reference premium level as the market price increases, in a way that a constant feed-in tariff (bottom limit) is ensured. For a certain range of the market price, the premium is kept constant, allowing the feed-in tariff (market price+premium), hence the producer income, to increase. When a certain level of feed-in tariff is reached (top limit), the premium is decreased again until 0, and producers receive the market price afterwards. Both for producers and the government, this model is not only advantageous if prices increase, but also it reduces the risk of low prices. In this study, this scheme is specified with cost and price dependent parameter values. In other words, the bottom and top limits are set to the 110% and 150% of the production cost in the year subsidization starts, whereas the reference premium is assumed to be equal to the expected market price in 6 years.

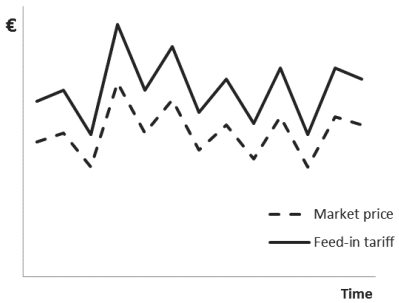


Figure 7.20: Percentage market price model
Adapted from Couture and Gagnon (2010)

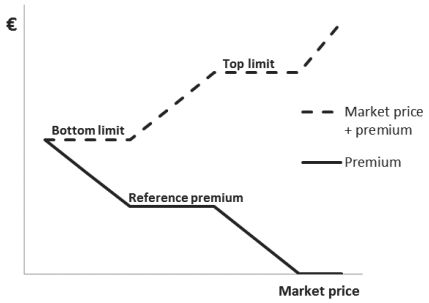


Figure 7.21: Variable premium model
Adapted from Couture and Gagnon (2010)

These 9 different subsidization schemes are assessed in this section, in terms of their robustness and impacts on the policy goals of the government. In the business-as-usual case (*P0*), the current spot market gap model is assumed to be implemented until 2050, and a no-

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policy option (*a*) is added, where the subsidization is stopped after 2016. In the other 9 options, the subsidization schemes are assumed to be implemented until 2030. In this way, besides comparing different subsidization schemes, the effects of a longer term and a very short term subsidization are also considered. The sections below explain and discuss the results of analyzing these subsidization options.

7.2.1 Analyzing the Subsidization Schemes with Static Metrics

7.2.1.1. Visual Comparison (Based on Kernel Density Estimates)

Similar to the cap policy, this section presents a visual comparison of the subsidization schemes based on the KDE's resulting from 5000 simulations, for the four time metrics. Figure 7.22 shows the results for *Renewable Gas Percentage*, which is the outcome indicator primarily targeted by the subsidization policy. The first observation is that the maximal share of renewable gas in the total gas supply can increase up to 50% with subsidization, but this percentage tends to be lower than 10% in the majority of simulations. For the *end states* and *minimum over time*, distributions do not show significant differences for this outcome indicator. The end state similarity is attributed to the early cease of subsidization (before 2062) and other limiting factors such as biomass availability mentioned in Chapter 5. The minimum values over time are almost identical for these policy options, mainly because these values are taken at the beginning of the simulation horizon, before the subsidization shows its effect.

As for the *maximum over time* and *cumulative* time metrics, subsidization with any option shifts the distribution towards higher, hence more preferable, values compared to the no policy option (*a*), indicating the necessity of subsidization for stimulating biomethane production. The rightmost distributions are obtained with options *g* and *f*, which are the front-end loaded tariff and fixed feed-in tariff with market-dependent inflation adjustment, respectively. This finding points out these two options as the most preferable ones for the *Renewable Gas Percentage*, based on a visual comparison. The reason of this better performance of options *g* and *f* can be attributed to increasing market prices, and higher subsidies provided by them with respect to such high prices.

The results for the costs of subsidization to the government oppose these findings about options *g* and *f*, as Figure 7.23 shows. Option *g*, the front-end loaded tariff model, has the rightmost density estimate for costs, followed by other fixed price models such as *f* and *e*. No policy option (*a*) has the narrowest and lowest uncertainty range for the costs, whereas the market-dependent options such as *h, i* and *j* result in wider and double-peaked density estimates, where the majority of simulations accumulate around a low mean value.

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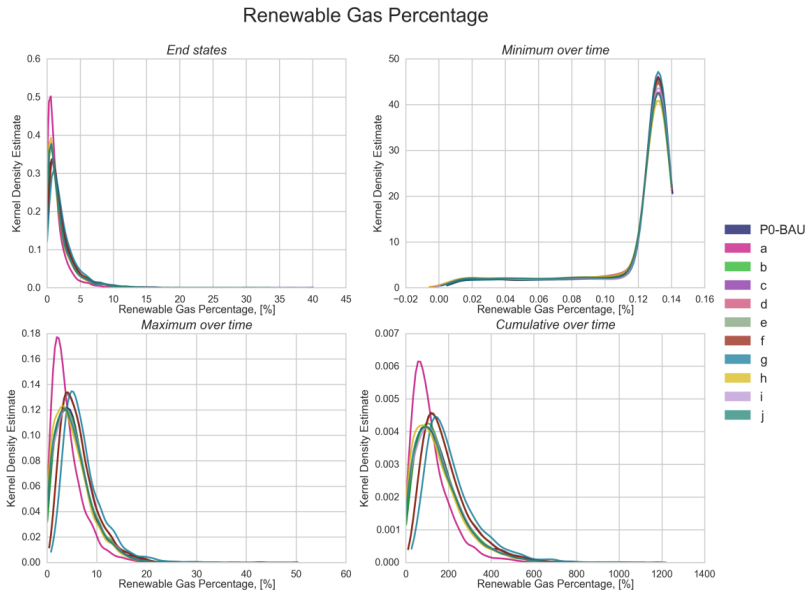


Figure 7.22: Density distributions of the subsidization options for 4 time-metrics, for *Renewable Gas Percentage*

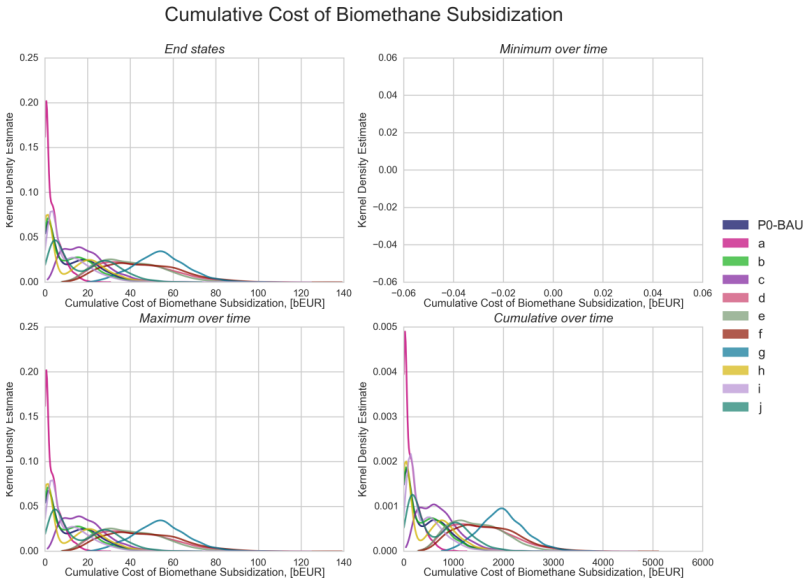


Figure 7.23: Density distributions of the subsidization options for 4 time-metrics, for *Cumulative Cost of Subsidization*

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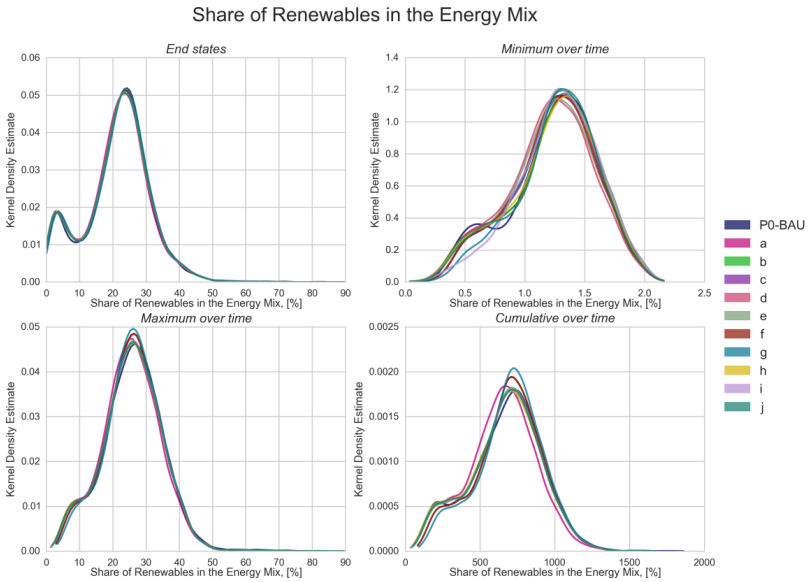


Figure 7.24: Density distributions of the subsidization options for 4 time-metrics, for *Share of Renewables in the Energy Mix*

For the remaining outcome indicators which are not directly affected by the subsidization policy, the differences between the options are small. The *Share of Renewables in the Energy Mix*, for which the renewable gas production is still an important factor, the subsidization options differ from each other mostly when the *minimum over time* and *cumulative* time metrics are used. As shown in Figure 7.24, option *h* (fixed market premium) and *g* (front-end loaded tariff) have the rightmost, and slightly narrower distributions with these two time metrics.

7.2.1.2. Numerical Comparison

Similar to Table 7.2, Table 7.4 shows the rank-order, or the selected set, of the 11 subsidization policy options for each time-metric, robustness metric and multi-criteria method. (For the additive methods, only the first and last two elements of the rank-order is shown.) The coloring in Table 7.4 quickly reveals that *P0*, which is the long term implementation of the spot market gap model, results as the most preferred option with many robustness and time metrics, and multi-criteria methods. This finding is attributed to long term implementation, rather than the spot market gap model, as it will be discussed below.

Pareto fronts do not yield distinctive non-dominated sets, as in the case of cap policy. Still, especially with the *Maximum regret* robustness metric and *minimum over time* values, options *e* (fixed feed-in tariff with fixed inflation adjustment) and *d* (fixed feed-in tariff) are dominated by others. In other words, there is at least one another option, which is better than or equal to option *e*, in terms of all outcome indicators, when the robustness is measured by the maximum of distances from the best option across the scenario space. Similarly, when the worst cases over time are considered, there is at least one option that outperforms option *d* (also *P0, e, h* and *j*, depending on the robustness metric). These findings can be interpreted as the disqualification of especially option *d* and *e* as the most preferred option.

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Table 7.4: Static solutions for the subsidization policy options, (cells colored according to the 1st rank, or the only selected, option)

Multi-criteria method		Lexicographic				Additive, equal weights				Additive, monte carlo				Pareto front			
Time		End	Min	Max	Cum	End	Min	Max	Cum	End	Min	Max	Cum	End	Min	Max	Cum
Robustness																	
Expected	**Min**	g>d>a		0	g>e	0>c>... h>i	0>j>... c>a	g>c>... h>i	g>c>... h>i	0>c>... h>i	0>j>... c>a	g>c>... h>i	g>c>... j>i	All	All-e	All-d,i	All
	Mean	0		0	c	0>b>... f>g	0>j>... c>a	0>b>... g>f	c>0>... f>g	0>b>... g>f	0>j>... c>a	0>b>... g>f	c>0>... g>f	All	All-d	All	All
Regret	**MaxRegret**	g>0		g>a	b>a>g>i	0>a>... i>f	0>j>... c>a	0>a>... i>f	0>a>... i>f	0>a>... i>f	0>j>... c>a	0>a>... i>f	0>a>... i>f	All-e	All-0,e	All-e,i	All-f
	Regret Thresholds	0		0	c>0	0>g>... i>j	0>i>... e>d	0>g>... i>j	g>0>... i>j	0>g>... i>j	0>i>... e>d	0>g>... i>j	0>g>... i>j	All	All-h,j	All	All
Statistical	**Mean/Std**	0		a>0>i	0	0>a>... d>f	g>i>... h>a	0>a>... d>f	c>a>... d>f	0>a>... d>f	g>i>... h>a	0>c>... d>f	c>b>... d>f	All	All-d,j	All	All
	Mean, Sk1	{0, j}	{i}	{0, g}	{c, d}	{0, c, e, f, g}	{0}	{0, g}	{0, c, e, f, g}	{0, c, e, g}	{0}	{0, g}	{0, e, g}	All	All-d	All	All
	Mean, Sk2	{0, j}	{i}	{0, g}	{c, j}	{0, b, c, e, g}	{0}	{0}	{0, c, g}	{0, b, c, e, g}	{0}	{0}	{0, g}	All	All-d	All	All
	Mean, IQR	{0}		{0, a}	{a, c}	{0, a}	{0}	{0, a, c, i}	{a, c}	{0, a}	{0}	{0, a, c, i}	{0, a, c}	All	All-d, e	All-j	All
	Mean, Kurtosis	{0}	{0}	{0, g}	{c, g}	{0}	{0}	{0, a}	{a, c}	{0, a}	{0}	{0, a}	{0, a, c}	All	All-d	All	All

0	a	b	c
d	e	f	g
h	i	j	

For using the lexicographic ordering method to compare the policy options, *Cumulative Cost of Biomethane Subsidization* is added as the 4th most important criterion, instead of the *Transport Capacity Utilization Rate*. Similar to the case of cap policies, either there is no solution found, mostly for the *minimum over time* metric, or there is a single or a few options selected, due to the strict rules of the heuristic used, and the conflict between especially the *Share of Renewables in the Energy Mix* and *Cumulative Cost of Subsidization*.

Even though *P0* (longer implementation of the spot market gap model) is the prevalent preferred option with the lexicographic ordering is used, there are some exceptions. For instance, when the *end states* (2062 values) or *cumulative* time metric and *Min* (worst cases) robustness metric are considered, the front-end loaded model results as the most preferred option. The reason for this is that this scheme has the highest minimum values of *Share of Renewables in the Energy Mix*, as seen in Figure 7.24. Similarly, with the *minimum over time* metric and both skewness measures, option *i* (percentage market price model) results as the most preferred one. This is attributed to lower left skewness of option *i* than the other options, for the minimum values of *Share of Renewables* over time, which is the most prioritized outcome indicator in the lexicographic ordering.

P0 is the prevalent preferred option also with the additive utility methods, although it is not the most preferred option for *Renewable Gas Percentage*, or for the costs. Still, it has an average performance for many outcome indicators besides these two, such as *Coverage of Domestic Gas Demand, Transport Capacity Utilization Rate, Average Consumer Price and Import Dependency*, explaining its high total performance and prevalence in Table 7.4.

The exceptions to P0 are observed especially with *cumulative* values, or *Min* and *Mean/Standard deviation* robustness metrics. For instance, in the case of equal weighting of the criteria, option *g* (front-end loaded tariff) results as the most preferred option with the *maximum over time* and *cumulative* time metrics, and the *Min* robustness metric. This is because option *g* is the most preferred one not only for the *Renewable Gas Percentage* and *Share of Renewables in the Energy Mix* as can be seen in Figure 7.22 and Figure 7.24, but also for the state revenues and societal acceptance, as well as because of its average performance on other outcome indicators. As for the option *c* (fixed cost percentage) which outperforms other options with the *cumulative* values and *Mean* and *Mean/standard deviation* robustness metrics, the reason is seen as an average good value for most of the outcome indicators, rather than a very good performance for a few.

Figure 7.25 illustrates the rank frequency of the subsidization policy options, when all multi-criteria methods are considered. Intermediate ranks are omitted from the figure for simplicity. As indicated also by Table 7.4, *P0-Spot market gap model until 2050* has the highest frequency of receiving the first rank, and the lowest frequency of the last rank. This finding is interpreted as a result of longer term implementation, rather than the characteristics of the spot market gap model, since the shorter implementation of this model, namely option *b*, does not demonstrate the same performance above other options. Besides, this finding shows the importance of long term subsidization in the Dutch gas sector.

For a better comparison of the subsidization models, *P0* is removed and the frequency histograms for the first and 10th ranks are formed as in Figure 7.26. With all three multi-

102A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

criteria methods, *front-end loaded tariff model* (option *g*) has the highest frequency of receiving the first rank, and a low frequency of the last rank, closely followed by the no-policy option (*a*) and the fixed cost percentage model (*c*).

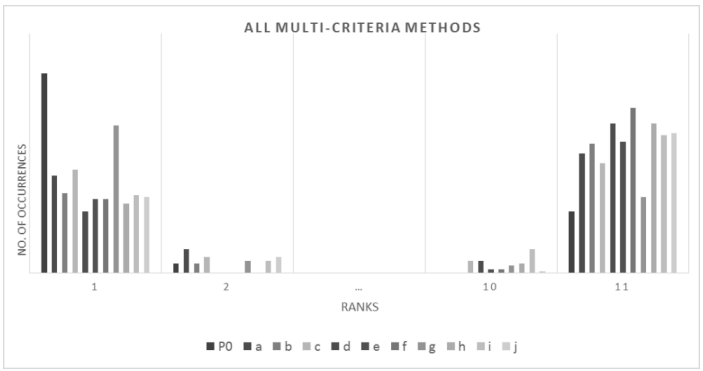
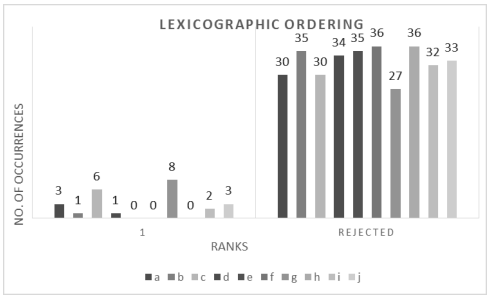
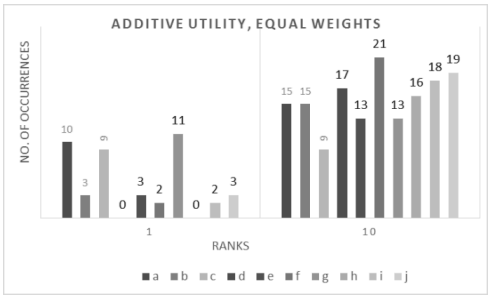


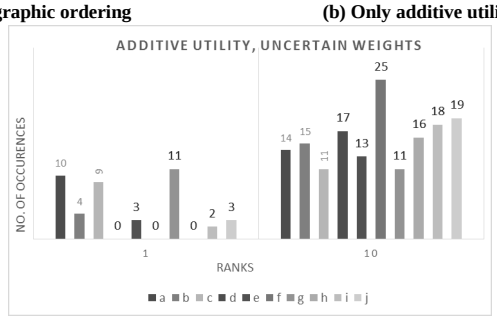
Figure 7.25: Rank Frequency of Subsidization Policy Options across the Solution Metrics



(a) Only lexicographic ordering



(b) Only additive utility with equal weights



(c) Only additive utility with uncertain weights

Figure 7.26: Rank Frequency of Subsidization Policy Options, without *P0*

Option *a* is the most preferred one after *P0*, especially with the *Maximum regret* and *Mean/standard deviation* robustness metrics, as Table 7.4 shows. Apart from being the most preferred option for the subsidization costs, and the least preferred one for *Renewable Gas Percentage*, the performance of the no-policy option on other outcome indicators depends on the metrics used. In general, it is preferable for *Transport Capacity Utilization Rate* and *Societal Acceptance* of natural gas (since low domestic production increases import activities and scarcity leads to higher acceptance of natural gas), and not preferable for *Average*

102B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Consumer Gas Price (again due to scarcity of domestic production) and *Share of Renewables in the Energy Mix*.

As for the fixed cost percentage model (option *c*), it is the most preferred option mostly for the *cumulative* values, and due to having an average performance for all outcome indicators, rather than having the highest performance for a few. For instance, with the robustness metric *Mean/standard deviation*, option *a* has the first rank for *Coverage of Domestic Gas Demand*, *Transport Capacity Utilization Rate*, *Total State Revenues from Natural Gas Production*, *Societal Acceptance* of natural gas, and the *Cumulative Costs of Biomethane Subsidization*, as Table 7.5 shows. Yet, it has the lowest (or very low) rank for *Average Consumer Gas Price*, *Renewable Gas Percentage*, *Share of Renewables in the Energy Mix* and *Import Dependency*, for which option *g* has the highest ranks. This conflicting performance of options *a* and *g* is the reason for leaving the first rank for the totality of the outcome indicators to option *c*, which has not very good but an average performance for all criteria.

Table 7.5: Impact table for the additive utility method with equal weights, for the robustness metric *mean/std. deviation* and the time metric *cumulative* (for each column, the greens are the preferred options)

	Cov. Gas Dem.	Transport Cap.Util. Rate	Av. Gas Price	Rnw. Gas Per.	Tot. State Rev.	Soc. Accp.	Share of Rnw	Import Dep.	Cost of Sub.
a	4.916	9.623	2254.81	1.237	2.763	3.341	2.719	1306618	27178
b	4.875	9.600	2199.04	1.386	2.776	3.289	2.749	1275633	167219
c	4.771	9.605	2179.03	1.616	2.782	3.248	2.916	1247585	274074
d	4.769	9.600	2179.20	1.609	2.784	3.246	2.916	1246880	973560
e	4.770	9.603	2178.08	1.609	2.783	3.246	2.915	1246880	788076
f	4.772	9.605	2178.61	1.613	2.782	3.248	2.916	1247246	1060228
g	4.662	9.589	2171.51	1.698	2.791	3.213	3.075	1232796	913316
h	4.894	9.614	2214.85	1.276	2.774	3.301	2.681	1279612	213785
i	4.878	9.616	2198.67	1.352	2.776	3.292	2.725	1276098	194652
j	4.870	9.596	2210.86	1.330	2.776	3.293	2.717	1280695	347801

Another striking observation from Figure 7.26 is that option *d* (fixed feed-in tariff), *f* (fixed FIT with variable inflation adjustment) and *h* (fixed premium on market price) almost never receive the first rank, regardless of the time and robustness metric, and their frequency of receiving the last rank is much higher than that of any other rank. The reason for these results, i.e. which outcome indicators are improved by these options and which are worsened, depends on the robustness and time metric. Yet, this finding eliminates the options *d*, *f* and *h* from the list of strong candidates.

Uncertainty in the Criteria Weighting

As in the case of cap policies, the additive method with uncertain weights is applied with 1000 Monte Carlo simulations representing 1000 different weight sets. The histograms of rank distributions obtained from these Monte Carlo simulations can be seen in Appendix 7.4. Based on the eventual results shown in Table 7.4, the results of uncertain weighting do not differ significantly from those of equal weighting. Still, the first-rank option varies with some of the robustness and time metrics, depending on the weight set used, although, as a longer term implementation, *P0* is a very robust option. For instance, when the robustness metric *Regret Thresholds* is used with *end state* values, option *g* or option *a* can beat *P0*, as Figure

103A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

7.27 shows. The conflict between *Renewable Gas Percentage* and *Cumulative Cost of Biomethane Subsidization* is apparent in this figure, since the front-end loaded model (*g*), which is the more stimulating but more expensive option, requires very low weights given to the cost criterion, and high weights to the renewable gas criterion. In contrast, the no-policy option (*a*) requires very low importance given to *Renewable Gas Percentage*, and high importance to the costs.

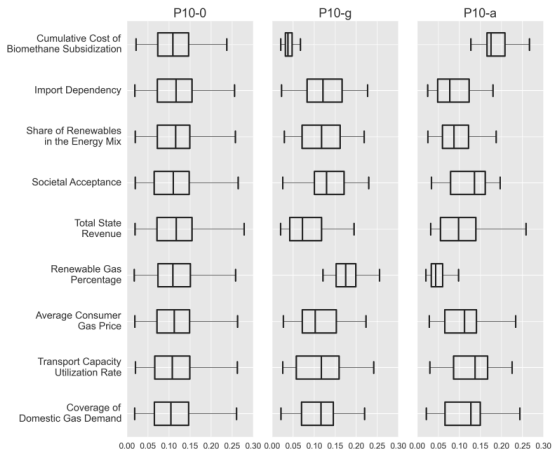


Figure 7.27: Weight subspaces leading to the most preferred policy options, when *Regret Thresholds* robustness metric and *End* values are considered

When *P0* is removed from the list of options for a better comparison of subsidization schemes, *Renewable Gas Percentage* and *Cumulative Cost of Biomethane Subsidization* are still the most distinguishing outcome indicators in determining the most preferred option, regardless of the robustness and time metric. **Figure 7.28** exemplifies this in the case of robustness metric *Mean* and *cumulative* values. The fixed cost percentage model (*c*) is the most prevalently selected option with these metrics, by a wide range of weights for each criteria. The spot market gap model (*b*) replaces option *c*, when *Cumulative Cost of Biomethane Subsidization* receives higher weights, and the *Renewable Gas Percentage* receives lower weights. This can be related to the lower costs of subsidization to the government if the spot market gap model is used, although the production of renewable gas cannot be stimulated as much as in the case of fixed cost percentage model. The weight subspaces for options *a* and *g* are similar to those obtained, and explained, for the *Regret thresholds* metric, i.e. the former requiring high weights for the costs and low weights for the renewable gas percentage, whereas the latter is the most preferred option in the opposite case.

103B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

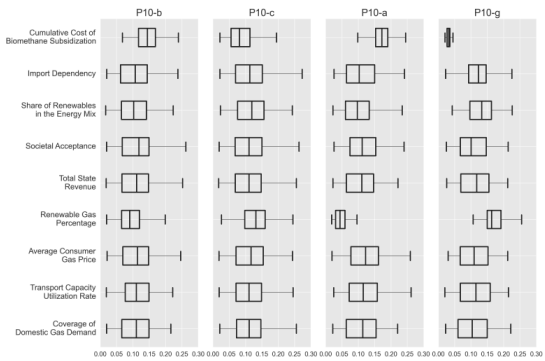


Figure 7.28: Weight subspaces leading to the most preferred policy options, with mean robustness metric and cumulative values

Appendix 7.5 shows the weight subspaces leading to the most preferred option, excluding *P0*, for each robustness and time metric.

7.2.2 Analyzing the Subsidization Schemes Dynamically

Similar to Section 7.1.2 on the cap policies, this section presents a dynamic analysis of the 11 subsidization options, i.e. their performance at each time point in the 50-year simulation horizon, for each robustness measure computed from the results of 5000 simulations at the corresponding time point, and for each multi-criteria method. Below, each section presents and discusses the results for the corresponding multi-criteria method.

7.2.2.1. Lexicographic Ordering

Figure 7.29 shows the most and least preferred subsidization options, when the first five robustness metrics and the lexicographic ordering method are used. Due to the strict heuristic of the method, there is no solution found in many cases, or there is a single solution found which is indicated by an option marked as the most and least preferred one simultaneously. Only with the *Min* robustness metric, option *g* is the prevalent most preferred option throughout time, while the results vary over time for other robustness metrics. A general observation is that market-dependent options such as *h* and *i* are preferred with multiple metrics earlier in time, but abandoned later, attributed to their increasing costs to the government in response to increasing prices. Besides, fixed feed-in tariffs, namely *d*, *e* and *f*, do not show a frequent high performance, and especially *e* and *f* are not preferred with any metric, almost at any point in time.

As for the two-dimensional statistical metrics, the results shown in Figure 7.30a-d demonstrate a wide variety of most preferred options, as well. It must be reminded that the solution at each time point is a Pareto set; and if there is a single option in the Pareto set it is colored blue, if there are multiple options, they are colored red. With the two skewness metrics, the Pareto set contains many options in the simulation horizon, especially in the early decades, which prevents reaching a conclusion on a single option. Besides, the results of the two skewness metrics are very similar to each other. The dispersion metric IQR leads to the selection of market dependent metrics before 2020, whereas later it shows a variation between

104A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the two spot market model options, no policy and fixed cost percentage model. Lastly, with the mean and kurtosis metric, a multiplicity and wide variety of selected options is observed.

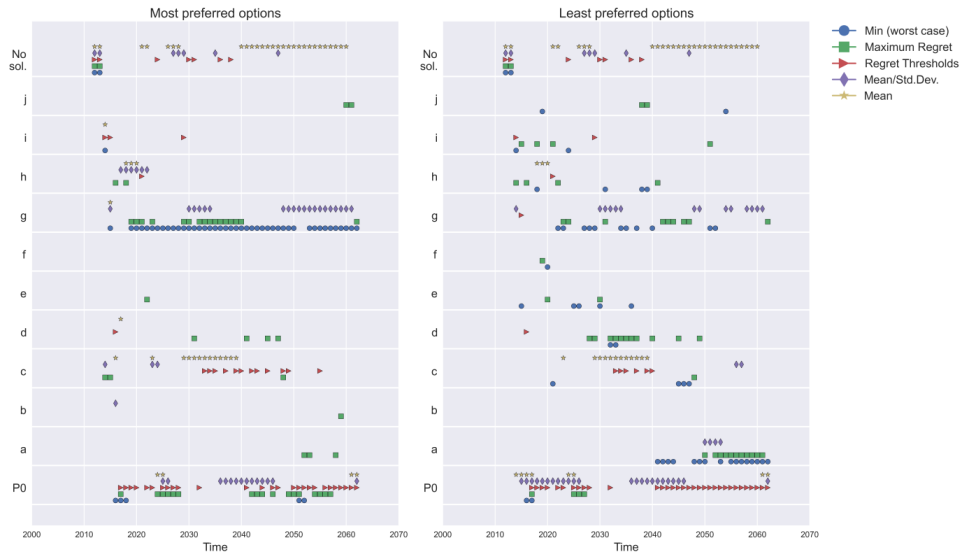


Figure 7.29: Preferred subsidization scheme over time, with 5 robustness metrics and for lexicographic ordering

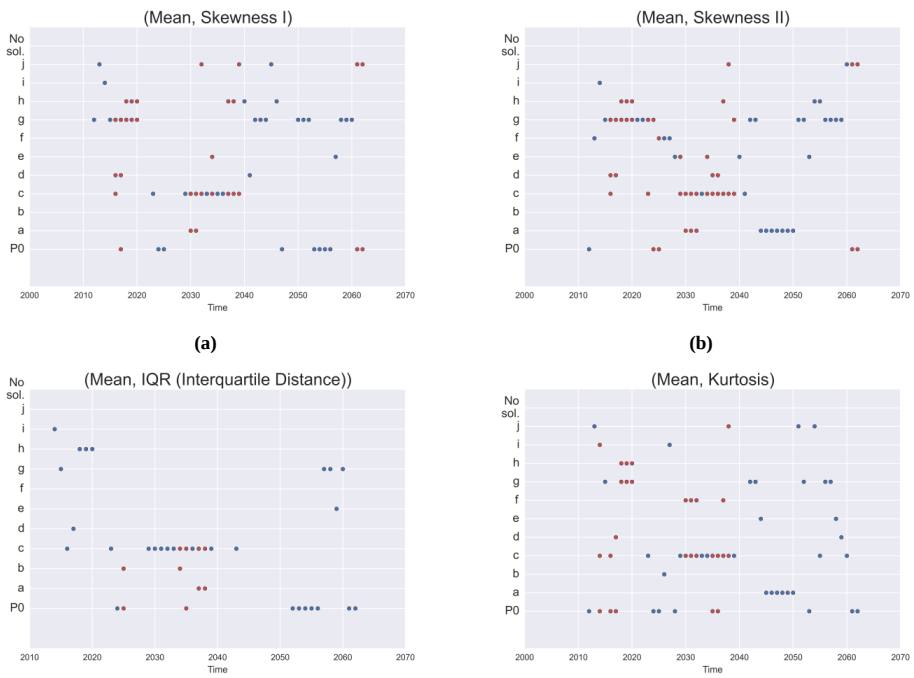


Figure 7.30: Preferred subsidization schemes over time, with the 2 dimensional metrics and for lexicographic ordering

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7.2.2.2. Additive Utility Method with Equal Weights

When the additive utility method is used with equal weighting of criteria, the most preferred options are more dependent on the robustness metric than time, since the most preferred option with a metric changes only a few times during the simulation horizon, as seen in Figure 7.31. Similar to lexicographic ordering, market-dependent options such as *h, i,* and *j* perform well only in the first few years, but later they are even the least preferred options with *Min* and *Regret thresholds* metrics. Moreover, the fixed feed-in tariff options (*d, e* and *f*) are never chosen as the preferred option, and they result as the least preferred option with some of the metrics.

The *Min* robustness metric favors option *g* for a long duration, switching to option *c* in the last two decades. Although the subsidization ends in 2030 with both options, this change can be interpreted as a better long-term effect of the fixed cost percentage model than the front-end loaded model on the worst cases. A similar switch from option *c* to option *P0* is observed with the *Mean* robustness metric, indicating a more preferred effect of ongoing subsidization on the mean values. As a pessimistic robustness metric, minimizing *Maximum regret* favors a variety of options initially, such as *c, h* and *a*, with a switch to the business-as-usual option (*P0)* in the late stages. The *Regret thresholds* metric is rather stable at the long-term spot market gap model (*P0*), with a short-term switch to the front-end loaded model (*g*) after 2030. This switch can be ascribed to the cost-wise advantage of option *g* after subsidization ends in 2030, compared to *P0*. Lastly, the *Mean/standard deviation* metric favors the fixed cost percentage model, with a switch to *P0* and the no-policy option later.

Another observation from the results of additive utility method with equal weights is that options *b, c, h* and *e* are hardly ever marked as the least preferred option. This finding establishes a high preference for option *c*, since it is marked as the most preferred option with many robustness metrics and at several time points, if all the outcome indicators are considered equally important.

Figure 7.32 shows the results of the additive utility method with equal weights, for the two dimensional statistical robustness metrics. Similar to the results of lexicographic ordering method, the two skewness metrics result in very similar Pareto sets at each time point, which mostly include options *c, e, f, g* and later *P0.* The *IQR* and *Kurtosis* metrics measuring dispersion of the density estimate also result in similar Pareto sets with this multi-criteria method, which initially include only option *c*, and later contain options *a, i* and *P0.*

As in the case of cap policies, the results of additive utility method with uncertain weights are very similar to those of equal weighting. Due to this similarity, the resulting figures and the discussion are not presented here, to avoid repetition. It must be noted that this similarity can be interpreted as the robustness of the selected options to different criteria prioritization.

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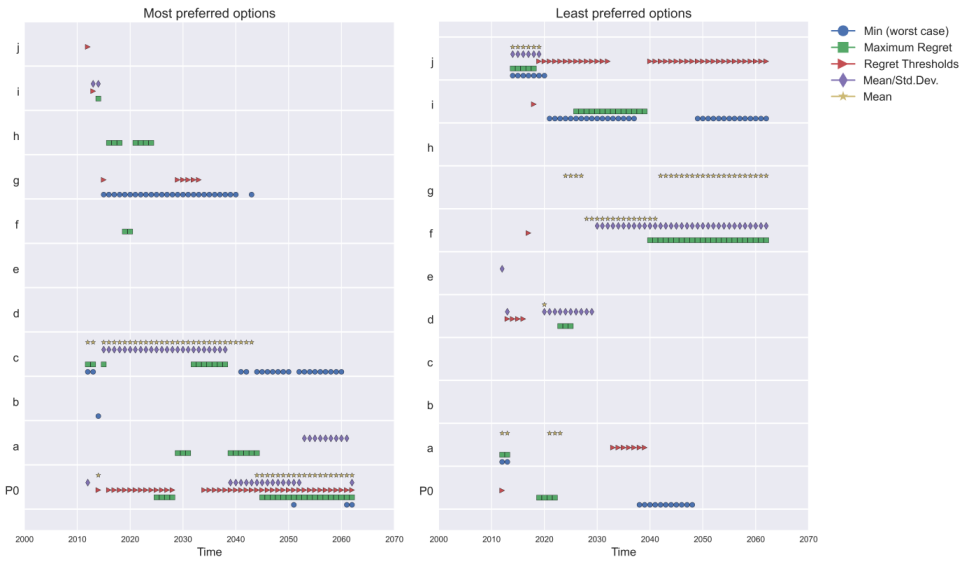


Figure 7.31: Preferred subsidization scheme over time, with 5 robustness metrics and for additive utility method with equal weights

7.2.3 Selecting a Subsidization Scheme for Further Analysis

Due to the dependence of results on the robustness metric and multi-criteria method used, it is not straightforward to select a subsidization scheme from 11 options. Still, the analyses and discussion above lead to the selection of the **fixed cost percentage model** (option *c*) to be used as the representative subsidization scheme in the policy comparison analysis of the next chapter, based on the following argumentation:

The market-dependent (*h, i ,j*) and fixed-price models (*d, e ,f*) do not yield high performance with neither static nor dynamic analysis, except a few robustness metrics. Therefore, they are not considered as an option to be selected. Among the remaining options, *P0* is the dominant option with static metrics but dynamic analysis shows that it is favored more in the last decades. This indicates that its high performance is related to long-term implementation, rather than being a spot-market gap model. Hence it is also removed from the list of remaining options, while keeping in mind that long-term implementation of the subsidization policy may be more preferable.

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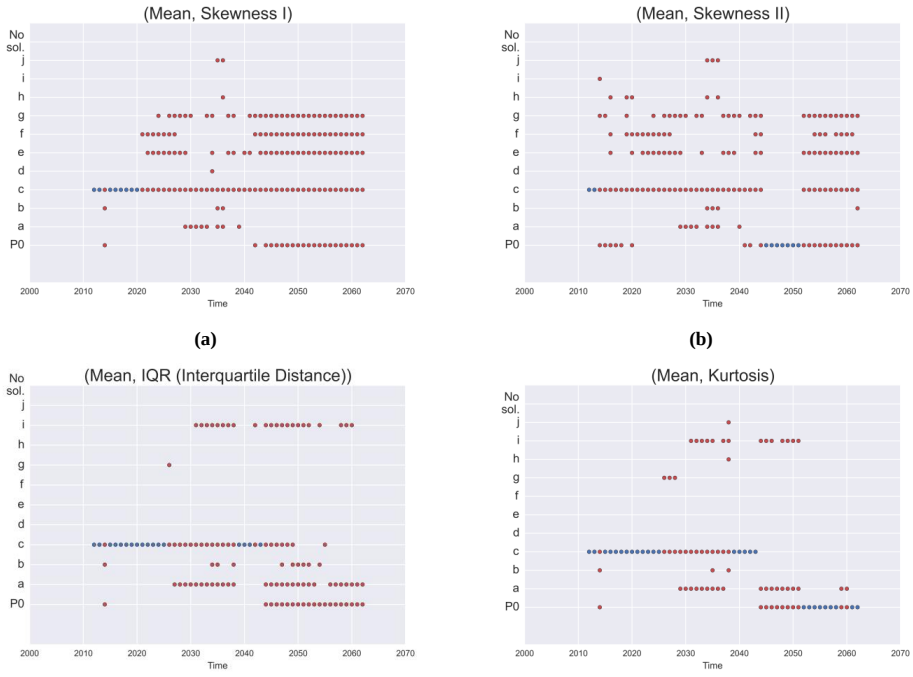


Figure 7.32: Preferred subsidization schemes over time, with the 2 dimensional metrics and additive utility method with equal weights

After *P0*, the front-end loaded model (*g*) is the second most preferred option with static time metrics, relatively robust against robustness metrics and multi-criteria methods. However, the metric combinations with which it is marked as the most preferred option is limited in the case of dynamic analysis. Therefore, option *g* is not considered for selection. A similar argument holds for the no-policy option (*a*) since it shows a high performance in the results of the static analysis, but not with the dynamic analysis, hence is not considered further.

Among the remaining two options, namely the spot market gap model (*b*) and the fixed cost percentage model (*c*), option *b* has a lower frequency of receiving the first rank and a higher frequency of receiving the last rank, compared to option *c*, in the static analysis. Besides, option *c* is marked as the most preferred one in the dynamic analysis with more robustness metrics, especially with the statistical metrics, both with the lexicographic ordering and additive methods. Therefore, option *c*, the fixed cost percentage model, is selected as the subsidization scheme to be used in further analysis in this study.

In this study, the fixed cost percentage model is assumed to be implemented with a basis price 12% higher than the production cost (hence, the nonnegative difference between 112% of the cots and the market price is paid as subsidy), and for 18 years until 2030. Despite its relatively higher performance compared to other schemes, the performance of this policy can be improved with a different setting. For instance, as the analysis above showed, longer implementation, e.g. until 2050 as in the case option *P0*, may yield better results. Eker and

106A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

van Daalen (2015) investigate the improvement opportunities for this subsidization scheme with a multi-objective robust optimization approach. Having the total renewable gas production, subsidization costs and the reduction in CO_2 emissions the key objectives, the optimization results indicate a relatively low subsidy percentage (11-19%) but longer implementation (25-26 years). Therefore, the subsidization policy compared to other gas sector policies in the next chapter will be assumed as fixed cost percentage model, with basis price percentages 11% and 16% (higher than the production costs) for renewable gas via digestion and gasification, respectively, and 26 years of subsidization.

7.3. CONCLUSIONS

This chapter presented an analysis of two major policies in the Dutch gas sector, namely the production cap on the Groningen field and the subsidization of renewable gas, with respect to three important dimensions of decision making under uncertainty. These three dimensions were time of measurement in a future time horizon, robustness of a policy option across an ensemble of scenarios, and a combination of multiple goals into a performance measure. This analysis attempted to connect these three dimensions, by implementing multiple methodological options for each dimension.

Regarding the time dimension, the two main options were a static analysis with predetermined time points, and a dynamic analysis, i.e. repeating the analysis for each point in time. The dynamic solutions have shown that the performance of a policy option varies over time, even if it stays stable for a short period. Therefore, taking a particular point in time into consideration may be misleading, although it provides a more solid opportunity for quantitative comparison of the policy options.

The results have also shown a strong dependence on which robustness metric is used, especially in the case of cap policies. The long term implementation is prevalently preferred in the case of subsidization policies, regardless of the robustness metric. However, this finding is attributed to the longer subsidization, rather than the robustness of this option to robustness metric choice. Without this long-term option, the results for subsidization options also show a variety depending on the robustness metric.

While dealing with multiplicity of the policy goals with an additive method, the uncertainty in prioritization of the outcome indicators has also been taken into account. Regarding that, this chapter included a demonstration of which weight spaces lead to which policy options to be preferred, and identified the outcome indicators with a major conflict. For the cap policies, the security of gas supply and the share of renewables in the energy mix were the two outcome indicators with the most evident conflict and with the highest influence of policy preference. As for the subsidization schemes, such two outcome indicators were found as the market share of renewable gas, and the cost of subsidization to the government.

Besides the abovementioned conclusions, the application of the three dimensional analysis framework on the cap and subsidization policies has enabled identifying two major methodological shortcomings of the framework. Firstly, it has been observed that the policy options differ significantly in terms of the performance on the outcome indicators they directly affect, for instance the subsidization policies on the *Renewable Gas Percentage*, but

106B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

insignificantly in terms of other outcome indicators. Given such little discordance between the policy options in terms of a subset of the outcome indicators, the ranking approach used in this study may be misleading, i.e. it can favor policy options which are not considerably better than the others since it does not take the extent of differences into account.

The second shortcoming was a loss, or indistinctness of information, while attempting to combine the robustness and multi-criteria dimensions of decision making. Information about the relation between a policy option and a particular outcome indicator is valuable for stakeholders involved in a policy discussion. However, the compactness of information obtained from the robustness and multi-criteria metrics prevents reaching an immediate conclusion about the impact of a policy on a particular outcome indicator. The multiplicity of future scenarios, and potential differences between the policy impacts in each of these scenarios, raise a tradeoff between valuing robustness to deal with uncertainty, and valuing clear, non-complex information. Based on this tradeoff, this finding points out future research directions about the value of robustness to stakeholders, and the usability of robustness information in stakeholder dialog.

Following this chapter which focused on the analysis of exchangeable policy options towards a selection, the next chapter presents the application of the three dimensional analysis framework for the comparison of policy options targeting different outcome indicators.

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When elephants fight, it is the grass that suffers.
African proverb

8

COMPARISON OF DIFFERENT POLICES FOR THE DUTCH GAS SECTOR

Chapter 2 listed a number of policies that are to be assessed in this study. These policies were grouped into three, as targeting the natural gas production, natural or renewable gas demand, and renewable gas production. Chapter 7 analyzed the exchangeable options of the cap policy in the first group and the subsidization policy in the third group, based on the framework introduced in Chapter 6. In this chapter, based on this framework again and using the results of Chapter 7, the 8 policies listed in Chapter 2 (9, including the business-as-usual case) are assessed in terms of their effectiveness on the 8 outcome indicators and of dealing with uncertainty. As in Chapter 7, the entire list of model uncertainties and the full range of their possible values are taken into account. This assessment is geared towards a comparison of the policies to each other in order to determine an effective subset, as well as their relative performances.

With this purpose, this chapter is structured as follows: Section 8.1 describes the assumptions made for the implementation of the 8 policies (and the business-as-usual policy) in the system model. Section 8.2 visually compares these policies in terms of the scenario sets generated by the simulation model. Then, in Section 8.3 the framework with multi-criteria, robustness and time dimensions is implemented for a systematic and quantitative analysis of these policies, important findings are highlighted and the results are discussed. Section 8.5 presents the use of a scenario discovery method to find out the reasons for change in the policy preferences over time, and the vulnerabilities of the preferred policies outlined in Section 8.4. Section 8.6 concludes the chapter with a discussion on findings presented in this chapter, and shortcomings observed.

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8.1. POLICY OPTIONS

In this chapter, the effectiveness of 9 different policies including the business-as-usual case will be investigated. In this section, they will be explained in more detail, and the assumptions made about the implementation of these policies will be clarified.

P1 – Groningen Cap

The first policy targeting the natural gas sector is the production cap on the Groningen field, of which several options were investigated in Chapter 7. From the analysis in Chapter 7, a long-term limitation of the Groningen production was concluded as the scheme to represent the cap policy in this chapter. This scheme was specifically represented by a 10-year limit on the total (cumulative of 10 years) production, where this limit is updated in every 10 years until 2050 and set to 50% of the *Developed Reserves* available in the update year.

P2 – High State Profit Share (SPS)

The State Profit Share (SPS) is the tax collected by the government on the producers' profit. Currently, combined with the corporate income tax, SPS amounts to 50% of the total profit of the producers. In other words, producers pay 50% of the profit they obtain for each unit of gas sold to the state. Although it is not on the agenda of the Dutch government currently, we propose a higher SPS, namely 60% instead of 50%, as a policy option which directly targets the *Total State Revenue* outcome indicator and has a potential to affect other outcome indicators, too.

P3 – Permission for Shale Gas Production

The third policy option targeting the natural gas sector is *Permission for Shale Gas Production*. The government announced that the decision on shale gas extraction is going to be made in 2015. This decision is represented by a binary mechanism in the model, where the permission activates the field lifecycle process of shale gas from exploration to extraction, under the market conditions starting from 2015. Without the permission (business-as-usual policy option), shale gas exploration and production is not allowed, hence the contribution of shale gas to the gas supply remains at zero level.

P4 – High Value Added Tax (VAT) for Gas Consumption

Value Added Tax (VAT) is an instrument with which the government can influence the consumer price of gas, and the demand subsequently. Currently, the VAT percentage is 21% for all gas demand sectors except agriculture, which is subject to 6% VAT. Following the Scandinavian countries, increasing the VAT percentage to 25% for all demand sectors is undertaken as a policy alternative to be analyzed in this chapter.

P5 – Low Energy Levy for Renewable Gas Consumption

Another policy option targeting the demand sector by influencing the consumer price of gas is changing the energy levy, also known as Regulatory Energy Tax (REB). Currently, the energy levy varies for each demand sector (depending on the volume consumed), yet it is the same for both natural and renewable gas as shown in Table 8.1. (The values in Table 8.1 include the ODE (opslag duurzame energie) tax, which is the tax added to the energy bill to finance renewable energy.) As a policy option to stimulate renewable gas consumption, P5 is assumed

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to decrease the energy levy values of renewable gas to 25% lower than those of natural gas, as seen in Table 8.1. Table 8.1 also includes the current energy levy values in the columns for the business-as-usual policy (P0).

Table 8.1: Energy Levy values in the cases of policy options P0 and P5, for each demand sector and gas type[12]

	Households		Agriculture		Industry		Transport	
in EUR/m³	*P0*	*P5*	*P0*	*P5*	*P0*	*P5*	*P0*	*P5*
NG	0.1940	0.1940	0.0311	0.0311	0.0168	0.0168	0.1280	0.1280
RG	0.1940	0.1455	0.0311	0.0233	0.0168	0.0126	0.1280	0.0960

P6 – Long-term Biomethane Production Goal

As mentioned in Chapter 2, the government has a goal to reach 3 bcm renewable gas production by 2020, and employs communicative policies, e.g. Energy Agreement for Sustainable Growth (SER), in order to stimulate the industry to use and produce more renewable gas. This renewable gas goal can be extended beyond 2020, meaning that the government employs communicative support options for renewable gas in the long-term, too. Therefore, the policy option P6 is assumed to have a long-term biomethane production goal, where this goal gradually increases to 20 bcm in 2050 from 3 bcm in 2020, with an annual increase rate of 6.5%.

P7 – Renewables Obligation

The second policy targeting the renewable gas production is setting a scheme which obliges utility companies to provide a percentage of their supply from renewable sources as in Germany (Renewable Heat Quota) and in the UK (Renewable Electricity Obligations). To set such an obligatory renewable gas supply, it is assumed that there will be a shift from natural gas demand to renewable gas demand due to this policy, in a way that the renewable gas demand eventually reaches 10% of the total demand. In the model implementation, it is assumed that this policy is imposed gradually over a 10-year period from 2015 to 2025, with an 0.1% natural gas substitution by renewable gas.

P8 – Biomethane Subsidization

The third policy targeting renewable gas supply is the subsidization of biomethane production. Several subsidization schemes were discussed in Chapter 7, and the 'fixed cost percentage model' was concluded as the scheme to represent the subsidization policy in this chapter, and to be compared to other policies.

The fixed cost percentage model sets the price paid to producers equal to a certain multiple of the unit cost, i.e. 112%. The subsidy paid by the government is the difference between this producer price and the market price, and this subsidization model is assumed to be implemented until 2030.

[12] Since the energy levy is consumption dependent, households and agriculture consumers are assumed to be in the 0-170,000 m^3 group, and industry in 1-10 million m^3 group. The energy levy for the transport sector is separately set for Compressed Natural Gas. The complete list of current energy levy and ODE values can be seen in http://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/zakelijk/overige_belastingen/belastingen_op_milieugrondslag/energiebelasting/.

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P0 – Business-as-Usual

The *P0* option, namely the business-as-usual case is where no additional policy is implemented or no policy is changed. With respect to the abovementioned eight policies, *P0* includes

- a 10-year cap on the Groningen field until 2020,
- the tax percentage for SPS equal to 50%,
- no permission to shale gas exploration and production,
- 21% VAT for all demand sectors except agriculture,
- the current energy levy values (*P0*) shown in Table 8.1,
- a 3 bcm goal by 2020 for biomethane production,
- no renewables obligation,
- biomethane subsidization with the spot market gap model until 2050.

Hence, P0 is not only a description of the status quo option, but also a basis to compare and discuss the individual performance of each policy.

Prior to a quantitative analysis in Section 8.3, the next section will visually compare these 9 policies in terms of the ranges and densities of scenarios corresponding to each of these policies.

8.2. VISUAL COMPARISON

In this section, two visual tools are used to compare the policy options to each other in terms of each outcome indicator. The first tool is an envelope containing the scenarios corresponding to each policy, which shows the range between the minimum and maximum value of the scenarios at each point in time. The second tool is Kernel Density Estimates (KDE) of the scenarios at one point in time, e.g. end states. The envelopes can be wide due to a few scenarios, but density plots indicate where the majority of scenarios accumulate, and provide more insight about the impact of a policy. The discussion below on the comparison of policies utilizes both envelope and density plots.

The figures below shows the envelopes and KDE's of 5000 scenarios obtained from 5000 simulations of the model, each with a different combination of the possible values of uncertainties. The model is simulated for the period between 2012 and 2062. For each outcome indicator, KDE's of 2020, 2030, 2050 and 2062 values are plotted below an envelope. In these KDE plots, the density value on the x axis refers to an estimation of the number of scenarios in which the outcome indicator receives the value shown on the y-axis.

Figure 8.1 shows the envelopes and KDE's for *Coverage of Domestic Gas Demand*. Before 2040, *P0* shows the widest range of scenarios, indicating higher demand coverage values. (Note that the values higher than 100% is due to the definition of this variable, which is the ratio of the sum of total domestic production and imports to the domestic demand. This definition is based on the assumptions that all excess natural gas is exported and natural gas is imported only when domestic production cannot meet the demand.) However this is due to a very small number of scenarios as the density plots do not show an evident difference

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between the policies. Only in 2020, low natural gas production causes the cap policy (*P1*) to distinctly have a high density around lower demand coverage values. The almost identical density distributions in the later years are attributed to the balancing mechanism between supply and demand, as well as increasing imports to replace domestic production. Hence, the policy options do not show a prominent impact on the uncertainty ranges of this outcome indicator.

As for the *Total State Revenue from Natural Gas Production*, Figure 8.2 shows that a high SPS (*P2*) results in a wider range of scenarios with more scenarios resulting in high values, compared to other policies in the first half of the simulation horizon. This finding is conceivably ascribed to the direct effect of the SPS policy on state revenues. Besides, in the early decades, the cap policy has the lowest density estimates, indicating low revenues due to low domestic production. In the last two decades of the simulation horizon, the shale gas policy (*P3*) results in a wider range of scenarios with higher state revenue values, and its density estimate is shifted upwards compared to the other policies. This finding implies that shale gas production makes the highest impact on the state revenues in the long term, since conventional natural gas reserves are depleted.

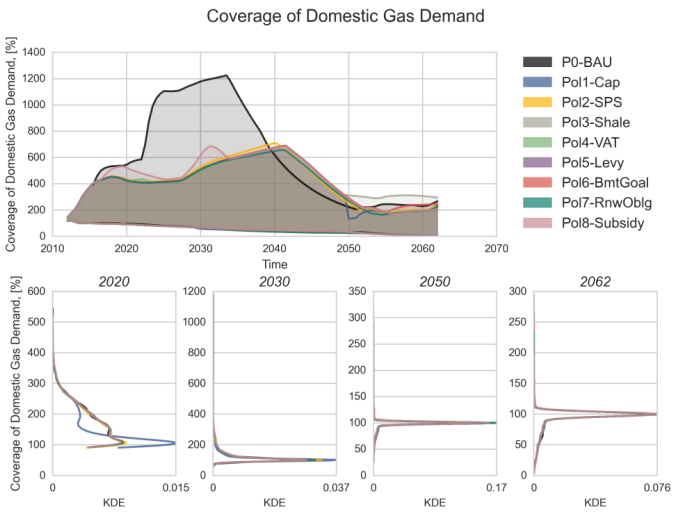


Figure 8.1: Envelopes of *Coverage of Domestic Gas Demand* for each policy and KDE's in 2020, 2030, 2050 and of the end states

According to Figure 8.3, options *P6* (biomethane goal) and *P8* (subsidization) are the most influential policies on the *Renewable Gas Percentage*. Since these two options primarily target the renewable gas production, this result is expected. However, the renewables obligation policy (*P7*) does not demonstrate a similar performance, indicating that increasing the demand for renewable gas does not necessarily stimulate its production. In the short term, the subsidization policy results as a more effective option on the *Renewable Gas Percentage*, since its density estimate tends to accumulate around higher values. However, in the long term, the long-term biomethane goal outperforms the subsidization. This finding can be interpreted as direct intervention in capacity construction based on agreements with the industry being more effective in increasing the share of renewable gas, compared to providing only financial incentives and leaving the capacity construction decision to the producers. Still,

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in the long term the positive impact of *P6* diminishes, too, due to the limited biomass resources. The density estimates of 2050 and 2062 accumulating around very low values indicate this decreasing impact, despite the possibility of very high values.

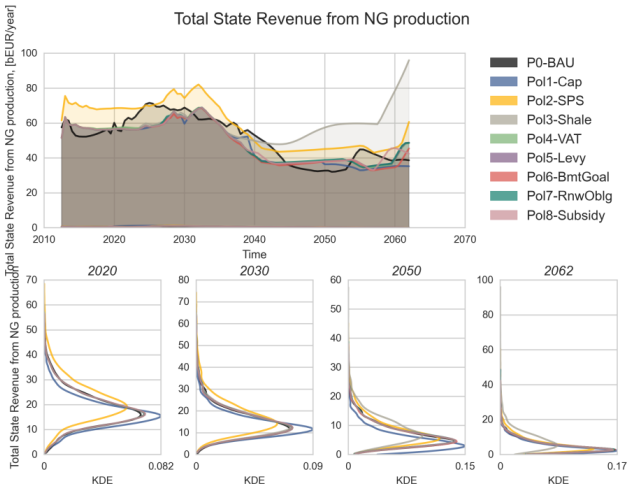


Figure 8.2: Envelopes of *Total State Revenues from Natural Gas Production* for each policy and KDE's in 2020, 2030, 2050 and of the end states

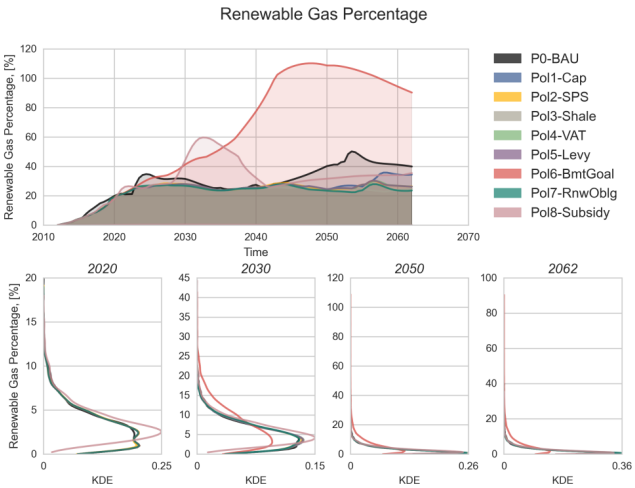


Figure 8.3: Envelopes of *Renewable Gas Percentage* for each policy and KDE's in 2020, 2030, 2050 and of the end states

The *Share of Renewables in the Energy Mix*, i.e. the share of renewable technologies in the total energy mix including both gas and electricity, is another outcome indicator in terms of which the policy options do not show significant differences. In other words, both the envelopes and density estimates of each policy's scenario set are similar to each other, as seen in Figure 8.4. Still, the long-term biomethane goal (*P6*) and the cap policy (*P1*) have slightly upward shifted density distributions, implying a slightly better performance. In the last two decades, although the envelope ranges are still similar to other policies, the shale gas policy (*P3*) results in higher densities of low values, which indicates a negative impact of shale gas production on the deployment of renewable energy technologies.

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The figures for the other 4 outcome indicators, namely *Transport Capacity Utilization Rate*, *Average Consumer Gas Price*, *Societal Acceptance (Groningen)* and *Import Dependency* can be seen in Appendix 8.1. The main conclusion from these four figures is that the policies do not show striking differences in terms of these outcome indicators. An exception to this general conclusion is that consumer prices are slightly higher in the case of *P4 (Higher VAT)*. Furthermore, *Import Dependency* has less favorable density distributions with the cap policy (i.e. higher import dependency) in the long term, whereas the permission to shale gas results in more favorable density distributions of this outcome indicator.

Although they do not result in distinctive figures in terms of the 8 outcome indicators, some policies such as *Policy 4* and *Policy 5* targeting demand, or the cap policy targeting the natural gas production, are expected to show differences from other policies in terms of these model variables that they directly affect. Figures A8.5-7 in Appendix 8.1 show the envelopes and density estimates for these three variables, namely the *Total Natural Gas Production Rate*, *Total Natural Gas Demand* and *Total Renewable Gas Demand*. According to these figures, the cap policy distinctively results in lower production rates in the early decades, whereas the shale gas policy leads to higher production rates in the later decades. However, the scenario ranges and density estimates of the demand variables are very similar to each other. Only the renewables obligation (*P7*) policy yields a distinctive but slightly higher density estimates for the renewable gas demand (lower for the natural gas demand). The VAT and energy levy policies do not show prominent impacts on the demand variables, implying that such price differences are not strongly influential on the demand.

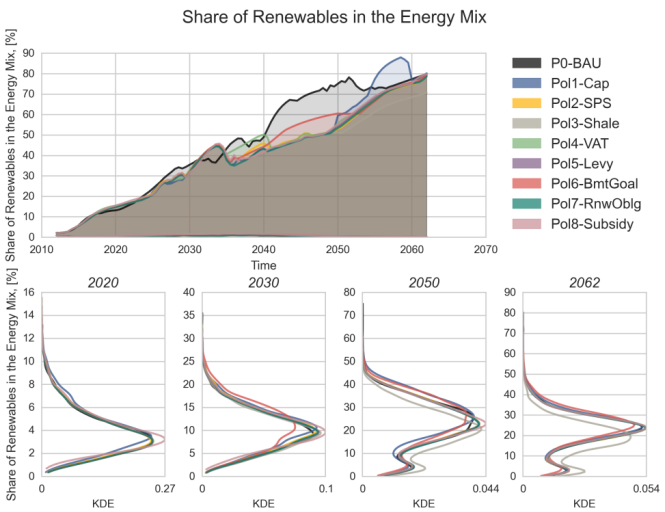


Figure 8.4: Envelopes of *Share of Renewables in the Energy Mix* for each policy and KDE's in 2020, 2030, 2050 and of the end states

From this visual comparison of the policies in terms of the 8 outcome indicators, it can be concluded that a policy influences the range and density of the scenarios significantly only in terms of the outcome indicator it affects directly. In most of the cases, the impact of a policy in the system is lessened by other elements and interactions in the system, leading to very similar envelope and density estimate figures. Hence, it can be said that there is no policy,

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among the options included in this analysis, that performs well in terms of all policy objectives based on a visual comparison. The next section complements this visual comparison with a more thorough analysis based on the framework presented in Chapter 6, to combine the robustness, time, and multi-criteria aspects of the comparison of these policies.

8.3. ANALYZING THE POLICY OPTIONS

In this section, the 9 policies presented in Section 8.1 will be systematically analyzed based on the framework which was presented in Chapter 6, and is composed of 3 dimensions corresponding to 3 aspects of decision making under uncertainty with multiple criteria. Each of these three dimensions, namely the robustness, multi-criteria and time dimensions, has several methodological options, which are included in this framework to investigate the effect of methodological uncertainty on the assessment of policies. Particularly, the time dimension has two options, being static and dynamic solutions. The static solutions include solving the multi-criteria problem with four different time metrics, and the dynamic solutions are based on assessing the policy options (i.e. solving the multi-criteria problem) at each point in time, e.g. in every year during the simulation horizon.

In this chapter, the static option is not included, and only the dynamic solutions are used to assess the policy options. The first reason for this choice is that the purpose of this chapter does not require a single rank-order or selection of a policy option, which is possible with the static option but not with the dynamic option since multiple points in time are considered. The second reason is the similarity in the results (density distributions for each policy) when static metrics such as minimum over time or end states are used. Such values are concluded in Chapter 7 to be more dependent on other factors in the system than they are dependent on policy interventions. Therefore, a comparison based on such time metrics do not clearly differentiate policies from each other, and the dynamic results can be more insightful in these cases. Therefore, the sections below present and explain the results obtained from a dynamic analysis of policies with each multi-criteria method.

8.3.1. Lexicographic Ordering

As discussed in Chapter 6 and 7, the lexicographic ordering method is based on a priority ordering of the policy objectives (assessment criteria). Besides, the decision heuristic was adjusted to select policy options which are ranked high according to this ordering of the criteria and which are not the worst option for any of the first four most important criteria. The ordering of the criteria was as follows, where "a $\succ$ b" implies that the importance of criterion a is higher than that of criterion b.

Share of Renewables in the Energy Mix $\succ$ *Coverage of Domestic Gas Demand* $\succ$ *Import Dependency* $\succ$ *Total State Revenue from NG prod.* $\succ$ *Average Consumer Gas Price* $\succ$ *Renewable Gas Percentage* $\succ$ *Societal Acceptance* $\succ$ *Transport Capacity Utilization Rate*

Figure 8.5 shows the results of the lexicographic ordering method, when the first five robustness metrics (single point metrics) are used. Each subplot of this figure corresponds to a robustness metric, and in each subplot, a policy option is marked with the color corresponding to its rank in the solution set at each point in time. With the *Min* and *Mean/Std. deviation*

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robustness metrics, Policy 8 (subsidization) is the most preferred option until approximately 2050, when Policy 6 (biomethane goal) takes over the first rank. This finding can be interpreted as a high positive impact of the subsidization and biomethane goals policies not only on the worst cases of the share of renewables, but also on the density of moderately desired scenarios for this outcome indicator. The results are similar when *Mean* robustness metric is used, except that after the cease of subsidization in 2030 the cap policy performs better than subsidization.

Considering the regret-based metrics, the results are more time-dependent, as indicated by more frequent shifts in the corresponding subplots of Figure 8.5. The shale gas permission and the biomethane goal policy result as the first and second most preferred option with the *Maximum Regret* robustness metric. However, the maximum regret values of the policies are very similar for the *Share of Renewables in the Power Mix* and *Coverage of Domestic Gas Demand* as shown in Figure A8.11 in Appendix 8.2, meaning that the rank-order in Figure 8.5 is based only on little discordance. The variety over time with the *Regret Thresholds* metric is indeed due to the varying robustness values, implying that the percentage of the most desired scenarios (scenarios in the 5% region of the zero-regret) changes significantly over time. The BAU policy is the most preferred option in the early years based on a slight difference from the others, yet the preference for the biomethane goal policy is based on its significantly higher performance on the *Share of Renewables in the Energy Mix* after 2030. It is important to note that the VAT policy more persistently results as the second most preferred option with this robustness metric.

Figure 8.6 depicts the resulting Pareto sets when the lexicographic ordering method is used with the two dimensional robustness metrics, i.e. the couplings of 'mean' and a dispersion metric. If a policy is the only selected one in the Pareto set, then it is marked in blue; if there is more than one policy in the Pareto set, they are all marked red. A common observation is that the results with these 4 metrics are similar to each other and to those of the *Min, Mean* and *Mean/Std. deviation* metric, in the sense that the subsidization policy (*P8*) is dominant in the first decades, so is the biomethane goal policy (P6) in the last decades. The two skewness metrics, which indicate the density of more desirable scenarios, yield very similar results, having the cap policy as a promising alternative in the mid-decades as in the case of *Mean* metric. As for the couplings of *Mean* with *Interquartile distance(IQR)* and *Kurtosis* which indicate the steepness of density estimates around the mean, *IQR* results as a more restrictive robustness metric since there is less variation in the Pareto set over time and there are time points with a single element in the Pareto set. The *Mean-Kurtosis* metric maintains the subsidization policy in the Pareto set for a longer time, whereas the *Mean-IQR* metric selects the biomethane goal also in the early decades instead of the subsidization policy.

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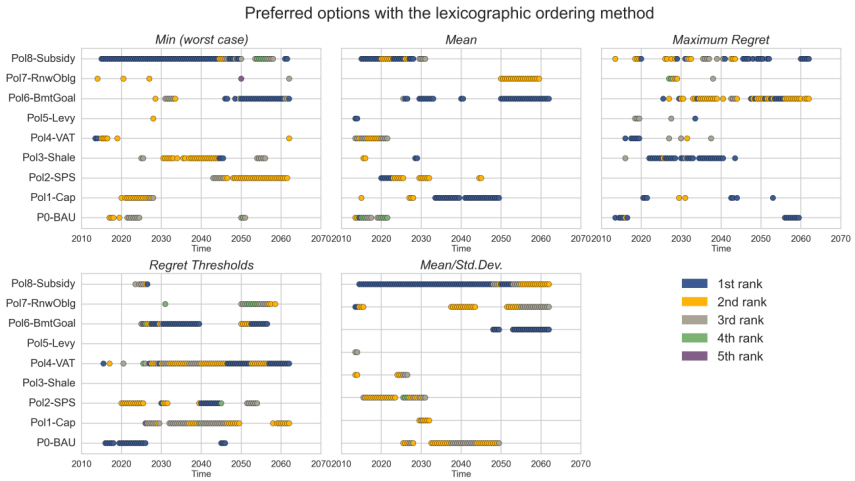


Figure 8.5: Preferred policy options over time, with lexicographic ordering and the first 5 robustness metrics

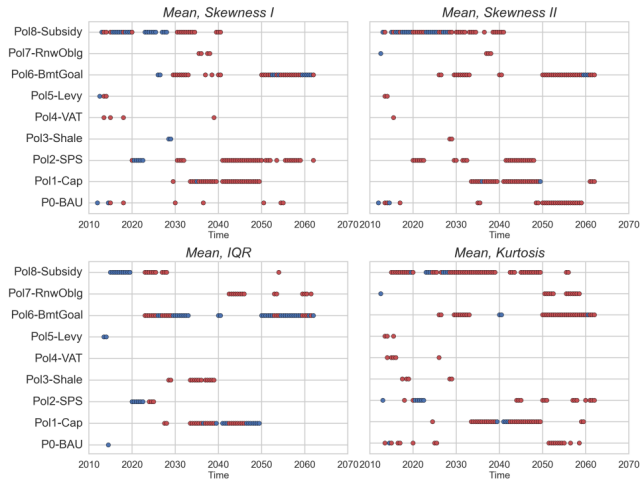


Figure 8.6: Preferred policy options over time, with lexicographic ordering and the two dimensional robustness metrics

Conclusively, the results of the lexicographic ordering method show dependence on time and the robustness metric, meaning that there is no policy option robust against dynamics over time and robustness metric choice. Still, many robustness metrics favor the subsidization policy in the early decades, the cap policy after 2030 and the biomethane goal in the last decade. This finding is because *Share of Renewables in the Power Mix* is the most prioritized outcome indicator in the lexicographic order, hence the policies positively affecting this outcome indicator are favored. The sections below will discuss considering all outcome indicators equally, or with different weightings, rather than strictly prioritizing a few of them.

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8.3.2. Additive Utility Method with Equal Weights

The additive utility method is based on summing the robustness values corresponding to the 8 outcome indicators, to obtain an indicator of the overall performance of a policy on the 8 decision criteria. To implement the equality assumption on the importance of criteria, the robustness values are assigned equal weights in this summation.

Figure 8.7 illustrates the first rank policies over time, when this method is used with the first 5 robustness metrics. Despite some variation over time, three policies are shown to obtain the first rank persistently over time, which are *P0*, *P6* and *P8. Min* and *Mean* robustness metrics favor first the subsidization policy (*P8*), then the biomethane goal (*P6*), with different switch points in time. The results vary more over time with the *Maximum Regret* metric, still the BAU policy (*P0*), subsidization (*P8*) and the biomethane goal (*P6*) are the policies which take the first place at several points in time. With the robustness metric *Regret Thresholds*, the BAU policy (*P0*) is ranked the first during almost the entire simulation horizon, following a preference for the SPS policy (*P2*) in the first decade. Similarly, the *Mean/Standard deviation* metric favors the subsidization policy (*P8*) for almost the entire simulation horizon, except the last few years.

These results can be traced back to the additive robustness values for each metric, which are shown in Figure A8.8 in Appendix 8.2 and reveal the relative performance of the policy options. For instance, the subsidization policy (*P8*) has a considerably higher additive robustness value than other policies with the *Min* robustness metric, according to which it is the best option for a long duration. Similarly, the BAU policy (*P0*) result in a distinctively high additive value with the robustness metric *Regret Thresholds.* However, for other robustness metrics, there are no wide differences observed between the first-rank policy and other policies for long durations of time. Another noteworthy result seen in Figure A8.8 is that the BAU policy which results as the first-rank option with *Regret Thresholds* is mostly the last-rank with *Maximum Regret* and *Mean/Standard deviation* metrics.

Furthermore, Figures A8.9-12 in Appendix 8.2 show how the robustness value of each outcome indicator changes over time, for each robustness metric. In other words, these figures depict the comparison of policies in terms of each outcome indicator separately, and help to understand why a policy receives a high rank than the others as a result of the additive robustness approach. Figure 8.8 exemplifies this for the robustness metric *Mean/Standard deviation*, which result in the subsidization policy as the first-rank option for a long duration, and in the renewables obligation policy in the last few years. As seen in Figure 8.8, the subsidization policy has a distinctively higher robustness value in terms of the *Renewable Gas Percentage* and *Share of Renewables in the Energy Mix* for a long period, despite its similar performance to other policies on other outcome indicators. The switch to the renewables obligation policy at the end of the simulation horizon is attributed to higher performance of this policy (*P7*) on *Import Dependency*, and an average performance on all other outcome indicators.

When the two-dimensional robustness metrics (i.e. the couplings of mean value and a dispersion metric) are used, the resulting Pareto sets at each point in time are obtained as in

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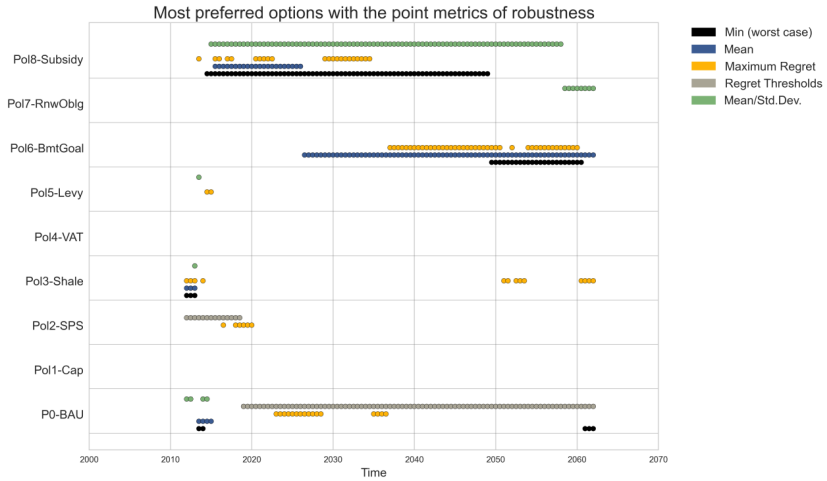


Figure 8.7: Preferred policy options over time, with the additive utility method (equal weights) and the first 5 robustness metrics

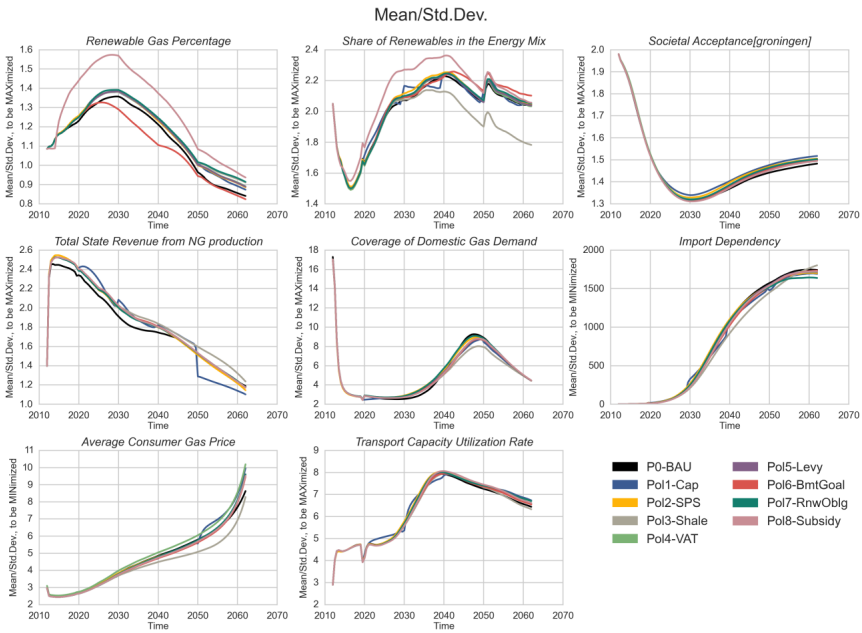


Figure 8.8: Robustness values over time for each outcome indicator, with the metric *Mean/Standard deviation*

Figure 8.9. The results are not highly dependent on the robustness metric, since the Pareto sets of each metric contain mostly the same policies. Despite a few occurrences of *P4*, *P5* and *P7* in the Pareto set with a few robustness metrics, these policies do not result as promising options. *P0* and *P2* are included in the Pareto sets for longer durations with all metrics, yet not as persistently as the other four policies. That is, the cap policy (*P1*), the shale gas policy (*P3*), the biomethane goal (*P6*) and the subsidization policy (*P8*) result as more promising

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options with these 4 metrics focusing on desirable scenario distributions, and with the additive approach treating all criteria equally.

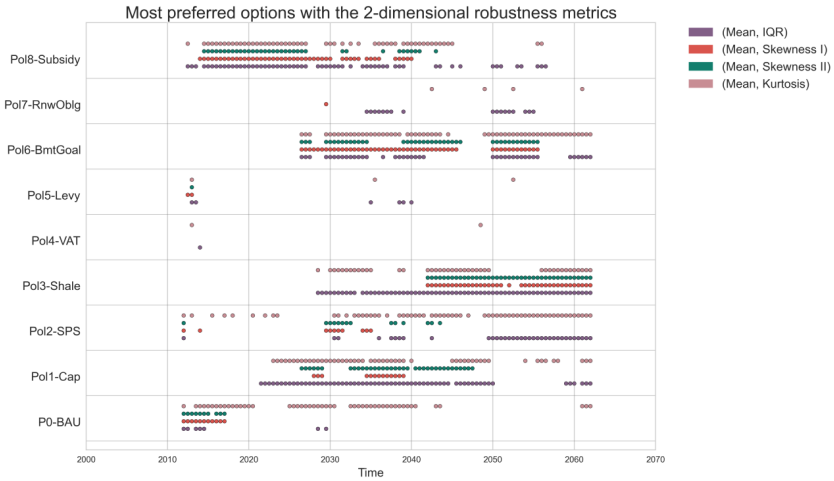


Figure 8.9: Preferred policy options over time, with the additive utility method (equal weights) and the 2-dimensional robustness metrics

8.3.3. Additive Utility Method with Uncertain Weights

Besides the equality assumption about the importance of outcome indicators, the additive approach is also used in the case of uncertain weighting of the criteria. Following the procedure described in Chapter 6 and exemplified in Chapter 7, 1000 different weight sets are assigned to the outcome indicators, and 1000 multi-criteria problems are solved at each point in time, for each robustness metric.

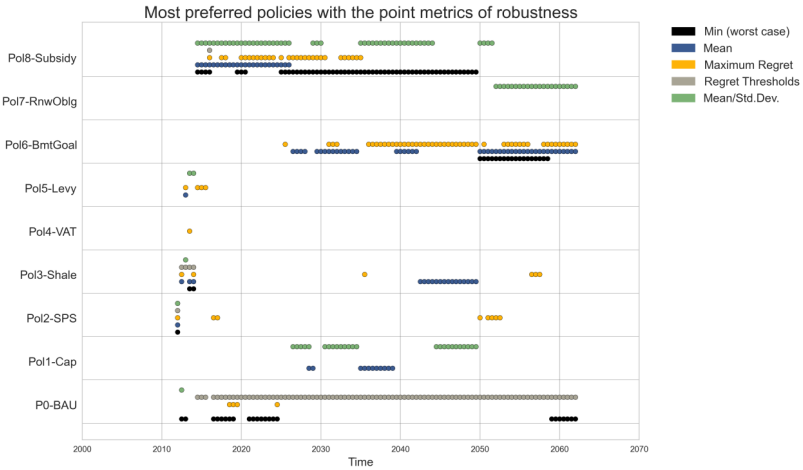


Figure 8.10: Preferred policy options over time, with the additive utility method (uncertain weights) and the first 5 robustness metrics

Figure 8.10 shows the policies which receive the highest mean-rank among these 1000 solutions over time, for the first 5 robustness metrics. These results are similar to the results of

114A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

equal weighting, yet some differences are observed. For instance, the *Min* robustness metric yields the BAU policy as the highest mean-rank option before and after 2020, instead of the subsidization policy. Similarly, although the biomethane goal is the selected policy for a long period of time with the *Mean* metric in the case of equal weighting, the cap policy and the shale gas policy outperforms the biomethane goal for short durations in the same period, in the case of uncertain weighting. Despite such variations, the results still favor the BAU policy, subsidization and the biomethane goal as the promising policies.

When the two dimensional robustness metrics are used, the results are more similar to those of equal weighting, since the Pareto sets shown in Figure 8.11 demonstrate differences only occasionally. In short, the BAU, cap and subsidization policy are favored in the early and mid-decades, whereas the shale gas permission and the biomethane goal are dominantly in the Pareto sets in the last decades, when these robustness metrics focusing on the distribution of scenarios are used.

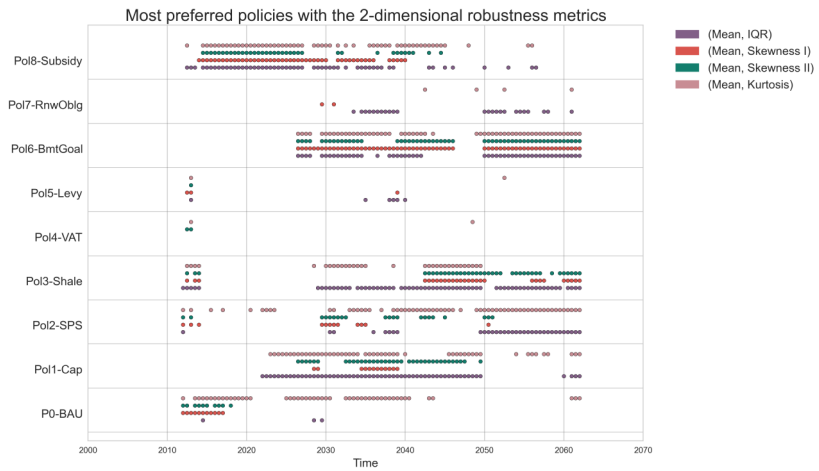


Figure 8.11: Preferred policy options over time, with the additive utility method (uncertain weights) and the 2-dimensional robustness metrics

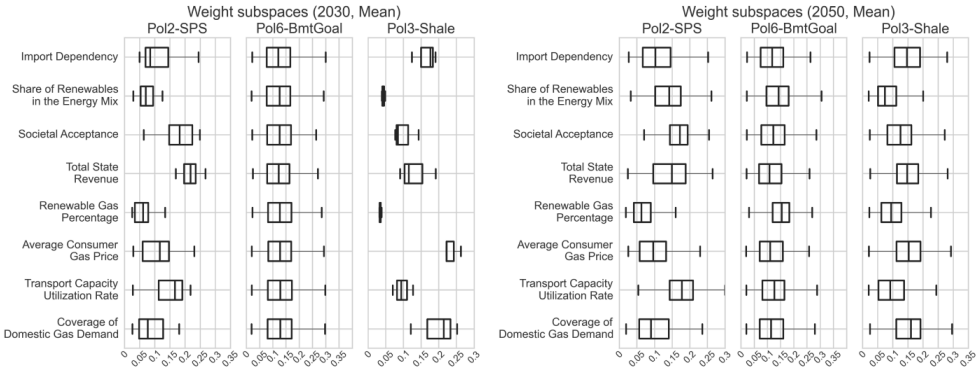
The effect of weighting on the first-rank policy

The figures above showed the policy options that receive the highest mean-rank, but they did not provide any insight about how the first-rank policy changes according to the weights. The figures below address this issue, by showing the weight subspaces which enable a policy to outperform the others. For such an analysis of the relation between weights and first-rank policies, four points in time are selected, namely 2020, 2030, 2050 and 2062, instead of repeating this analysis for each year in the simulation horizon, which would have yielded a vast number of, hence not easily comprehensible, results.

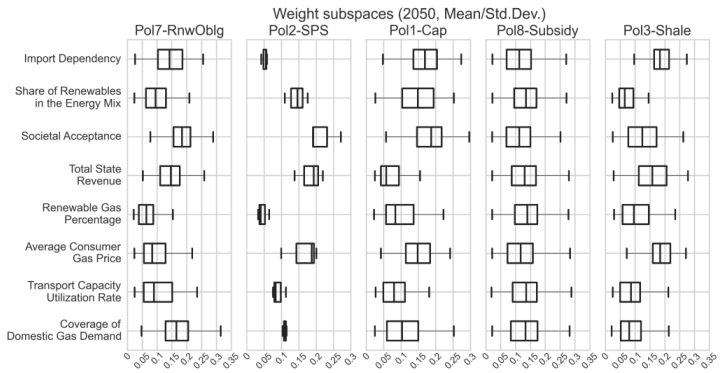
Figure 8.12a-c demonstrate three selected weight subspaces, corresponding to *Mean* (in 2030 and 2050) and *Mean/Std. deviation* metrics (in 2050). In each of these figures, the policy with the highest mean-rank (see Figure 8.10) has a wide set of average weights, for each outcome indicator. However, different policies receive the first rank when weight spaces for particular outcome indicators move towards lower or upper ends. For instance, in 2030 with the *Mean*,

114B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the SPS policy outperforms the biomethane goal policy when the importance of *Share of Renewables* and *Renewable Gas Percentage* is low, and that of *Societal Acceptance* and *Total State Revenue* is high. As for the shale gas policy, it receives the first rank in smaller region of the weight space, namely when the importance of *Share of Renewables* and *Renewable Gas Percentage* is very low, and the importance of consumer price and demand coverage is relatively high. The results are different in 2050, in the sense that the weight subspaces of the subsidization policy and the shale gas policy are not as small as those in 2030. This increased indifference to weights is due to the decreased impact of the biomethane goal policy in 2050, due to decreasing biomass availability. In other words, in 2030, the impact of biomethane goal on the *Share of Renewables* and *Renewable Gas Percentage* is high, and only when the importance of these outcome indicators is low, and the importance of state revenues (SPS) and consumer price (shale) is high, can the SPS and shale gas policies outperform the biomethane goal. In 2050, the impact of biomethane goal is lower, which does not necessitate such a distinct prioritization of the outcome indicators for the biomethane goal to be outperformed. Figure 8.12c shows similar results even if a different metric (*Mean/Std. deviation*) is used: The SPS and shale gas policies require very low importance paid to the two outcome indicators related to renewable energy in order to outperform the subsidization policy, which is the first mean-rank option.



(a) In 2030, with the robustness metric *Mean* **(b) In 2050, with the robustness metric *Mean***



(c) In 2050, with the robustness metric *Mean/Std.deviation*

Figure 8.12: Examples of weight subspaces leading to the most preferred policy options

115A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Such weight subspaces leading to the first-rank policies for other robustness metrics and time points can be seen in Appendix 8.3. Some of these figures show common relations between the weights of particular outcome indicators and policies regardless of the robustness metric and time as in the above example about the SPS and shale gas policy, and the renewable energy indicators. However, some results show dependence on the metric selection, and prevent a general conclusion about the relation between a policy's performance and weight subspaces of a particular outcome indicator. For instance, the shale gas policy receives the first rank in 2062 with the *Maximum Regret* metric when the weights of *Renewable Gas Percentage* and *Average Consumer Gas Price* are low, whereas in the case of the *Mean/Std.deviation* metric, these two outcome indicators require very high importance for the shale gas policy. (The shale gas policy receiving the first rank when the importance of *Renewable Gas Percentage* is high is due to the low standard deviation.) Therefore, as already concluded in Chapter 7, one cannot strongly argue that a policy is good for a particular set of policy objectives, since the results depend on the robustness metric used to assess these policies.

8.3.4. Pareto Set

Finding the Pareto set, i.e. the non-dominated solutions among the policy options, is a basic method that does not consider any inter-criteria relations and treats all criteria equally. Figure 8.13 shows the Pareto set at each point in time, and for each robustness metric. The first observation from these figures is that with all metrics and for long durations, the Pareto sets include all policy options, meaning that there is no policy option which is worse than any other policy option in terms of all criteria. Still, in the first decade, the cap policy (*P1*) and the biomethane goal (*P6*) are dominated policies with all robustness metrics. In the mid-decades, *Mean/Std. deviation* metric results in the BAU policy (*P0*) being removed from the Pareto set, whereas the SPS policy (*P2*) is dominated when *Maximum Regret* is used.

As in Chapter 7, the Pareto solutions are not very insightful about which options perform better since they include either a large set or all of the policies. However, they clarify that if a decision is to be made for short-term performance, the biomethane goal and the cap policy appear as not viable options, despite their potential advantages in the long-term.

8.1.1. Discussion on the Preferred Policies

This section presented the results of evaluating the 9 policies in terms of time, robustness and multi-criteria performance with different methods and metrics. The results showed variations with respect to the options on these dimensions, but also many important commonalities, implying that some policies are noted for their considerable methodological robustness. Namely, the subsidization and the biomethane goal policy received the first rank, or included in the Pareto set, in a large number of robustness metric and multi-criteria method combinations for long durations of time. The cap, BAU and shale gas policies are also found to be the following promising options based on this framework.

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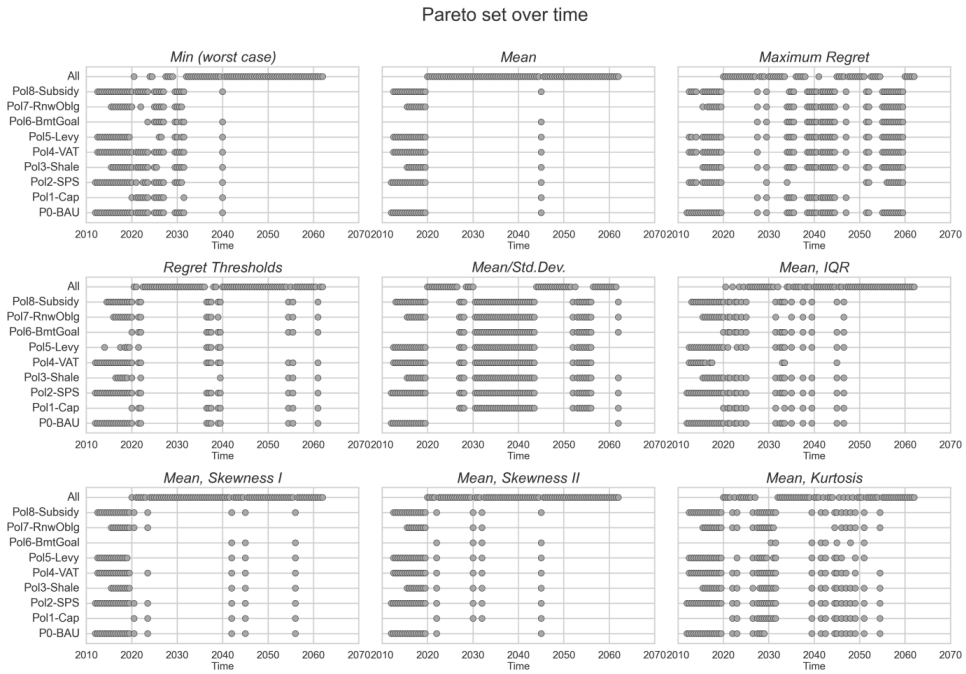


Figure 8.13: Policy options in the Pareto set over time and for each robustness metric

In terms of the robustness metrics, the expectation-based and statistical metrics usually generated similar results, even though the timing of switches between the first-rank policies varies. However, the regret-based metrics show differences from the expectation-based and statistical metrics. For instance, the *Regret Thresholds* metric favors the BAU policy both with the additive and lexicographic methods, although it is not favored by other metrics considerably. Similarly, the *Maximum Regret* metric favors the shale gas and the VAT policy with the lexicographic ordering approach, or shows more variety over time with the additive approach. These differences of the regret-based metrics can stem from their evaluation of the policies in each scenario first, and then generalizing this evaluation for the entire set of scenarios, rather than basing the decision on some characteristics of the entire scenario set, such as the mean value or dispersion, in one step.

In terms of the time dimension, the most preferred policies changes over time for most of the metrics, yet such switches occur at different time points and with different frequencies depending on the robustness metric and multi-criteria method. Still, three periods of time are identified, between which the results persistently shift with many metrics. These are the period before 2020, the period between 2020 and 2050, and the period after 2050 until the end of the simulation horizon. In the first period before 2020, the subsidization policy (*P8*) and the BAU policy (*P0*) outperform the others with many robustness metrics. In the mid-decades, namely between 2020 and 2050, the biomethane goal policy (*P6*) takes over the dominant position of the subsidization policy. These two policies are followed by the cap policy (*P1*), the shale gas policy (*P3*) and the BAU policy (*P0*). It is important to note that the BAU and the SPS (*P2*) policies are dominated solutions, hence not in the Pareto sets in this period, with

116A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

the *Mean/Std.deviation* and *Maximum Regret* metrics, respectively. In the last period, the biomethane goal policy is still the dominant option, while the shale gas policy arises as a prevalent first-rank policy even before subsidization. Table 8.2 summarizes these overall findings, in which the policies receiving the first rank with the most methods are colored darkest.

Table 8.2: Summary of the results in terms of the most preferred policies

Before 2020	*2020 - 2050*	*2050 - …*
P8-Subsidization	P6-Biomethane Goal	P6-Biomethane Goal
P0-BAU	P8-Subsidization	P3-Shale
	P1-Groningen Cap	P8-Subsidization
	P3-Shale	P2-SPS
	P0-BAU	P0-BAU

8.2. SCENARIO DISCOVERY FOR ANALYZING THE POLICY PREFERENCE CHANGES AND VULNERABILITIES

Scenario discovery is a novel approach used for characterizing uncertainties associated with certain sets of output conditions generated by simulation models. Technically speaking, for a scenario discovery study, first simulation models are used to generate large sets of scenarios in the form of large data sets, then statistical data-mining algorithms are applied to these data sets to identify uncertainties (i.e. input conditions) that are associated with predetermined output conditions such as the failure of a policy (Groves and Lempert 2007, Bryant and Lempert 2010). Scenario discovery has been used in several domains such as water resource management (Groves and Lempert 2007), material scarcity (Kwakkel, Auping, and Pruyt 2013) and energy policy (Gerst, Wang, and Borsuk 2013, Bryant and Lempert 2010, Hamarat, Kwakkel, and Pruyt 2013, Eker and van Daalen 2015), parallel to several methodological improvements such as combining scenario discovery with time series clustering (Kwakkel, Auping, and Pruyt 2013), or improving the search algorithm used (Dalal et al. 2013, Kwakkel, Cunningham, and Pruyt 2014). Besides, Parker et al. (2015) evaluates the use of scenario discovery in decision making by consulting stakeholders, and concludes that this quantitative approach is superior to qualitative scenario development approaches in several aspects such as being less ambiguous and less subjective but more informative, despite the need for improving the narrative quality of quantitatively-derived scenarios.

The current main statistical algorithm used in scenario discovery studies is the Patient Rule Induction Method (PRIM) (Friedman and Fisher 1999). PRIM is a hill-climbing algorithm that divides the output data into boxes (groups of cases) and finds the boxes with maximum percentage of the cases that meet the predetermined classification condition. The resulting uncertainty subspace corresponding to these boxes informs the user about which uncertainties are influential in reaching the predetermined condition, e.g. the success or failure of a policy. In the analysis below, we use an implementation of PRIM algorithm in Python developed by Jan Kwakkel as described in (Kwakkel, Auping, and Pruyt 2013).

In this section, we use the scenario discovery approach to answer a number of questions arising from the analysis of policies in Section 8.3. These questions point out why the preferred policy changes at a particular point in time, or address the vulnerabilities of a preferred policy, e.g. under what conditions a policy shows poor performance although it is

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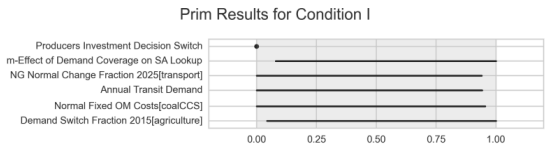
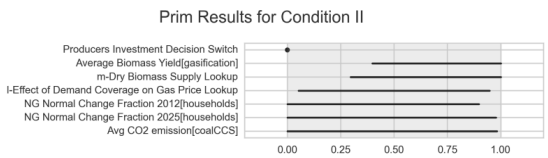
chosen as a good policy. The sections below will discuss such questions and the scenario discovery results that help to answer them.

Why switching from *P8* to *P6* in 2026, when the *Mean* metric and additive approach is used?

As discussed before and seen in Figure 8.7, the subsidization policy (*P8*) is the most preferred policy in the first two decades when the *Mean* robustness metric is used with the additive utility method. However, the biomethane goal policy (*P6*) replaces *P8* in 2026 and remains as the first-rank policy until the end of the simulation horizon. Figure A8.10 in Appendix 8.2 provides more information about this switch to *P6* in 2026. The mean value of *Renewable Gas Percentage* and *Share of Renewables in the Energy Mix* across the scenario space in the case of *P6* exceeds the mean value in the case of *P8* in that year, while the results of these two policies on other outcome indicators are very similar to other policies. Therefore, the reason of switch is ascribed to this superior mean-value performance of *P6* compared to *P8* on *Renewable Gas Percentage* and *Share of Renewables*.

To further investigate the reason of these higher mean values, the PRIM algorithm is used to find the scenarios in which *P6* has a higher performance than *P8*, or an increasing performance, and the characteristics of these scenarios in terms of the most influential uncertainties. Two output conditions are defined for scenario discovery, which specify higher performance of *P6* than *P8* on the two outcome indicators in 2026 (Condition I), and its increasing performance around 2026 (Condition II). Table 8.3 shows how these conditions are denoted and how many scenarios of interest meeting these conditions are found in a total of 5000 scenarios. The last column illustrates the results obtained from the execution of PRIM algorithm for each of these conditions. These results are in the form of subsets of normalized uncertainty ranges of parameter uncertainties, and subsets of discrete options for categorical uncertainties. In other words, the grey shaded are in this figures correspond to the entire uncertainty range of an uncertain parameter, whereas a black line shows which portion of this uncertainty range is included in the cases that lead to the scenarios of interest.

Table 8.3: PRIM Conditions and Results for Switch to *P6* from *P8* with *Mean*

	Scenario Classification Condition	*Scenarios of interest*	*Results*
Condition I	$O_{RGP,P6}(2026) > O_{RGP,P8}(2026)$ *and* $O_{SR,P6}(2026) > O_{SR,P8}(2026)$	2675/ 5000	
Condition II	$O_{RGP,P6}(2027) - O_{RGP,P6}(2025) > \mu_{RGP}^{2027} - \mu_{RGP}^{2025}$	1839/ 5000	

The scenarios that meet Condition I, i.e. where the impact pf *P6* on both *Renewable Gas Percentage* (RGP) and *Share of Renewables* (SR) higher than the impact of *P8*, are

117A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

distinguished from other scenarios only by the categorical uncertainty *Producers Investment Decision Switch* (*PIDS*), since other uncertainties are not represented by a small portion of their ranges in the scenarios of interest. The simulation model includes two alternative structures to formulate how renewable gas producers make their capacity installation decisions based on profitability. The first alternative (*PIDS*=0) is the option where producers are assumed to base their decisions on the Net Present Value (NPV) of next 12 years' expected income (including subsidy), whereas the second alternative (*PIDS*=1) assumes that this decision is made based on the current profitability of biomethane production, i.e. the current ratio of market price (including subsidy) to the unit cost. This result can be interpreted as follows: If producers make their decisions based on a short-term view, initially high subsidy values (the 'fixed cost percentage model' reduces the subsidy as the cost declines) stimulate capacity installation, hence the renewable gas share. In that case, subsidization is a better policy than the biomethane goal. However, if producers have a longer term view with an NPV approach, they estimate a declining income, and capacity installation is not as high as in the previous case. In that case, the subsidization policy (*P8*) is not as effective as before, and the biomethane goal policy (*P6*) outperforms it, as in the classification condition of this scenario discovery.

The second condition focuses on the increasing mean-value of *Renewable Gas Percentage* only in the case of *P6*. The scenarios of interest are specified as those in which the 2-year increase from 2025 to 2027 is higher than the increase in the mean-value in these years. The results indicate that the factors leading to a high increase in the *Renewable Gas Percentage* in the case of a long-term biomethane goal are (i) an NPV-based decision mechanism of renewable gas producers (*Producers Investment Decision Switch=0*), (ii) high efficiency of biogas production via the gasification technology (Average Biomass Yield[gasification]) and (iii) high availability of dry biomass, which is the biomass type used in gasification (*m*-Dry Biomass Supply Lookup). Therefore, biomass availability and the efficiency of gasification technology are shown to be important factors increasing the share of renewable gas in the gas consumption, in addition to a long-term view of producers in capacity installation.

Why switching from *P8* to *P6* in 2049, when the *Min* metric and additive approach is used?

Similar to the case of the robustness metric *Mean*, the most preferred policy changes from *P8* to *P6* also in the case of the metric *Min*, but in 2049. According to Figure A8.9 in Appendix 8.2, in that year the minimum value of *Renewable Gas Percentage* (also *Share of Renewables*) obtained with *P6* exceeds the minimum value obtained with *P8*. Namely, the worst case of *Renewable Gas Percentage (RGP)* with *P8* declines over time, and drops below that of *P6* in 2049. To investigate the reason of this switch in the minimum values, we look at these worst case scenarios individually, rather than using the PRIM algorithm. An analysis of the output data reveals that in the period right before 2049, the worst case scenario with *P6* is Scenario A (blue lines in Figure 8.14), the worst case scenario with *P8* is Scenario B (purple line in Figure 8.14). *P6* has a higher worst case value with Scenario A in 2049 (blue line), and then with Scenario B (green line), ranking it as the most preferred policy with this robustness metric. Therefore, the decline of *RGP* with both policies in Scenario B, but slightly higher values in the case of *P6* are seen as the reason of shift in the most preferred policy. The

117B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

factors that make *RGP* values higher with *P6* than with *P8* in Scenario B are a higher *Total Biomethane Production Rate* and a lower *Domestic Gas Consumption*, as seen in plots a and b of Figure A8.13 in Appendix 8.4. High production rates are attributed to a high biogas allocated for upgrading to biomethane (Figure A8.13-c), due to a high biomethane producer price (Figure A8.13-e). As for high producer prices of biomethane, it is due to continuation of subsidization until 2050 in the case of *P6* as in *P0*. *Domestic Gas Consumption* is lower with *P6*, mainly because the renewable gas demand is lower than the case of *P8* (Figure A8.13-d), which is due to higher market prices for biomethane (Figure A8.13-f).

Which factors cause the *Renewable Gas Percentage* to be low in 2062 in the case of *P6*?

The biomethane goal policy (*P6*) resulted as an effective policy with many robustness and multi-criteria methods in the mid- and last decades. Still, as Figure 8.3 shows, a large number of scenarios tend to result in low *Renewable Gas Percentage* values at the end of the simulation horizon, implying that this policy is still vulnerable to some factors despite its relatively high performance. By using the scenario discovery algorithm PRIM, we investigate what these factors are, i.e. the vulnerabilities of *P6*. To classify the scenario space, we set the condition (Condition *P6* in Table 8.4) for undesired scenarios as *RGP* being less than 3% (in the case of *P6*) in 2062. The uncertainties which take only a subspace of their possible values in these scenarios are shown in Table 8.4, too.

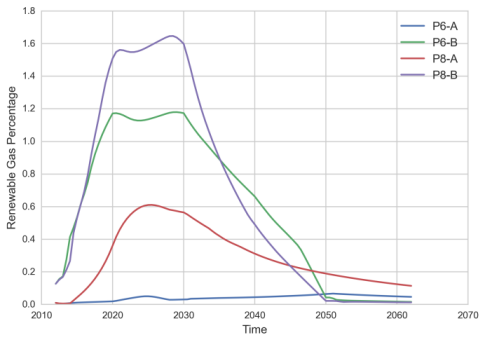


Figure 8.14: Worst Case Scenarios (*Min*) with *P6* and *P8*

According to these results, the biomethane goal policy is most vulnerable to low availability of wet biomass (for digestion) and producers' investment decision on biomethane production capacity based on short-term profitability (*PIDS=1*). *Wet Biomass Supply* is expected to stagnate in future, hence its low values significantly affect the biogas production, biomethane production, and hence *Renewable Gas Percentage* in a negative manner. As for the finding about *Producers Investment Decision Switch*, it supports the finding about this model structure assumption regarding the superior performance of *P6* over *P8* in 2026 (see the first question above). As an NPV-based decision of producers with a long-term view (*PIDS*=0) was argued to reduce the effectiveness of subsidization and make *P6* a better policy, a short term view of producers (*PIDS*=1) does not take increasing prices into account, hence estimates profitability less than it would be with the NPV approach, and leads to scenarios in which *RGP* is low even with *P6*.

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Table 8.4: PRIM Conditions and Results for the Vulnerabilities of *P6* and *P8*

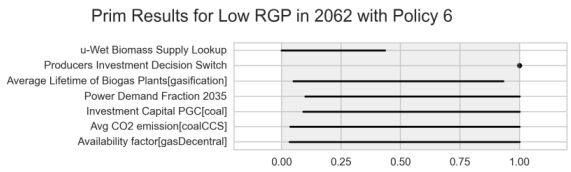
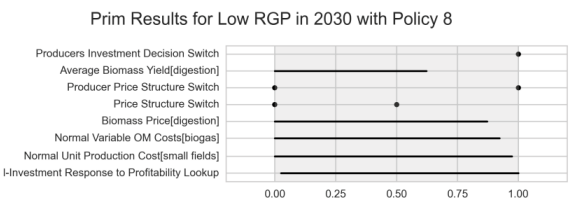
	Scenario Classification Condition	*Scenarios of interest*	*Results*
Condition *P6*	$O_{RGP,P6}(2062) < 3\%$	2496/ 5000	
Condition *P8*	$O_{RGP,P8}(2030) < 3\%$	891/ 5000	

Figure 8.15 shows *Renewable Gas Percentage* dynamics in the (undesired) scenarios of *P6* corresponding to the PRIM results for wet biomass supply and the investment decision mechanism of biomethane producers. This figure confirms that a low amount of wet biomass and a short-term profitability view of producers in investment making result in much lower values of *RGP* not only in terms of the dynamic values but also in terms of the end state densities.

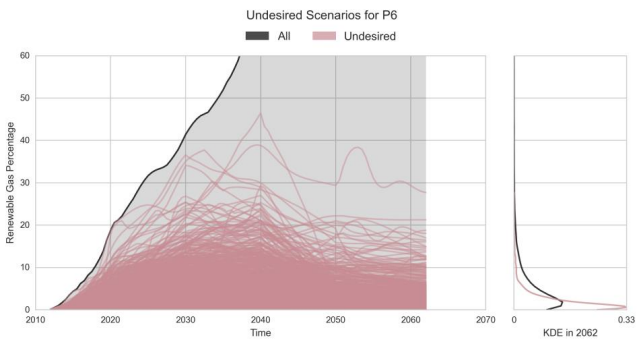


Figure 8.15: *Renewable Gas Percentage* undesired scenarios with Policy 6 according to PRIM results

Which factors cause the *Renewable Gas Percentage* to be low in 2030 in the case of *P8*?

Similar to *P6*, the subsidization policy (*P8*) resulted as an effective policy with many methodological options in the early and mid-decades, and it still results in low values of RGP as Figure 8.3 shows. Therefore, we investigate the vulnerabilities of *P8* as well, namely the uncertainties that are influential in obtaining scenarios in which *RGP* is lower than 3% in 2030. The second row of Table 8.4 specifies this scenario discovery condition and shows the resulting uncertainties.

Average Biomass Yield of digestion, namely the average biogas produced from one unit of biomass via digestion, results as the most influential parameter uncertainty. Following this, it

118B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

can be said that in the early years when biomass scarcity is not high and digestion is the dominant technology, low efficiency of digestion is one of the main barriers to a high share of renewable gas in the total consumption.

Three categorical uncertainties referring to structural uncertainties in the model result as the other most influential uncertainties in the undesired scenarios of *P8*. A short-term view of biomethane producers (*PIDS=1*) is a major barrier for *P8* as in the case of *P6* discussed above. *Producer Price Structure Switch (PPSS)* determines the model structure representing how gas producers, both natural and renewable, respond to price changes for future desired producer prices. The first option (*PPSS*=0) assumes that producers do not change their desired profit markup according to the market price changes, the second option (*PPSS*=0.5) assumes that producers are greedy to obtain more profit as the market price increases, and the last option (*PPSS*=1) assumes that producers are careful and reduce their desired profit markup as the market price declines. According to the PRIM results, the first and last option which do not impose an increase in the desired markup and which do not lead to further price increase are seen as barriers to high renewable gas share in the gas market. Since this uncertainty affects the price of both natural and renewable gas, this finding stresses the importance of high market prices of both natural and renewable gas in stimulating renewable gas production. Besides, high prices lead to low total consumption of gas, which further increases the percentage of renewable gas in the total consumption.

Lastly, the first two of the three options of *Price Structure Switch (PSS)* are shown to results in undesirably low *RGP* values in 2030 with *P8. PSS* is the parameter that determines which alternative price setting mechanism explained in Chapter 4 is used in the model. The first two options determine market prices according to the desired price of producers, whereas the last one does so according to an accepted margin by traders, who reduce the profit margin of producers as the price increases. When producers do not respond with an increasing desired price to increasing market prices (*PPSS*=0 or 1), the first two mechanisms (*PSS*=0 or 0.5) result in low market prices, which result in low production of biomethane and high consumption, leading to low *RGP* values.

Figure 8.16 shows such undesired scenarios of *P8* in which these four uncertainties take the values found by the PRIM algorithm. Although these scenarios also demonstrate an increasing *RGP* and reach relatively high values (e.g. more than 20%), the density of very low values in these scenarios is much higher than that in the entire set of *P8* scenarios. Furthermore, the three of these four uncertainties, namely the major vulnerabilities of the subsidization policy are related to how producers and traders behave in the market, or how the market price is determined. This finding imply that, being a financial incentive, the impact of subsidization is highly dependent on the market dynamics, which are deeply uncertain.

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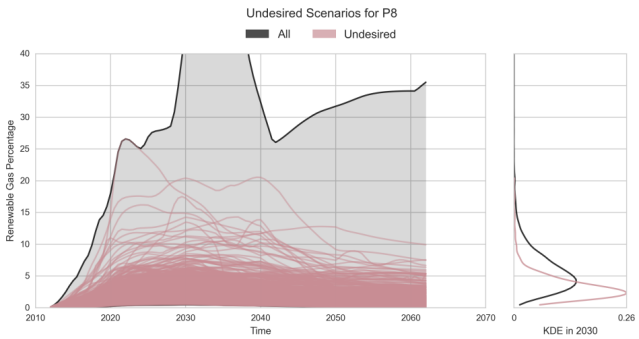
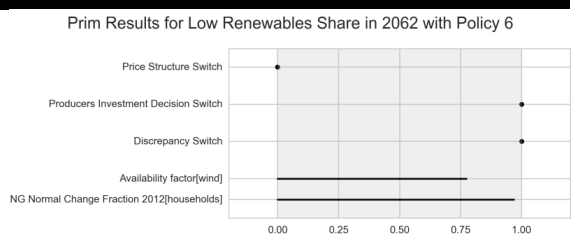
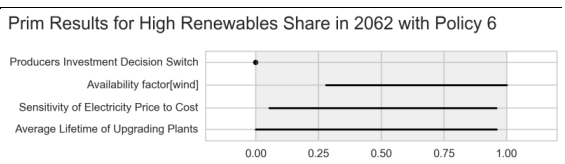


Figure 8.16: *Renewable Gas Percentage* in the undesired scenarios with Policy 8 according to PRIM results

What causes the *Share of Renewables* to accumulate around either high or low values?

An interesting observation from the scenario results of *Share of Renewables in the Energy Mix* seen in Figure 8.4 is that after 2050, the scenarios tend to be divided into two groups indicated by double-peaked density estimates, such as the ones having values lower than ~10% and higher than ~10%. The reason of this split is also investigated by using the scenario discovery approach, with the output conditions shown in Table 8.5, which separate the scenario space into two at 11% share of renewables. Table 8.5 shows the classification setting and the results only for the biomethane goal policy (*P6*) and the year 2062, but the scenario discovery experiments are repeated for *P1* and *P8*, and for the year 2050. The results of these experiments can be seen Appendix 8.4, and they are similar to those obtained for *P6* in 2062.

Table 8.5: PRIM Conditions and Results for the Two Groups of *Share of Renewables in the Energy Mix*

Scenario Classification Condition		*Scenarios of interest*	*Results*
Low Peak	$O_{SR,P6}(2062) < 11\%$	771/ 5000	
High Peak	$O_{SR,P6}(2062) > 11\%$	4228/ 5000	

According to the results shown in Table 8.5, model structure uncertainties regarding the price and decision making mechanisms of electricity and renewable gas producers are the key uncertainties leading to the first group scenarios which result in low values of *Share of Renewables*. In other words, when the market price of gas and electricity is determined according to the desired price of producers and expected price of traders (*PSS*=0), renewable gas producers have a short-term view on the profitability of capacity installation (*PIDS*=1), and electricity producers make further capacity installation decisions based on the discrepancy

119B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

between the expected future demand and current production rates rather than the current installed capacity (*Discrepancy Switch*=1), then the *Share of Renewables in the Energy Mix* results in low values. The double peaks, e.g. the two groups of scenarios, are attributed to the discrete nature of model structure uncertainties. Besides, *Availability factor of wind*, e.g. what portion of the time during a year the wind energy is available to produce electricity, resulted as an important parametric uncertainty, with low values leading to low renewable share. In contrast, the same uncertainties with opposite value ranges resulted as influential ones leading to the second group of scenarios around the upper peak of density estimate. (Although the results for *P6* in 2062 show only *PIDS* and *Availability factor of wind*, the results for other policies include *PSS* and *Discrepancy Switch*, too.)

The storyline of scenarios corresponding these results is as follows: When the market price of gas and electricity is determined as an agreement between the desired price of producers and expected price of traders (*PSS*=1), the resulting market prices are relatively low, due to the reducing effect of traders. Such low gas prices imply a high competitiveness of natural gas both in the gas and electricity market, and inhibit the development of renewable technologies, resulting in low *Share of Renewables.* As discussed previously, a short-term view of renewable gas producers while making capacity installation decisions prevents taking the positive impact of increasing market prices into account and results in relatively low renewable gas production, contributing to a low *Share of Renewables in the Energy Mix.* Lastly, when the future supply discrepancy in the electricity sector is considered as the difference between future demand expectations and current production rates (*Discrepancy Switch*=1), the future supply discrepancy is underestimated, especially for the wind energy due to low *Availability factor of wind*. Such low discrepancy estimations inhibit capacity installation, and hence, the renewable sources have a low share in the total energy mix.

Figure 8.17 shows these two groups of scenarios, where the 'low peak' group includes scenarios coinciding to the PRIM results, i.e. *PSS*=0, *PIDS*=1, *Discrepancy Switch*=1, and *Availability factor of wind*<0.45 (in the lower half of its uncertainty range). The low density of scenarios in the intersection of the ranges of these two groups of scenarios, and the distinct peaks of density estimates confirm the PRIM findings.

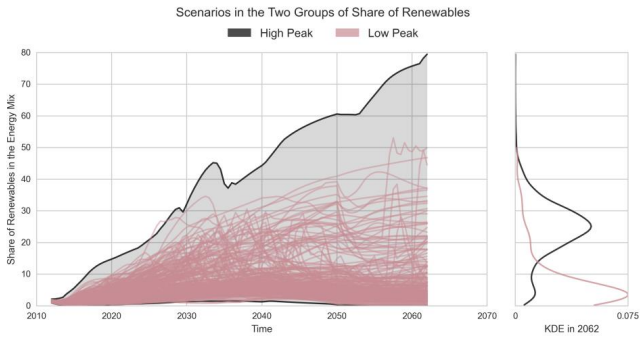


Figure 8.17: *Share of Renewables* in the 'low peak' and 'high peak' groups of scenarios

This section demonstrated how scenario discovery can be used to identify the reasons of policy preference switches, as well as vulnerabilities of a policy and uncertainties that can be

120A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

grasped as opportunities. The resource availability for biomethane production, and the technological efficiency (biomass yield) are found to be the major vulnerabilities of the policies targeting biomethane production, as well as the reasons for switches between the preferred policies. In addition to these factors, biomethane producers' decision mechanism and the model structure about price setting resulted as the most influential uncertainties.

8.3. CONCLUSIONS

This chapter presented an analysis of 9 different policies targeting natural gas production, renewable gas production and demand, in terms of 8 outcome indicators related to the policy objectives discussed in Chapter 2. This analysis was based on a three-dimensional framework introduced in Chapter 6, aiming to deal with the time, robustness and multi-criteria dimensions of decision making under uncertainty.

The purpose of testing these policies on many outcome indicators which they do not directly affect was to avoid any potential unintended effects. The results showed that a policy differs from the others only in terms of an outcome indicator it directly affects. (For instance, the biomethane goal policy differs from other policies in terms of *Renewable Gas Percentage*, but not *Total State Revenue from NG Production*). Therefore, it can be said that the policies tested here do not have considerable unintended effects on the scenario range (not in individual scenarios). Besides, the biomethane goal (*P6*) or the subsidization (*P8*) policy are shown to have a high performance with many robustness and multi-criteria methods for long durations of time. These policies owe their high performance not to their positive impact on all outcome indicators, but to their positive impact on a few outcome indicators without negatively affecting the others.

Regarding the assessment of policies based on the three-dimensional framework, a few policies such as the biomethane goal (*P6)* and subsidization (*P8*) demonstrated a considerable methodological robustness, since they received the first rank with many robustness and multi-criteria methods for long durations of time. Still, the results showed variation of the most preferred policy across the robustness metrics and multi-criteria methods, and over time, similar to the results in Chapter 7. This expected method-dependence again emphasizes the importance of taking multiple methodological options into account, since it implies probable fallacies if the robustness against uncertainties and multiple decision criteria are dealt with single methodological choices. Moreover, the shortcomings of this framework discussed in Chapter 7 are also observed in the analysis of this chapter, regarding the ranking approach and substituting the impact of a policy on an outcome indicator by its impact on robustness. These issues will be discussed in detail in Chapter 9.

The scenario discovery experiments presented in the second half of this chapter were useful to identify important uncertainties and how they influence the effectiveness of the policies. These experiments helped to develop storylines of the scenario groups of a particular interest, rather than examining these scenarios individually. A striking general result of the scenario discovery analysis is the high impact of the uncertainties about the market price setting and producer behavior on the performance of policies. Being a financial incentive, the subsidization policy is found to be more vulnerable to these uncertainties than the biomethane

120B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

goal policy, which employs communicative tools to stimulate renewable gas production in addition to subsidization. In other words, although intervening in the gas market with the subsidization of renewable gas is a powerful policy, it is vulnerable to market uncertainties, and it must be supported with communicative policies which do not intervene in the market price directly, hence escape the negative impact of uncertainties.

The uncertainties about the market price setting and producer behavior represent different possible assumptions about the model structure, as mentioned before. Therefore, the scenario discovery results stressing these uncertainties also imply the importance of including structural uncertainties in the model, because the certitude in a single model representation of these phenomena could result in different and misleading outcomes.

From the experiments presented in this chapter, it can be concluded that scenario discovery is a useful tool to deal with uncertainty in decision making, especially in terms of analyzing the scenario space and reaching meaningful conclusions. Still, it must be kept in mind that the results are not fully accurate, because the PRIM algorithm matches the inputs (uncertainties) with a group of scenarios (output), and only a percentage, not all, of the scenarios in this group meet the predetermined condition. Since the scenario discovery results are based on an input-output match, they do not imply a causality between the influential uncertainties and the output conditions, but inform the analyst about the important causalities in the system model linked to these influential uncertainties.

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9

CONCLUSIONS AND REFLECTION

This chapter concludes the thesis by highlighting important findings of the previous chapters and with a discussion on the methodological choices, limitations and future research possibilities. First, Section 9.1 addresses the research questions defined in Chapter 1 and clarifies how they are answered throughout this thesis. Section 9.2 explains the policy recommendations derived from this study, corresponding to the research objective and the main research question outlined in Chapter 1. Section 9.3 presents reflections on methodological choices and several methodological issues raised by this study. Then, Section 9.4 discusses the limitations of this study, and Section 9.5 points out further research possibilities based on these limitations.

9.1. RESPONSES TO THE RESEARCH QUESTIONS

In Chapter 1, the objective of this study was defined as providing policy recommendations to the Dutch government and to the key actors in the gas sector. With this objective, the main research question of this thesis was formulated as follows:

Which policy options are effective in meeting the conflicting interests of the key actors in the Dutch (natural and renewable) gas sector and robust against uncertainties in the long-term?

In order to answer this question, two research questions were defined in Chapter 1, the first one enquiring a systems-analytic formulation of the policy problem, and the second one examining the performance of various policy options. The two sections below will discuss the responses provided for these questions in the thesis.

122A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

9.1.1. How can the policy problem of the Dutch gas sector be formulated within the systems analysis framework?

Problem diagnosis is the first and a crucially important phase of a policy analysis study, and a systems analytic approach enables a structured and thorough handling of this phase. In Chapter 2, the policy problems in the Dutch gas sector were examined with a systems analysis approach, and the components of the policy problem, such as policy goals, policy options, the system of interest and uncertainties, were identified.

Policy goals and outcome indicators

Considering the gas sector at the national level and consequently having the central government as the problem owner, the policy goals were grouped into three as social, economic and environmental goals. The social goals relate to the security of supply, affordability and safety of natural gas, which reflect the public interests safeguarded by the government. Maintaining a high state revenue from natural gas production, and making the Netherlands the gas hub of Northwestern Europe to maintain the economic activity constitute the major economic goals of the government. The environmental goals include reducing the greenhouse gas emissions and increasing the share of sustainable energy sources. In general, the policy goals of the government emerge mainly from the desire to maintain the convenience provided in the country by natural gas as an energy source, and from the need to reduce emissions and to switch to sustainable sources. These two factors are also the sources of conflict between the policy goals, since a dedication to sustainable sources changes the prominent position of natural gas in the energy system.

Following the identification of policy goals, each of these was matched with an operational and measurable outcome indicator to assess the developments in the system and the effectiveness of policies on the policy goals. These outcome indicators were

- Coverage of Domestic Gas Demand
- Average Consumer Gas Price
- Import Dependency
- Societal Acceptance (Groningen)
- Total State Revenue from NG production
- Transport Capacity Utilization Rate
- Share of Renewables in the Energy Mix
- Renewable Gas Percentage

In this phase, a tradeoff between the representativeness and the number of outcome indicators was encountered, because a higher number of outcome indicators implies a more comprehensive representation of policy goals, but the transparency and understandability of the analysis becomes worse. Therefore, the list of 8 outcome indicators formed in this study with simplifications and assumptions could be formed differently, shortened, or extended with more variables. However, the representativeness and the complexity of the problem would also have been different. During the analysis in this study, it has been observed that 8 variables is already quite a lot, causing a high complexity in the multi-criteria problems solved in Chapters 7 and 8. Still, this computational and analytical complexity was inevitable,

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since the list of 8 indicators captures the variety of the policy goals and the complexity of the policy problem.

System of interest

Section 2.3 outlined the system of interest related to the policy problem, with information on the real system and how it is preliminarily transformed into a system model. In this step, a supply-demand view was taken, because the outcome indicators identified previously relate to the phenomena emerging from the relationships between supply sources and demand groups. For instance, *Import Dependency* refers to the share of imported natural gas in the total gas consumption in the Netherlands, and *Share of Renewables in the Energy Mix* refers to the ratio of all renewable sources in the total gas and electricity production.

In this supply-demand view, the system was conceptualized with three main supply options, being domestically produced natural gas (from the Groningen field, small fields and shale reservoirs), imported natural gas, and domestically produced renewable gas. These supply options were matched with the natural gas demand from households and commercial buildings, industry, agriculture, transport, and electricity production sectors, and with the renewable gas demand from the first four sectors (except electricity). Internal development and deployment of each of these supply and demand options were included in the system model, with varying degrees of resolution. The supply options are considered with a higher degree of resolution, i.e. in more detailed representations of these subsystems, in order to allow a better understanding and testing of supply policies. The interactions between these supply options and the competition between them for market share were also considered as elements important in determining the future of the system and included as key mechanisms in the system model. This conceptualization of the system of interest focused on a descriptive representation of the technical, economic and social elements of the system, rather than normative assumptions on only technical or economic aspects as employed in many energy systems models reviewed in Chapter 3.

Actors and stakeholder perspectives

The systems-analytic problem diagnosis in Chapter 2 includes an overview of key actors involved in the Dutch gas sector, and how they influence the system of interest. Grouped according to the system components, the list of actors mainly includes natural gas producers such as NAM, renewable gas producers, traders such as GasTerra, small and large scale consumers and the transmission system operator GasUnie. Based on this review of actors, it can be concluded that the actors at the supply side of natural gas (e.g. producers, traders and operators, as well as the government) are in coherence in terms of their interests. This is attributed to the institutional structure which closely connects these actors via ownership and to the long history of collaboration, despite recent liberalization of the market and unbundling of infrastructure ownership and operations. Therefore, these actors are not expected to cause future conflicts and uncertainty. However, as a new group of actors in the gas market, renewable gas producers are shown to be an important uncertainty source (see vulnerability analysis in Chapter 8). Besides, the interests of consumers conflict with the interests of producers in principle, and the government's policy goals tend to cover the interests of both groups.

123A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

In addition to the main actors in the Dutch gas sector, this study included the six stakeholder perspectives identified in a different project of the EDGaR research program. The main expectation of each these perspectives can be summarized as (i) natural gas will be an important fuel in the future, (ii) renewable gas will have an important share in the future, (iii) the gas sector will adapt to the future conditions, (iv) austerity conditions will be encountered, (v) many different energy sources will be utilized, and (vi) the importance of entrepreneurs and local companies will increase. These stakeholder perspectives are further analyzed in Chapter 5 in terms of their components and the relations between these components.

In particular, the analysis of stakeholder perspectives showed that many future conditions envisioned by a perspective are conflicting with each other, given the causality assumptions in the model. For instance, Perspective 1 expects high import volumes in future, as well as high domestic production. Yet, these conditions are conflicting, since natural gas is imported only when domestic production is not sufficient to cover the domestic demand in the model. Similarly, Perspective 4 expects high gas prices in future and a low share of renewables in the energy mix due to lack of investments, and Perspective 5 expects the opposite, with low prices and high shares of renewables. Such expectations of an inverse relation between the gas price and renewables share are found to be contradictory to the causal relations between these factors, because a high gas price is actually a stimulant for the development of renewable energy, and vice versa.

Policies

The following element of the policy problem identified in Chapter 2 was a list of policies which are currently or have been previously implemented in the Netherlands and in other countries, or can be potentially implemented in future. These policies were chosen from a longer list of energy policies in general, with respect to the intensity of their effects on the gas sector. Still, a large number and wide extent of policies were eventually mentioned in Chapter 2, due to the interwovenness in the energy system. Later, this list of policies was shortened for analysis by selecting policies which are most focused on the gas sector in particular, and most controversial in the current policy arena.

This final list of policies varied in terms of the instruments and implementation areas, and focused on three major areas, such as natural gas production, renewable gas production and demand. The natural gas policies included the highly debated production cap on the Groningen field, permission for shale gas production and a higher State Profit Share (SPS) in the natural gas profits. As for the renewable gas policies, subsidization, agreements with the industry to reach a certain production goal (biomethane goal), and the obligatory renewable gas supply of utility companies were the three policies included in the analysis. The two demand side policies were amendments to the consumer price, e.g. a lower energy levy for renewable gas consumption, and a higher value-added tax (VAT) for both types of gas.

Uncertainties

Lastly, the systems-analytic problem diagnosis in Chapter 2 included the identification of uncertainties in the future of the Dutch gas sector. In this step, the sources of these uncertainties in the energy system were discussed, as well as their nature (i.e. if they are uncertain due to epistemic reasons or ambiguity) and severity levels. Three elements of the

123B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

systems analytical framework were identified as the major sources uncertainty. The source of uncertainties in the first group was factors external to the system, such as the availability of natural gas and biomass resources, characteristics of new energy technologies and gas demand. The second group included uncertainties about the system structure, mainly associated with price changes. In the third group, uncertainties were related to the value system of the problem owner, namely how the policy goals are prioritized by the government. Transforming these system uncertainties into model uncertainties, Chapter 5 introduced a longer list of uncertainties, composed of parametric and structural uncertainties included in the simulation model.

Having the central government as the problem owner of this policy analysis study, this delineation of the policy problem and the decomposition of the system elements was from the perspective of the government. Since the government's interests are diverse, the policy goals and uncertainties have several commonalities with those of other actors in the system, such as producers or consumers. Still, it must be emphasized that this problem definition and the subsequent analysis was in the view of a single actor associated with the problem.

9.1.2. What is the performance of various policy options identified under a wide set of possible futures?

The second research question was about the performance of various policy options identified in Chapter 2. The overarching policy analysis approach adopted to answer this question was a rational-style, model-based analysis as explained in Chapter 3. Answering this question required answering a series of sub-questions, which outlined the structure of this study. The paragraphs below discuss these questions and responses given to them in this thesis.

How can the system of interest identified for this problem be represented in a simulation model?

As explained in Chapter 3, Exploratory Modeling and Analysis (EMA) has been adopted as the main research methodology in this study to address the importance of uncertainties, and basing decisions on a multiplicity of futures. This methodology suggested the use of quantitative models for generating a large number of scenarios to explore future possibilities. Therefore, a simulation model was developed to quantitatively represent the system of interest initially conceptualized in Chapter 2, which could form a platform to allow testing the impact of uncertainties and policies on the outcome indicators. System dynamics was selected as the methodology of such a simulation model, as explained in Chapter 3, since it enables generating transient (dynamic) scenarios based on a description of causal relations in the system, which is a suitable basis for EMA. Instead of using an existing energy system model, developing a new model was preferred. The reason for this choice was the absence of a model that coincides with the problem context and that captures uncertainties extensively so that it can be suitably used in an exploratory manner.

In developing the model, several means and information sources were used, and several challenges were encountered. The input to the model building process was the information collected about the system from literature and interviews, as well as existing models which include similar phenomena, or analogies with system dynamics models developed for

124A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

different contexts. Such input was processed in several iterations of modeling, with the aim to find a balance between inclusiveness and simplicity of the model. This balance was the main challenge encountered in model development, since EMA requires a simple model, while the problem context requires a broad view and a deep understanding.

Chapter 4 described the system dynamics simulation model resulting from an iterative process. Parallel to the system model explained in Chapter 2, this model was based on a supply-demand view, where several supply options co-exist and compete to meet the gas demand from various sectors. The center of gravity in the model is more towards the supply side, since each supply option is modeled explicitly whereas an aggregate demand change mechanism is used for the sectors except electricity generation. In other words, the model included the field lifecycle of natural gas, the production chain of renewable gas and the trading mechanism of imported natural gas in a relatively detailed way, allowing to obtain insights about supply side improvements and to test the respective policies easily.

It is important to emphasize that this model is not claiming to be 'the' model of the Dutch gas sector, but used as 'a' model. Namely, as any model, it is an assumption-based representation of reality, despite the efforts for a sound representation and inclusiveness of uncertainties. Below, Section 9.2 discusses the implications of this model-based study on policy recommendations, and Section 9.3 and Section 9.4 include a reflection on and shortcomings of the model, respectively.

How can the performance of a policy option under uncertainty be measured?

In this study, the performance of a policy option is evaluated and compared to the others based on a framework introduced in Chapter 6. This framework attempted to address a gap in the literature on decision making under uncertainty by combining three aspects of decision making. Firstly, the policy problem involved multiple policy objectives represented by 8 outcome indicators, and to deal with this aspect, multi-criteria decision analysis methods are used. Secondly, in order to deal with the uncertainties in the policy problem, the framework included a robustness dimension to measure the performance of a policy across the scenario space. Thirdly, the framework included a time dimension, to aggregate the information obtained from dynamic scenarios which cover a 50-year time horizon. These three dimensions are combined to measure the performance of a policy as follows: First, the value of each outcome indicator in each scenario is determined based on the time metric (e.g. at one point in the time horizon). Then, the robustness value is obtained from the scenario space for each outcome indicator at this time point, and eventually a multi-criteria measure is computed, which combines the robustness values of 8 outcome indicators.

It must be reminded that a single, specific metric was not chosen for any of these three dimensions. Instead, 4 multi-criteria decision analysis methods, and 9 robustness metrics were included in this framework, along with a number of time-metric options. The multi-criteria decision analysis methods included finding the non-dominated solutions (Pareto set), the lexicographic ordering method with a particular prioritization order of the criteria, and additive utility methods with equal and uncertain weights. As for the robustness dimension of this framework, expectation-based, regret-based and statistical metrics are used. Each of these groups included several options found in previous studies or devised in this study. In the time

124B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

dimension, the information from transient scenarios is either aggregated into a static metric or used for assessing the policy options dynamically over the simulation horizon.

The reason for this choice was to take methodological uncertainty into account and to avoid any fallacies that might be caused by sticking to a single metric/method. With this choice, which results in the dependence of outcomes on the selected method, a concise conclusion about policy performance was traded off for more information about methodological robustness and which policies are preferred with which methods.

Briefly, this framework was an attempt to combine multi-criteria, robustness, and time aspects of decision making with multiple methodological options. A reflection on this framework will be provided in Section 9.3, in addition to a discussion in Section 9.4 on its limitations observed during the analysis.

What is the long-term impact of present and future policy options on the identified outcome indicators and what is their performance under uncertainty?

In Chapters 7 and 8, the framework introduced in Chapter 6 was used to assess the long-term impact of several policy options on the 8 outcome indicators identified previously, and their performance to deal with uncertainty. In Chapter 7, different implementation schemes of two primary policies in the gas sector, namely the production cap on the Groningen field and the subsidization of renewable gas, are compared to each other. The options for each policy was exchangeable in this chapter, meaning that different implementation schemes of a policy were compared to each other, but in Chapter 8, different policies that can compete with or complement each other were assessed and compared.

Chapter 7 showed that the four options for the cap policy (business-as-usual, no-cap, prolonged cap and annual cap) do not differ from each other in terms of several outcome indicators such as demand coverage and consumer prices. Still, it is observed that the prolonged cap option (limiting the Groningen production until 2050) results in lower natural gas production and higher shares of renewables in the gas and energy mix. However, although this policy aims to preserve the reserves for future production, high import dependencies are observed in future with the prolonged scheme in many scenarios. This is mainly because the Groningen reserves decrease to very low values anyhow by the end of the cap policy, and the production volumes do not increase much afterwards, given the relatively low market prices (compared to the cost of production) which have adjusted to the import price. The ranking of cap policy options based on the framework indicated a strong dependence on methodological choices, yet the prolonged cap option is recommended as a more promising option due to its relatively high performance with many methodological choices.

As for the subsidization policy, 11 schemes were analyzed, and their results were also similar to each other in terms of several outcome indicators. Yet, the trade-off between high renewable gas production and high subsidization costs to the government was apparent in the results. For instance, the fixed price models with inflation adjustment, which have the highest cost, resulted in the highest renewable gas percentage values. Based on the framework which combined the performance on multiple outcome indicators and against uncertainty, the fixed cost percentage model of subsidization resulted as the most preferable scheme. According to

125A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

this scheme, the government pays the difference between a multiple of the unit production cost, such as 115% of the cost implying 15% profit, and the market price to producers as long as the market price is lower than the cost. This choice was not due to a strong predominance of this scheme on the others, but due to its acceptable performance with most of the methodological options.

In Chapter 8, three groups of policies, i.e. targeting the natural gas supply, gas demand, and renewable gas supply, are analyzed and compared to each other. In the first group, increasing the state share in the natural gas profits expectedly increased the state revenue, without causing a considerable adverse effect on other outcome indicators. A long-term cap policy did not perform differently (than other policies) in terms of increasing the demand coverage or reducing future import dependency, yet it provided a considerable opportunity for renewables to grow their market share both in the gas and the total energy sector. Permission to produce shale gas was shown to increase state revenues and to lower import dependency without resulting in low societal acceptance, but it resulted in worse outcomes for the deployment of renewable technologies. It must be reminded that the reason for societal acceptance not being adversely affected by the shale gas production was the assumption that high gas prices lead to high acceptance of shale gas, counterbalancing the effect of disturbance caused by extraction.

The second group of policies targeting the demand side by changing the consumer price with two different taxation instruments did not result in significant changes in the future. In the third group, obliging the utility companies to provide a portion of their supply as renewable gas did not result in a higher performance than the BAU policy. However, subsidization and communicative policies to enhance renewable gas production demonstrated a distinctive effectiveness especially in terms of the renewable gas percentage and import dependency, without worsening any of the other outcome indicators.

The framework-based analysis favored these two renewable gas policies, namely the subsidization and biomethane production goal policy, due to their positive impacts on the abovementioned outcome indicators, and their high robustness performance with many metrics. Still, the results were time-dependent, and in the first decade the BAU policy was shown to be promising besides subsidization, whereas the shale gas policy was shown to follow the biomethane goal policy in the last decade in terms of preferability.

Having these results about the long-term performance of the policy options, the next section discusses the policy recommendations derived from these results and the underlying analysis.

9.2. POLICY RECOMMENDATIONS

This section addresses the main objective of the research presented in this thesis, i.e. providing policy recommendations to the Dutch government, who is the problem owner of this study. Prior to the recommendations about an overall strategy, the sections below discuss the recommendations about natural gas and renewable gas policies specifically, and the uncertainties which significantly affect the impact of these policies.

125B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Natural gas policies

In this study, four implementation options for limiting the natural production from the Groningen field are analyzed. These options included the formerly set 10-year limit for the period of 2010-2020, a no-cap option, a continuation of the 10-year cap until 2050 with renewals in every 10 years, and a scheme corresponding to earthquake-related reductions in the annual limits as set in 2013. For most of the outcome indicators they are compared on, these options did not differ from each other significantly in terms of their effects on the entire scenario space created by uncertainties. Yet, the prolonged cap resulted in higher shares of renewables in the energy mix, and higher import dependencies in the future. From this finding, the following insights can be drawn:

Firstly, although the cap policy primarily aims either to preserve the gas reserves for future or to increase the public safety and to deal with the social distress, it has a positive side effect on the sustainability goals by increasing the share of renewables. This new frame for the Groningen cap reinforces the position of natural gas in the new energy policy as a transitional fuel (a fossil fuel with lower CO_2 emissions, hence can support the transition towards renewable sources), which is a view already accepted by the Dutch natural gas industry. Secondly, higher import dependencies in the case of a long-term cap policy (until 2050) imply that this policy is not effective on its primary intention. Therefore, a higher stimulation of renewable energy to replace natural gas and further incentives to reduce gas consumption can be thought of as options to overcome high import dependency.

As for the shale gas policy, permission for shale gas production results as a preferable option especially in the long-term, attributed to its positive impacts on demand coverage, state revenues, and import dependency. However, despite hindering the growth of the renewable energy share, shale gas production does not lead to very low import dependencies in a large portion of future scenarios, as desired. Therefore, based on this model-based analysis, it is shown to have some positive effects on, but not to be a game-changer in the Dutch gas sector.

Renewable gas policies

Subsidization is a key policy for stimulating the production of renewable gas, and Section 7.2 of this thesis compared several subsidization schemes based on their impacts on the 8 outcome indicators and their robustness against uncertainties. Eventually, the share of renewable gas in the total gas consumption and the cost of subsidization to the government were the two outcome indicators that differentiated these schemes. The spot market gap model currently used by the Dutch government was shown to perform well on these two criteria and against uncertainties, yet it is outperformed by the fixed cost percentage model (which sets the subsidy amount to the difference between the market price and a multiple of unit cost) with many methodological options and for long periods of time. The difference of these two models was that the former sets a lower subsidy price based on a net present value calculation, hence taking the inflation and cost reduction into account, whereas the latter sets a slightly higher subsidy price assuming a fixed cost throughout the lifetime of a project at its start. Therefore, the fixed-cost percentage model results in higher costs to the government on average, but more renewable gas production and a higher robustness against uncertainties.

126A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Regarding the duration of subsidization, this study included two options: A longer implementation until 2050 but only for the spot market gap model, and a shorter implementation until 2030 for all other schemes. The longer option resulted in higher renewable gas production with acceptably higher subsidization costs. (It must be noted that the comparison of a long and a short duration is not carried out for all schemes.) Besides, the multi-objective robust optimization study of Eker and van Daalen (2015) which aimed to balance conflicting goals of production maximization and cost minimization also resulted in a long-term implementation, such as 25-26 years from 2012. Based on these findings, it can be said that a long-term implementation of subsidization maintains a high installation rate of new production facilities and hence increases production, although each installation is subsidized only for 12 years. Therefore, it is recommended to keep the subsidization policy in force in the coming two decades.

The model results also showed that a persistent 'biomethane goal', in other words maintaining a long-term communication with the industry to install more production facilities is an effective policy. This communicative policy was shown to be more effective than financial or regulative policies on the gas sector (assuming that the agreements on production capacity installation are followed), in terms of the outcome indicators such as the share of renewables both in the gas and total energy consumption, and import dependency, without worsening any other policy objective. Therefore, it is advisable not to underestimate the influence of communicative policies, and to maintain the agreements, or to establish new ones, with the industry on capacity installation.

Vulnerabilities and opportunities

In Section 8.4, uncertainties about the market price change and producer behavior were found to be highly influential on the performance of policies. Being a financial incentive, especially the subsidization policy was found to be vulnerable to such uncertainties. This result is based on model assumptions, yet it can be insightful for policy recommendations.

Two uncertainties about the producer behavior are found to be especially influential. The first one is how renewable gas and electricity producers make capacity installation decisions. If producers have a short-term view and make capacity installations based the current cost and price values, then both subsidization and the biomethane goal policies are less effective than they could be. However, if producers make an NPV-based decision, since prices tend to increase in most scenarios, the profitability measure is higher and this results in higher shares of renewable gas and energy. Still, supporting the subsidization policy with communicative policies that can stimulate renewable gas production, as shown by the biomethane goal policy, is an advisable option to escape the negative impact of such market-related uncertainties.

The second uncertainty related to producer behavior is about how producers respond to market price changes, e.g. by increasing their desired market price or decreasing it. If producers do not respond to price increases by increasing them further, then market price does not increase to a level that renewable gas production becomes profitable. In other words, despite the negative connotation from a consumer perspective, a price increase initiated by natural gas producers stimulates renewable gas production. Besides, high prices lead to low demand, which further increases the renewable gas 'percentage'. If this sequence of relations

126B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

is interpreted backwards, low gas demand leads to low prices (via increasing demand coverage) and this puts a barrier against renewable energy production. Therefore, to avoid the adverse effects of the uncertainty in producer behavior and to increase the renewable gas production parallel to a decreasing gas demand (which is also desired for higher energy efficiency and savings), a long-term subsidization can be suggested, until renewable gas becomes competitive at the market prices.

Furthermore, the scenario discovery results reinforce the beliefs in the gas industry about the importance of gasification technology for producing renewable gas. The availability of dry biomass supply for gasification, and the efficiency of this technology were found to be effective in obtaining a higher renewable gas share and less import dependency in the future. Therefore, although low values pose a threat, high values of biomass supply and gasification efficiency, or further efforts to increase them, can be grasped as opportunities to obtain a higher share of renewables in the energy system and lower dependence on imported natural gas.

A policy strategy for the gas sector

Following the multi-method analysis of candidate policies presented in Section 8.3, Table 8.2 summarized the findings in the form of most preferred policies. This summary highlights the subsidization and BAU policy before 2020, the biomethane goal, subsidization and the cap policies between 2020 and 2050, and the biomethane goal and shale gas policy after 2050. These findings can constitute a basis for a policy strategy for the Dutch gas sector, which combines the most preferred policies.

Having the subsidization policy as the most preferred one followed by the BAU policy stresses the importance of subsidization, but with the fixed cost percentage model. It is important to note that the subsidization scheme included in the analysis also incorporated a less restricting cap on the Groningen field (10-year cap until 2020) and a biomethane goal imposing 3 bcm annual production by 2020, implying that what works well is not only subsidization but a combination of these three until 2020. After 2020, the biomethane goal and the prolonged cap policies are in the top of the most preferred policies list in addition to the subsidization policy. Therefore, a strategy should include the extension of both the cap policy and the biomethane goal, after 2020 until approximately 2050.

This study did not include testing the abovementioned combination of the subsidization, cap and biomethane goal policies or other combinations of policies tested initially (e.g. the SPS and VAT policies). The first reason for not re-considering other policies in combinations was obtaining almost the same results with many methods. In other words, the policies such as subsidization, the biomethane goal and the cap policy were distinctly preferable compared to other policies, hence the others were not taken into account further. Besides, due to the assumptions made for the BAU case, the preferred policies included instances of each other. For instance, the subsidization policy included ‘biomethane goal’ until 2020, or the ‘biomethane goal’ until 2050 included the cap policy until 2020. These assumptions do not encompass a thorough combination of the policies tested. Yet, they were insightful about the policy combinations in the interpretation of results.

127A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The limitations of this study which are discussed in Section 9.4 and which lead to future research areas must be borne in mind, as caution in the use of these policy recommendations.

9.3. REFLECTION ON THE RESULTS AND METHODOLOGY

Following the overall results of this study summarized as responses to the research questions and eventual policy recommendations, this section provides a reflection on the results and the general approach. In particular, Section 9.4.1 reflects on the policy-related results and issues, whereas Section 9.4.2 focuses on observations related to the methodology.

9.3.1. Reflection on the policy-related results

Regarding the policy-related results of this study, this section reflects firstly on the difference between the actual political context and the analysis results in the context of the cap policy, then on the generalizability of outcomes. This section also presents thoughts about the future of the Dutch gas sector.

Actual political context vs. the analysis results

One of the key policies analyzed in this study is the production cap on the Groningen field, which is a highly debated policy in the current Dutch policy arena. Throughout the course of this study, the actual political situation has changed very rapidly, and the debate shifted from the question of whether the Groningen reserves should be preserved for future or used now, to the question of how the concerns about safety due to earthquakes can be overcome without harming the security of gas supply and state revenues. Following this development, the Minister of Economic Affairs abandoned the 10-year cap which was set on the Groningen field for the period of 2010-2020 and established annual caps for 2014 and 2015 at much lower values. These different schemes are taken into account in this study, but a further reduction was planned in June 2015, which set the total 2015 production as 30 bcm instead of an earlier decision on 40 bcm (NOS, 2015). Therefore, the latest limits on the Groningen field are much stricter than the ones used in the policy analysis in this study.

Given these recent developments in the actual policy arena, the findings of this research contradict with the actual policies, because the suggested cap policy was a long-term one but with higher cap values than the actual ones. This contradiction can be explained by two factors. Firstly, in the actual policy arena, the reason for this large reduction in the cap was the priority given to safety and 'societal acceptance', and forgoing other interests such as the state revenues and import dependency. Different weightings of policy objectives are taken into account in this study, including this prioritization of societal acceptance. Hence, the results were not determined by a single and definite weighting scheme prioritizing societal acceptance. Secondly, the societal acceptance mechanism in the model included the effects of price and scarcity on public opinion, in addition to the disturbance caused by natural gas extraction. In the last few years, the dominant effect on societal acceptance in the Netherlands was the disturbance, since no serious problem related to scarcity and high prices has been observed yet. This difference between the actual short-term dynamics and model assumptions is seen as the second reason for the discrepancy between the actual political situation and the results of this study.

127B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Many policies tested in this study did not show unexpected adverse effects on the policy objectives that are not directly targeted by the policy itself. From the perspective of a policy maker, this result is surely favorable since these policies do not complicate the problem further by causing unintended consequences. Yet, from the perspective of an analyst, the reasons of such an outcome can be questioned. Such an indifference of one subsystem to the policy interventions in another subsystem points out a disconnectedness between the two subsystems.

This disconnectedness may be due to the absence of some important links in the model, or the distinct components of the subsystems governing the behavior, rather than their connected components. The latter is thought to be the reason in this study. For instance, the natural gas and renewable gas subsystems were linked through their impacts on price and the demand shifts between them. These links represent the major relations between the subsystems, yet the resource availability, both for natural gas and renewable gas, is found be a more important factor than the demand and price in determining the future behavior. Since resource availability does not depend on the links between the natural gas and renewable gas subsystems, an indifference is observed in the behavior of these two subsystems to each other. In other words, natural gas and renewable gas systems influence each other via the market price, but since their individual resource availability is more influential on their future dynamics, policies targeting renewable gas (e.g. subsidization) do not significantly affect the natural gas system, or policies targeting natural gas (e.g. State Profit Share) do not significantly affect the renewable gas system.

Generalizability of outcomes

When the generalizability of the results is considered, two questions arise referring to two scales: Firstly, and more fundamentally, can these results be used in real policy making in the Netherlands? Secondly, can these results be generalized to the gas sectors of other countries?

Regarding the usability of results in real policy making, we suggest caution. As discussed in the early chapters of this thesis, the role of policy analysis is to inform policy making and provide recommendations, but not to dictate any decision with full credibility in science. Especially when (inevitably assumption-based) quantitative models are used for sociopolitical problems, the results should be taken into account along with the assumptions made, and their effects on the results. In this study, the use of exploratory modeling and including different options (for model structure and parameter values) helped to eliminate a potential pitfall due to single and misleading assumptions. Still, there are several assumptions made about the scope of the study and the possibilities of uncertainties, and therefore, the results should be employed by considering these assumptions.

As for the generalizability to other countries, we can argue that the general approach used in this study from a systems analytic problem definition to exploratory system dynamics modeling and robust decision making, would be helpful for the energy policy problems in other countries, too. The model itself can also be used in the context of another country's gas system, because several aspects of natural gas field lifecycle, biomethane production chain and market competition are general phenomena. However, using this model may still require several modifications besides changing only the parameter values. Having large natural gas

128A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

reserves, especially the Groningen field as a swing producer and the social distress around it, the well-established gas market with close connections between the actors, and the importance given to renewable gas are the primary characteristics of the Dutch gas sector which may not have direct counterparts in other countries. Therefore, a similar study can be conducted for a different country, but with customizations especially in the system model and policy objectives.

Future of the Dutch gas sector and the policy arena

This study explored a wide range of future possibilities in the Dutch gas sector, without assigning or deriving a likelihood for any of these possibilities. Observing this wide range of possibilities with unknown likelihoods and the multiplicity of stakeholder views on the future, it is not straightforward to anticipate the direction in which the Dutch gas sector will evolve, i.e. whether it will maintain its current role in the energy system, become extinct or adapt. Still, based on the engagement in a 4-year research project on the sector, this section will discuss a number of subjects that will potentially prevail in the future debate in the sector and in the policy arena.

The first topic is, as it has been in the last decade, the transition to renewable energy and the role of natural gas in this transition. One of the primary goals of the energy transition was to deal with climate change. Climate change policies at the global or local scale are grouped into two, as mitigation and adaptation policies. As a country which is expected to be severely affected by sea level rise, the Netherlands is currently focusing on adaptation strategies, such as the Adaptive Delta Management approach of the Delta Programme (Delta Programme Commissioner, 2014). The results of the mitigation policies have been observed as follows: The total CO_2 emissions (from both ETS and non-ETS sectors) in 2014 were only 1.8% below the 1990 levels. This reduction mainly came from the households and agriculture sector, which reduced its emissions by 18% and 26% respectively, whereas the energy sector emitted 15% more CO_2 in 2014 than the 1990 level. As for the total greenhouse gas emissions (CO_2, methane and nitrous oxide), it was 2,1% lower than the 1990 levels. (CBS, 2015a). The share of renewables in the energy mix is currently 5.6% (CBS, 2015b). Considering the goal to have 14% renewable energy by 2020, the current state is not promising and requires a much higher commitment in future.

The Dutch natural gas industry does not take an opposing position to the transition towards renewables and argues that natural gas is a fuel that can enable this transition. With this argument, it is not natural gas that is being positioned against renewable energy, but coal, which results in higher CO_2 emissions than natural gas when burnt. The consumption of coal for electricity production has increased by 12% from 2010 to 2014, whereas that of natural gas decreased by 25% in the same period (CBS, 2015c). This development is thought-provoking, because the ultimate goal of increasing the renewable energy share is to reduce CO_2 emissions, and increasing coal combustion certainly has a negative effect on this.

In this regard, it is undeniable that natural gas is a better fuel to support the energy transition not only due to its lower CO_2 emissions compared to coal, but also due to its flexible production capacity that can balance the intermittent production from renewable sources. In this study, the major obstacle to an increasing renewable gas share is not found as natural gas,

128B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

but internal factors in the renewable gas sector, such as resource availability or producer behavior. Still, in general and based on market principles, it can be argued that the strong presence of fossil fuels in the market is an obstacle to the deployment of renewable technologies. Renewable energy subsidies aim to overcome this obstacle by bringing renewable options to a competitive position compared to fossil fuels. Yet, this battle can also be approached from the other side, such as by removing the implicit subsidies given to fossil fuels (e.g. government participation in natural gas exploration and production activities).

The second topic is the consumer side of the supply-demand balance, and public participation in the energy policy debate. Some stakeholders have already mentioned that a higher consumer power is expected in future (Perspectives 5 and 6 in Section 2.4.2). Consumers are expected to be more active in two aspects of the energy system, as producers contributing to decentral production and as direct participants in the policy debate.

The latter aspect has been exemplified by two recent cases in the Netherlands. Firstly, as discussed before, the public opposition to natural gas production in Groningen has been effective in the government policy to cut the Groningen production. Secondly, a court ruling in June 2015 ordered the Dutch state to reduce the CO_2 emissions by 25% in five years compared to the 1990 levels, in a suit brought by Urgenda Foundation (Urgenda Foundation v. the State of the Netherlands, 2015). The Dutch government has recently appealed to this court verdict, admitting that they will comply with the court decision by the time the appeal results in an outcome (Randerson, 2015). Besides these two examples particularly in the energy policy domain, the study of den Ridder and Dekker (2015) shows that the Dutch citizens are less positive about politics in general. The authors report that there is a clear public desire for a greater representation of public opinion and more responsiveness of politicians. Therefore, based on such developments and research findings, consumer power and public opinion are expected to become more influential in the future energy policy debate.

Following these two issues on the producer side and consumer sides, the third issue expected to be debated more often in future is the role of the government between these two sides. As stated in Chapter 1, the energy markets, both gas and electricity, were liberalized in the 2000's, allowing more private companies and actors to enter the market and diminishing the power of the government. Yet, the role of the government is expected to be questioned again due to the need to coordinate increasing decentral production and a higher urge to reduce emissions. On the one hand of this debate, several researchers emphasize the importance of an institutional change to support the energy transition. Kemp and Rotmans (2005) suggest transition management as an alternative governance structure to the central planning and implementation approach which cannot include "the multitude of microconcerns at the decentralized level". Similarly, Goldthau (2014) proposes polycentrism in governance instead of a central coordination, in line with the decentral infrastructure.

On the other hand of this debate, Monstadt (2007) emphasizes high transaction costs of decentralization, because as regional and local authorities leave their regulatory, operative and financing roles to new cooperative and market-oriented governance forms, the coordination becomes more challenging and expensive. As a solution to reduce such costs, Monstadt (2007) suggests coordination at the regional level, with clear definition of roles by the

129A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

national government. White (2014) argues that the government can play a central coordinator role to deal with such shortcomings of decentral production. Furthermore, central governments are urged to take more command and control type actions, such as in the case of the Norwegian government banning the investment of public funds on coal (Mohsin and Holter, 2015) or as in the US where the government is called to ban fossil fuel extraction (Dokoupil, 2015).

Linked to the fundamentals of the current political and economic system, and due to the urgency to reach a conclusion, this debate is expected to be challenging. As for its implications specifically on the gas sector, it relates both the production and consumption of gas. The abovementioned issues of decentralization hold for decentral renewable gas production. Regarding the role of the government, a strict control of the production of natural gas and the consumption of it in power generation are the major issues.

These three topics we briefly discussed in this section are not unique to the Netherlands. Many countries around the world face similar issues, and host debates about these topics to varying extents. Therefore, as the problem of climate change is global, these topics related to its solutions are expected to be debated globally, too.

9.3.2. Reflection on the methodology

This section presents a reflection on two methodological aspects of the observations made during this study. These two aspects are related to model-based policy analysis and quantification of robustness, as discussed in the paragraphs below.

Model-based policy analysis

In Chapter 3, the benefits of using a model-based policy analysis approach and the reasons for selecting it are discussed. In this study, the main reason was to generate scenarios in order to explore the effects of uncertainties on the future dynamics of the system. Yet, this approach also assisted understanding how the system works and why it does not move in the desired direction. For instance, the systematic approach that takes multiple elements of the system into account and the relations between them helped to question the assumptions and potential inconsistencies in the stakeholder perspectives.

Besides the benefits, several challenges of a model-based approach are observed in this study. In this section, these challenges will be discussed with respect to the steps of the modeling cycle they are observed at. This discussion will also consider the implications of exploratory modeling on these steps, and how these challenges relate to the systems analytical ‘model’ of the problem itself.

Related to the problem identification step, the first challenge was the definition of scope. In defining the model boundaries, it was not only the identification of breadth of the system (i.e. which subsystems to include) that was challenging, but also the depth (i.e. the detail level) of the system model. In general, the exploratory modeling approach suggests to use small models, avoiding unnecessary detail and focusing on uncertainties. This requires finding a fine balance between the complexity of the problem and the simplicity of the model. To deal with this challenge, iterative model building with different model boundaries was inevitable in

129B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

our opinion, as well as eventual pragmatic decisions about the extent of the model boundaries. Also, prior to hands-on model building, a careful and critical inquiry of which aspects of the system are relevant and should be in the model is suggested to reduce the number of such iterations and to reach a solid scope definition eventually. The remaining limitations of this study related to the scope are discussed in Section 9.4.

In the conceptualization step of the modeling cycle, a key challenge was the incorporation of uncertainties into the model. This challenge had two aspects, first related to the type of model element an uncertainty corresponds to, i.e. a parameter or a group of variables, and second, related to the representation of model structure uncertainties. Regarding the first aspect, for instance, all stakeholders interviewed for the identification of systems analysis elements said that the market price of gas is the major uncertainty they encounter. Following this, it was a scope-related modeling question to include the market price as an uncertain parameter in the model or as a variable that results from uncertain relations. Since the market price is the balancing factor between supply and demand, it is assumed to be a variable in the model, in order to obtain the dynamics of the system resulting from supply and demand reactions.

Regarding the second aspect of the conceptualization challenge, we observed that it is difficult for a single modeler to conceptualize multiple plausible representations of the system to include model structure uncertainty, because one tends to think similarly or to stick to the initial conceptualization. We tried to overcome this challenge with critical thinking on assumptions and by using different model structures that are found in previous studies for the same phenomenon. Multiple model structures about the producer behavior and the market price mechanism were examples of these in the model. The results showed the importance of considering structural uncertainties, because they resulted as the most influential uncertainties on policy performance, such as the producers' decision making mechanism being the primary vulnerability of the subsidization policy.

The specification step was associated with the challenge of setting the model parameters and functions despite the lack or ambiguity of data. The lack and ambiguity of data are major sources of uncertainty and the exploratory modeling approach aims to deal with this by using a range of possible values instead of a single certain value for a parameter or a function. However, in this case, the problem does not disappear completely but is transformed into a relatively easier one. In this study, for the reference simulation, we selected the parameter and graphical function values by relying on the most credible source of data, by using the average of the available values or by following a formal calibration procedure. Accordingly, the uncertainty ranges set for exploration were inclusive of all alternative values obtained from different sources, or the entire possibility range such as [0, 1] for a fraction, or a wide interval around the reference values.

It can be argued that some of these choices on the uncertainty ranges, especially the last type, are subjective. In our opinion, such a subjectivity is present in many uncertainty analysis studies, for instance the uncertainty ranges in sensitivity analysis are also set based on educated choices of the modeler/analyst. To accommodate this, we opted to clearly communicate our choices in this study, by presenting the entire list of uncertainty ranges in Appendix 5.1.

130A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

In the model testing step, the main challenge was the definition of validity for exploratory models, which differ from traditional system dynamics models in terms of purpose, as discussed in Chapter 5. In this study, our approach to deal with this challenge was closer to validation in traditional system dynamics modeling. Yet, this issue is also addressed as a shortcoming of the exploratory modeling approach in Section 9.4 and further research is suggested for validation methods of exploratory models.

The main challenge related to model use is the communication of the model and results. Engaged in a particular modeling methodology, modelers and analysts use the language of this methodology, which is often not understood and spoken by the audience. The audience may be stakeholders, members of the multi-disciplinary project team or anyone out of the modelling field, who all have their own mental models about the system and their own terminology for the related concepts. In this regard, Hall *et al.* (2014) identify three obstacles to an effective communication of models, and propose strategies to deal with each of these obstacles. The obstacles stated in their study are confusion regarding a concept, difficulty picturing the overall system, and conflicts with pre-existing cultural models. The strategies include elucidating explanation of concepts, depiction of the overall system in a summary image, and transformative explanation, i.e. first acknowledging the pre-existing models and then transforming them with an alternative explanation. These obstacles were observed in our experience, too, especially the confusion about the terms used and the difficulty to capture the overall system. The suggested strategies were helpful, too, such as clarifying the terms used by both the modeler and audience and agreeing on consistent use of a common term, or first providing an overview of the model.

In addition to the points raised by Hall et al. (2014), the time needed for effective communication can be emphasized. Starting with the overall picture of the system and then going into detail step by step is beneficial. Yet, the detailed formulations of the model often remain undiscussed due to the time limitations in any communication setting or because the audience is not willing or ready for such a detailed discussion. Therefore, in the cases where model formulations should be discussed in detail, for instance for validation purposes, the modeler/analyst is suggested to prepare the communication setting accordingly and efficiently.

Quantification of robustness

The analysis framework used in this study included several robustness metrics grouped into three as expectation-based, regret-based and statistical metrics. These metrics are introduced in Chapter 6, with a discussion on the benefits and shortcomings of each, yet no comparison between them is made with the aim of selecting a single metric. Instead, it is preferred to consider all these options to deal with methodological uncertainty. Still, based on their definitions and the observations during the analysis, it can be said that several of these metrics are prone to misconceptions, as discussed below.

Firstly, the expectation-based metrics focus on a single aspect of the scenario space, such as the worst scenario (*Min* metric) or the average value (*Mean*). Assessing the performance of a policy against uncertainties with these metrics cannot be claimed to be wrong, yet it can be argued to be from a very limited view. Especially when a high number of scenarios is taken

130B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

into account as in this study, for instance, the *Min* metric retrieves a single scenario among these and neglects the rest of information about the scenario space. Robustness metric choice also depends on how risk-averse or risk-prone the decision maker is. Still, it is advised to use robustness metrics which are more comprehensive than others in terms of capturing various characteristics of the scenario space, such as the skewness towards more desired outcomes or the peakedness indicating a narrow uncertainty range.

The second group of metrics, namely the regret-based ones, are powerful due to their assessment of each policy in each scenario, in contrast to statistical metrics which measure the impact of a policy on the entire scenario space. Still, statistical metrics can be favored over the regret-based metrics when scenarios have an uneven distribution in the scenario space, e.g. represented by a very steep density curve, or when such characteristics of the scenario space are important for the decision maker.

Among the five statistical metrics used in this study, the first one was a single (one-dimensional) measure (*Mean / Standard deviation)*, whereas the others were two dimensional metrics that couple the *Mean* value with a statistic representing the dispersion of the scenario space. The *Mean/Std.dev.* metric was computationally simpler, but since it does not differentiate between the importance of the mean value and the standard deviation of a scenario space, it can cause misleading results. For instance, as shown in Section 8.3.3, with particular weight sets and in 2062, the permission to shale gas extraction results as the most preferred policy for the share of renewables in the gas and in the total energy mix if the *Mean/Std.dev.* metric is used. Given the adverse effects of the shale gas production on the share of renewables in the market, this finding is controversial, but it stems for a lower standard deviation created by the shale gas policy rather than a higher mean of the impact scores in the scenario space, compared to the other policies. This result is acceptable only if a narrow uncertainty space is more favorable than a better value of the outcome indicators by the decision maker, which is often not the case. Hence, despite its advantages in computational implementation and understanding, the *Mean/Std.dev.* metric should be used with caution.

As for the two-dimensional statistical metrics, namely the couplings of *mean* with *interquartile distance, kurtosis,* and two different *skewness* metrics, they do not lead to the pitfall of *Mean/Std.dev.* because the two statistics are treated as two different, equally important decision criteria. In other words, the policies are compared to each other both in terms of the mean value and the dispersion metric, and the ones which are not dominated by another in terms of any of the two metrics are included in the Pareto set. This approach is considered to be more reliable and transparent, although it brings another layer of computational complexity, and may lead to large Pareto sets implying no distinct results about preferred policies. It must also be noted that a high number of outcome indicators, as in this study, increases the computational complexity of this robustness approach and reduces the understanding of results, because eventually the policies are compared to each other on criteria twice as many as the outcome indicators.

131A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

9.4. LIMITATIONS OF THE STUDY

This section discusses the shortcomings of this study, that should be taken into account together with the results, and that pinpoint further research possibilities. These shortcomings are grouped into three, as related to the scope of the study in general, as related to the exploratory modeling approach, and as related to the analysis framework developed and used in this study.

Limitations related to the scope

This study dealt with a national-level policy problem in the energy sector, which involved several technological, economic and social issues as well as many actors with different interests associated with them. The complexity that resulted from the interconnections in such a broad context was high, and capturing this complexity in such a quantitative, model-based analysis required assumptions about the scope of the study. These scoping assumptions impose three major limitations, which are discussed below:

Firstly, the number of outcome indicators representing the variety of policy goals was limited to eight. As discussed before, this number was still relatively high due to the analytical complexity it caused. Yet, more policy objectives and more outcome indicators derived from them could be included in such a study, with corresponding system boundaries.

Secondly, the system boundaries were determined with a focus on the gas market. The gas sector is not completely isolated from the rest of the energy system, but several issues which are not directly linked with the gas system are left out. For instance, several new technologies are being introduced to the energy market, which can affect either the supply or the demand of gas. The power-to-gas technology which produces renewable gas from excess electricity with short-term fluctuations is currently the most promising technology, which brings the gas and electricity systems closer to each other. However, this supply option is not included in the model due to the discrepancy in the time scales, i.e. the short term intermittency of renewable electricity production vs. the long-term view of this study. The scope of this study also excludes several other technologies that are not viable yet, but that may directly or indirectly influence the gas sector. Besides, the international gas market is not explicitly taken into account, but represented by uncertain parameters such as ‘import availability’ and ‘reference import price’.

The third limitation related to the scope stems from the extent of uncertainties that are considered to influence the system. A long list of uncertainties from various sources are included in this study, yet there is still a number of uncertainties which have been deliberately or unintentionally left out. For instance, the impact of abovementioned technologies which are not within the system boundaries is an example of uncertainty excluded from the scope of this study. Furthermore, the scope also excludes abrupt events occurring at an unknown time in future, such as natural disasters or an unexpected political crisis. Lastly, as the severest degree of uncertainty implies, there may be unknown unknowns, e.g. the uncertainties which were not known either to the actors and stakeholders or to the analysts, hence could not be captured in the scope of this study.

131B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Limitations of (exploratory) modeling

Models have long been used in policy analysis and their limitations have long been discussed. It is needless to repeat here that the main benefit of using a simulation model is the ability to experiment with policy decisions, which is very costly or impossible in real life, while the main limitation of a model is reported as being only a representation of the real life, hence capable of generating wrong estimates.

This limitation of models was a starting point of the development of exploratory modeling, as discussed in Chapter 3. Conventional models are usually used to provide point-estimates of a future phenomenon for a decision problem, which may be misleading even if the model breadth and depth is wide. In contrast, exploratory models aim to provide range-estimates based on small models, and assess the decision options based on these ranges. In this regard, the exploratory modeling approach is useful to deal with uncertainty, and it is continuously developed with the addition of analysis tools such as scenario discovery, behavior clustering, multi-objective robust optimization and adaptive policy design.

Despite this progress, two limitations of exploratory modeling have been experienced during this study. Firstly, having a large ensemble of scenarios generated by the model, it is not straightforward to understand the structure-behavior relationship and contribute to the decision makers' understanding about the system. This information about how the model structure and behavior are related also helps to understand why a policy works or not. Understanding the structure-behavior relationship is already difficult even in the traditional use of average sized system dynamics models, and the methods to deal with this difficulty are not fully developed (Ford, 1999; Kampmann and Oliva, 2006). Therefore, it is a more challenging analysis when policies are compared in terms of their effects on a scenario space. In this case, such information about the structure-behavior relationship can be obtained either by analyzing each scenario, which is computationally exhaustive, or by grouping the scenarios according to the behavior pattern and investigating the factors that lead to these patterns. The scenario discovery method is helpful to determine uncertainties influential in obtaining a group of scenarios, as shown by Kwakkel *et al.* (2013), yet it lacks a causal storyline and does not completely explain why a particular dynamic behavior occurs.

Secondly, a comprehensive description of the validity of 'exploratory' models is absent in the exploratory modeling approach, as well as a corresponding validation scheme. Regardless of the modeling methodology used, there are established validation tests to ensure that a model fits its development purpose. For exploratory models, the development purpose is known, i.e. generating a variety of model-based scenarios to explore the future, yet there are no commonly accepted guidelines to check if the model fits this purpose. Usually, the modelers apply a validation scheme they prefer, such as consulting experts and stakeholders, or applying some of the traditional validation tests, as done in this study, or they skip this step on testing the reliability of the model. Therefore, investigating how exploratory models can be validated and establishing a commonly-accepted validation scheme would be beneficial not only to enhance the usability of exploratory models but also to strengthen their position in the model-based decision analysis domain.

132A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Limitations of the analysis framework

This study proposed a framework for the analysis of policy options according to their effectiveness on multiple performance criteria, robustness against uncertainties, and when in time their effects are considered. There are three major issues related to the use of this framework in decision making under uncertainty, and they will be discussed below.

The first issue is related to the use of the 'robustness' concept in multi-criteria decision analysis (MCDA) methods instead of direct 'impact' (or 'utility') of a policy. In this study, robustness is used as an approximate indicator of policy performance rather than the 'utility' of a policy. Still, this view can be contested based on the argument that robustness and utility symbolize different concepts and the multi-criteria methods are designed for the latter. Although using robustness to represent the policy performance does not contradict the axioms of the multi-attribute theory as discussed in Chapter 6, it can be further examined. This examination can especially be about how the decision makers and stakeholders value robustness compared to the direct effect of a policy on a particular outcome indicator in a single scenario.

The second issue arises from the ranking approach used in comparing the policies. Once an aggregate measure of the policy performance is obtained based on the three dimensional framework, it is straightforward to rank the policies with respect to these measures. However, this ranking approach overlooks the magnitude of the difference between two options, and immediately assumes that one of them outperforms the other. Therefore, when there is little discordance between the options, i.e. when they are differentiated by a small magnitude as observed in some cases in this study, this ranking approach may be misleading by favoring the policy options which are not considerably better than the others. Besides, the focus on ranking of policies may lead to overlook interesting insights that can be obtained from an EMA study. Using scenario discovery to understand the effect of uncertainties on policy performance is a powerful tool in this case to eliminate such drawbacks.

The third issue relates to the transparency of information obtained from an analysis based on this framework. The results of such an analysis provide information about the preferred policies and how they depend on the methods used. Yet, the information about how a policy performs in various scenarios and with respect to various policy objectives is aggregated into a single value. On the one hand, the compactness of this information enables a concise comparison of policy options. On the other hand, it prevents reaching an immediate conclusion about the impact of a policy on a particular outcome indicator, or impedes understanding the reasons of a particular outcome. Tracing such reasons back is certainly possible, but it requires further analysis which may be computationally intense and interpretation-wise difficult. Therefore, there is a tradeoff associated with this framework, between the clarity and simplicity of resulting information and the ability to provide decision advice based on a quantitative analysis of robustness and multi-criteria performance of the policy options.

132B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

9.5. FUTURE RESEARCH

While discussing the limitations of this study, the previous sections hinted at the points of departure for future research to deal with them. In this section, this future research potential is discussed with respect to the topics that should be further examined in the gas sector, and the methodological improvements in exploratory modeling and the framework introduced for robust decision making.

As discussed in Section 9.3.1, the significance of societal acceptance in the Dutch gas sector regarding natural gas production, and its impact on the policies has developed very rapidly. This study included a simple model structure that can indicate the dynamics of societal acceptance and its influences on the natural gas investments and consumer choice between natural and renewable gas, yet it was a preliminary attempt. Considering the developments in the last three years, and the expected importance of public opinion not only regarding natural gas extraction but also in the entire energy sector, it is worthwhile to investigate how the societal acceptance of an energy technology can change in future, and how this societal acceptance affects the growth or decline of a technology. Especially in terms of representing behavioral futures in quantitative models and the heterogeneity of public opinion, such work on societal acceptance can build upon the review of Wilson *et al.* (2014) on the behavioral features of end-user decision making, and the behavioral realism in integrated assessment models.

Regarding the exploratory modeling approach, conceptualizing the validity of exploratory models and investigating how such validity can be evaluated is a highly important subject and it is expected to significantly contribute to the use of exploratory models for decision making under uncertainty. Two approaches can be adopted to initiate this research on the validation of exploratory models: Firstly, discussions with the developers and users of exploratory models about the conceptualization of validity and how they assess the fit of a model to the purpose are expected to be insightful to initiate this research. Secondly, the validation tests used in conventional modeling studies with various methodologies, such as discrete-event simulation (Balci, 1994), system dynamics (Barlas, 1996; Sterman, 2000) and agent-based modeling (Windrum *et al.*, 2007), can be examined. These tests can be classified according to their usability for exploratory models, since the purpose of exploratory models differs from that of conventional models, and not every test is suitable for the former. If suitable, adoption or adaptation of these tests could be beneficial.

The study of Keijser *et al.* (2012) was an initial attempt to overcome the second limitation of exploratory modeling about the behavior analysis, i.e. understanding the relations between particular groups of scenarios and the model structure. This study used the Loop Deactivation Method (Ford, 1999), which is a well-known behavior analysis technique in system dynamics literature. However, this technique is not powerful for mid-size and large models, and the categorization of behavior patterns does not yield accurate results yet. Therefore, this research on using the Loop Deactivation Method can be continued to improve the behavior analysis aspect of exploratory systems dynamics modeling. Alternatively, the Eigenvalue Elasticity Analysis technique (Kampmann and Oliva, 2006), which is another formal analysis technique for system dynamics models, can be incorporated into exploratory modeling and analysis

133A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

tools, for a computationally more intensive but mathematically more thorough analysis of behavior patterns observed in the exploration of scenarios.

In this study, we used a model-based representation of different stakeholder perspectives to analyze these perspectives and their corresponding scenario spaces. This analysis was helpful to understand the most restricting conditions of a perspective, and the conflicting objectives and system elements in the gas sector in general. In future work, this analysis can be extended to policy testing, i.e. comparison of policies to each other from each perspective, to search for policies that are acceptable by each of these perspectives, or for policies that cause highest disagreement. Such a study is deemed valuable to strengthen the policy recommendations by including a multi-actor view in an exploratory modeling and analysis study.

As for the three dimensional framework proposed in this study for the analysis of policies, using robustness to represent the performance of a policy in multi-criteria decision analysis is a contestable choice, as mentioned before. Therefore, the use of robustness as an attribute in multi-criteria decision analysis methods should be further investigated. For this purpose, how robustness is valued by stakeholders compared to the actual value of a policy objective should be examined when this framework is to be used for policy analysis under uncertainty. In other words, the potential users of this framework are advised to discuss the implications of this framework and each methodological option in the three dimensions of it with the stakeholders of a particular problem, and the eventual multi-criteria methods and robustness metrics used should be based on this communication. Furthermore, different Multi-Criteria Decision Analysis methods can be used in this framework, for instance outranking methods, in order to take the degree of discordance between policy options.

The last point for future research is related to the use of this framework in adaptive policy design. As mentioned in Chapter 3, static robust policies and adaptive policies represent two of the policy approaches to deal with uncertainty. These approaches both acknowledge the multiplicity of future possibilities and suggest to make a change in the system, yet this change is static in the former approach, while it is dynamic in the latter. This study adopted the static robust policy approach in selecting the analysis techniques and making policy recommendations eventually. However, the dynamic comparison of policies over time, e.g. in every year during the simulation horizon, reveals when the preference for a policy changes, and the scenario discovery helps to investigate why this change occurs. This information is valuable to plan adaptive policies which suggest changes in the actions depending on the changes in the system. Therefore, future research can focus on the design of adaptive policies for the gas sector, using the information obtained from the time series of preferred policies and the triggers of change in preferences.

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134A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

134B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Appendices to Chapter II

APPENDIX 2.1: THE LIST OF INTERVIEWEES

Interviewee	Position	Organization	Date and Place
Hans van der Meer	Regulatory Affairs Manager	NAM (Natural gas producer)	17/10/2012, Assen
Gert Jan Kramer	Manager of Energy Futures Department, Professor of Sustainable Energy	Shell (Natural gas Producer)	09/11/2012, Phone call
Guido Hoetz Ewout Pikaar	Leader of Technology Projects Public Affairs Advisor	EBN (The government-owned natural gas company)	24/10/2012, Utrecht
Gerard Martinus Warner ten Kate	Energy Transitions Project Leader Public Affairs Advisor	GasTerra (Trader)	16/10/2012, Groningen
Albert van der Molen	Asset Management Expert	Stedin (Distribution System Operator)	31/10/2012, Rotterdam
Mathieu Dumont	Senior policy consultant	Netherlands Enterprise Agency (The government agency for policy implementation formerly known as Agentschap NL)	26/03/2014, Utrecht

135A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Appendices to Chapter IV

APPENDIX 4.1: EXPLORATION AND DEVELOPMENT COST OF UNIT NATURAL GAS PRODUCED

As mentioned in the explanation of natural gas economics in Section 4.2.1, the exploration and development costs of one unit gas extracted immediately from the *Developed Reserves* are not equal to the unit costs of exploration and development *(C_{exp} and C_{dev})* because of the delays between exploration and production. The effect of these delays is modeled with a co-flow structure and the average exploration cost and average development cost of one unit of developed reserves *($C_{exp,DRv}$* and *$C_{dev,DRv}$*, respectively*)* to be added to the total cost of one unit of gas sold.

Figure A4.1 shows this co-flow chain where each stock variable represents the total exploration cost of resources or reserves in the corresponding stock variable. For instance, *Total Exploration Cost of Contingent Resources* accumulate over time as the new resources are discovered at a cost value equal to *Unit Exploration Cost*, and the economically recoverable resources leave this stock at a cost equal to the *Average Exploration Cost of Contingent Resources.* (Note that the flow formulation are multiplications of the cost and resource flow.) This average cost is simply the division of *Total Exploration Cost of Contingent Resources* by *Contingent Resources*. This structure is repeated for each element of the chain, resulting in the *Average Exploration Cost of Developed Reserves*, which is the average cost paid for the exploration of one unit of gas extracted at that time.

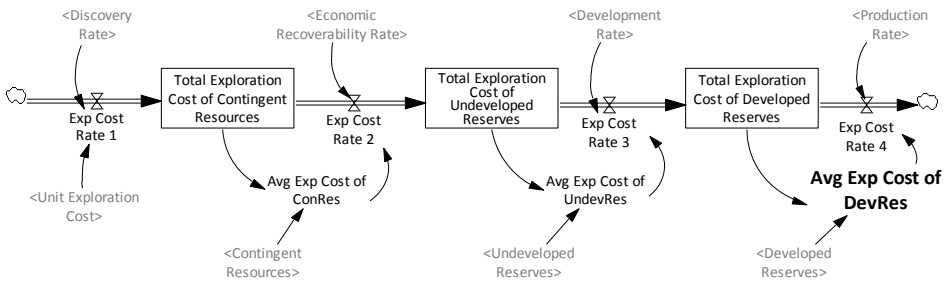


Figure A4.1: Co-flow structure for the average exploration cost

This co-flow structure is simpler for the *Average Development Cost of Developed Reserves* since *Developed Reserves* is the only stock variable that causes a delay after development. Figure A4.2 shows this structure, where the formulations are the same as those explained in the previous paragraph.

135B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

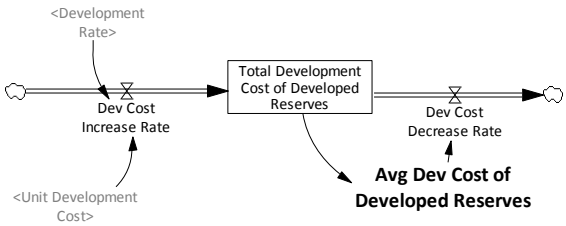


Figure A4.2: Co-flow structure for the average development cost

APPENDIX 4.2: NET COST OF BIOMETHANE PRODUCTION (NC_I)

This formulation replicates the cost calculations of ECN. As in the main text, *i* denotes the number of years ahead, and *r* is the interest rate. The annual equivalent of the investment cost (EAC_{bm}) and the variable unit cost of biomethane (VUC_{bm}) are formulated similar to those of biogas, as in Equations 40 and 39, respectively. (In Equation 40, the term after IC_{bg} gives the annual equivalent of the investment cost.) *Participation Tax* is the income tax, and equal to 25%.

$$NC_i(t) = Annual\ O\&M\ Costs_i(t) - Tax\ Amount_i(t) + EAC_{bm}$$

$$Annual\ O\&M\ Costs_i(t) = Inflator_i * VUC_{bm}(t)$$

$$Inflator_i = (1+0.02)^{i-1}$$

$$Tax\ Amount_i(t) = -\%ParticipationTax * \begin{pmatrix} -Annual\ O\&M\ Costs_i(t) + Annual\ Interest_i(t) \\ +Depreciation \end{pmatrix}$$

$$Depreciation = -\frac{Investment\ Cost}{T}$$

$$Annual\ Interest_i(t) = -r^* * Investment\ Cost * \left(1+r^*\right)^{i-1} - EAC_{bm} * \left(1+r^*\right)^{i-1}$$

APPENDIX 4.3: IMPORT PRICE

The formulation of *Import Price* is given in Equation A4.1. In this equation, $p_{imp}(0)$ stands for *Reference Import Price*, *RI* for *Reference Imports*, and δ for *Import Demand Curve Constant*. This formulation is based on analysing the geometry of the supply and demand curves. The supply and demand curves are assumed to be linear for simplicity, and intersect each other initially at the point (p_1, q_1) as shown in Figure A4.3 below. Besides, this formulation implies that the price response to demand change is dependent on parameters like reference import amount, reference price and demand curve constant, which define the demand curve. Since the response of price to demand change is actually uncertain, varying these parameters would allow investigating different price responses.

$$p_{imp}(t) = \frac{p_{imp}(0)}{\delta}\left(CID(t)\frac{\delta - p_{imp}(0)}{RI} + \delta\right) \qquad \text{(A4.1)}$$

136A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

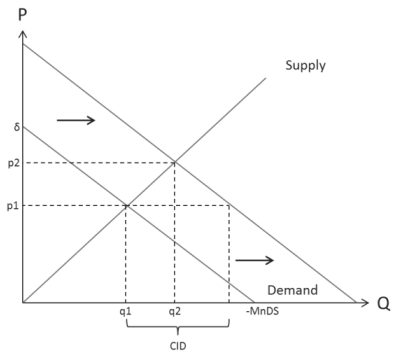


Figure A4.3: Geometric representation of the Import Price change with supply and demand curves

An increase in the import demand as the domestic production decreases causes the demand curve to shift upwards, the new equilibrium occurs at (p_2, q_2). p_2 is the price value sought for, which gives the formula of $p_{imp,j}$. (j=pipeline, LNG)

The equation of the supply curve that passes through (p_1, q_1) can be written as

$$p = \frac{p_1}{q_1} q$$

The equation of the demand curve is as the following, where m is the slope and δ is the point that it intersects the price (p) axis:

$$p = -mq + \delta$$
$$p_1 = -mq_1 + \delta \Rightarrow m = \frac{-p_1 + \delta}{q_1}$$

Since the shifted demand curve has the same slope and passes through the point (p_1, q_1+CID) where *CID* stands for the Change in Demand, the equation of the new demand curve is (with x representing where this curve intersects with the x axis, which is –MnDS on Figure A4.3)

$$p = -mq + x$$
$$p_1 = -m(q_1 + CID) + x$$
$$-mq_1 + \delta = -mq_1 - mCID + x$$
$$\Rightarrow x = mCID + \delta$$
$$\Rightarrow p = -mq + mCID + \delta$$
$$\Rightarrow p = -\left(\frac{-p_1 + \delta}{q_1}\right) q + \left(\frac{-p_1 + \delta}{q_1}\right) CID + \delta$$

The intersection of this new demand curve and the supply curve gives the point (p_2, q_2).

136B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$p = -\left(\frac{-p_1+\delta}{q_1}\right)q + \left(\frac{-p_1+\delta}{q_1}\right)CID + \delta = \frac{p_1}{q_1}q$$

$$\Rightarrow q_2\left(\frac{p_1}{q_1} + \frac{-p_1+\delta}{q_1}\right) = \left(\frac{-p_1+\delta}{q_1}\right)CID + \delta$$

$$q_2 = \frac{\left(\frac{-p_1+\delta}{q_1}\right)CID + \delta}{\frac{\delta}{q_1}}$$

$$p_2 = \frac{p_1}{q_1}q_2 \Rightarrow p_2 = \frac{p_1}{q_1}\left(\left(\frac{-p_1+\delta}{q_1}\right)CID + \delta\right)\frac{q_1}{\delta}$$

$$p_2 = \frac{p_1}{\delta}\left(CID\frac{\delta - p_1}{q_1} + \delta\right)$$

In the general formula, p_1 is replaced by Reference Import Price ($p_{imp,j}(0)$) and q_1 is replaced by Reference Imports (RI_j). Import Demand Curve Constant (δ_j) is the parameter that shows the point that the demand curve intersects the price axis, namely it is the price when demand is zero.

APPENDIX 4.4: OWN-PRICE DEPENDENT CHANGE RATE

Price elasticity of demand is defined as "the percentage by which the quantity demanded will change if the price of the item rises by 1%". In general terms, having *Q* as the demand quantity and *P* as price, price elasticity of demand is as shown in Equation A4.2:

$$e = \frac{\Delta Q/Q}{\Delta P/P} \tag{A4.2}$$

$$\Delta Q = Q * e * \frac{\Delta P}{P} \tag{A4.3}$$

From this definition, the percentage change in the quantity demanded is derived as the multiplication of the elasticity and the percentage change in price, assuming a constant elasticity value. Hence, the actual change in demand becomes the multiplication of the quantity demanded, elasticity parameter and the percentage change in price, as Equation A4.3 shows. Equation A4.4 denotes the use of this formulation for *Own-price Dependent Change Rate (ODCR)* of renewable gas demand in particular. In this equation, D_{RG} is the *Renewable Gas Demand*, e_{RG} is the own-price elasticity of the renewable gas demand, and $p_{bmt}(t)$ is the biomethane price at time t. Since *ODCR* represents the annual change rate in demand, the change in price is determined on an annual basis, too. Hence, the percentage change in price is calculated as the ratio of the difference between two subsequent years to the previous year's price value.

$$ODCR_{RG}(t) = D_{RG}(t)e_{RG}\frac{p_{bmt}(t) - p_{bmt}(t-1)}{p_{bmt}(t-1)} \tag{A4.4}$$

APPENDIX 4.5: SUBSTITUTION RATE BASED ON *ELASTICITY OF SUBSTITUTION*

Elasticity of Substitution (EoS) is defined as "a proportionate change in the ratio of two factors corresponding to a proportionate change in their marginal rate of substitution or in

137A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

their price ratio" (Mundlak, 1968, 1). Equation A4.5 denotes this definition, where Q_1 and Q_2 are the quantity demanded for good 1 and 2, and U_1 and U_2 are the values of the factor they are dependent on, e.g. utility.

$$e_{sub} = \frac{\frac{\Delta(Q_2/Q_1)}{Q_2/Q_1}}{\frac{\Delta(U_2/U_1)}{U_2/U_1}} \tag{A4.5}$$

Following this definition, and assuming a constant elasticity, the percentage change in the demand ratios of natural gas (NG) and renewable gas (RG) at each time step of the model (dt) is

$$\frac{\frac{d(D_{NG}/D_{RG})}{D_{NG}/D_{RG}}}{dt} = e_{sub}\frac{\frac{d(U_{NG}/U_{RG})}{U_{NG}/U_{RG}}}{dt} \tag{A4.6}$$

Denoting the right-hand-side of this equation by Y for now, and knowing that in the case of substitution $\frac{dD_{NG}}{dt} = -\frac{dD_{RG}}{dt}$, the (indicated) substitution rate $\frac{dD_{NG}}{dt}$ can be found as follows:

$$\begin{aligned}
&\frac{\frac{d(D_{NG}/D_{RG})}{D_{NG}/D_{RG}}}{dt} = Y \;\Rightarrow\; \frac{d(D_{NG}/D_{RG})}{dt} = \frac{D_{NG}}{D_{RG}}Y \\
&(\textit{quotient rule}) \;\Rightarrow\; \frac{\frac{dD_{NG}}{dt}D_{RG} - \frac{dD_{RG}}{dt}D_{NG}}{D_{RG}^2} = \frac{D_{NG}}{D_{RG}}Y \\
&\left(\frac{dD_{RG}}{dt} = -\frac{dD_{NG}}{dt}\right) \Rightarrow \frac{dD_{NG}}{dt}(D_{NG}+D_{RG}) = D_{RG}^{\cancel{2}}\frac{D_{NG}}{\cancel{D_{RG}}}Y \\
&\Rightarrow \frac{dD_{NG}}{dt} = \frac{D_{NG}D_{RG}}{D_{NG}+D_{RG}}Y
\end{aligned} \tag{A4.7}$$

The term with utilities in Y represents the percentage change in the relative utility of *NG* to *RG*. In the model, instead of defining two variables, one for NG and one for RG, and looking at their ratios, the relative utility, *u(t)*, is defined as a single variable, i.e. with the ratios of prices and societal acceptance levels of the two gas types (see Equation 93). Therefore, having the percentage change in the relative utility as in Equation A4.8, Y is re-written as in Equation A4.9, which leads to the *Substitution Rate* formulation in Equation A4.10.

$$\frac{\frac{d(U_{NG}/U_{RG})}{U_{NG}/U_{RG}}}{dt} = \frac{u(t)-u(t-1)}{u(t-1)} \tag{A4.8}$$

$$Y = e_{sub}\frac{u(t)-u(t-1)}{u(t-1)} \tag{A4.9}$$

$$SR(t) = \frac{D_{NG}(t)D_{RG}(t)}{D_{NG}(t)+D_{RG}(t)}e_{sub}\frac{u(t)-u(t-1)}{u(t-1)} \tag{A4.10}$$

137B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Appendices to Chapter V

APPENDIX 5.1: BASE-RUN VALUES AND UNCERTAINTY RANGES OF MODEL PARAMETERS

Natural Gas Sub-model

	Parameter	*Symbol*	*Unit*	*Base Run Value*	*Uncertainty Range*
Initial conditions	GIIP[groningen]	$PRs_{gr}(0)$	bcm	0	-
	GIIP[small fields]	$PRs_{sf}(0)$	bcm	800	400-1000
	GIIP[shale]	$PRs_{sh}(0)$	bcm	110000	48000-230000
	Contingent Resources[groningen]	$CRs_{gr}(0)$	bcm	88	-
	Contingent Resources[small fields]	$CRs_{sf}(0)$	bcm	246	-
	Contingent Resources[shale]	$CRs_{sh}(0)$	bcm	0	-
	Undeveloped Reserves[groningen]	$URv_{gr}(0)$	bcm	207.2	-
	Undeveloped Reserves[small fields]	$URv_{sf}(0)$	bcm	129.4	-
	Undeveloped Reserves[shale]	$URv_{sh}(0)$	bcm	0	-
	Developed Reserves[groningen]	$DRv_{gr}(0)$	bcm	828.8	-
	Developed Reserves[small fields]	$DRv_{sf}(0)$	bcm	310.6	-
	Developed Reserves[shale]	$DRv_{sh}(0)$	bcm	0	-
	Cumulative Production[groningen]	$CPR_{gr}(0)$	bcm	1344	-
	Cumulative Production[small fields]	$CPR_{sf}(0)$	bcm	824	-
	Cumulative Production[shale]	$CPR_{sh}(0)$	bcm	0	-
Field lifecycle	Initial Unit Exploration Cost[small fields]	$C_{exp,sf}(0)$	bEUR/bcm	0.02	0.02-0.06
	Initial Unit Exploration Cost[shale]	$C_{exp,sh}(0)$	bEUR/bcm	0.04	0.02-0.15
	Unit Development Cost[groningen]	$C_{dev,gr}(0)$	bEUR/bcm	0.015	0.01-0.06
	Unit Development Cost[small fields]	$C_{dev,sf}(0)$	bEUR/bcm	0.016	0.01-0.1
	Unit Development Cost[shale]	$C_{dev,sh}(0)$	bEUR/bcm	0.06	0.03-0.15
	Average Lifetime[groningen]	T_{gr}	Year	18	-
	Average Lifetime[small fields]	T_{sf}	Year	13	-
	Average Lifetime[shale]	T_{sh}	Year	15	-
Economics	Normal Intended Inv. in Exploration[small fields]	$INV^0_{exp,sf}$	bEUR/year	0.15	0.-5-0.35
	Normal Intended Investment in Exploration[shale]	$INV^0_{exp,sh}$	bEUR/year	0.15	0.15-1
	Normal Intended Inv. in Development [groningen]	$INV^0_{dev,gr}$	bEUR/year	0.4	0.4-0.8
	Normal Intended Inv. in Development[small fields]	$INV^0_{dev,sf}$	bEUR/year	0.5	0.5-2.5
	Normal Intended Investment in Development[shale]	$INV^0_{dev,sh}$	bEUR/year	0.5	0.5-2.5
	Normal Econ. Recoverability Fraction [groningen]	r^0_{gr}	1/year	0.39	0-1
	Normal Econ. Recoverability Fraction [small fields]	r^0_{sf}	1/year	0.26	0-1
	Normal Econ. Recoverability Fraction [shale]	r^0_{sh}	1/year	0.2	0-1
	Normal Unit Production Cost[groningen]	$C^*_{prod,gr}$	EUR/cm	0.0075	0.005-0.08
	Normal Unit Production Cost[small fields]	$C^*_{prod,sf}$	EUR/cm	0.01	0.01-0.08
	Normal Unit Production Cost[shale]	$C^*_{prod,sh}$	EUR/cm	0.08	0.06-0.2

138A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

	Desired NG Profit Markup	PM^*_{NG}	Dmnl	3	3-6
	SA Reaction Delay	d_{SA}	years	2	1-5
	NG Producer Price Structure Switch	*PPSS*	Dmnl	0.5	0, 0.5, 1

Renewable Gas Sub-model

	Parameter	*Symbol*	*Unit*	*Base Run Value*	*Uncertainty Range*
Initial values	Initial Value of Biogas Prod. Capacity [digestion]	$BG_{C,dig}(0)$	bcm/Year	0.255	-
	Initial Value of Biogas Prod. Capacity [gasification]	$BG_{C,gas}(0)$	bcm/Year	0	-
	Initial Biomethane Production Capacity [digestion]	$BM_{C,dig}(0)$	bcm/year	1.00E-07	-
	Initial Biomethane Production Capacity [gasification]	$BM_{C,gas}(0)$	bcm/year	0	-
Biogas Production	Average Lifetime of Biogas Plants	d_T^{BG}	Year	25	20-30
	Small Plant Installation Delay	d_I	Year	1	1-3
	Average Biomass Yield [digestion]	y_{dig}	bcm/Mton	0.5	0.02-0.8
	Average Biomass Yield [gasification]	y_{gas}	bcm/Mton	0.5	0. 2-0.8
	Price Elasticity of Biogas Demand	e_H	Dmnl	-0.1	-1 - 0
	Price Adjustment Delay	d_P	Year	2	0.1 - 3
	Investment Cost of Biogas Capacity [digestion]	$IC_{bg,dig}$	bEUR/(bcm/Year)	0.53	0.46 - 0.61
	Investment Cost of Biogas Capacity [gasification]	$IC_{bg,gas}$	bEUR/(bcm/Year)	0.6	0.5 - 0.7
	Interest rate	r	1/Year	0.15	0.05- 0.15
	Normal Production Cost of Biogas [digestion]	$PC_{bg,dig}$	EUR/m^3	0.16	0.1 - 0.2
	Normal Production Cost of Biogas [gasification]	$PC_{bg,gas}$	EUR/m^3	0.35	0.3 - 0.45
	Learning Curve Parameter of Biogas [digestion]	$l_{bg,dig}$	Dmnl	0.35	0.1 - 0.6
	Learning Curve Parameter of Biogas [gasification]	$l_{bg,gas}$	Dmnl	0.35	0.1 - 0.6
	Initial Total Biogas Production	$C_{bg}(0)$	bcm	2.76	-
	Biomass Price [digestion]	p_{bms}	EUR/ton	15	0 - 35
	Biomass Price [gasification]	p_{bms}	EUR/ton	15	15 - 35
	Biogas Desired Profit Markup	PM_{bg}^*	Dmnl	0.05	0 - 0.25
Biomethane Production	Average Lifetime of Upgrading Plants	d_T	year	25	20 -30
	Upgrading Efficiency	υ	Dmnl	0.74	0.68 - 8
	Investment Cost of Biomethane Capacity [digestion]	$IC_{bm,dig}$	bEUR/(bcm/Year)	0.45	0.35 - 0.7
	Investment Cost of Biomethane Cap. [gasification]	$IC_{bm,gas}$	bEUR/(bcm/Year)	0.5	0.4 - 0.75
	Normal Production Cost of Biomethane [digestion]	$PC_{bm,dig}$	EUR/m^3	0.163	0.12 - 0.25
	Normal Production Cost of Biomethane [gasification]	$PC_{bm,gas}$	EUR/m^3	0.25	0.2 - 0.35
	Learning Curve Parameter of Biomethane	l_{bm}	Dmnl	0.5	0 - 0.5
	Desired Profit Markup of Biomethane	PM_{bm}^*	Dmnl	0.1	0 - 0.25
	Reference Biomethane Price	$p_{bm}^*(0)$	EUR/m^3	0.59	-
	Producers' Decision Structure Switch	*PIDS*	Dmnl	0	0, 1

138B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Import Sub-model

Parameter	*Symbol*	*Unit*	*Base Run Value*	*Uncertainty Range*
Initial Import Capacity[pipe]	$Imp_{C,pipe}(0)$	bcm/year	49.5	-
Initial Import Capacity[lng]	$Imp_{C,lng}(0)$	bcm/year	0	-
Transport Capacity Avg Lifetime[pipe]	T_{pipe}	year	60	30-90
Transport Capacity Avg Lifetime[lng]	T_{lng}	year	60	30-90
Annual Transit Demand		bcm/year	22	0-30
Fixed Import Cost[pipe]	$FC_{imp,pipe}$	EUR/cm	0.75	0.75-1.5
Fixed Import Cost[lng]	$FC_{imp,lng}$	EUR/cm	0.65	0.5-1.5
Reference Estimated Gas[pipe]	EIA^*_{pipe}	bcm/year	50	10-50
Reference Estimated Gas[lng]	EIA^*_{lng}	bcm/year	20	10-80
Reference Import Cost[pipe]	$TUC^*_{imp,pipe}$	EUR/cm	1.5	1-2
Reference Import Cost[lng]	$TUC^*_{imp,lng}$	EUR/cm	1.5	1-2
Import Potential[pipe]	IP_{pipe}	bcm/year	100	20-100
Import Potential[lng]	IP_{lng}	bcm/year	30	10-100
Political Restriction Fraction[pipe]	$\rho_{imp,pol}$	Dmnl	0	0-0.5
Political Restriction Fraction[lng]	$\rho_{imp,pol}$	Dmnl	0	0-0.5
Average Market Price outside NL	p_{intl}	EUR/cm	0.115671	0.1-0.5
Import Demand Curve Constant[pipe]	δ_{pipe}	EUR/cm	0.8	0.2-1.2
Import Demand Curve Constant[lng]	δ_{lng}	EUR/cm	0.5	0.2-1.2
Reference Imports[pipe]	RI_{pipe}	bcm/year	8	5-15
Reference Imports[lng]	RI_{lng}	bcm/year	10	5-15
Reference Import Price[pipe]	$p_{imp,pipe}(0)$	EUR/cm	0.2	-
Reference Import Price[lng]	$p_{imp,lng}(0)$	EUR/cm	0.2	-

Demand Sub-model

	Parameter	*(subscript)*	*Symbol*	*Unit*	*Base Value*	*Uncertainty Range*
Initial values	Initial Natural Gas Demand	households	$D_{NG,h}(0)$	bcm/year	18	-
		industry	$D_{NG,i}(0)$		5	-
		agriculture	$D_{NG,a}(0)$		15.7	-
		transport	$D_{NG,t}(0)$		0	-
	Initial Renewable Gas Demand	households	$D_{RG,h}(0)$	bcm/year	0.0025	-
		industry	$D_{RG,i}(0)$		0.0025	-
		agriculture	$D_{RG,a}(0)$		0.0025	-
		transport	$D_{RG,t}(0)$		0.0025	-
External change rate	NG Demand Normal Change Fraction	households	$f_{NG,h}$	1/year	2000: -0.004 2012: 0 2025: 0 2035: 0	2012: -0.005 - 0.03 2025: -0.015 – 0.02 2035: -0.02 – 0.02
		industry	$f_{NG,i}$	1/year	2000: 0.005 2012: 0 2025: 0 2035: 0	2012: -0.005 - 0.03 2025: -0.015 – 0.02 2035: -0.02 – 0.02
		agriculture	$f_{NG,a}$	1/year	2000: 0.005 2012: 0 2025: 0 2035: 0	2012: -0.01 - 0.03 2025: -0.015 – 0.02 2035: -0.02 – 0.02
		transport	$f_{NG,t}$	1/year	2000: 0.001 2012: 0 2025: 0 2035: 0	2012: 0 – 0.1 2025: -0.02 – 0.1 2035: -0.01 – 0.05
	RG Demand Normal Change	households	$f_{RG,h}$	1/year	2000: 0 2012: 0.05	2012: -0.005 - 0.03 2025: -0.01 - 0.02

139A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

	Fraction					2025: 0.03 2035: 0	2035: -0.02 – 0.02
		industry	$f_{RG,i}$	1/year	2000: 0 2012: 0.01 2025: 0.01 2035: 0	2012: 0 - 0.02 2025: -0.01 - 0.02 2035: -0.02 – 0.02	
		agriculture	$f_{RG,a}$	1/year	2000: 0 2012: 0.05 2025: 0.03 2035: 0	2012: -0.001 - 0.03 2025: -0.02 - 0.02 2035: -0.01 - 0.02	
		transport	$f_{RG,t}$	1/year	2000: 0 2012: 0.05 2025: 0.05 2035: 0	2012: 0 - 0.075 2025: -0.02 - 0.05 2035: -0.01 - 0.035	
Own-price depen. change	Ownprice elasticity of NG Demand	households	$e_{NG,h}$	Dmnl	0.177	-2 – 0	
		industry	$e_{NG,i}$	Dmnl	-0.936	-1.5 – 0	
		agriculture	$e_{NG,a}$	Dmnl	-0.1487	-1.5 – 0	
		transport	$e_{NG,t}$	Dmnl	-0.73	-1 - 0	
	Ownprice elasticity of RG Demand	households	$e_{RG,h}$	Dmnl	0	-1.5 – 0	
		industry	$e_{RG,i}$	Dmnl	-0.01	-2 – 0	
		agriculture	$e_{RG,a}$	Dmnl	-0.01	-1.5 – 0	
		transport	$e_{RG,t}$	Dmnl	-0.01	-1 – 0	
Substitution rate	Cross-price elasticity of NG Demand to RG Demand	households	$e_{NG,RG,h}$	Dmnl	0.05	0 – 2	
		industry	$e_{NG,RG,i}$	Dmnl	0.05	0 – 1.5	
		agriculture	$e_{NG,RG,a}$	Dmnl	0.05	0 – 1.5	
		transport	$e_{NG,RG,t}$	Dmnl	0.05	0 – 2	
	Elasticity of Substitution RG for NG	households	$e_{sub,h}$	Dmnl	2	0 – 4	
		industry	$e_{sub,i}$	Dmnl	1	0 – 2	
		agriculture	$e_{sub,a}$	Dmnl	2	0 – 4	
		transport	$e_{sub,t}$	Dmnl	1	0 – 2	
	Elasticity of NG Demand to Societal Acceptance	households	$e_{SA,NG,h}$	Dmnl	1.5	0 – 2	
		industry	$e_{SA,NG,i}$	Dmnl	0.8	0 – 1	
		agriculture	$e_{SA,NG,a}$	Dmnl	0.8	0 – 1	
		transport	$e_{SA,NG,t}$	Dmnl	1.5	0 – 2	
	Weight of Societal Acceptance	households	$w_{SA,h}$	Dmnl	0.5	0 – 1	
		industry	$w_{SA,i}$	Dmnl	0.5	0 – 1	
		agriculture	$w_{SA,a}$	Dmnl	0.5	0 – 1	
		transport	$w_{SA,t}$	Dmnl	0.5	0 – 1	
	Substitution Rate Switch	-	-	Dmnl	1	0, 1	

Electricity Production Sub-model

	Parameter	*Symbol*	*Unit*	*Subscript*	*Base Value*	*Uncertainty Range*	*Subscript*	*Base Value*	*Uncertainty Range*
Initial values	Power Generation Capacity	*PGC(0)*	*GW*	biogas	0.06	-	gasDecentral	5.84	-
				biomassCo	0.37	-	gasCCS	0	-
				biomassCHP	0.1	-	nuclear	0.45	-
				coal	3.74	-	solar	0.01	-
				coalCCS	0	-	wind	0.45	-
				gas	8.39	-			
	Cumulative Electricity Production	CP_E	*TWh*	biogas	5	-	gasDecentral	150	-
				biomassCo	5	-	gasCCS	0	-
				biomassCHP	15	-	nuclear	25	-
				coal	250	-	solar	0.1	-
				coalCCS	0	-	wind	10	-
				gas	250	-			
	Societal	SA_E	*Dmnl*	biogas	1	-	gasDecentral	0.9	-

139B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

	Acceptance of Electricity			biomassCo	1	-	gasCCS	0	-
				biomassCHP	1	-	nuclear	0.1	-
				coal	0.5	-	solar	0.95	-
				coalCCS	0	-	wind	0.98	-
				gas	0.9	-			
	Power Demand	D_E	*TWh/year*		108.33	-			
Capacity installation	Investment Capital	IC_E	*EUR/GW*	biogas	1.50e+08	1 - 1.5 e+09	gasDecentral	5.90e+08	5 - 6.5 e+08
				biomassCo	1.80e+09	1.5 - 2 e+09	gasCCS	9.00e+08	8e+08-1e+09
				biomassCHP	1.80e+09	1.5 - 2 e+09	nuclear	2.10e+09	1.5-3 e+09
				coal	1.90e+09	1.6 -2.2 e+09	solar	4.60e+09	3.5- 5.5 e+09
				coalCCS	2.00e+09	1.8-2.5 e+09	wind	3.00e+09	2.5 - 4 e+09
				gas	5.80e+08	5 - 6.50 e+08			
	Normal Fixed OM Costs	OMC_E^*	*EUR / (year* GW)*	biogass	2.00e+07	7- 8.5 e+07	gasDecentral	1.25e+07	1- 1.5e+07
				biomassCo	6.00e+07	5- 7 e+07	gasCCS	2.60e+07	1.5-3.5e+07
				biomassCHP	8.40e+07	7e+07-1e+08	nuclear	5.20e+07	4.8-5.6e+07
				coal	2.00e+07	1.5-2.5e+07	solar	1.70e+07	1.2-2.2e+07
				coalCCS	3.00e+07	2 - 4 e+07	wind	1.53e+07	1 - 2 e+07
				gas	1.50e+07	1.25-1.75e+7			
	Normal Variable OM Costs	VC_{OM}^*	*EUR / MWh*	biogas	0.453	5 - 6	gasDecentral	1.98	1.5 – 2.3
				biomassCo	0.936	0.85 - 1	gasCCS	1.08	0.7 – 1.3
				biomassCHP	0.936	0.85 - 1	nuclear	1.8	1.7 – 2.1
				coal	0.936	0.85 - 0.95	solar	23	18 – 28
				coalCCS	3.456	2.5 - 5	wind	0	0 – 20
				gas	0.036	0.03 - 0.04			
	Elec. Learning Curve Parameter	L_E	*Dmnl*	biogas	0.1	0 – 0.25	gasDecentral	0.05	0 – 0.25
				biomassCo	0.1	0 – 0.25	gasCCS	0.05	0 – 0.5
				biomassCHP	0.1	0 – 0.25	nuclear	0	0 – 0.1
				coal	0	0 – 0.1	solar	0.05	0 – 0.5
				coalCCS	0.05	0 – 0.5	wind	0.1	0 – 0.5
				gas	0	0 – 0.1			
	Fuel Price[coal]	$c_{fuel,coal}$	*Eur/GWh*		12238	8000-16000			
	Avg CO2 emission	e_{CO2}	*Ton / GWh*	biogas	11	0 – 15	gasDecentral	400	300 – 450
				biomassCo	350	150 -450	gasCCS	245	60 - 300
				biomassCHP	18	0 – 35	nuclear	0	-
				coal	1000	750 - 1050	solar	0	-
				coalCCS	396	130 – 450	wind	0	-
				gas	469	350 - 500			
Annual Production	Availability factor	a	*Dmnl*	biogas	0.673	0.6 – 1	gasDecentral	0.810	0.8 – 0.95
				biomassCo	0.833	0.6 – 0.9	gasCCS	0.776	0.7 – 0.95
				biomassCHP	0.865	0.75 – 0.95	nuclear	0.882	0.85 – 0.95
				coal	0.807	0.7 – 0.9	solar	0.161	0.05 – 0.25
				coalCCS	0.885	0.7 – 0.9	wind	0.545	0.3 – 0.6
				gas	0.801	0.7 – 0.95			
	Power Demand Fraction	$f_{D,E}$	*1/year*	2000	0.01	-			
				2012	0.008	0.005-0.015			
				2025	0.002	-0.001-0.005			
				2035	0.002	-0.001-0.005			
Natural gas demand	Heat generated per unit electricity	h_E	*TJ/TWh*	biogas	0	-	gasDecentral	5524	5000 – 6000
				biomassCo	173	50 – 250	gasCCS	912	800 – 1000
				biomassCHP	1350	800 – 1800	nuclear	0	-
				coal	173	50 – 250	solar	0	-
				coalCCS	173	50 – 250	wind	0	-

140A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

				gas	912	800 - 1000
	Calorific value of natural gas	W_{NG}	*GWh/ bcm*		9800	-
	Discrepancy Switch	*DS*	*Dmnl*		0	0, 1

Market Sub-model

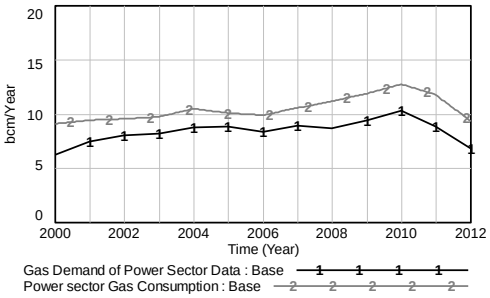
	Parameter	***Symbol***	***Unit***	***Base Run Value***	***Uncertainty Range***
	Initial Expected Market Price	$P_{market}(0)$	EUR/cm	0.11	-
Parameters	Sensitivity of Price to Costs	k_C	Dmnl	1	0.75 – 1.25
	Sensitivity of Price to Demand Coverage	k_{DC}	Dmnl	-1	-1.25 - -0.75
	Coverage Perception Time	d_{DC}	Year	1	1 – 5
	Initial Traders' Accepted Margin Gas	TAM^*	Dmnl	8	-
	Price Structure Switch	*PSS*	Dmnl	0	0, 0.5, 1

140B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

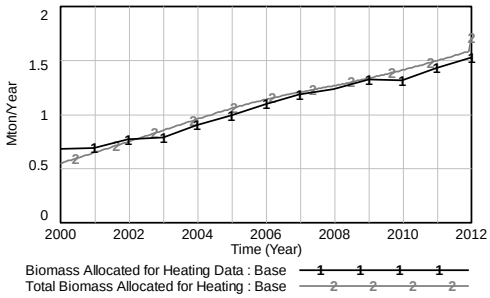
APPENDIX 5.2: SIMULATION RESULTS

Behavior Reproduction Tests

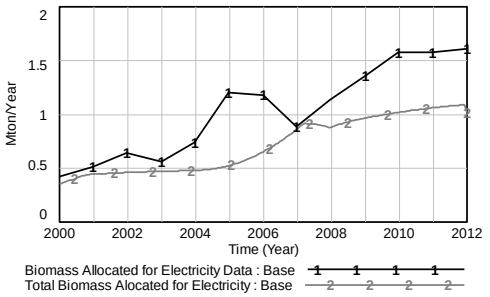
Natural Gas Demand from the Power Sector



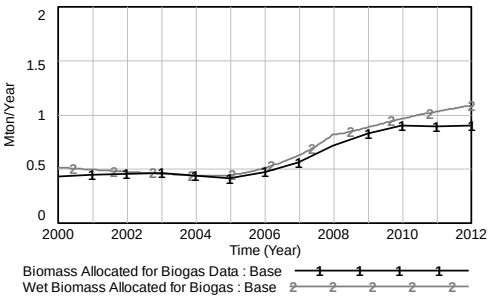
Biomass Allocated for Heating



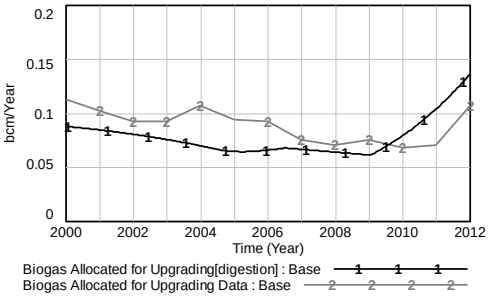
Biomass Allocated for Electricity Production



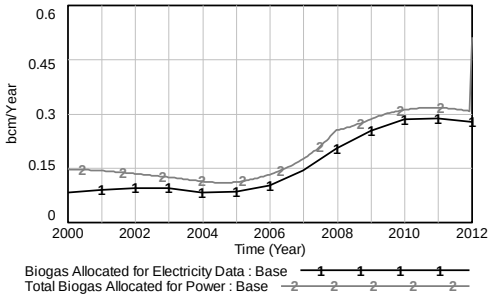
Biomass Allocated for Biogas Production



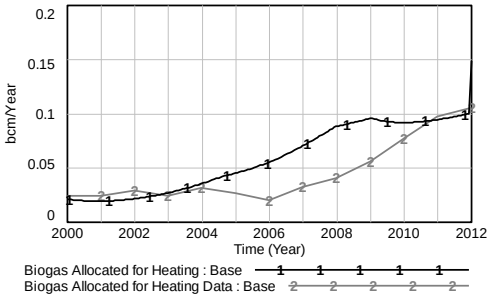
Biogas Allocated for Biomethane Production



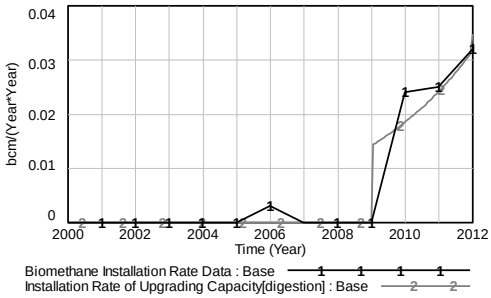
Biogas Allocated for Electricity Production



Biogas Allocated for Heating



Installation Rate of Biomethane Capacity

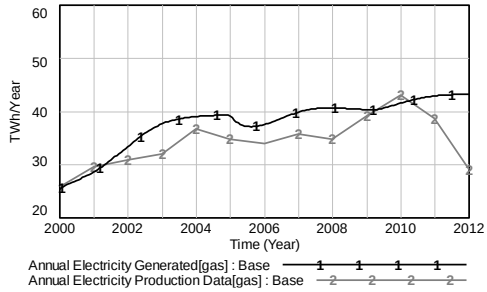


Electricity Production Rate in Central Natural Gas

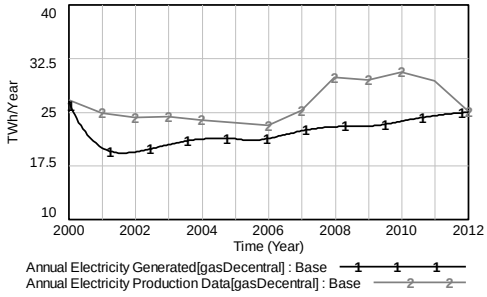
Electricity Production Rate in Decentral Natural Gas

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Plants



Combustion Units



Reference Simulation Behavior

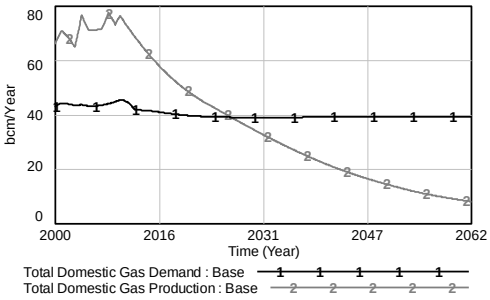


Figure A5.4: Behavior of *Total Domestic Gas Production and Demand* in the reference simulation

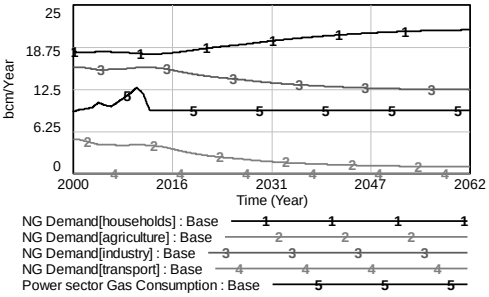


Figure A5.5: Behavior of *Natural Gas Demand* from 5 sectors in the reference simulation

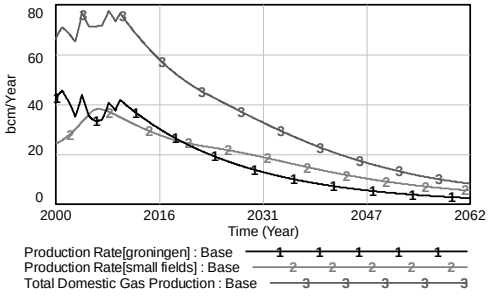


Figure A5.6: Behavior of the natural gas production rates in the reference simulation

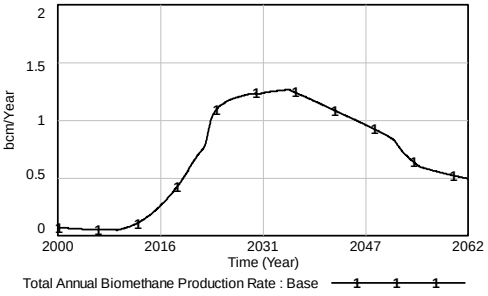


Figure A5.7: Behavior of the renewable gas production rate in the reference simulation

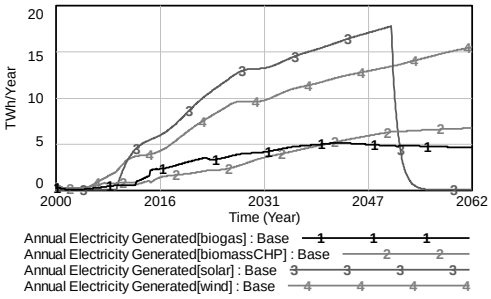


Figure A5.8: Behavior of the renewable electricity production rates in the reference simulation

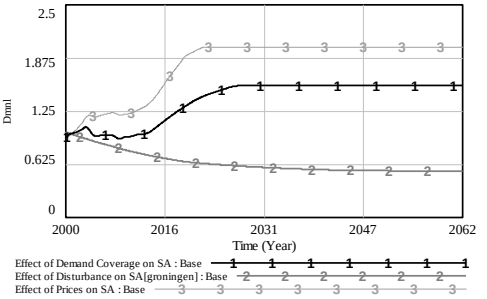


Figure A5.9: Behavior of factors affecting *Societal Acceptance* in the reference simulation

141B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

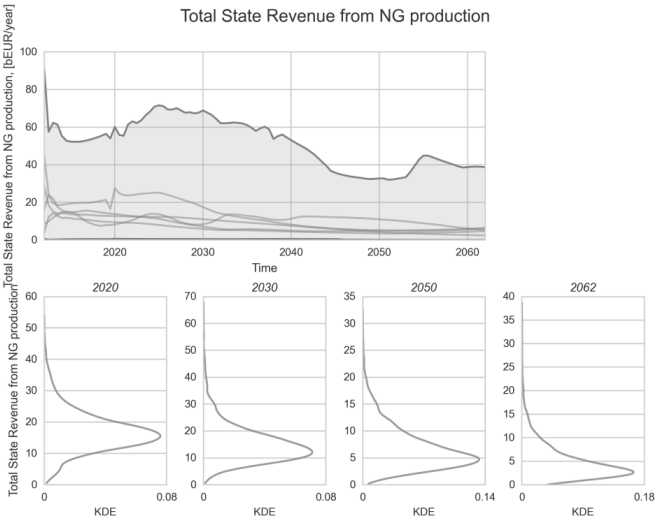


Figure A5.7: Envelope of *Total State Revenue from Natural Gas Production* and the KDE's in 2020, 2030, 2050 and 2062

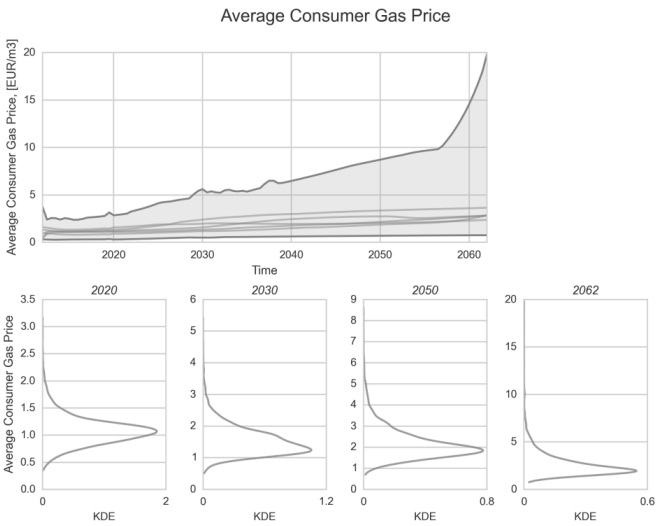


Figure A5.8: Envelope of *Average Consumer Gas Price* and the KDE's in 2020, 2030, 2050 and 2062

142A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

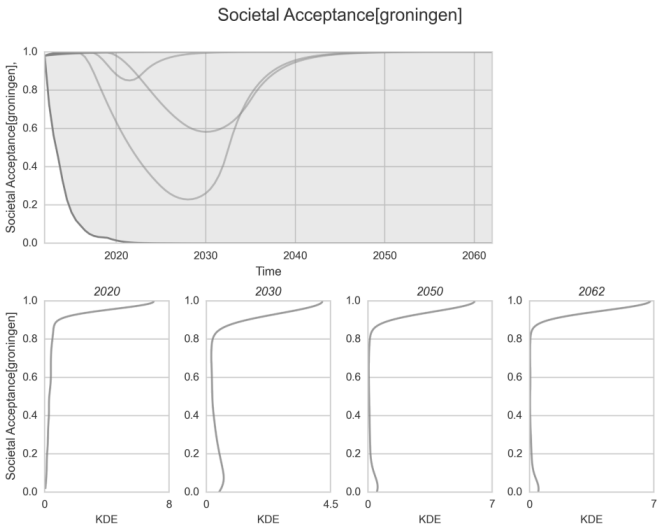


Figure A5.9: Envelope of *Societal Acceptance* and the KDE's in 2020, 2030, 2050 and 2062

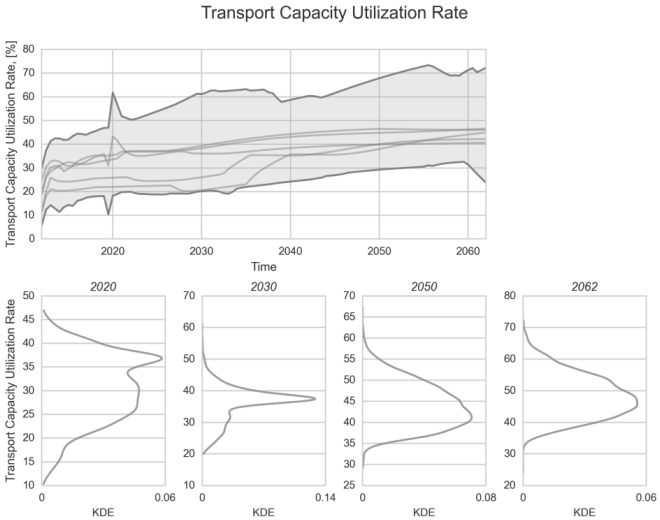


Figure A5.10: Envelope of *Transport Capacity Utilization Rate* and the KDE's in 2020, 2030, 2050 and 2062

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APPENDIX 5.3: MODEL-BASED REPRESENTATION OF PERSPECTIVES

Input conditions

Model element	Normal unc. range	Perspective 1		Perspective 2		Perspective 3		Perspective 4		Perspective 5		Perspective 6	
		Ind.	Range	Ind.	Range	Ind.	Range	Ind.	Range	Ind.	Range	Ind.	Range
Normal Intended Investment in Exploration[small fields]	0.15-0.35	High	0.3-0.35	Low	0.15-0.2					High	0.3-0.35		
Normal Intended Investment in Exploration[shale]	0.15-1	High	0.75-1	Low	0.15-0.35					High	0.75-1		
Normal Intended Investment in Development[small fields]	1-2.5	High	2.1-2.5	Low	1-1.5					High	2.1-2.5		
Normal Intended Investment in Development[shale]	0.5-2.5	High	2-2.5	Low	0.5-1					High	2-2.5		
Effect of Disturbance on SA Lookup		Low		High						Low		Low	
m	-0.5-0.5	Low	-0.05-0.05	High	0.25-0.5						-0.5-0		-0.5-0
p	0-2		0.5-1.5		0.5-1.5						0-1		0.5-1.5
l	0.75-1.5		0.75-1		0.75-1						0.75-1		0.75-1
u	0-1.5		1-1.5		0-0.5								1-1.5
Weight for SA[households, industry , agriculture, transport]	0-1	Low	0-0.25	High	0.75-1			Low	0 – 0.25	Low	0 – 0.25	Low	0 – 0.25
Effect of Prices on SA Lookup		Low		High				High		Low		High	
m	-0.75-0.75		-0.05-0.05		-0.25-0.25				0.25-0.75		-0.05-0.05		-0.25-0.75
p	0-2		0.5-1.5		0.5-1.5				0.5-1.5		0.5-1.5		0.5-1.5
l	0.5-2		1.5-2		0.5-1				0.5-1		1.5-2		0.5-1.5
u	0.75-1.25		0.75-1		0.75-1				1-1.25		0.75-1		1-1.25
Demand Switch Fraction [households]		Low		High		High		Low					
2015	0-0.01		0-0.001		0.005-0.01		0.005-0.01		0-0.001				
2025	0-0.02		0-0.005		0.01-0.02		0.01-0.02		0-0.005				
2035	0-0.05		0-0.01		0.025-0.05		0.025-0.05		0-0.01				

143A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

143B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Output conditions

Model element	Perspective 1	Perspective 2	Perspective 3	Perspective 4	Perspective 5	Perspective 6
Total Domestic Gas Production	High			Low	High	
Annual Import Volume (LNG)	High				High	
Share of Natural Gas in the Power Mix	High	Low				
Total Natural Gas Demand	High	Low	High	High	High	
Societal Acceptance (Groningen)	High	Low				Low
Average Gas Price for Consumers	Low			High		Low
Renewable Gas Percentage	Low	High		Low		
Share of Renewables in the Power Mix	Low	High	High	Low		High
Coverage of Domestic Gas Demand	High		High	Low	High	
Coverage of Domestic Electricity Demand				Low	High	
Substitution Of Natural Gas By Renewable Gas	Low	High				High
Share in Power mix[gasDecentral]		Low		Low		
Transport Capacity Utilization Rate			High		High	
Total Natural Gas Demand except Industry			Low			
Societal Acceptance (small fields)			Low			Low
Societal Acceptance (unconventional)			Low			Low
Import dependency				Low	High	Low
Foreign Demand Coverage				Low		
Biomethane Production via Gasification						Low

APPENDIX 5.4. SCENARIO COUNTS FOR CONFLICT ASSESSMENT

Perspective 1

	No. of scenarios with single condition	Number of scenarios in the case of 2-combinations									
		Renew. Gas Perc.	Annual Import Vol[lng]	Tot. NG Demand	Share of Rnw. in Power Mix	Cover.e of Dom. Gas Dem.	Total Dom. Gas Prod.	Average Con. Gas Price	Societal Accept. [gr.]	Share of Nt. Gas Power Mix	Total Cum. Subst. Rate
Renewable Gas Percentage	4999		3288	3283	2871	1783	1879	2039	2561	2237	2582
Annual Import Volume[lng]	4998	3288		3928	2497	1634	1703	2510	2791	2547	2514
Total NG Demand	4998	3283	3928		2339	1131	1748	2247	2860	2386	3110
Share of Renew. in Power Mix	4999	2871	2497	2339		2701	2489	3150	2447	3349	2565
Coverage of Dom. Gas Dem.	4842	1783	1634	1131	2701		3141	3044	2041	2732	2396
Total Domestic Gas Production	4998	1879	1703	1748	2489	3141		2628	2287	2584	2479
Average Con. Gas Price	4999	2039	2510	2247	3150	3044	2628		2553	3363	2695
Societal Acceptance [gr.]	4874	2561	2791	2860	2447	2041	2287	2553		2498	2526
Share of Nt. Gas in Power Mix	4998	2237	2547	2386	3349	2732	2584	3363	2498		2654
Total Cum. Substitution Rate	4998	2582	2514	3110	2565	2396	2479	2695	2526	2654	

Perspective 2

	No. of Scenarios withsingle condition	Number of scenarios in the case of 2-combinations						
		Total Nat Gas Dem.	Share in Pow. mix (gas decentral)	Societal Accept. (Gr.)	Total Cum. Subst. Rate	Share of Nat. Gas in Power Mix	Renew. Gas Perc.	Share of Renew. in Power Mix
Total NG Demand	4998		2776	2891	3165	2538	3311	2440
Share in Pow mix (gas decentral)	4998	2776		2616	2624	3365	2630	3284
Societal Acceptance (Gr)	4832	2891	2616		2661	2540	2549	2532
Total Cumulative Substitution Rate	4998	3165	2624	2661		2624	2483	2492
Share of Natural Gas in Power Mix	4998	2538	3365	2540	2624		2244	3319
Renewable Gas Percentage	4998	3311	2630	2549	2483	2244		2737
Share of Renew.in Power Mix	4998	2440	3284	2532	2492	3319	2737	

144A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Perspective 3

	No. of Scenarios with single	Number of scenarios in the case of 2-combinations						
		Total NG Demand	Cov. of Dom. Gas Demand	Societal Accept. (shale)	Total NG Dem. except Industry	Share of Renew. in Pow. Mix	Transport Cap. Util.Rate	Societal Accept. (small fields)
Total NG Demand	4999		4412	2218	622	2514	3838	4999
Coverage of Domestic Gas Demand	8403	4412		4199	3982	4264	4368	8403
Societal Acceptance (shale)	4908	2218	4199		2662	2563	2184	4908
Total NG Demand except Industry	4858	622	3982	2662		2348	1342	4858
Share of Renewables in Power Mix	4901	2514	4264	2563	2348		2415	4901
Transport Capacity Utilization Rate	4931	3838	4368	2184	1342	2415		4931
Societal Acceptance (small fields)	9857	4999	8403	4908	4858	4901	4931	

Perspective 4

	No. of Scenarios with single conditions	Number of scenarios in the case of 2-combinations									
		Foreign Dem. Cov.	Total NG Dem.	Share of Renew. in Pow. Mix	Cov. of Dom. Gas Dem.	Total Dom.Gas Prod.	Share Pow. mix (gas decent)	Avg Cons. Gas Price	Import Depend.	NG Perc.	Cov. of Dom. Elect. Dem.
Foreign Demand Coverage	4963		2890	2604	2162	2510	2351	2029	3014	2759	2492
Total NG Demand	4999	2890		2357	3837	3209	2450	2761	3824	3297	2557
Share of Renew. in Power Mix	4939	2604	2357		2243	2546	1684	1741	2449	2806	2086
Cov. of Dom. Gas Demand	4973	2162	3837	2243		3121	2607	3140	3420	3131	2554
Total Dom. Gas Prod.	4957	2510	3209	2546	3121		2358	2591	4057	3107	2494
Share in Pow.mix (gas decent.)	4927	2351	2450	1684	2607	2358		3210	2382	2402	3216
Average Consumer Gas Price	4913	2029	2761	1741	3140	2591	3210		2627	2947	2517
Import Depend.	4966	3014	3824	2449	3420	4057	2382	2627		3359	2522
Natural Gas Perc.	4962	2759	3297	2806	3131	3107	2402	2947	3359		2449
Cov. of Dom. Elect. Dem.	4942	2492	2557	2086	2554	2494	3216	2517	2522	2449	

144B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Perspective 5

	No. of Scenarios with conditions	Number of scenarios in the case of 2-combinations						
		Total NG Demand	Coverage of Domestic Gas Demand	Import Dependency	Annual Import Volume[lng]	Total Domestic Gas Production	Transport Capacity Utilization Rate	Coverage of Dom. Electricity Demand
Total NG Demand	4998		1863	2999	3558	2639	3474	2525
Coverage of Domestic Gas Demand	5107	1863		1852	1825	2889	1661	2557
Import Dependency	4998	2999	1852		3709	895	3814	2545
Annual Import Volume[lng]	4998	3558	1825	3709		2096	4352	2486
Total Domestic Gas Production	4998	2639	2889	895	2096		2000	2478
Transport Capacity Utilization Rate	4998	3474	1661	3814	4352	2000		2517
Cov. of Dom. Electricity Demand	4998	2525	2557	2545	2486	2478	2517	

Perspective 6

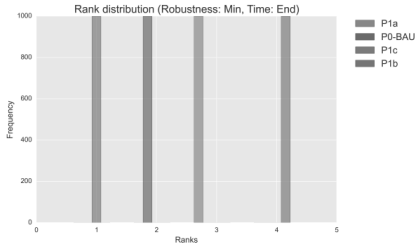
	Scenarios with single conditio	Number of scenarios in the case of 2-combinations						
		Societal Accept. (shale)	Average Consumer Gas Price	Import Dependency	Total Cum.Subst. Rate	Share of Renew. in Power Mix	Cum. Biometh. Prod. (gasif)	Soc. Accep. (small fields)
Societal Acceptance (shale)	4993		2350	2674	2681	2555	2577	3500
Average Consumer Gas Price	4993	2350		2589	2380	1757	2557	2082
Import Dependency	4993	2674	2589		2231	2459	2401	2979
Total Cumulative Substitution Rate	4992	2681	2380	2231		2504	2625	2677
Share of Renewables in Power Mix	4992	2555	1757	2459	2504		2030	2606
Cumulative Biomethane Production (gasification)	4993	2577	2557	2401	2625	2030		2553
Societal Acceptance (small fields)	4885	3500	2082	2979	2677	2606	2553	

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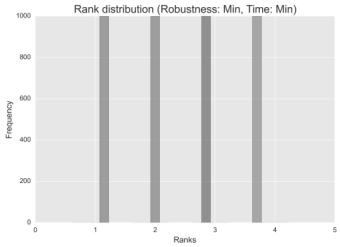
APPENDIX 7.1: RANK DISTRIBUTIONS OF THE CAP POLICIES WITH RESPECT TO UNCERTAIN WEIGHTING OF CRITERIA

Robustness Metric: *Min*

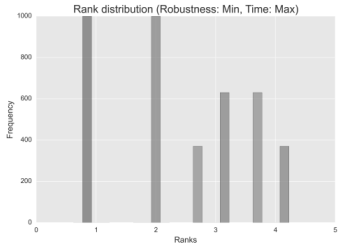
END - **Rank order: P1c > P0 > P1a > P1b**



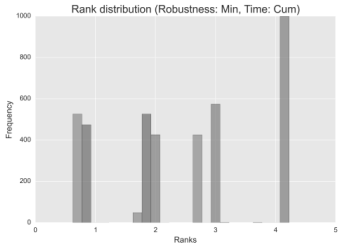
MIN - **Rank order: P1b > P1c > P0 > P1a**



MAX **Rank order: P0 > P1c > P1b > P1a**

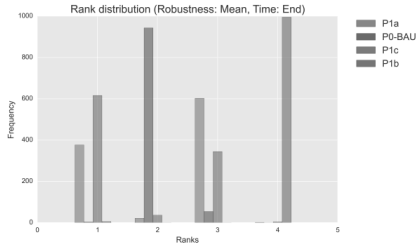


CUM **Rank order: P0 > P1a > P1c > P1b**

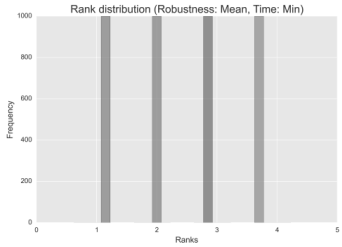


Robustness Metric: *Mean*

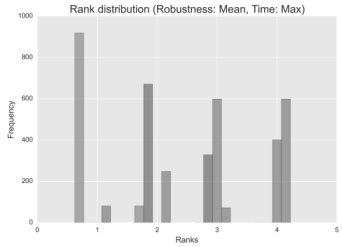
END **Rank order: P1c > P0 > P1a > P1b**



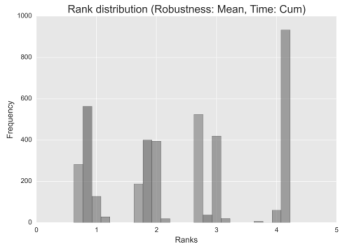
MIN **Rank order: P1b > P1c > P0 > P1a**



MAX **Rank order: P1a > P0 > P1b > P1c**



CUM **Rank order: P0 > P1a > P1c > P1b**

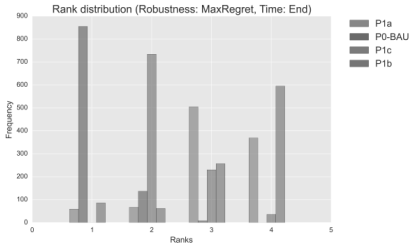


145B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Robustness Metric: *MaxRegret*

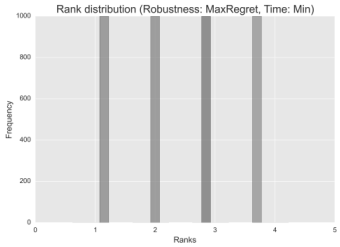
END

Rank order: P0 > P1c > P1a > P1b



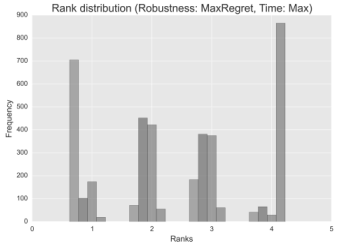
MIN

Rank order: P1b > P1c > P0 > P1a



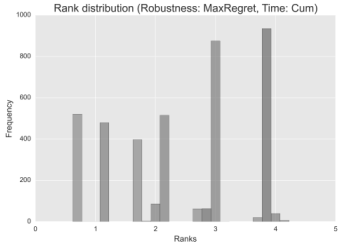
MAX

Rank order: P1a > P1c > P0 > P1b



CUM

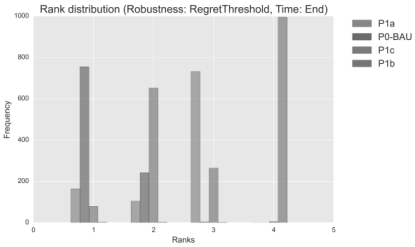
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Robustness Metric: *Regret Thresholds*

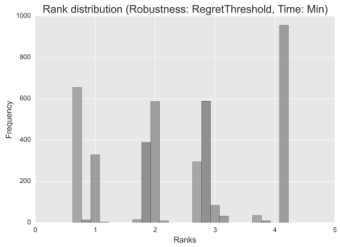
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Rank order: P0 > P1c > P1a > P1b



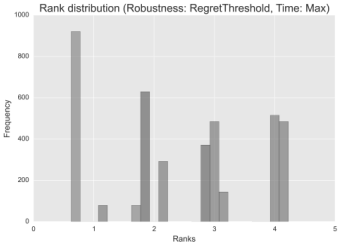
MIN

Rank order: P1a > P1c > P0 > P1b



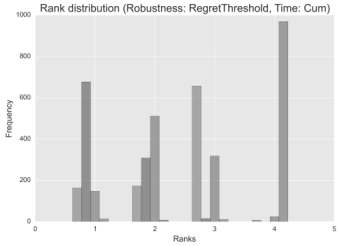
MAX

Rank order: P1a > P0 > P1b > P1c



CUM

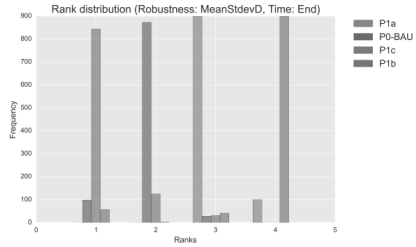
Rank order: P0 > P1c > P1a > P1b



Robustness Metric: *Mean to Std. Deviation*

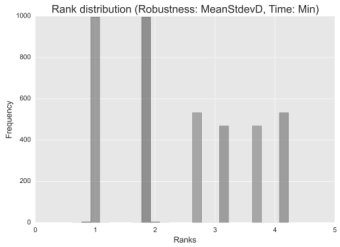
END

Rank order: P1c > P0 > P1a > P1b



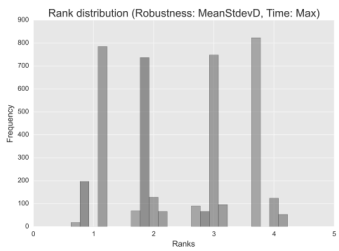
MIN

Rank order: P1c > P0 > P1b > P1a



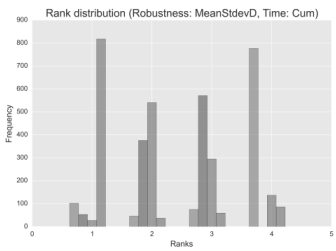
146A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Rank order: P1b > P0 > P1c > P1a



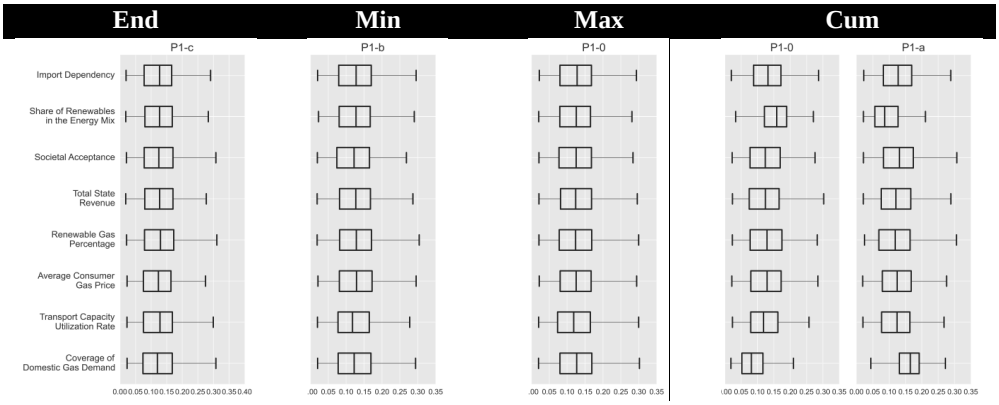
CUM

Rank order: P1b > P0 > P1c > P1a

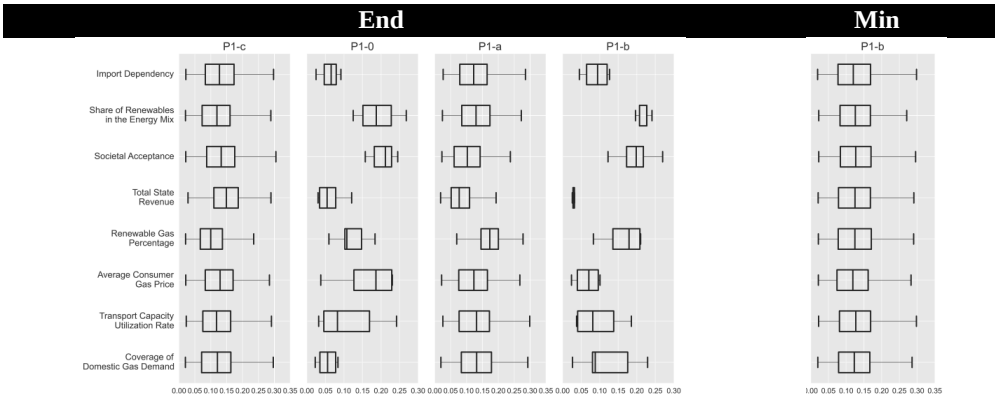


APPENDIX 7.2: THE SUBSPACES OF THE CRITERIA WEIGHTS LEADING TO THE MOST PREFERRED CAP POLICY OPTIONS

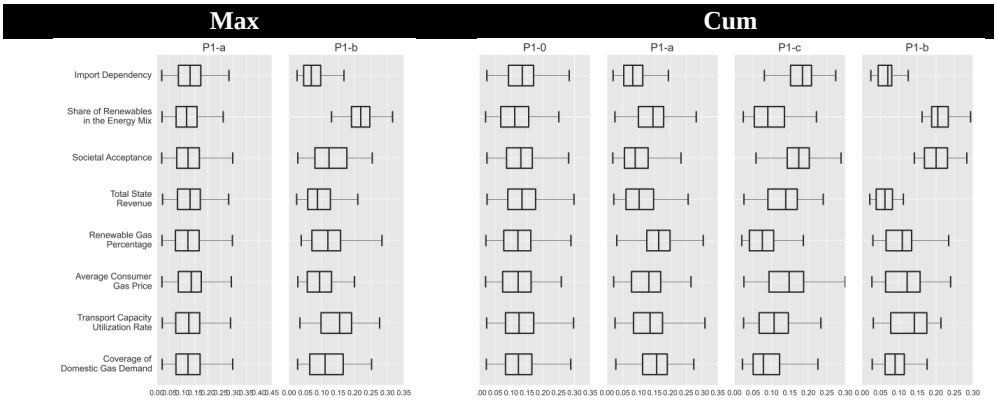
Robustness Metric: *Min*



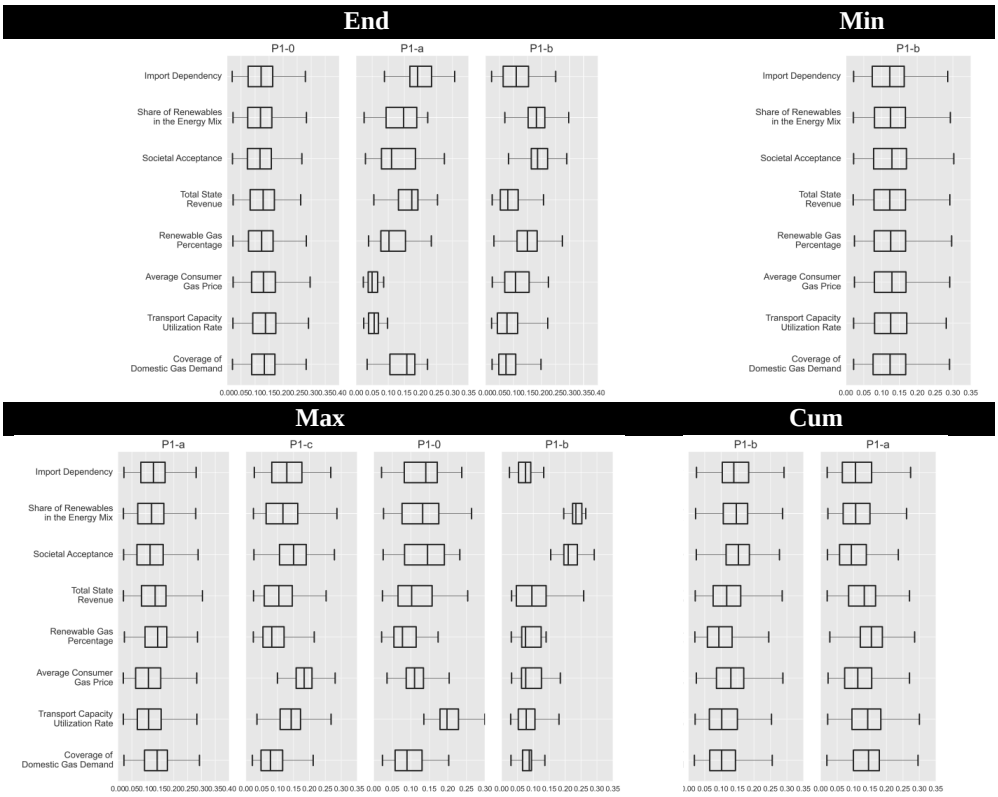
Robustness Metric: *Mean*



146B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

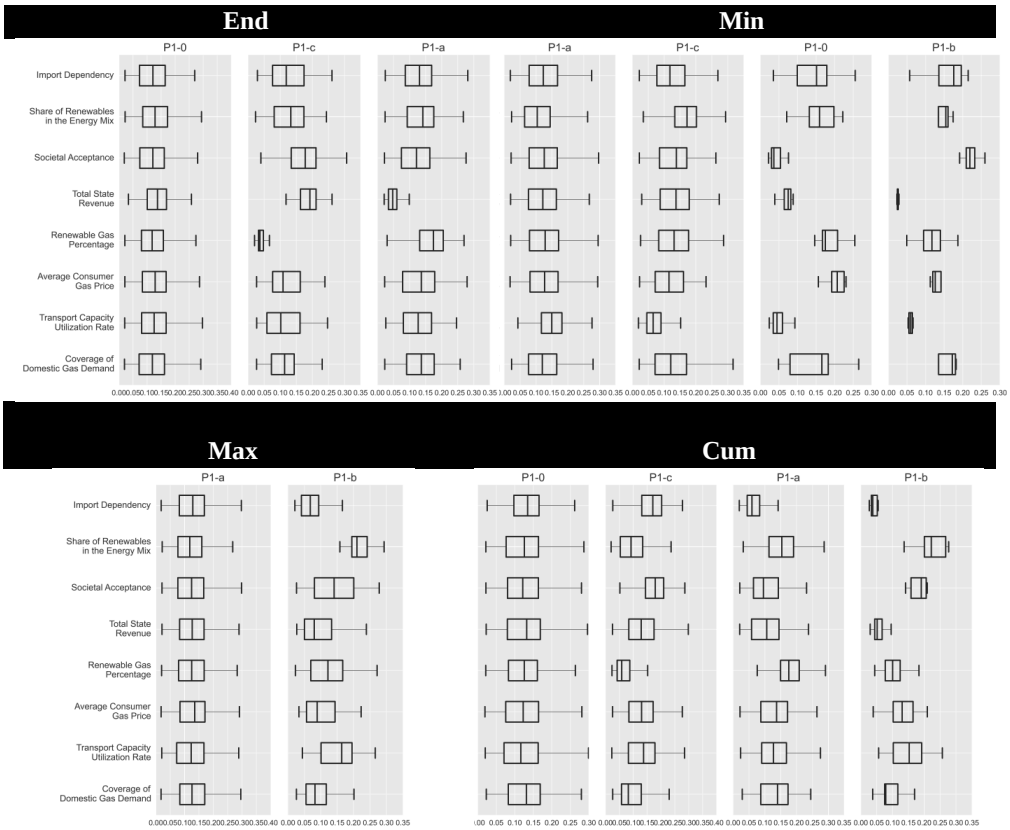


Robustness Metric: *MaxRegret*

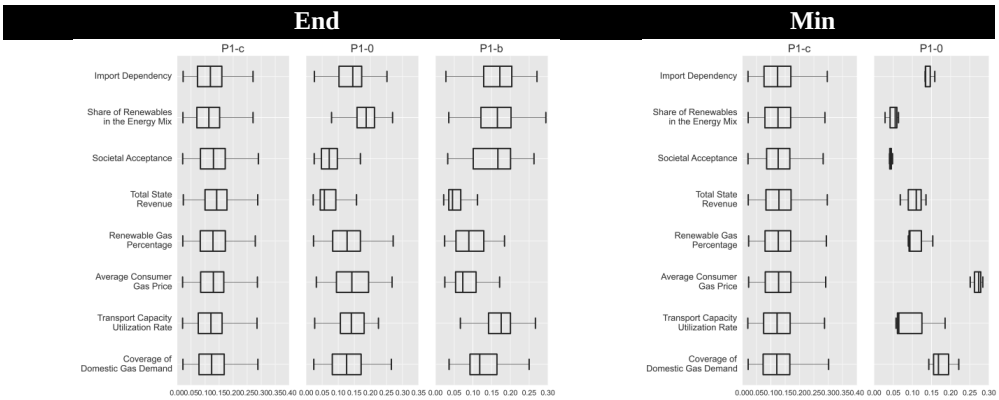


147A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

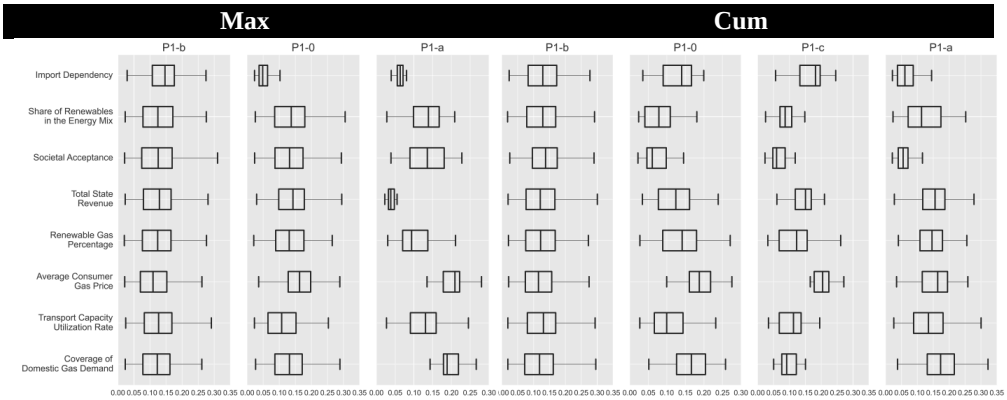
Robustness Metric: *Regret Thresholds*



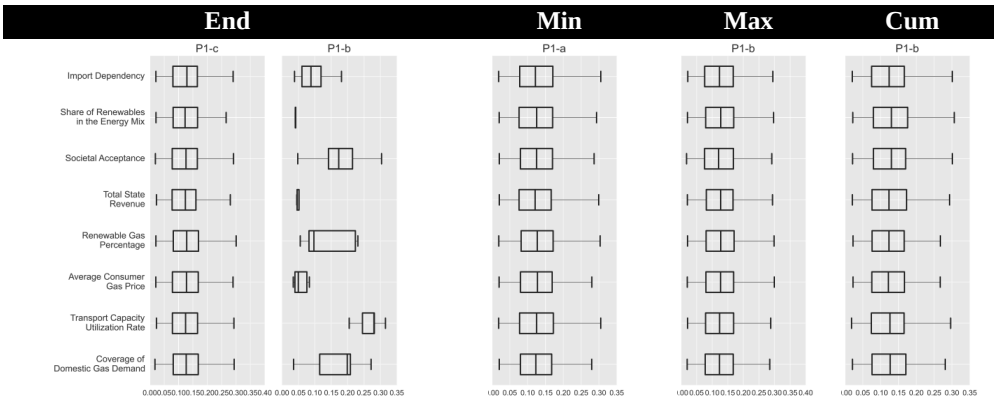
Robustness Metric: *Mean to Std. Deviation*



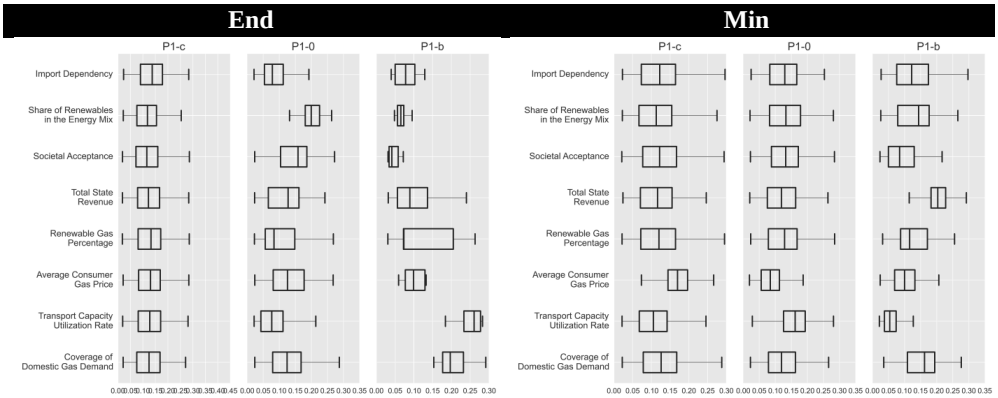
147B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm



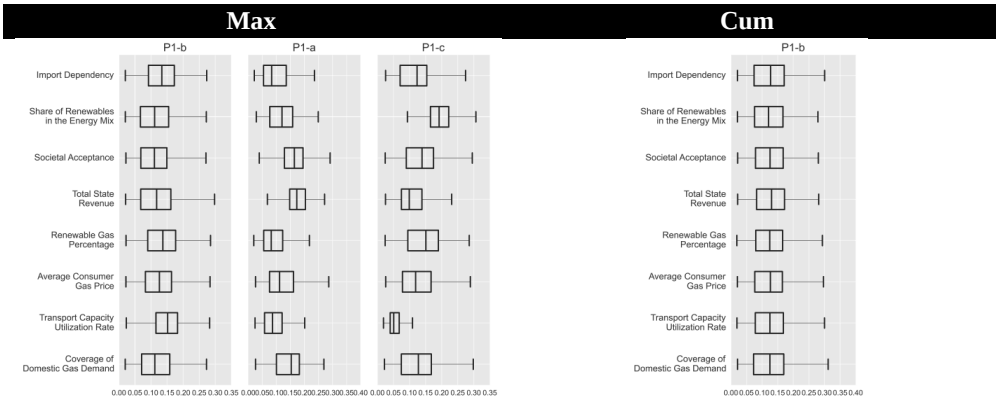
Robustness Metric: *Skewness I*



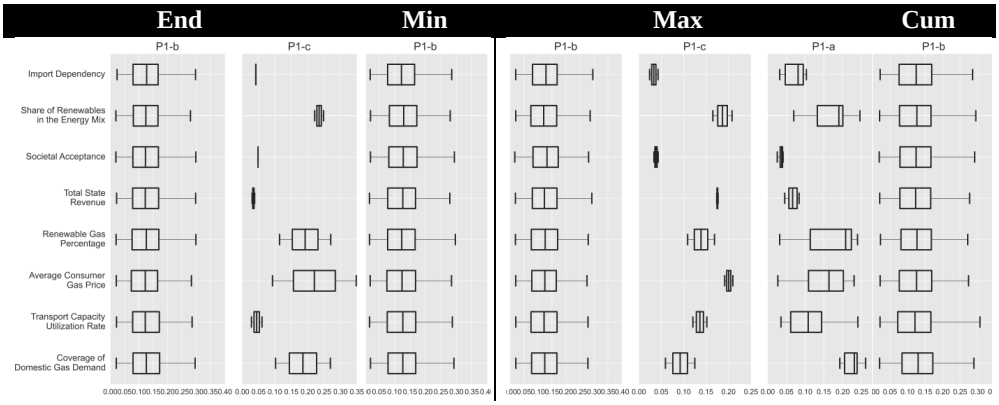
Robustness Metric: *Skewness II*



148A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm



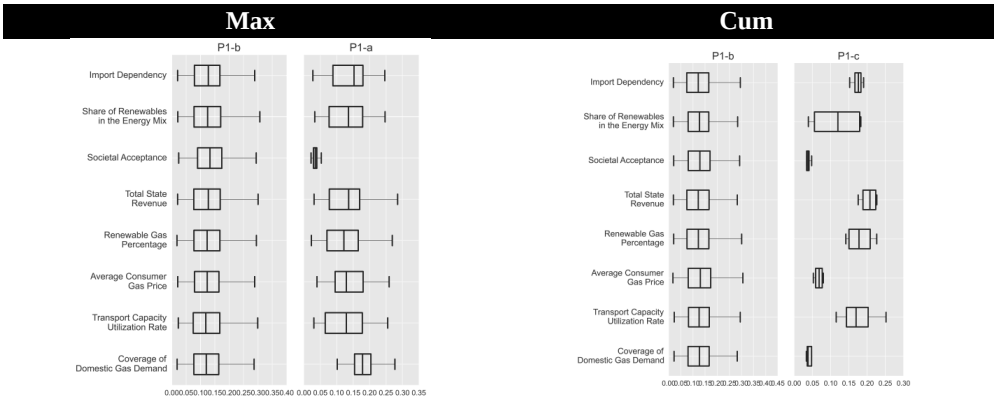
Robustness Metric: *IQR*



Robustness Metric: *Kurtosis*



148B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm



APPENDIX 7.3: MODEL IMPLEMENTATION OF THE SUBSIDIZATION SCHEME OPTIONS

Spot Market Gap Model

i) The cost of the policy to the government

$$t \quad : \sum_{k=2010}^{t} TP_t^k \, S_t^k$$

Assuming a constant subsidy period, i.e. each producer is provided with subsidy for 12 years, a subscript *i* is defined, such that $i \in [t\text{-}1, t\text{-}12]$. Therefore,

$$TP^i(t) = InstallationRate^i(t) * AverageCapacityUtilization(t)$$
$$InstallationRate^i(t) = DELAY\ FIXED\big(InstallationRate(t),\ i,\ 0\big)$$
$$bp^i(t) = DELAY\ FIXED\big(bp(t),\ i,\ 0\big)$$
$$AnnualCostBiomethaneSubsidization(t) = \sum_{i=t-12}^{t-1} \max\big(bp^i(t) - mp(t),\ 0\big) * TP^i(t)$$

Note that there is a second set of indices for the biomethane production technology (digestion, gasification), which is not shown in this notation for simplicity.

ii) Setting the feed-in tariff

Assuming that the equity share is equal to zero, i.e. producers buy all of the investment cost as a loan, basis prices is assumed to be

$$Basis\ Price = \frac{-NPV\big(AnnualNetIncome, 12\%, 12\,yrs\big)}{(1 - \%ParticipationTax) * NPV\big(AnnualSales, 12\%, 12\,yrs\big)}$$

Net costs and net sales are assumed to be on a unit basis, e.g for $1m^3$/year production. (It is not possible to use the NPV functions of Vensim, because they calculate the NPV of cash flows in the past periods. This means that, I can calculate the NPV of a 12 year period only at time t=12, although I need to use this at time t=0. Therefore, I've decided to use the NPV formula itself, rather than an

149A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

embedded function.) For the NPV of sales, having AS as Annual Sales, r as the rate of return (12%) and T as the subsidy period (12 years).

$$NPV(AS, r, T) = \sum_{i=1}^{T} AS \frac{1}{(1+r)^i} = AS \frac{1}{1+r} \sum_{i=0}^{T-1} \left(\frac{1}{1+r}\right)^i$$

$$= AS \frac{1}{1+r} \frac{1-\left(\frac{1}{1+r}\right)^T}{1-\left(\frac{1}{1+r}\right)} = AS \frac{1}{1+r} \frac{\frac{(1+r)^T-1}{(1+r)^T}}{\frac{1+r-1}{1+r}}$$

$$= AS \frac{1}{1+r} \frac{\left((1+r)^T-1\right)(1+r)}{(1+r)^T r}$$

$$= \frac{AS}{r} \frac{(1+r)^T-1}{(1+r)^T}$$

A similar formula is used for the NPV of Annual Income, i.e.

$$NPV(AI_i, r, T) = \sum_{i=1}^{T} AI_i \frac{1}{(1+r)^i}$$

However, since annual income flow is not constant in this case due to costs varying over time, the subscript structure defined for the cost calculation above is used to calculate the NPV, having indices representing the future values this time, rather than the past. Following the equations 1.3-1.3.3, the following formulations are used in the model, where r^* is the reduced interest rate.

$$NPV(AI_i(t), r, T) = \sum_{i=1}^{T=12} \frac{AI_i(t)}{(1+r)^i}$$

$$AI_i(t) = -Annual\ O\&M\ Costs_i(t) + Tax\ Amount_i(t) - EAC$$

$$Annual\ O\&M\ Costs_i(t) = Inflator_i * BiomethaneVariableCost(t)$$

$$Inflator_i = (1+0.02)^{i-1}$$

$$Tax\ Amount_i(t) = -\%ParticipationTax * \begin{pmatrix} -Annual\ O\&M\ Costs_i(t) + Annual\ Interest_i(t) \\ +Depreciation \end{pmatrix}$$

$$Depreciation = -\frac{Investment\ Cost}{T}$$

$$Annual\ Interest_i(t) = -r^* * Investment\ Cost * \left(1+r^*\right)^{i-1} - EAC * \left(1+r^*\right)^{i-1}$$

Basis price is determined for each biomethane technology, therefore these formulations have a second index in the model, standing for the technology.

iii) Producers' Decision

In their capacity installation decision, the producers are assumed to

- calculate an expected market price for each year in the coming 12 year period,
- looking at the difference between these expected prices and the basis price, which gives the Expected Producer Price
- and calculating their NPV with annual cash flows equal to the sum of Expected Producer Price and Annual Income variable used above, which is equal to the unit annual cost.

$$Expected\ Market\ Price^i(t) = FORECAST\left(Market\ Price(t),\ 5,\ i\right)$$

$$Expected\ Producer\ Price^i(t) = MAX\left(Basis\ Price(t), Expected\ Market\ Price^i(t)\right)$$

$$NPV(t) = \sum_{i=1}^{i=12} \frac{Expected\ Producer\ Price^i(t) + AI_i(t)}{(1+r)^i}$$

149B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Multiplicative Feed-in Tariff

In this scheme, the government still pays the difference between the market price and the basis price as in the spot market gap model, however, the basis price is determined differently. It is set to be a multiple of the unit production costs of biomethane, where the multiplier is based on a profit percentage, e.g. 15%. Hence,

$$Basis\ Price(t) = (1+s) * Biomethane Unit\ Cost(t)$$

where s is the subsidy percentage provided.

Fixed Feed-in Tariff

i) The cost of the policy to the government

The annual cost of subsidization to the government is calculated similarly to the spot market gap model. Subscripts are used to store the production volumes and feed-in tariff values of the past years.

i) Setting the feed-in tariff

The fixed feed-in tariff to be paid to the producers for a period of 12 years is set to be a multiple of the initial unit cost of production. A low multiplier value (ρ) is used, because cost reduction is assumed to provide sufficient profit to the producers in the coming years.

$$F^t = F(t) = \rho * Biomethane Unit\ Cost(t)$$

ii) Producers' decision

In the case of a fixed feed-in tariff, Expected Producer Price will be the same for each year in the 12-year period, and it will be equal to the feed-in tariff. Hence,

$$Expected\ Producer\ Price^i\ (t) = F(t)$$

$$NPV(t) = \sum_{i=1}^{i=12} \frac{F(t) + AI_i(t)}{(1+r)^i}$$

Fixed Price Model with (Full) Inflation Adjustment

We assume a full inflation adjustment, once in every three years.

i) The cost of the policy to the government

$$2010:\ TP_{2010}^{2010}\ F_{2010}^{2010}$$

$$2011:\ TP_{2011}^{2010}\ F_{2010}^{2010} + TP_{2011}^{2011}\ F_{2011}^{2011}$$

..

$$2013:\ TP_{2013}^{2010}\ \mathbf{F_{2013}^{2010}} + TP_{2013}^{2011}\ F_{2011}^{2011} + TP_{2013}^{2012}\ F_{2012}^{2012} + TP_{2013}^{2013} F_{2013}^{2013}$$

...

$$t \quad : \sum_{k=2010}^{t} TP_t^k\ F_j^k;\ \ j = \begin{cases} if\ t-k=3, & t \\ else, & k \end{cases}$$

150A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

For this cost calculation, it is necessary to keep the array of past feed-in tariffs as in the previous schemes, however, the effect of inflation adjustment should be represented on this array. How it's done will be explained in the following section.

ii) Setting the feed-in tariff

The initial feed-in tariff is set the same as the fixed price model, which is

$$F_t^t = \rho * BiomethaneUnit\,Cost(t)$$

The inflation adjustment is done with a constant multiplier, since this scheme is introduced as a market independent scheme. However, it is possible to make this adjustment based on market price change, too.

$$F_{t+3}^t = F_t^t * i(t)$$

$$i(t) = \begin{cases} 1.02, & if\ market-independent \\ \dfrac{Market\ Price(t)}{Past\ Market\ Price(t)}, & if\ market-dependent \end{cases}$$

$$Past\ Market\ Price(t) = DELAY\ FIXED\left(Market\ Price(t), 3\right)$$

In the subscripted representation, the past prices are recorded as

$$F^k(t) = F_t^k = \begin{cases} if\ k = 4,7,10; & DELAY\ FIXED\left(F_t^{k-1}, 1,\ 0\right) * i(t) \\ else; & DELAY\ FIXED\left(F_t^{k-1}, 1,\ 0\right) \end{cases}$$

where F_t^k is the feed-in tariff paid to the producers who subscribed *k-1* years ago in year *t*. The following matrix shows how this array is calculated:

k->	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
t=1	F1	0	0	0	0	0	0	0	0	0	0	0
t=2	F2	F1	0	0	0	0	0	0	0	0	0	0
t=3	F3	F2	F1	0	0	0	0	0	0	0	0	0
t=4	F4	F3	F2	F1*	0	0	0	0	0	0	0	0
t=5	F5	F4	F3	F2*	F1*	0	0	0	0	0	0	0
t=6	F6	F5	F4	F3*	F2*	F1*	0	0	0	0	0	0
T=7	F7	F6	F5	F4	F3*	F2*	F1**	0	0	0	0	0

In year *t*, when a producer is to make a capacity installation decision, she needs an estimate of the future feed-in tariffs. For this, a producer price array is also needed in the model. The following section explains how such an array is formed for producers, and their decision making mechanism.

iii) Producers' decision

As in the previous cases, the net present value of a unit sold is

$$NPV(t) = \sum_{k=1}^{k=12} \frac{Expected\ Producer\ Price^k(t) + AI_k(t)}{(1+r)^k}$$

150B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

With this scheme, producers are certain about the future prices. The producers are assumed to estimate the future producer price (feed-in tariff) based on market price estimations. In other words, they use the ratio of expected market price of 3, 6 or 9 years ahead to the current market price as the inflation corrector, as the equations below show.

$$Expected\ Producer\ Price^{k}(t) = \begin{cases} if\ k = 4,7,10; & F_t^k * i_m^k(t) \\ else; & F_t^k \end{cases}$$

$$i_m^k(t) = \begin{cases} 1.02 & , \ if\ market-independent \\ \dfrac{FORECAST\left(Market\ Price(t),\ 5,\ k\right)}{Market\ Price(t)} & , \ if\ market-dependent \end{cases}$$

Front-end Loaded Tariff Model

The feed-in tariff is assumed to be reduced by 10% once in every years, i.e.

$$F_t^{t+5} = 0.9 * F_t^t$$

The model representation is similar to the fixed price model with inflation adjustment. The differences are:

- The feed-in tariff is adjusted once in every 5 years, instead of 3
- The adjustment multiplier is constant, not dependent on the market price
- The initial feed-in tariff is set according to the market price, being higher than it.

i) The cost of the policy to the government

$$2010:\ TP_{2010}^{2010}\ F_{2010}^{2010}$$

$$2011:\ TP_{2011}^{2010}\ F_{2010}^{2010} + TP_{2011}^{2011}\ F_{2011}^{2011}$$

..

$$2015:\ TP_{2015}^{2010}\ \mathbf{F_{2010}^{2015}} + TP_{2015}^{2011}\ F_{2011}^{2011} + TP_{2015}^{2012}\ F_{2012}^{2012} + TP_{2015}^{2013} F_{2013}^{2013} + \ldots$$

...

$$t \quad : \sum_{k=2010}^{t} TP_t^k\ F_k^j;\ \ j = \begin{cases} if\ t-k=5, & t \\ else, & k \end{cases}$$

ii) Setting the feed-in tariff

The initial feed-in tariff is set as a multiple of the market price, and reduced to 90% of this one in every 5 years, as mentioned above:

$$F_t^t = m * Biomethane\ Unit\ Cost(t)$$

$$F_t^{t+5} = 0.9 * F_t^t$$

m is assumed to be 40% higher than the unit cost. In the subscripted representation, the past prices are recorded similar to the previous model again, with a 1-year fixed delay.

151A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

$$F^k(t) = F_t^k = \begin{cases} if\ k = 5,10; & DELAY\ FIXED\left(F_t^{k-1}, 1,\ 0\right) * 0.9 \\ else; & DELAY\ FIXED\left(F_t^{k-1}, 1,\ 0\right) \end{cases}$$

iii) Producers' decision

In this subsidization scheme, producers have full knowledge of the future producer prices, therefore the expected producer prices used in their NPV calculation are as follows:

$$Expected\ Producer\ Price^k\ (t) = \begin{cases} if\ k = 5,10; & F_t^t * i^k(t) \\ else; & F_t^t \end{cases}$$

$$i^k(t) = \begin{cases} 0.9, & if\ k = 5 \\ 0.81, if\ k = 10 \end{cases}$$

Fixed Premium Price Model

The initial difference between the unit cost and the market price is assumed to be the subsidy price.

i) The cost of the policy to the government

The cost of the government throughout the lifetime of the project is constant, but still since the subsidy amount changes each year, the subsidy amount of the previous years should be kept in an array.

$2010:\ TP_{2010}^{2010}\ S^{2010}$

$2011:\ TP_{2011}^{2010}\ S^{2010} + TP_{2011}^{2011}\ S^{2011}$

..

$$t \quad : \sum_{k=2010}^{t} TP_t^k\ S^k$$

ii) Setting the feed-in tariff

$$F_t^k = S^k + Market\ Price(t)$$

$$S^k = Biomethane\ Unit\ Cost(k) - Market\ Price(k)$$

where F_t^k is the feed-in tariff that producers receive, and S^k is the subsidy price that the government pays.

iii) Producers' decision

Expected Producer Price to be used in NPV calculation of producers is determined based on the market prices, since the subsidy is constant.

$$Expected\ Market\ Price^k(t) = FORECAST\left(Market\ Price(t),\ 5,\ k\right)$$

$$Expected\ Producer\ Price^k\ (t) = S^k + Expected\ Market\ Price^k(t)$$

Percentage of the Retail Price

In the model, since the government is assumed to pay a subsidy, i.e. the difference between the market price and the feed-in tariff, the premium percentage is set to a value higher than 1. The premium

151B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

percentage is assumed to be renewed every year for new subscribers, based on the expected market price and costs.

iv) The cost of the policy to the government

The annual cost of the policy is the sum of subsidies paid to the producers who subscribed in the previous years. Since the premium percentage changes every year, it is necessary to keep the previous years' premium percentage in an array.

$$2010:\ TP_{2010}^{2010}\ S_{2010}^{2010}$$
$$2011:\ TP_{2011}^{2010}\ S_{2011}^{2010} + TP_{2011}^{2011}\ S_{2011}^{2011}$$
$$..$$
$$t\quad :\sum_{k=2010}^{t} TP_t^k\ S_t^k$$

where

$S_t^k = Market\ Price(t) * \left(p^k - 1\right)$, p^k being the premium percentage set in year k.

v) Setting the feed-in tariff

The feed-in tariff (F_t^k) and the subsidy price (S_t^k) is

$$F_t^k = p^k * Market\ Price(t)$$
$$S_t^k = F_t^k - Market\ Price(t) = \left(p^k - 1\right) * Market\ Price(t)$$

The premium percentage is set based on the expected market price in 6 years (midway of the subsidization period) and the current costs.

$$p^t = \frac{Expected\ Market\ Price(t)}{Biomethane\ Unit\ Cost(t)}$$
$$Expected\ Market\ Price(t) = FORECAST\left(Market\ Price(t),\ 5,\ 6\right)$$

vi) Producers' decision

Expected Producer Price used in NPV calculation of the producers is calculated with the current, fixed premium percentage, and the expected market price for each coming year in the 12-year period, as below:

$$Expected\ Producer\ Price^k(t) = p^t * Expected\ Market\ Price^k(t)$$
$$Expected\ Market\ Price^k(t) = FORECAST\left(Market\ Price(t),\ 5,\ k\right)$$

Variable Premium Feed-in Tariff

The policy has three levers: Bottom limit (B), top limit (T) and Premium of reference (s_r). The values of these policy levers are assumed to be renewed each year by the government for new subscribers.

i) The cost of the policy to the government

$$2010:\ TP_{2010}^{2010}\ S_{2010}^{2010}$$
$$2011:\ TP_{2011}^{2010}\ S_{2011}^{2010} + TP_{2011}^{2011}\ S_{2011}^{2011}$$
$$..$$
$$t\quad :\sum_{k=2010}^{t} TP_t^k\ S_t^k$$

152A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

The annual cost of the policy to the government is calculated as before, where S_t^k represents the premium paid in year t to a producer subscribed in year k, based on the bottom, top and reference prices determined in year k. In the graph above, the premium amount is equal to the difference between the bottom limit (which is the feed-in tariff) and the market price. In the second region, the sum of the reference premium and the market price gives the feed-in tariff, whereas in the third region the premium is the difference between the top limit and the market price.

$$mp_1 = B - s_r \quad and \quad mp_2 = T - s_r$$

Hence,

$$S_t^k = \begin{cases} if\ \text{Market Price(t)} < \text{B}^{\text{k}} - \text{s}_{\text{r}}^{\text{k}} & ; \quad B^k - Market\ Price(t) \\ if\ \text{B}^{\text{k}} - \text{s}_{\text{r}}^{\text{k}} \le \text{Market Price(t)} < \text{T}^{\text{k}} - \text{s}_{\text{r}}^{\text{k}} & ; \quad s_r^k \\ if\ \text{Market Price(t)} \ge \text{T}^{\text{k}} - \text{s}_{\text{r}}^{\text{k}} & ; \quad \max\left(T^k - Market\ Price(t),\ 0\right) \end{cases}$$

ii) Setting the feed-in tariff

The three policy levers, namely the reference premium, and the bottom and top limits are assumed to be determined by the government based on the cost and expected market price values. The market price estimation is for 6 years ahead.

$$B^t = 110\% * Biomethane\ Unit\ Cost(t)$$
$$T^t = 150\% * Biomethane\ Unit\ Cost(t)$$
$$s_r^t = Expected\ Market\ Price(t)$$
$$Expected\ Market\ Price(t) = FORECAST\left(Market\ Price(t), 5, 6\right)$$

iii) Producers' decision

Producers are assumed to calculate the *Expected Producer Price* of each coming year (k) with the expected market price for that year (k), and the current top (T^t) and bottom limit (B^t), and reference premium (s_r^t) values.

$$Expected\ Producer\ Price^k(t) = \begin{cases} if\ \text{Expected Market Price}^k\text{(t)} < \text{B}^t - \text{s}_{\text{r}}^t & ; \quad B^t \\ if\ \text{B}^t - \text{s}_{\text{r}}^t \le \text{Expected Market Price}^k\text{(t)} < \text{T}^{\text{t}} - \text{s}_{\text{r}}^{\text{t}} & ; \\ \qquad\qquad s_r^t + Expected\ Market\ Price^k\text{(t)} \\ if\ \text{Expected Market Price}^k\text{(t)} \ge \text{T}^t - \text{s}_{\text{r}}^t & ; \\ \qquad\qquad \max\left(T^t,\ Expected\ Market\ Price^k(t)\right) \end{cases}$$

$$Expected\ Market\ Price^k(t) = FORECAST\left(Market\ Price(t),\ 5,\ k\right)$$

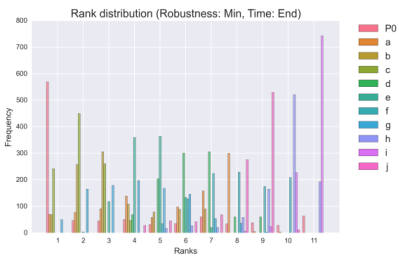
152B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

APPENDIX 7.4: RANK DISTRIBUTIONS OF THE SUBSIDIZATION SCHEMES WITH RESPECT TO UNCERTAIN WEIGHTING OF CRITERIA

Robustness Metric: *Min*

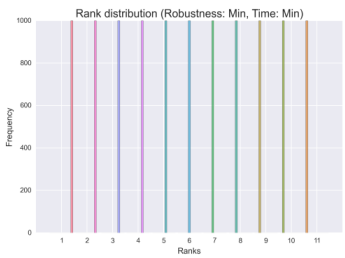
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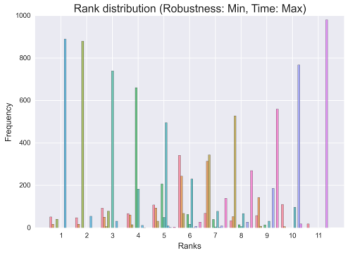
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Rank order:
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c>a



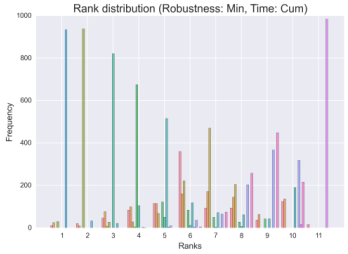
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Rank order:
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CUM

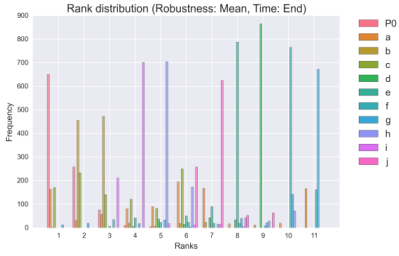
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j>i



Robustness Metric: *Mean*

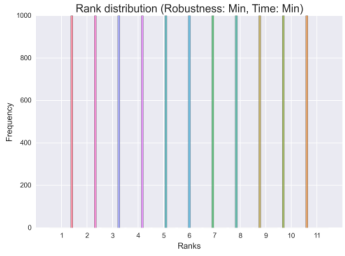
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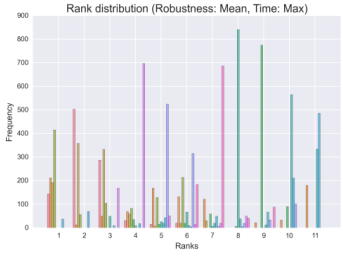
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Rank order:
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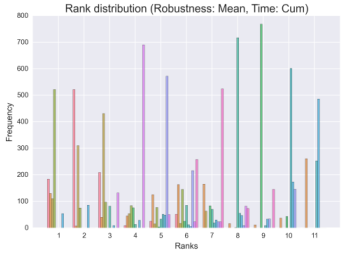
MAX

Rank order:
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g>f



CUM

Rank order:
c>0>...
g>f

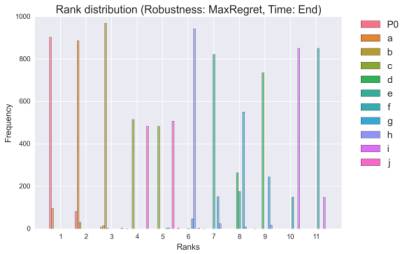


153A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Robustness Metric: *Maximum regret*

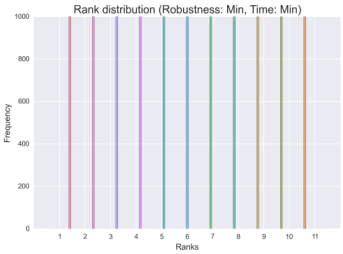
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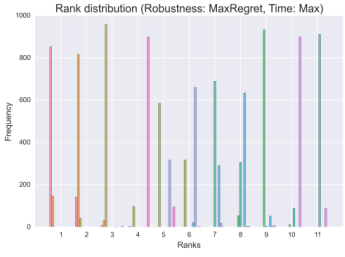
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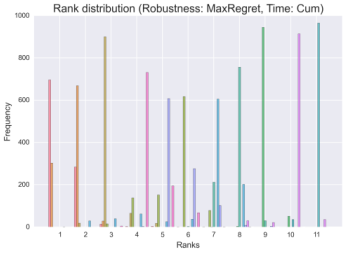
MAX

Rank order:
0>a>... i>f



CUM

Rank order:
0>a>...
i>f



Robustness Metric: *Regret thresholds*

END

Rank order:
0>g>...
i>j



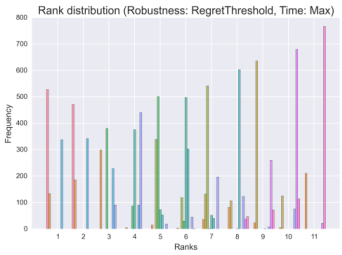
MIN

Rank order:
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e>d



MAX

Rank order:
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i>j



CUM

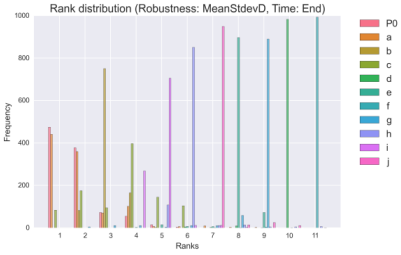
Rank order:
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i>j



Robustness Metric: *Mean/Standard deviation*

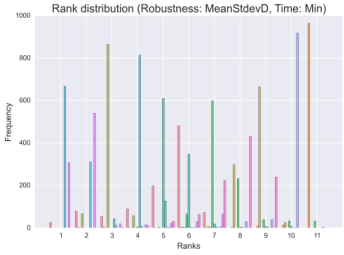
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MIN

Rank order:
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h>a



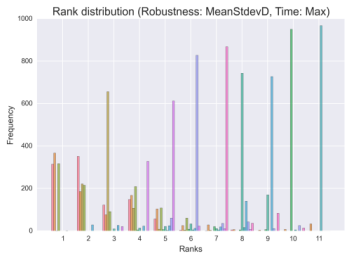
153B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

MAX

Rank order:

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d>f

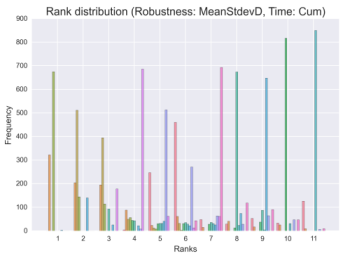


CUM

Rank order:

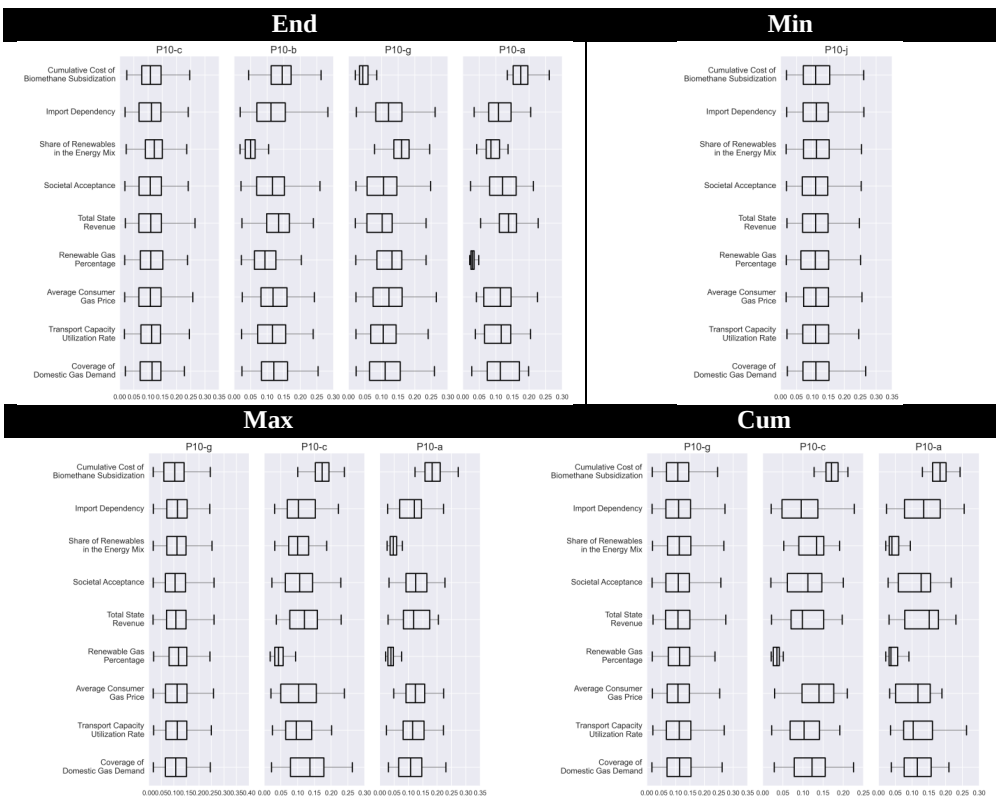
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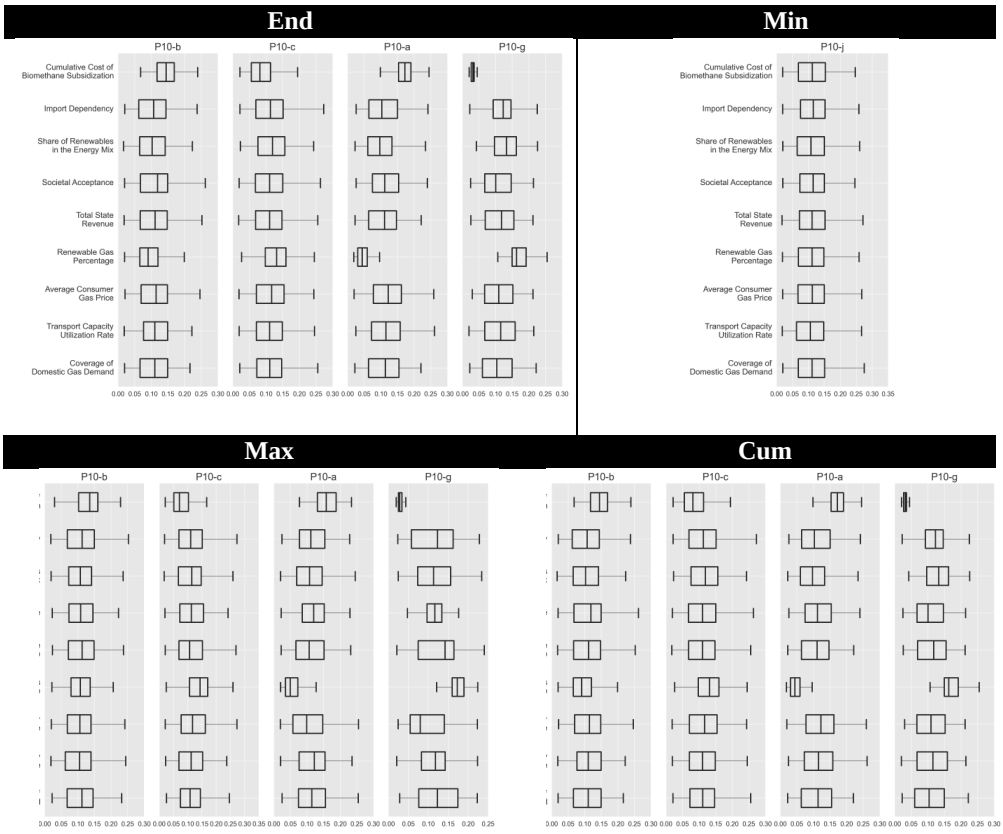
APPENDIX 7.5: THE SUBSPACES OF THE CRITERIA WEIGHTS LEADING TO THE MOST PREFERRED SUBSIDIZATION POLICY OPTIONS

Robustness Metric: *Min*

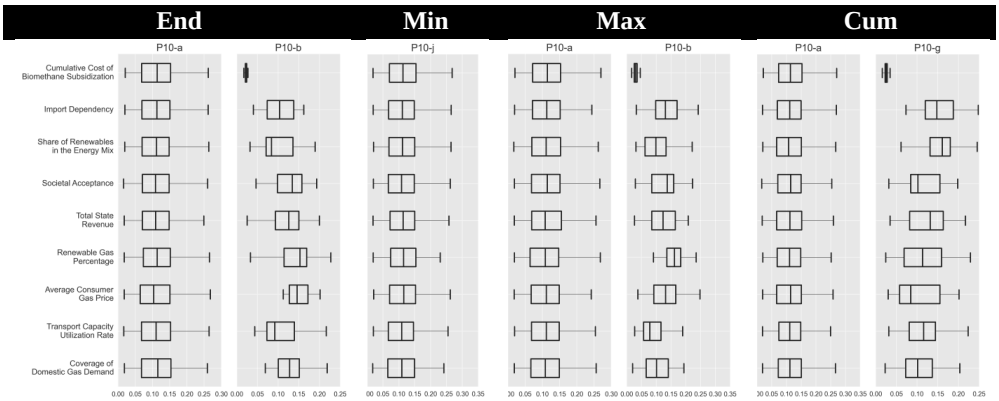


154A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Robustness Metric: *Mean*

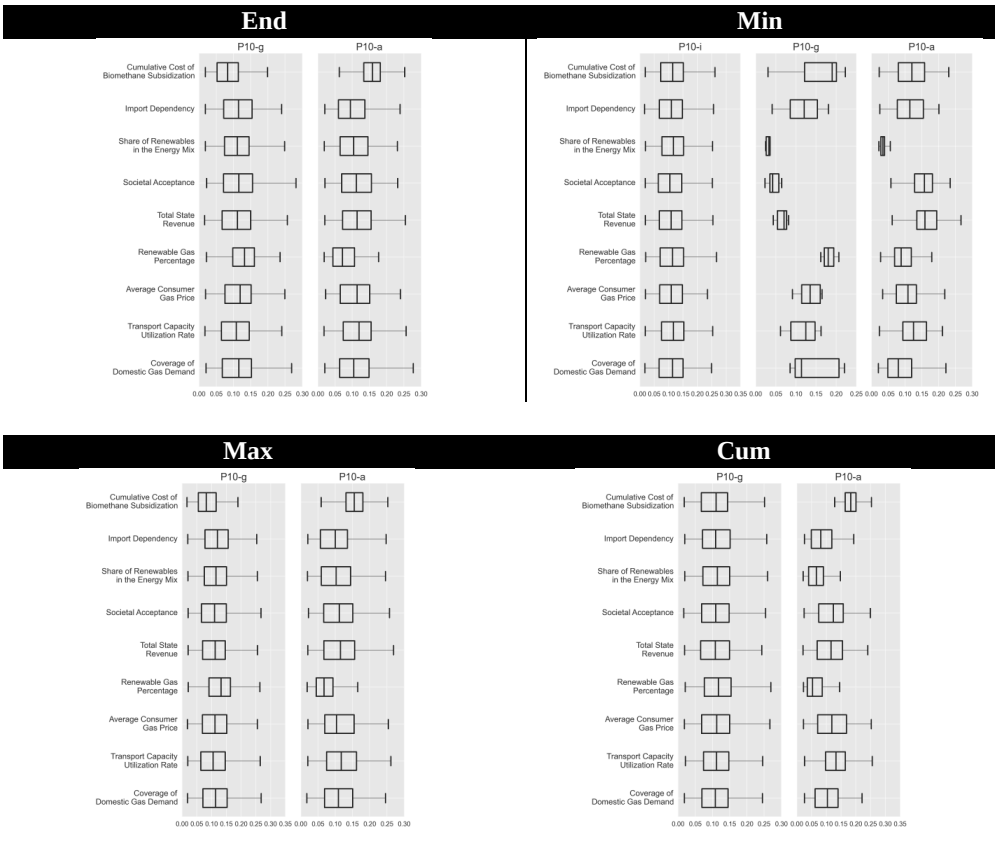


Robustness Metric: *Maximum regret*



154B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

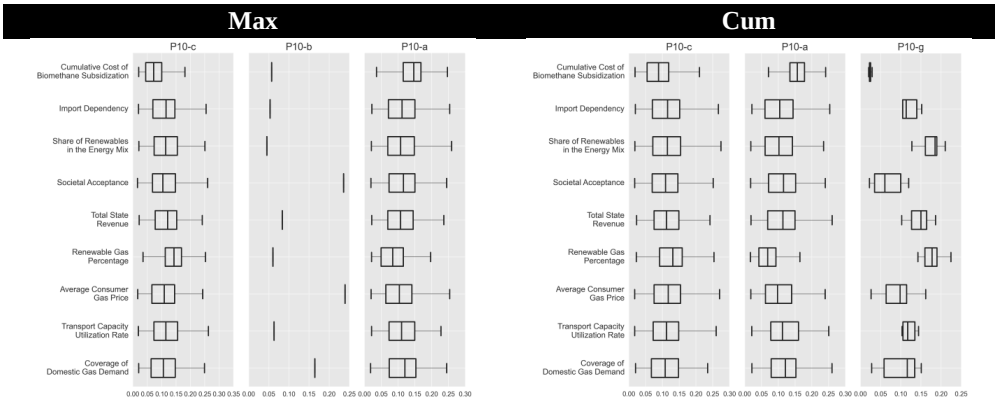
Robustness Metric: *Regret thresholds*



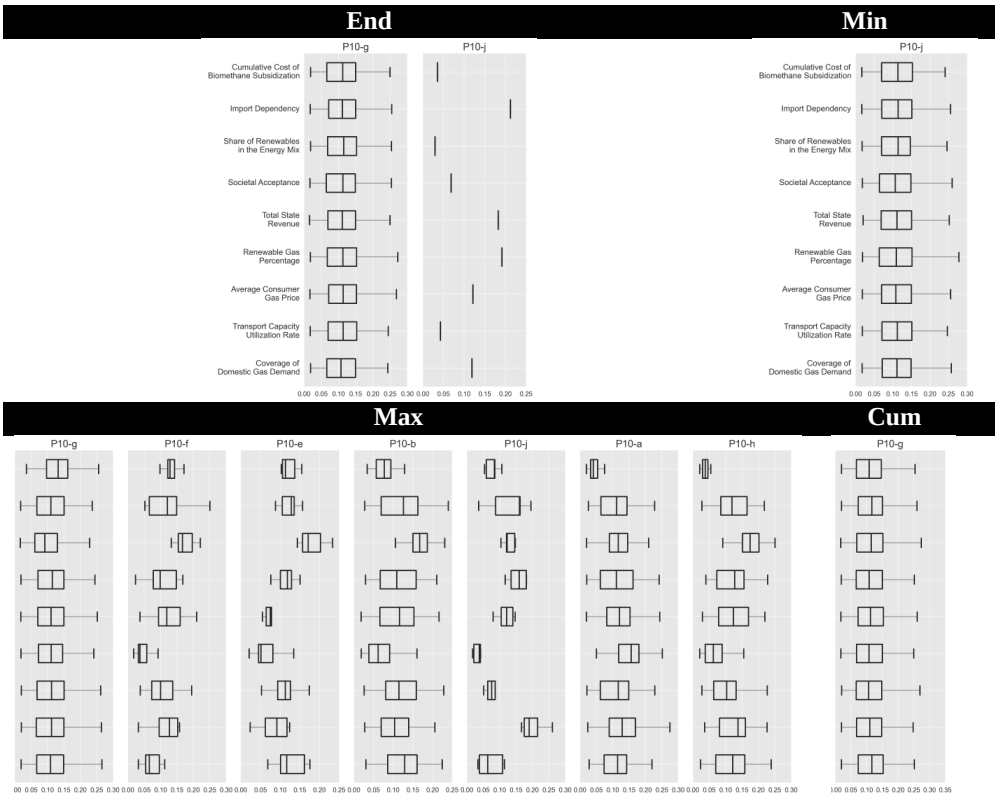
Robustness Metric: *Mean/Standard deviation*



155A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

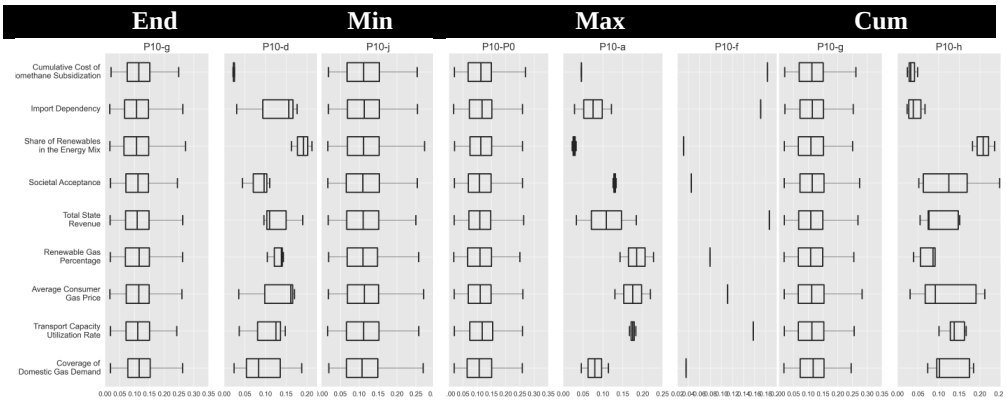


Robustness Metric: *Skewness I*

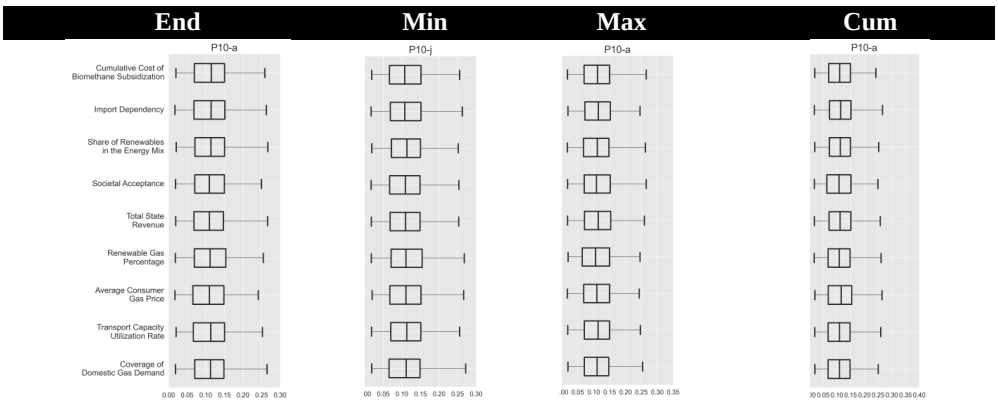


155B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

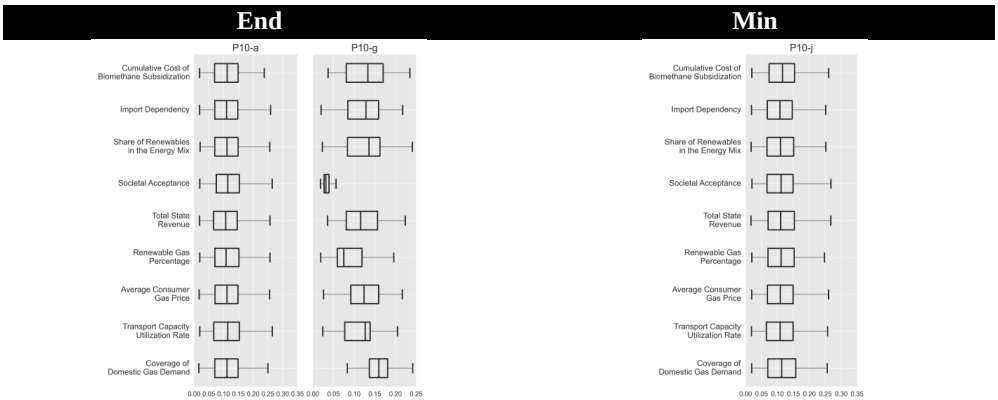
Robustness Metric: *Skewness II*



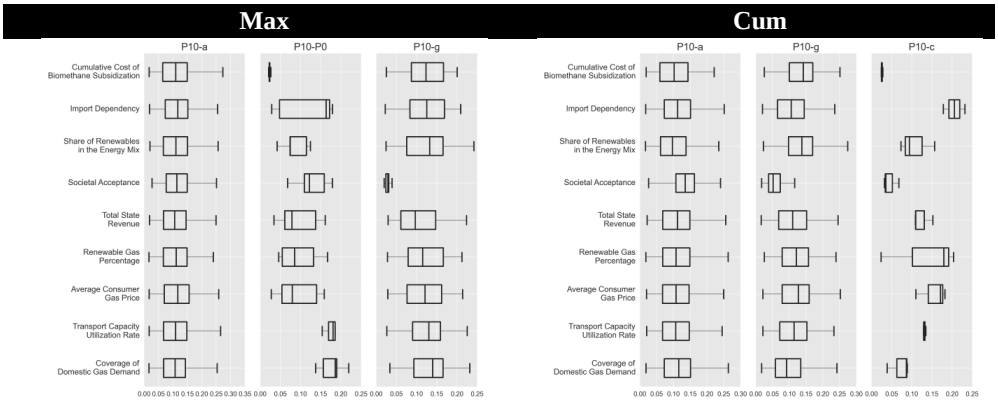
Robustness Metric: *IQR*



Robustness Metric: *Kurtosis*



156A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm



156B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Appendices to Chapter 8

APPENDIX 8.1: ENVELOPE AND KDE FIGURES FOR VISUAL COMPARISON

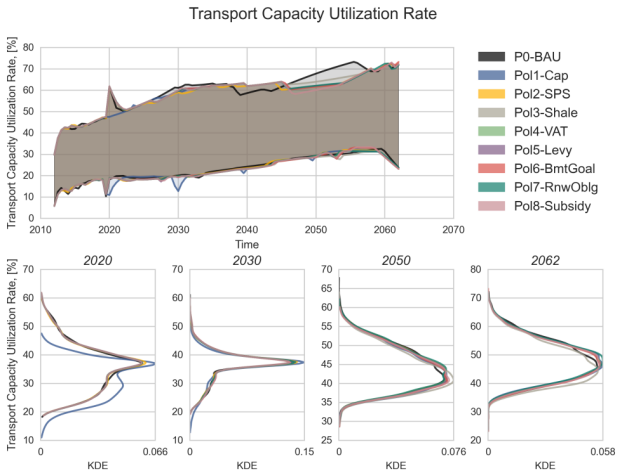


Figure A8.10: Envelopes of *Transport Capacity Utilization Rate* for each policy and KDE's in 2020, 2030, 2050 and of the end states

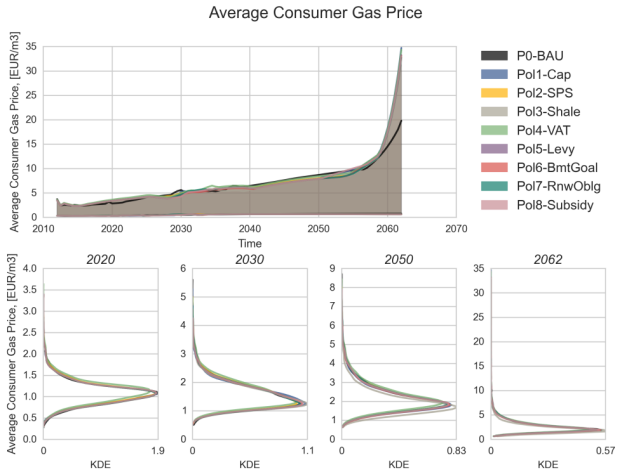


Figure A8.2: Envelopes of *Average Consumer Gas Price* for each policy and KDE's in 2020, 2030, 2050 and of the end states

157A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

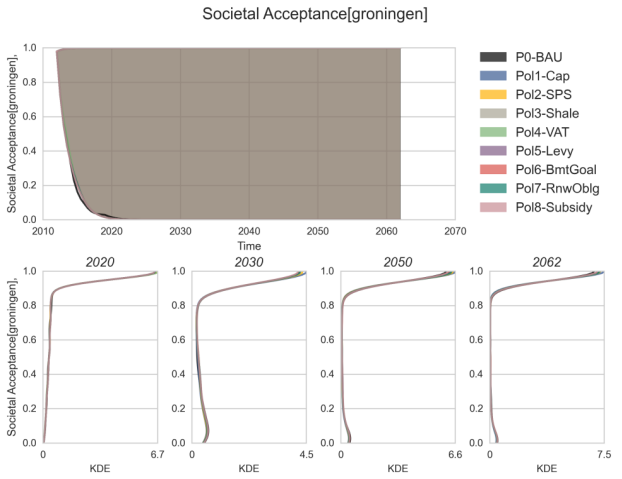


Figure A8.3: Envelopes of *Societal Acceptance* for each policy and KDE's in 2020, 2030, 2050 and of the end states

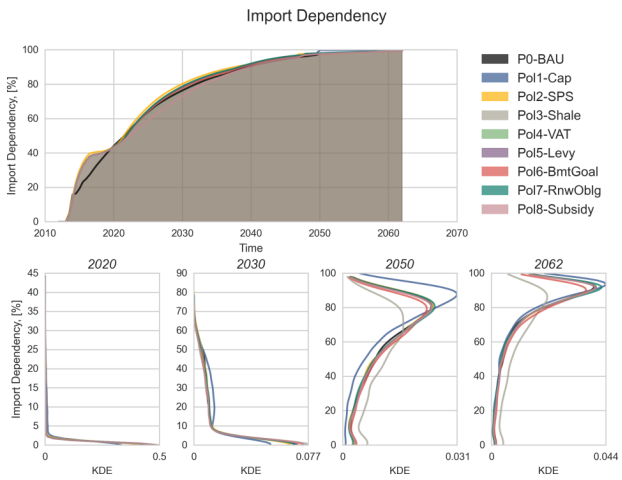


Figure A8.4: Envelopes of *Import Dependency* for each policy and KDE's in 2020, 2030, 2050 and of the end states

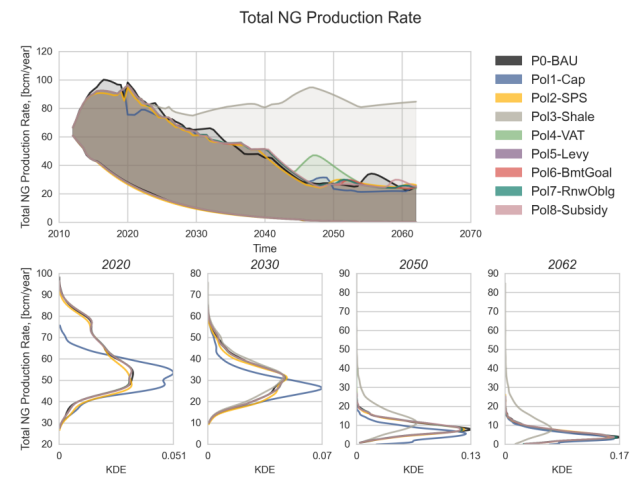


Figure A8.5: Envelopes of the *Total Natural Gas Production Rate* for each policy and KDE's in 2020, 2030, 2050 and of the end states

157B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

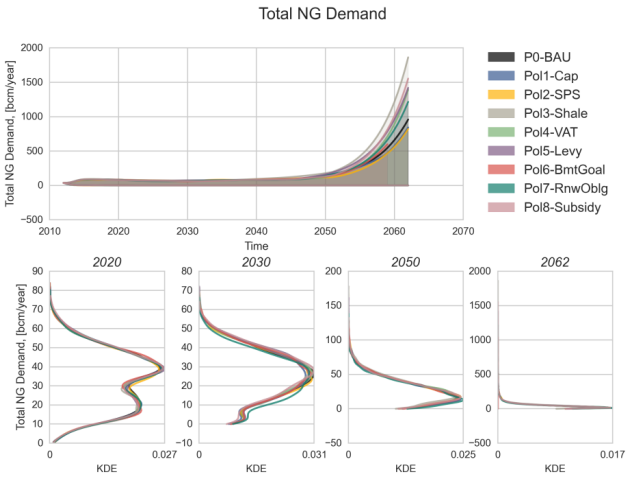


Figure A8.6: Envelopes of *Total Natural Gas Demand* for each policy and KDE's in 2020, 2030, 2050 and of the end states

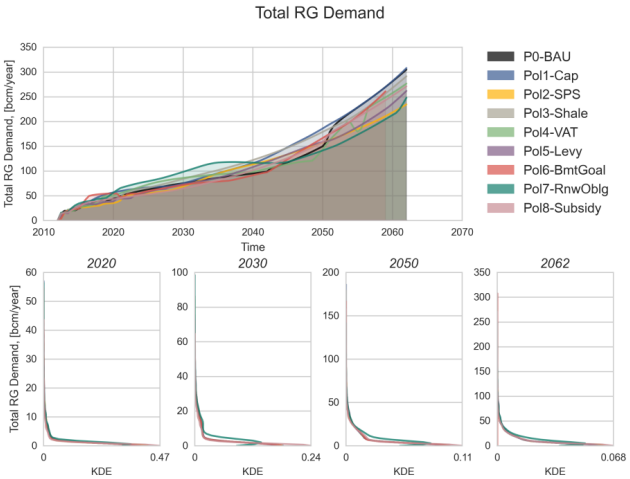


Figure A8.7: Envelopes of *Total Renewable Gas Demand* for each policy and KDE's in 2020, 2030, 2050 and of the end states

158A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

APPENDIX 8.2: ROBUSTNESS VALUES OVER TIME

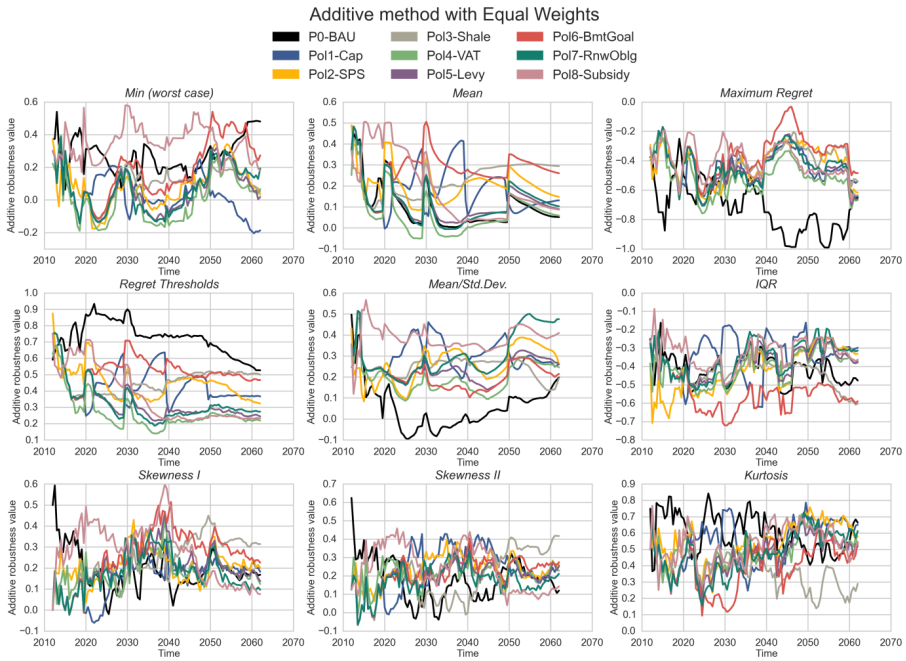


Figure A8.8: Additive robustness values over time for each metric

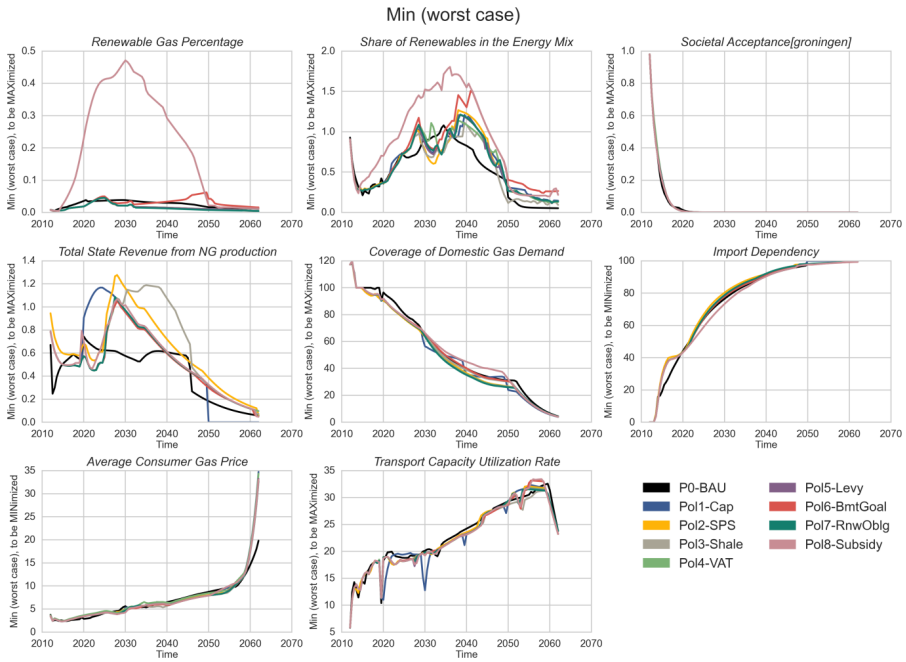


Figure A8.9: Robustness values over time for each outcome indicator, with the metric *Min*

158B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

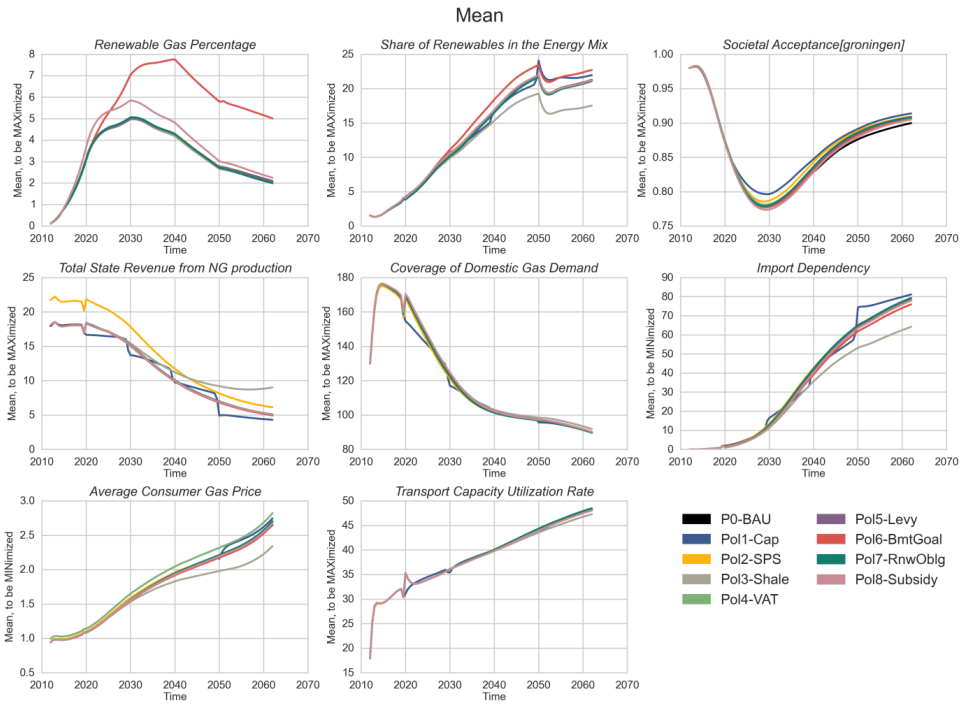


Figure A8.10: Robustness values over time for each outcome indicator, with the metric *Mean*

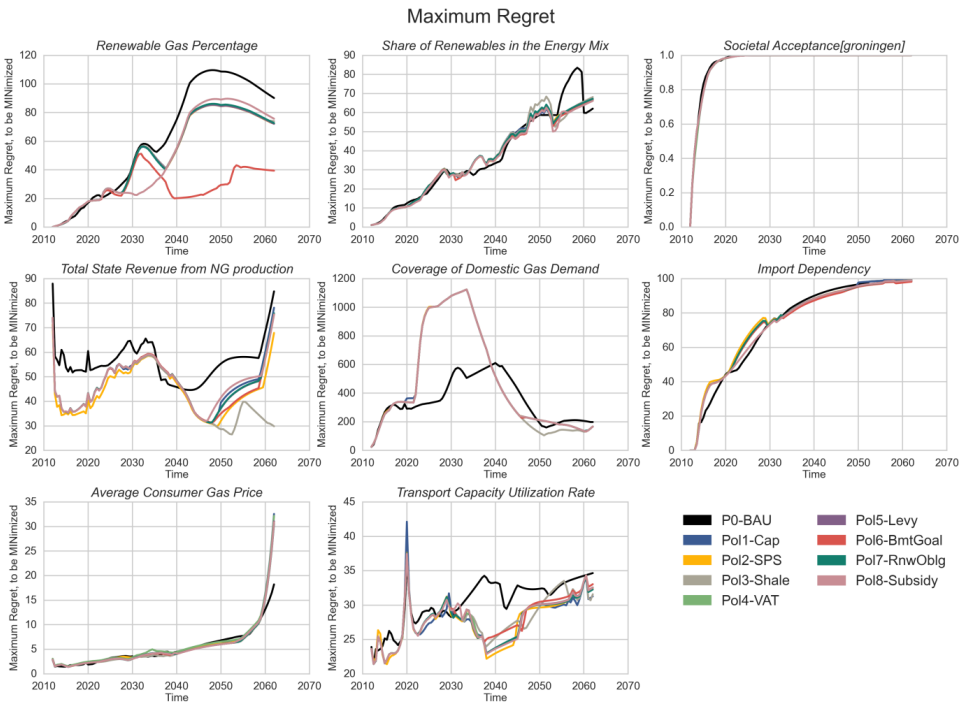


Figure A8.11: Robustness values over time for each outcome indicator, with the metric *Maximum Regret*

159A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

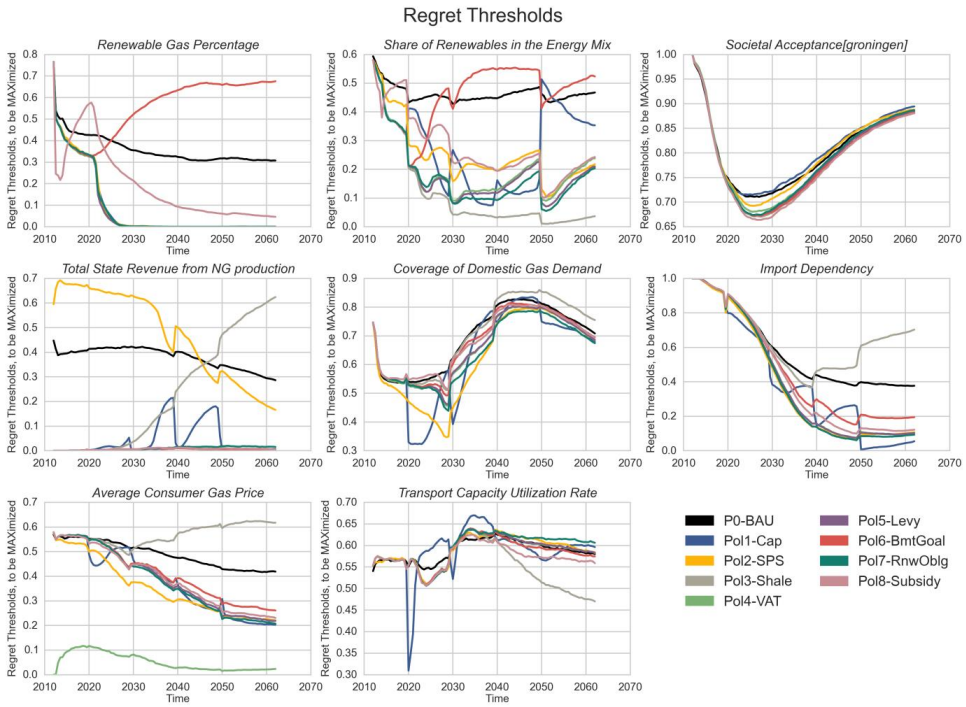
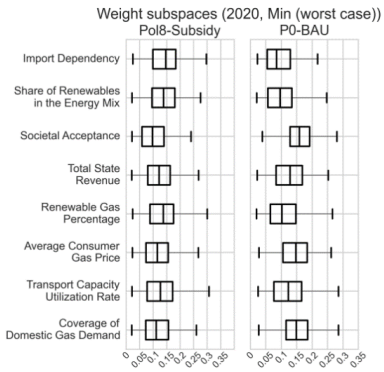


Figure A8.12: Robustness values over time for each outcome indicator, with the metric *Regret Thresholds*

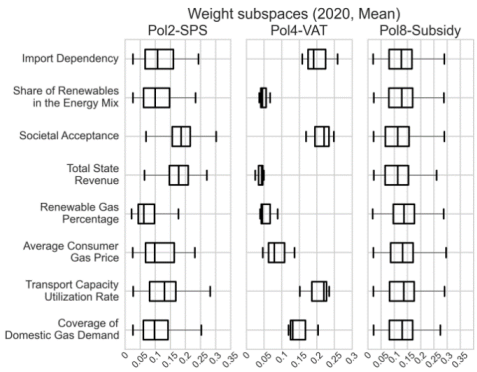
APPENDIX 8.3: WEIGHT SUBSPACES LEADING TO THE MOST PREFERRED POLICY OPTIONS

In 2020

(a) The robustness metric *Min*



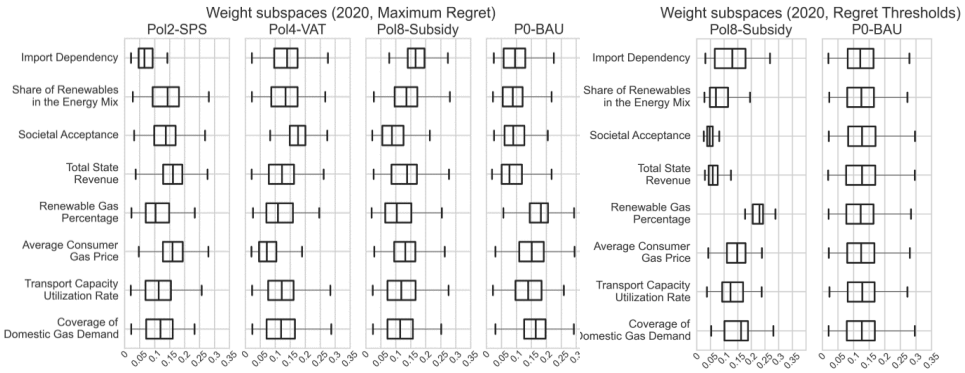
(b) The robustness metric *Mean*



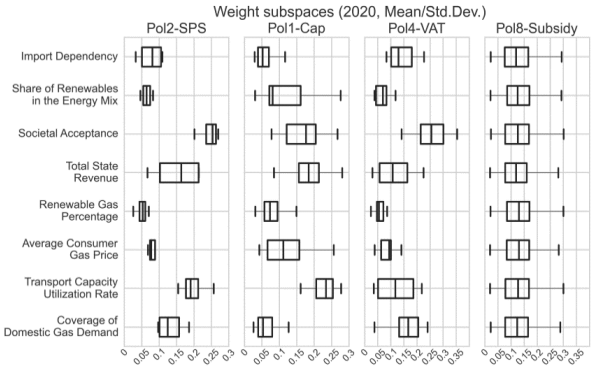
(c) The robustness metric *Max Regret*

(d) The robustness metric *Regret Thresholds*

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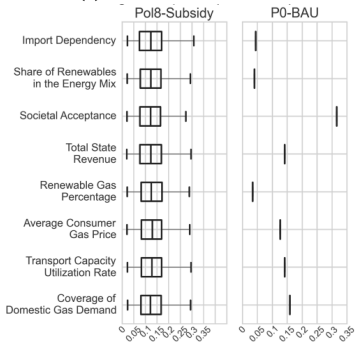


(e) The robustness metric *Mean/Std.deviation*

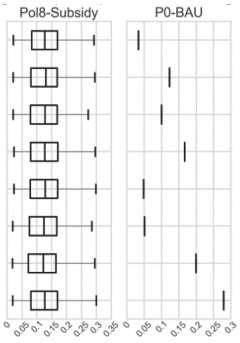


In 2030

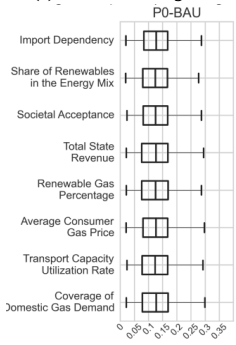
(a) The robustness metric *Min*



(b) The metric *MaxRegret*

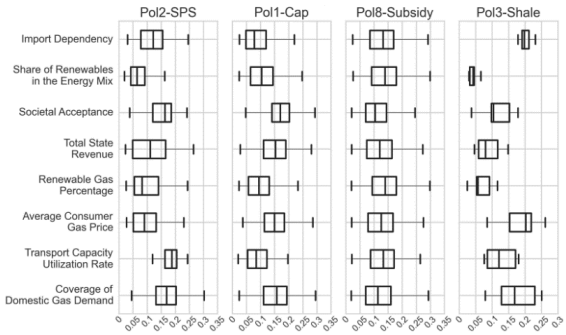


(c) The metric *Regret Thresholds*



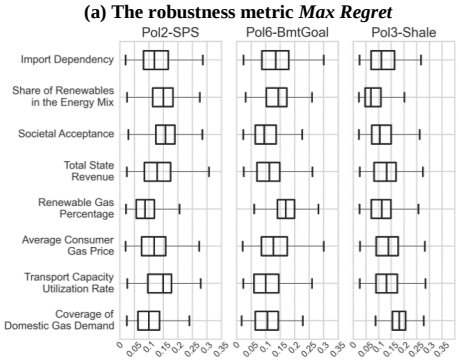
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(d) The robustness metric *Mean/Std.deviation*

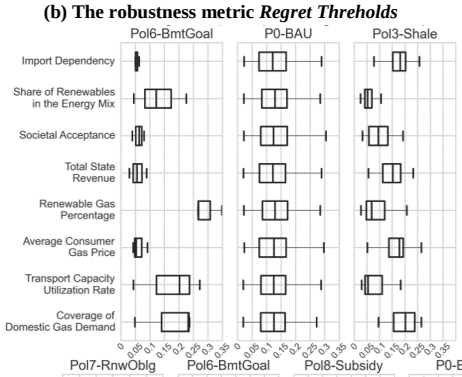


In 2050

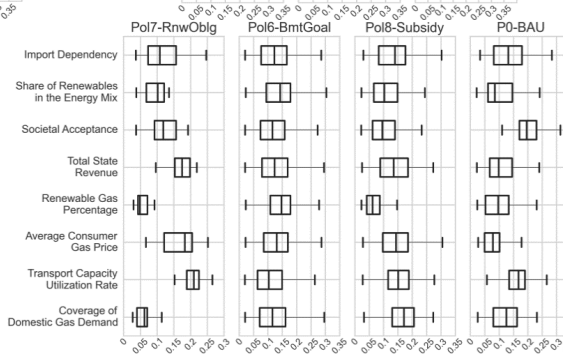
(a) The robustness metric *Max Regret*



(b) The robustness metric *Regret Threholds*

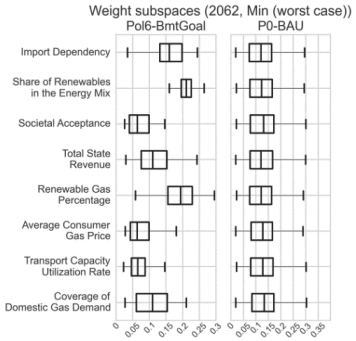


(c) The robustness metric *Min*

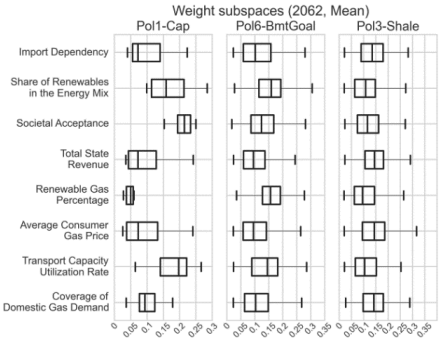


In 2062

(a) The robustness metric *Min*



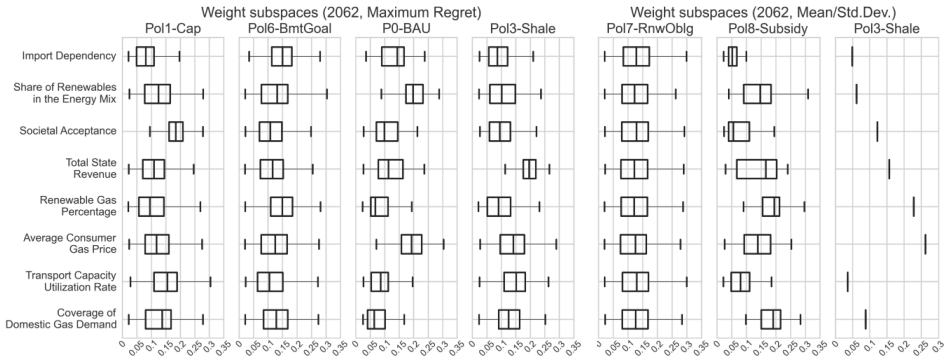
(b) The robustness metric *Mean*



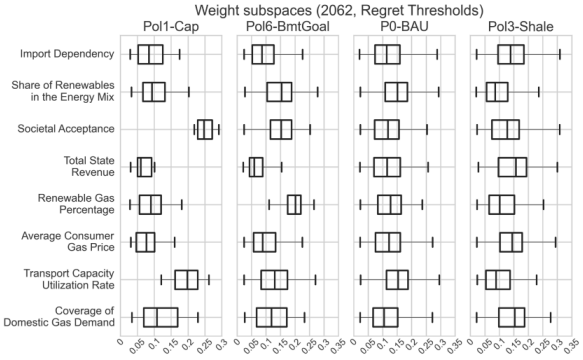
(c) The robustness metric *Max Regret*

(d) The robustness metric *Regret Thresholds*

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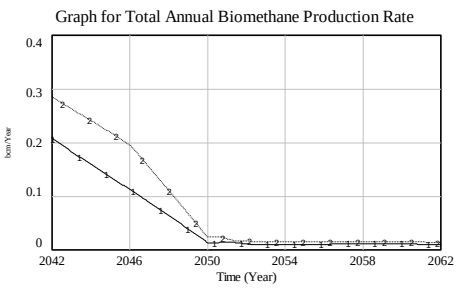
(e) The robustness metric *Mean/Std.deviation*



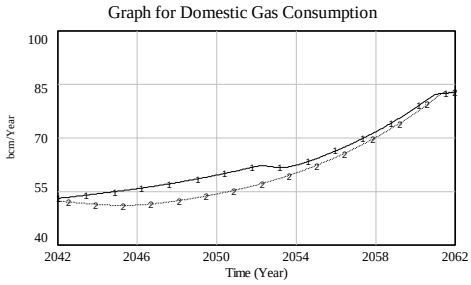
APPENDIX 8.4: ADDITIONAL SCENARIO DISCOVERY RESULTS

The Worst Case Scenario to Investigate the Switch from *P8* to *P6* with *Min*

-2- : Policy 6
-1- : Policy 8



(a)



(b)

161A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

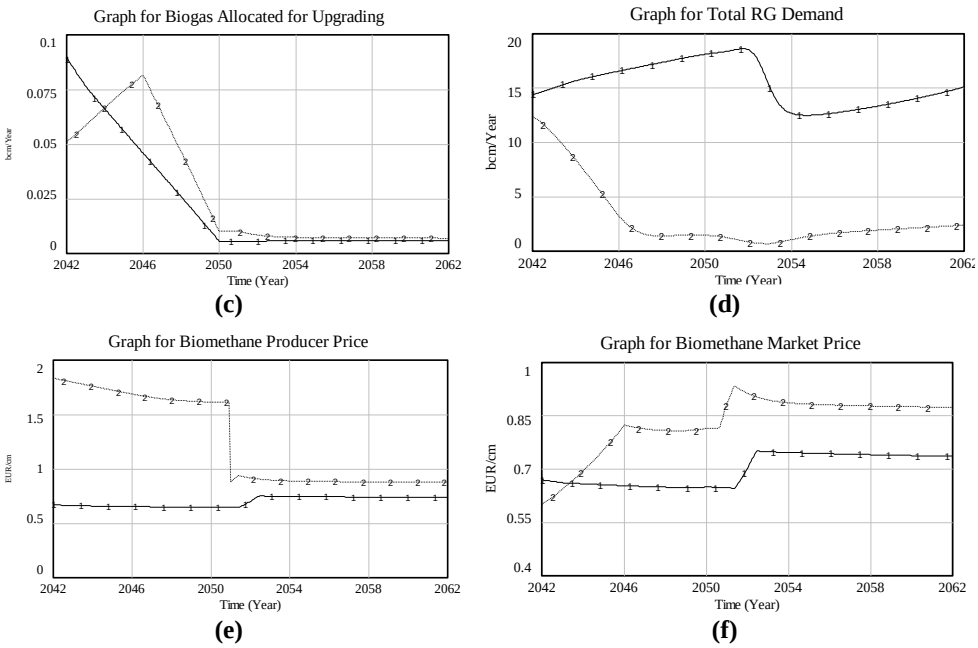
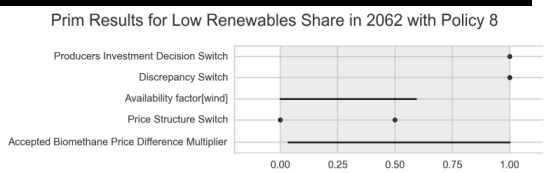
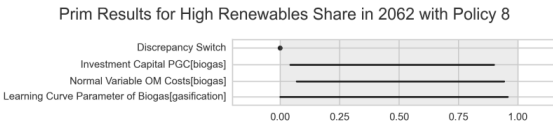
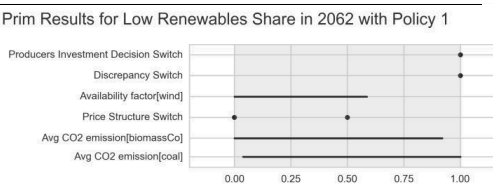
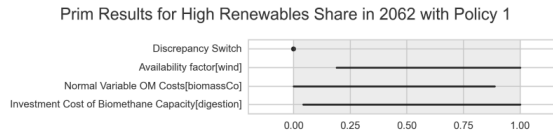
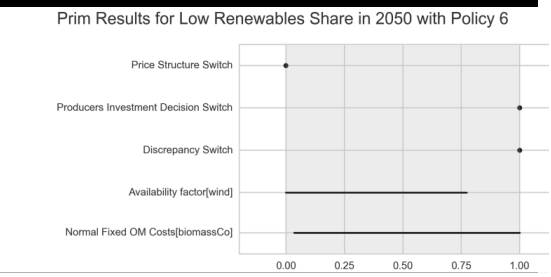
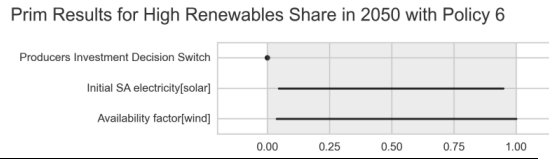
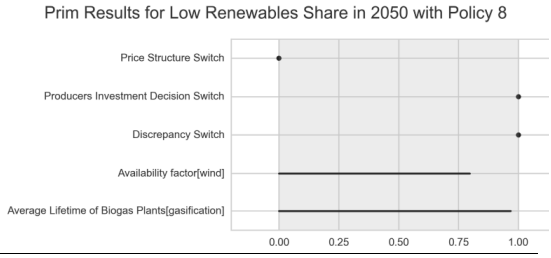
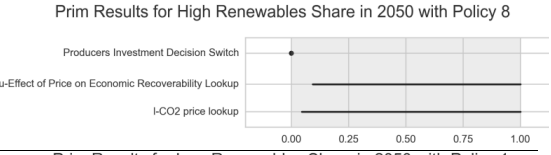
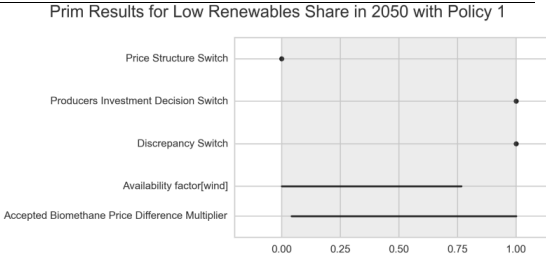
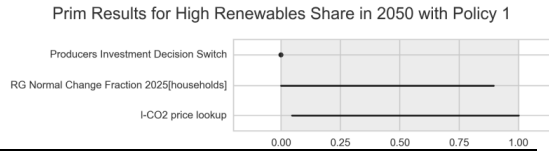


Figure A8.13: Worst case values between 2042 and 2062

PRIM Conditions and Results for the Double-Peak Density Estimates of the *Share of Renewables in the Energy Mix*

Scenario Classification Condition		*Scenarios of interest*	*Results*
Low Peak, P8	$O_{SR,P8}(2062) < 11\%$	848/ 5000	
High Peak, P8	$O_{SR,P8}(2062) > 11\%$	4151/ 5000	
Low Peak, P1	$O_{SR,P1}(2062) < 11\%$	808/ 5000	
High Peak, P1	$O_{SR,P1}(2062) > 11\%$	4191/ 5000	

161B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Scenario Classification Condition		Scenarios of interest	Results
Low Peak, P6, 2050	$O_{SR,P6}(2050) < 11\%$	752/ 5000	
High Peak, P6, 2050	$O_{SR,P6}(2050) > 11\%$	4247/ 5000	
Low Peak, P8, 2050	$O_{SR,P8}(2050) < 11\%$	779/ 5000	
High Peak, P8, 2050	$O_{SR,P8}(2050) > 11\%$	4220/ 5000	
Low Peak, P1, 2050	$O_{SR,P1}(2050) < 11\%$	733/ 5000	
High Peak, P1, 2050	$O_{SR,P1}(2050) > 11\%$	4266/ 5000	

162A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

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Acknowledgements

I had heard about the PhD position that led to this thesis in March 2011 from my master thesis supervisor Jill Slinger. I had faced a deep ambivalence in the following months, with the ambition to have a PhD and an academic career, and with the fear of a 4-year commitment to a research project and to live in the Netherlands. I eventually applied for the position and succeeded to get it. The rest was four years of blood, sweat and tears, as well as joy, learning and personal development.

My greatest supporter in these years was my co-promotor Els van Daalen who has always been kind, motivating and helpful. She guided me not only in shaping my research and managing my project, but also in developing as an autonomous researcher. She always impressed me with her critical thinking, effective communication and modesty. I always felt the confidence that she would have put me in the right way if I was going wrong. My promotor Wil Thissen contributed to this feeling of confidence greatly. His vast knowledge and experience, thorough review and constructive critique improved this thesis tremendously and inspired my thoughts about my career. I am grateful to my supervisory team for all the guidance and opportunities they provided to me. Thanks to them, I unfortunately have very high standards now if I ever supervise my own students one day in future.

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163A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Netherlands. She made me feel rooted, and many dusks in Delft I had her beautiful voice in my head singing “Gun biter gulusun kalir bende…” I am thankful to *Femke* for the ‘home’ she created and that hosted our joy, struggles and curiosities for three years. I am thankful to *Rene* for being so Dutch that made us have a barbecue under an umbrella and to my yoga teacher *David* who has no idea about how much he contributed to this thesis.

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I dedicate this thesis to my grandfather Huseyin, who passed away in 2007 and who always wanted me to have a high education but probably didn’t mean that much.

163B_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

About the Author



Sibel Eker was born on March 20, 1987 in Edirne, Turkey. She received her BSc degree in Industrial Engineering from Boğaziçi University (Istanbul) in 2009. She also studied Operations Management and Logistics at Eindhoven University of Technology for a semester in 2008 as an exchange student. She moved to the Netherlands again in 2009, and in 2011 she obtained her MSc degree in Systems Engineering, Policy Analysis and Management from Delft University of Technology with specializations in modelling and simulation. She joined the Policy Analysis section at TU Delft the same year for the Ph.D. project that eventually led to this book.

During her PhD, she was a visiting student at the Engineering Systems Division of MIT in 2013, and she was involved in several organizational activities of the Student Chapter of the System Dynamics Society between 2013 and 2015. Sibel's research interests center around modelling and simulation for complex policy problems, especially in the domains of energy, health and agriculture, and decision making under uncertainty. Sibel will continue her academic career as a Research Associate at the Bartlett School of Environment, Energy and Resources of University College London.

164A_Proefschrift Eker_Standv1.job_Press Sheet Size 17x24 cm

Dissemination

Peer-reviewed journal articles

Eker, S., van Daalen, E., Thissen W.A.H. (under review). A Multi-Method Approach to Evaluate Policy Robustness in Exploratory Modelling and Analysis. *European Journal of Operational Research*.

Eker, S., van Daalen, E. 2015. A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty. *Energy Policy, 82*, 178-196.

Eker, S., Slinger, J.H., Daalen, E. van and Yucel, G. 2014. Sensitivity Analysis of Graphical Functions. System Dynamics Review, 30(3), 186-205.

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Kwakkel, J., Pruyt, E., Eker, S. (in press). How robust is a robust policy? Comparing alternative robustness metrics for robust decision-making. In *Robustness Analysis in Decision Aiding, Optimization, and Analytics*, edited by C. Zopounidis and E. Grigoroudis. New York: Springer.

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Eker, S., Djong, J., Leston, D. 2014. Modeling the Dynamics of Canine Rabies and Policy Analysis under Uncertainty. Proceedings of the 32nd international conference of the system dynamics society (pp. 948-970) New York: System Dynamics Society.

Eker, S., van Daalen, E. 2014. Analyzing the Dynamics of the Bio-methane Production Chain and the Effectiveness of Subsidization Schemes under Uncertainty. Proceedings of the 32nd International Conference of the System Dynamics Society (pp. 971-1035) Delft, Netherlands: Systems Dynamics Society.

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Eker, S., van Daalen, E. 2012. Investigating the effects of uncertainties associated with the unconventional gas development in the Netherlands. Third International Engineering Systems Symposium CESUN 2012, Delft: TU Delft.

Eker, S., van Daalen, E. 2012. Uncertainties in the development of unconventional gas production in Europe. Proceedings of the 9th International Conference on European Energy Market (EEM), (pp. 292-299) Florence, Italy: IEEE.

Eker, S., van Daalen, E. 2012. Uncertainties in the development of unconventional gas production in the Netherlands. Proceedings of the 30th international conference of the systems dynamics society, Albany: System Dynamics Society.

Eker, S., Slinger, J.H. and Yucel, G. 2011. Investigating an automated method for the sensitivity analysis of functions. Proceedings of the 29th International Conference of the System Dynamics Society, Washington DC: System Dynamics Society.

International conference presentations

Eker, S. 2014. A systems modelling and exploratory uncertainty analysis of the future of the Dutch gas sector. Energy Systems Conference, June 2014, London: Elsevier.

Eker, S. 2013. Dealing with uncertainties in the Dutch gas sector. Technology, Management, and Policy Consortium Meeting, June 2013, Cambridge, MA: Massachusetts Institute of Technology.

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