Technology Assessment of sustainable technological options for the Dutch gas sector

A refined methodology combining Multi-Criteria-Decision Making with Pathway Analysis

Master Thesis for MSc. Management of Technology

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Preface

The following document is an outcome of my graduation project for the Master's Programme 'Management of Technology' at Delft University of Technology. The research was carried out in the department of Technology Dynamics & Sustainable Development in the faculty of Technology, Policy & Management. My choice for the particular subject of the thesis results from my personal interest in sustainable development as well as for the integration of technical, economic and social aspects of technologies in society.

I would like to take this opportunity to thank my graduation committee, Dr. Karel Mulder, Dr. Jaco Quist and Dr. Scott Cunningham for their guidance during my research. Special thanks go to my two supervisors Jaco Quist and Scott Cunningham. To Jaco, because he supervised me from the preliminary stage of my thesis on and helped me very much to nail down its scope and to overcome my initial difficulties with the research, when supervision was needed most. To Scott, because he assured that I prevail on top of the major steps of my research at all times. Also, he provided me with new perspectives and methods whenever needed. I perceived the meetings, the three of us had, as very inspiring and motivating. I always left them with new enthusiasm.

Second, I would like to thank Floris van Foreest from DNV Kema and Dr. Kas Hemmes for their time and practical insights during our interview on recent trends within the Dutch gas sector. The conclusions I could draw from our conversations were a very valuable counterweight to the often monotonous analyses I had found in the literature.

Apart from people of the academic and professional environment I would like to thank my friends Eduardo Allison, Jaime Michavila Gaspart, Pratap Thapa, Narita Tessanica Panjaitan and Hector Villanueva Lopez. Not only for their help during several assignments as well as my master thesis; also for the great personal support, joy and friendship during the last two years. I can repeat: *"Coming to TU Delft and meeting you all here was the best decision of my life."*

Moreover, I would like to thank Ninja Volz, who has been understanding and patient in any possible way. She has supported me very much, especially during the stressful periods of my studies.

Above all, I would like to express my gratitude to my family, who has stood by me during the ups and downs of my life and has enabled me to graduate from TU Delft this summer.

Delft, August 2013

Lennart Budelmann

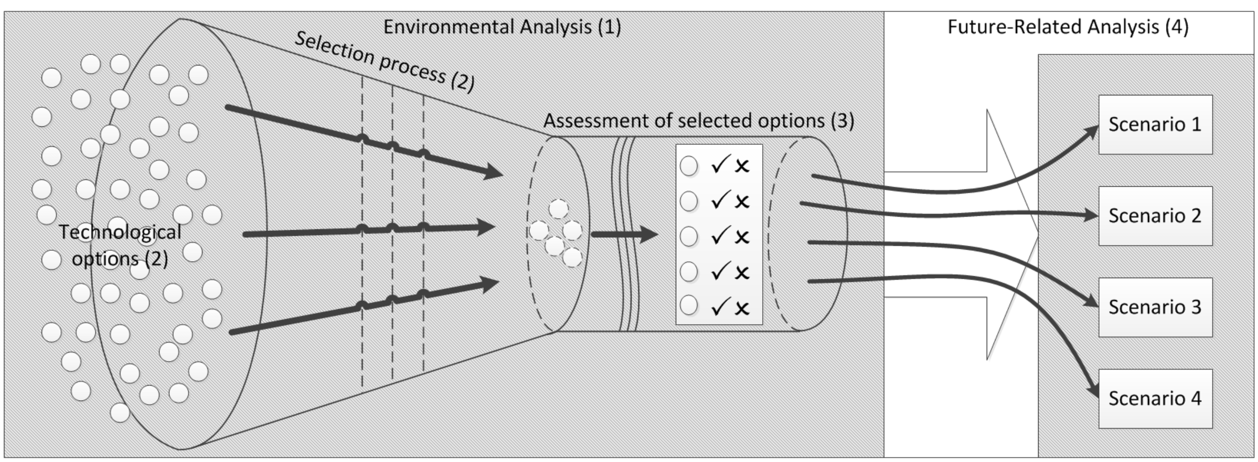
Executive Summary

Since the discovery of the gas field in Groningen, around 50 years ago, natural gas has been one of the pre-eminent drivers of the Dutch economy. However, the gas resources of the Netherlands are declining and, in its current form, the Dutch natural gas sector is steering towards a dead end. Against this background, the EDGaR program was founded, which aims to research how the Netherlands can "...*grow towards a sustainable energy mix from its current strong natural gas position"* (TPM, 2011). The following thesis is part of EDGaR's project 'The next 50 years: Developing robust strategies for the gas transition'.

Many projects related to emerging technologies face uncertainty related to the selection of the most promising technology to research. This problem also holds for projects of the EDGaR program. Given constraints of time and money, those projects need to reduce their scope and cannot research all technological options they identified.

The objective of this thesis is to assess a set of technological options regarding their relevance for continuative research. The assessment of these technologies will be carried out by analyzing factors and trends of innovation that are internal or external to the technologies and appear to determine their future development. Internal factors constitute aspects that are inherent to the technologies. External are those factors that emerge from the system, the technologies are embedded in.

The figure below outlines the approach of the thesis that is pursued to fulfil this objective, whereas the bracketed numbers specify the different stages of the research.



Whereas many other technology assessments are narrowed to only one or two of the stages indicated in the figure, this thesis aims to capture a more holistic picture. Therefore, the thesis (1) throws light on the environment emerging technological options are embedded in, (2) demonstrates the creation of an inventory some technological options are selected from, (3) conducts an assessment of the selected technological options and (4) reflects the results on potential future pathways of the Dutch gas sector. A brief insight into each of these four stages is provided in the following paragraphs.

The environmental analysis the thesis begins with describes the static and dynamic characteristics of the Dutch gas sector. It therefore first describes the physical assets in the current gas value chain of the

Netherlands. Second, it points out trends that have an influence on the Dutch gas sector. The most relevant trends identified by this research, which have an impact on the Dutch gas sector, are (1) the rise of new gas types (such as shale gas, coal bed methane, hydrogen, biogas or synthetic natural gas), (2) an increasing power position of societal stakeholders regarding the activities of the Dutch gas sector, (3) an increase of the gas import-export ratio of the Netherlands, (4) changing international power positions of gas producing countries and (5) an increase in households that require gas supply.

The technological screening that is conducted in the second phase of the thesis identifies 54 technological options that have been suggested in the research context of the thesis and screens them for (a) their potential to be operated sustainably, (b) being an integration option, (c) being a technology, (d) involving gas as a main energy carrier. Based on the screening, five technological options are selected, including (I.) the solar reforming of methane, (II.) the Superwind concept, (III.) Micro CHP units, (IV.) the power-to-gas concept and (V) hybrid fuel cell gas turbine systems. Each of these five options needs to be regarded as a non-regret options that appears generally promising for continuative research. The following stages of the thesis aim to differentiate further between these five options.

To do so, the third stage of the thesis assesses them regarding their (1) technical, (2) financial, (3) environmental and (4) social/economic/political characteristics. On top of that, the (5) dynamics of development for each option are analyzed. From the analysis of all five dimensions it can be concluded that the power-to-gas concept or Micro CHPs appear to be the most promising options. Private as well as public actors have frequently demonstrated their interest regarding both technological options. It appears that especially the power-to-gas concept has created a lot of expectations among researchers and could develop into a new paradigm.

However, the fourth stage of the thesis reveals that, when leaving the dimension ‘dynamics of development’ aside, the other three options are superior in many respects. A researcher who is unaffected by the interest of other researchers would, in fact, never choose for the power-to-gas concept and seldom for Micro CHP units, taking into account all possible preferences for the four remaining dimensions of assessment.

Moreover, the fourth stage of the thesis conducts a pathway analysis and relates the formation of different actor coalitions to the pathways identified. It is argued that different future pathways trigger the formation of distinct actor coalitions and that the preferences for the four remaining dimensions of the assessment framework change accordingly. As a result, conclusions can be drawn on the appropriateness of different technological options for diverging future pathways. In doing so, the thesis identifies the solar reforming of methane as the most appropriate technological option for sustainable development. Subsequently, it conducts a backcasting analysis that defines measures to enable the implementation of solar reforming plants in North Africa, as a means to steer towards sustainable development.

Given the above insights, the thesis directly benefits the research project it is conducted for because it provides a comprehensive picture of the five technological options, their environment as well as potential future pathways for the Dutch gas sector. Moreover, it points out that the solar reforming of methane appears as most promising for sustainable development, which is a high ranking goal of the EDGaR program.

In a more general context, the thesis offers great benefits to policy makers because it allows gaining a holistic picture of emerging technologies in a very structured manner. Thus, policy makers can save a lot of time, money and effort by applying the refined methodology of this thesis to problem-settings which require the selection of one, out of several possible, technological options. In doing so, the thesis is also of theoretical relevance for the literature on Multi-Criteria Decision Analysis because its relation of actor coalitions with the weighting of assessment dimensions is novel. By combining this practice with the backcasting analysis at the end of the thesis, the assessment framework of the third stage can be utilized as a strategic tool that enables the definition of measures, which lead to a favourable pathway, while taking into account the perceptions and actions of other actor groups.

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1 Introduction

1.1 Background

Around 50 years ago, a tremendous gas field was found in Groningen (Petroleum Economist, 2010). Up until now, it has been recognized as the largest gas field of Europe and the tenth largest gas field of the world. Following this discovery, the Netherlands rapidly built a growing gas infrastructure and made a remarkably fast transition from a coal to a gas-based economy (Correlje & Verbong, 2004).

In comparison with other fossil fuels the burning of gas amounts to relatively low emissions per unit. Therefore it is also called the "clean fossil fuel". Besides, it can be easily distributed, within and outside the Netherlands, and used for several purposes on different scales. These advantages resulted in a growing income of the Dutch gas market, which can be considered as one of the most pre-eminent drivers of the country's economy (Banning, 2009). However, within the last decade it has become apparent that the Dutch gas fields are running out and that the Dutch gas sector, in its current setting, steers towards a dead end. As a consequence, the EDGaR program was founded. It spends an effort on the development of strategies that aim to improve the prospective future of the Dutch gas sector.

1.2 EDGaR

The Energy Delta Gas Research program (EDGaR), is a national consortium of thirteen institutions that aims to investigate *"how can the Netherlands grow towards a sustainable energy mix from its current strong natural gas position?"* (TPM, 2011). To answer this question, EDGaR addresses three themes: 'From monogas to multigas', 'Future energy systems' and 'Changing gas markets' (EDGaR, 2013c).

This thesis is part of the last theme, 'Changing gas markets', which addresses the consequences that result from the dynamic character of the international gas market within the last decade (TPM, 2011). Trends such as *"…internationalization, deregulation, the introduction of liquefied natural gas (LNG) and the related need for different transport systems, and the quickly increasing role of shale gas"* are objects to research (TPM, 2011). Moreover, the theme aims to point out international dependencies that arise from these dynamics and to analyze what strategies can be derived from the above aspects to enhance the competitive advantage of the Dutch gas sector (EDGaR, 2013a; TPM, 2011). Particular attention is paid to the question how technological innovations and knowledge that boost the Dutch energy transition can be fostered and exported to other countries subsequent to the transition (EDGaR, 2013a; TPM, 2011). All three themes split into further research sub-themes that are dealt with in dedicated research projects. The further division of 'Changing gas markets' is illustrated in figure 1.1.

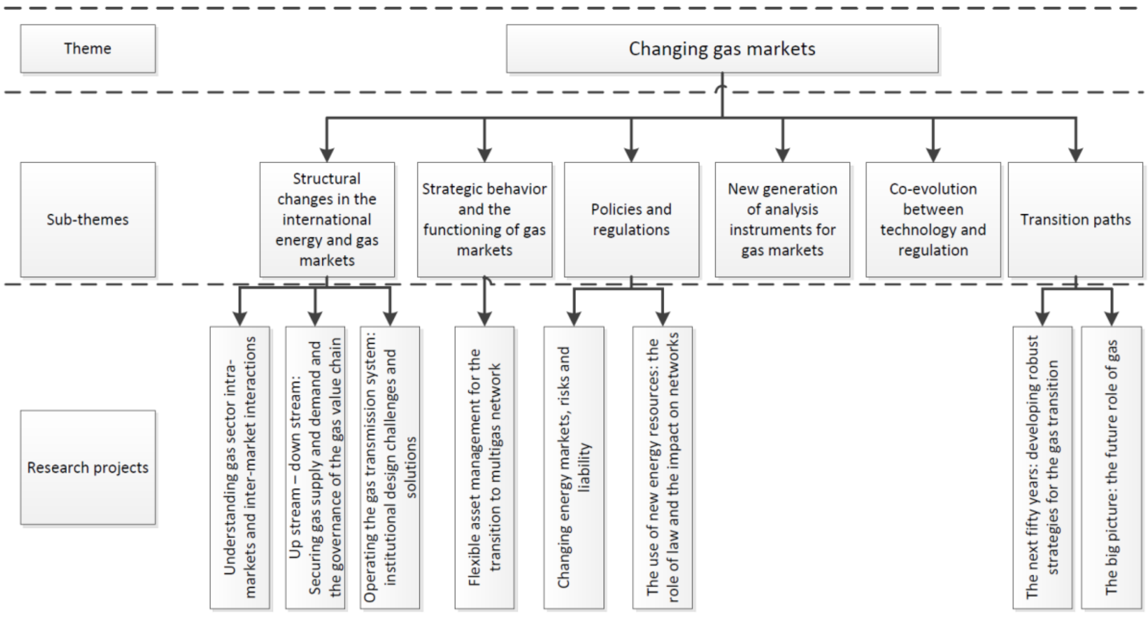


Figure 1.1: The organization of EDGaR's theme 'Changing Gas Markets' (Based on: (EDGaR, 2013b))

This thesis is part of the research project 'The next fifty years: Developing robust strategies for the gas transition' that is part of the sub-theme 'Transition paths'. Its objective and the practical contribution I like to make with my research are pointed out in the following section.

1.3 The next 50 Years: Developing Robust Strategies for the Gas Transition

The research project 'The next fifty years: developing robust strategies for the gas transition' is carried out jointly by the TU Delft, ECN and KEMA. It aims to identify "*…a robust long-term sustainability strategy for the gas sector*" (Hemmes, 2010). Within the project a particular weight is assigned to the analysis of social acceptance and technology development, to align with the market-oriented research conducted in the theme of 'Changing gas markets' (Hemmes, 2010).

The project is divided in three sub-projects: 'Technology Assessment', 'Societal Acceptance' and 'Dealing with uncertainties in policy strategies' (Hemmes, 2010). They are conducted simultaneously and aim to fulfil the project's overall objective. This thesis is part of the first subproject, 'Technology Assessment', which is carried out jointly by TU Delft and KEMA. It strives to analyze the relation between technology and society and thereby aims to identify desirable, socio-technical pathways towards a sustainable future of the gas sector (Hemmes, 2010). To do so, the following research questions are addressed:

1. Which technological options and system developments are relevant and thinkable for the gas sector in the coming 50 years?
2. To what extent are these covered in the current transition scenarios and pathways?
3. What are the possible impacts of these options and pathways on the functioning, position and performance of the gas sector?

KEMA is an energy consultancy that provides business and technical solutions, next to other services. The company *"…is committed to driving the global transition toward a safe, reliable, efficient, and clean* *energy future"* (Kema, 2013). During the last decades, it gained much experience in the field of gas technologies and gas infrastructure (Hemmes, 2010). Its expertise is therefore of particular relevance for the techno-economical analysis of incumbent gas technologies as well as the exploration of upcoming trends within the gas sector.

1.4 Research

On the one hand, EDGaR aims to conduct research of technological and strategic importance regarding the transition toward a sustainable energy system. On the other hand it is not known yet what drawbacks emerging gas technologies will face in future. To counteract this dilemma, the subproject 'Technology Assessment', this thesis is part of, aims to assess emerging technological options along the gas value chain of the Netherlands.

However, as can be derived from the classical theory of project management, there is a trade-off between the scope of the research project, its costs and its duration. Therefore, the problem owners aim to research in depth only technologies, which appear to be of particular importance to the overall goal of EDGaR. However, factors and trends of several dimensions are taking affect within and from outside the gas sector, causing it to be dynamic (TPM, 2011). Consequently, the pertinences of emerging technologies regarding the goal of EDGaR also change over time. Thus, in the current state of the research project, it is not possible to rationally allocate research funds to in-depth assessments of single technologies, chosen from the broad range of potential options.

Given previous attempts that have been made to identify emerging technologies for the Dutch gas sector (KEMA, 2012; Veringa et al., 2008), the resulting list of technologies that are potentially beneficial for the Dutch gas sector is too long to assess every technology in depth.

The objective of the research is to assess a set of technological options regarding their relevance for continuative research. The assessment of these technologies will be carried out by analyzing factors and trends of innovation that are internal or external to the technologies and appear to determine their future development. Internal factors constitute aspects that are inherent to the technologies. External are those factors that emerge from the system, the technologies are embedded in.

The thesis hence enables the decision for an in-depth assessment of a limited number of options. Based on the research it is possible to spend the research funds, allocated to the sub-project of 'Technology Assessment', on the most relevant options and thereby to fulfil the scope of the project with the given research funds in the most promising manner. The latter aspects constitute the practical relevance of this thesis.

1.4.1 Research Questions

The following section derives the research questions and sub-questions from the research objective formulated above. To begin with, the main questions are derived and their underlying sub-questions introduced. The subsequent paragraph explicitly reasons the choice for the formulated questions.

As stated above, the objective of "…the research is to assess a set of technological options". Given this statement the following three main questions and, if applicable, their underlying sub-questions are articulated.

1. ***How can the foresight of new technological options for the Dutch gas sector be integrated within a holistic approach?***

2. ***What are static and dynamic aspects of the Dutch gas sector?***
   2.1 What is the current socio-technical system associated with the Dutch gas sector?
   2.2 What are recent trends affecting the development of the Dutch gas sector?

3. ***What criteria are relevant for assessing technological options of the gas sector regarding their relevance for continuative research?***
   3.1 What criteria are relevant to narrow down the selection of options?
   3.2 What criteria are relevant to assess a limited set of technological options?

4. ***What is the value of the different technological options studied in view of the second set of assessment criteria?***
   4.1 What advantages and disadvantages do the different technologies face regarding different dimensions of assessment?
   4.2 What is the overall value of the options assessed?

Second, and as stated in the objective, the assessment of the different technologies is carried out against the background of *"…potential and correlating relevance for continuative research"*. Taking into consideration this aspect, the fifth main question of my research and its underlying sub-questions are formulated as follows.

5. ***What can be suggested by comparing the different technological options against the background of future uncertainties?***
   5.1 Given different future developments, what technologies appear to be a robust choice to research further?
   5.2 How can sustainable technological options be further developed?

The first main question points to the methodology of the thesis. As stated by Porter and Cunningham (2004), Technology Assessment (TA) can be considered as explorative research, which also holds for the thesis proposed (cf. section 1.4.2). Because explorative research involves *"…very little knowledge or information … on the subject under investigation"* (Sekaran, 2006), it is of value to make the design choices of the thesis explicit by means of a research question. This allows for a more elaborate, subsequent reflection on the research approach, from which future research can benefit.

The second main question is of introductive character. By pointing out trends in a systematic way that affect the Dutch gas sector, it aims to lay the foundation for the following chapters. Thereby, different dimensions will be analyzed in order to account for different perspectives on the dynamics of the sector.

The third main question will result in two lists of assessment criteria, the technological options will be confronted with. The first list relates to the first sub-question and aims to narrow the extensive list of technological options that results from foregoing studies of the research project. The second list of assessment criteria is only applied to those technological options that fulfil all criteria of the first list. The assessment criteria contained in this list are more detailed and used to assess the remaining technological options in detail.

The fourth main question results in an assessment of the different technologies in accordance to the second set of assessment criteria selected. To do so, the question is divided into two sub-questions. The first aims to analyze the technologies' advantages and disadvantages with regard to the different dimensions of the assessment criteria. The second sub-question summarizes the insights of the different dimensions assessed in an overall value for each option.

The fifth main question translates the insights gained previously into recommendations for the research project. Whereas the second, third and fourth main questions are mainly of descriptive character, this question aims to develop descriptive knowledge regarding the different technologies studied. To do so, its first sub-question requires the development of different scenarios for the Dutch gas sector and analyzes how the characteristics of the technologies relate to these scenarios. Thereby, this sub-question addresses how a robust decision for a technological option can be made despite uncertain developments of the future. The second sub-question aims to bridge the gained insight with the overall objective of EDGaR by suggesting measures that foster the sustainable development of the Dutch gas sector in general, and the development of sustainable options assessed in the thesis in particular.

1.4.2 Type of Research

The research will conduct a broad technology assessment, having the nature of an explorative research. As stated in the research objective, the thesis aims to identify options of high relevance regarding continuative research and therefore takes place at the beginning of the research project's 'assessment funnel'.

It is pointed out by Yin (2008), that explorative case studies do not test for hypotheses because the field of research is not fully identified yet. Similarly, in the current stage of the research project, no hypotheses can be formulated that address the distinct value of certain technological trajectories regarding the Dutch energy transition. First, because few technology assessments have been done that address the gas sector. Second, emerging fields of research have not been specified regarding their subordinate technologies and their underlying innovation processes (KEMA, 2012; Veringa et al., 2008). In order to fulfil its objective, the research thus needs to explore variations of the technological options and needs to define the criteria to assess these variations with. Thirdly, many gas technologies that are of potential for the Dutch gas system have not experienced broad market application yet and therefore, no common rules, institutions and actors have emerged (Suurs et al., 2009). Due to all three aspects, few insights have been gained on the innovation process of the Dutch gas sector as a whole. For the same reasons it is necessary to commence an assessment of the gas sector from the identification of emergent technologies, rather than from a system perspective and the subsequent formulation of technological needs.

As a matter of fact, explorative research aims to deliver working hypotheses. The outcome of this thesis, that is recommendations for further research needs to be considered as such. Also due to the explorative nature of the thesis, the research is mainly carried out as a desk study that collects qualitative and quantitative data, whereas the conduction of two expert interviews serves as an additional source of qualitative data.

1.4.3 Outline of the Thesis

The thesis is divided in five chapters. Whereas the first chapter provides an introduction to the thesis, the second chapter lays it's theoretical and methodological foundation. The third chapter describes the socio-technical aspects of the Dutch gas sector and pinpoints current trends that influence it. The fourth chapter identifies a number of technological options that have been suggested in the research context of the thesis and limits this number to a selection of five technological options. Subsequently, these options are described, assessed and compared. Within the sixth chapter, different future pathways are developed and means are suggested to foster sustainable development.

At the end of each chapter preliminary conclusions are drawn. After describing the structure of the chapter and the insights gained, a more general perspective is added that pinpoints how the results of the chapter can be generalized for the work of the EDGaR program and policy makers in general.

2 Theoretical Background of the Thesis

First, this chapter presents the theoretical background of the thesis that was identified during the literature study. Second, the research methods and techniques that are used in the upcoming chapters are introduced and it is argued how they contribute to the overall goal of the thesis.

The literature study that was conducted for this purpose focused on Theories of Technological Change, Management of Technology, Decision Making and Technology Assessment. Figure 2.1 illustrates the four main aspects of the literature study.

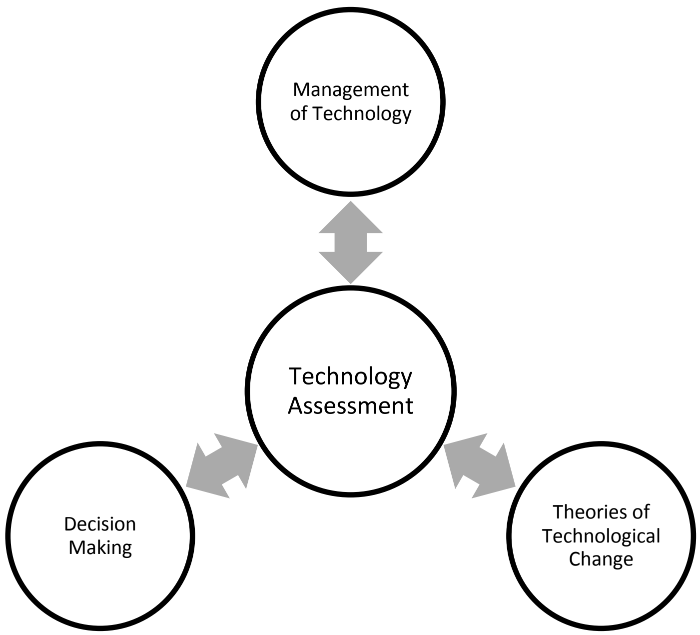


Figure 2.1: Main fields of the literature study

The emergence of technologies is a crucial theoretical background for the thesis which assesses emerging technological options that are relevant to the gas sector. Thus, it is important to develop an understanding of mechanisms that hamper and foster the development of these options in the past and future as well as the complexity that is present regarding this issue. Moreover, it is important to understand the process of technological development that results from the sum of different innovations in order to gain a bigger picture. The latter allows preferring technologies with predefined technological characteristics which relate to a bigger picture. Last, the body of knowledge of technology assessment is important to be aware of, because it aims to assess the aforementioned technological characteristics, to enable technologies with preferable characteristics and to foster technological development that coincides with the subjective values of the organization. Furthermore, it is important to understand technology assessment due to the project context of the thesis, described in section 1.3.

2.1 Theories of Technological Change

The emergence of technologies and the associated technological development have been explained from different angles of view. The following paragraphs introduce basic theories of evolutionary economics, the social construction of technology and network theory. All three aim to explain technological development, but take a different perspective. However, all three approaches have been preeminent in the past decades and are therefore highly relevant to understand the emergence of technologies in society.

2.1.1 Evolutionary Economics

Evolutionary economics aim *"…to understand and explain the process of technological change"* (Raven, 2005). Given the fact that the thesis aims to contribute to a transition from the current gas regime, mainly based on fossil fuel, to a sustainable energy system, theories of evolutionary economics are relevant to the research. In contrast to the events of the 1950s and 1960s in which the Dutch energy system performed a rapid transition from coal to gas (Correlje & Verbong, 2004), a change towards sustainability is likely to face more hurdles and thus to occur at a slower pace. There are several theories of evolutionary economics that account for this difference.

An overarching theory of evolutionary economics is the multi-level perspective and its underlying notion of technological transitions (Geels, 2002). The multi-level perspective incorporates the socio-technical landscape, *"…consisting of a set of deep structural trends"* (Geels, 2002), socio-technical regimes consisting of socio-technical *"…rules that enable and constrain activities within communities"* (Geels, 2002) and niches, protected selection environments (Geels, 2002; Raven, 2005).

After the discovery of the big gas field in the 1950s, gas was abound and thus became selected. In general, *"…selection refers to the survival and reproduction of successful agents or strategies in a system…*" (Van Den Bergh et al., 2006). However, in a socio-technical regime, actors are bound to certain rules that limit their selection criteria. Thus, there is a continuous paradigm determining the selection of technologies within socio-technical regimes (Raven, 2005). As a result, *"…repeated selection can result in path dependencies*", also called trajectories (Van Den Bergh et al., 2006). Likewise, the Dutch energy sector has focused increasingly on gas by raising its capacity and exporting gas to other European countries.

The current situation can be referred to as a lock-in (Van Den Bergh et al., 2006), because the Dutch energy system can hardly return to its initial configuration in which gas does not play a leading role. Besides, other energy technologies face difficulties to rise from the niche-level to a significant market share and need strategic approaches to be able to compete, with technologies of the regime, in the market (cf. Raven, 2005). The latter mechanism is fostered by the sailing ship effect according to which incumbent actors will improve their technologies further if new innovations enter their market (Geels & Schot, 2007). In relation to the Dutch energy system this effect is likely to trigger an improvement of natural gas technologies and thus hamper the diffusion of emerging, sustainable energy technologies.

2.1.2 Social Construction of Technology

The social construction of technology (SCOT) suggests that science and technology co-emerge and therefore should be studied together (Pinch & Bijker, 1984). More specifically, from the perspective of SCOT, *"…a crucial role is played by the social groups concerned with an artefact and by the meanings which those groups give to the artefact…"* (Pinch & Bijker, 1984). The latter is also referred to as *interpretative flexibility*. As a consequence, SCOT has the underlying assumption that all members of the same social group have a similar understanding of a certain artefact (Pinch & Bijker, 1984). Although a group is homogeneous for one artefact, it might be of heterogeneous nature for another artefact. As a result, it is necessary to decide for or against the division of social groups from case to case.

2.1.3 Network Theory

Another body of theory that is important to the emergence of technologies is constituted by networks. As pointed out by Quist, network theories have become a main pillar within several scientific fields and can be described as elements together with their relation among each other that jointly form a structure (Quist, 2007). Moreover, the author points out that *"…networks develop around specific topics, such as … the development of technologies…"* (Quist, 2007). Exactly this perspective is taken by the thesis proposed. As stated by Markard and Truffer (2008), the existence of related institutions, rules and actors depends on the development state of a technology. However, given the fact that for emerging gas technologies those structures might not have been shaped yet, networks appear to be a good approximation and particular attention will be paid to networks that develop among technologies and heterogeneous actors, which influence the development of emerging gas technologies. The reason is that these relations might increase their intensity in future and hence further materialize. Two specific network theories that are crucial to this perspective on technology development are actor network theory and industrial network. Both are further elaborated in the following paragraphs.

To begin with, actor network theory makes little difference between human and non-human actors (i.e. technologies) but rather distinguishes actors of low and high influence (Quist, 2007). As such, the actor network theory is an established means to explain innovation and the development of technology (Quist, 2007). Moreover, key to the theory is that *"…every form of change is reflected in the network"* (Quist, 2007). Consequently, the change, withdraw or entrance of a human actor or technology causes destabilization of the current network (Quist, 2007). Subsequently, it occurs a change of technologies, actors and their relations among each other until a new state of stability is reached that determines the roles of the network's actors (Quist, 2007). As a result of this stabilization process and its inherent entanglement of actors, *"…innovation and technology development is highly contingent and unpredictable"* (Quist, 2007).

Industrial network theory assumes relations among human actors regarding market and non-market aspects along the whole value chain of an industry (seen in Quist, 2007 based on Håkansson 1987; Håkansson 1989; Oerlemans 1996). Consequently, a network contains collaborating as well as competing firms, which are regarded to be in mutual interdependence with the network they are embedded in (Quist, 2007). More specifically, *"…the structure of the network, the actors involved, their relationships, power issues, and the particular combinations of resources and activities in the network*..." are crucial to the network's overall outcome (Quist, 2007).

According to this theory, an industrial network is build up by three components, including (1) actors, who perform (2) activities and manage (3) resources (seen in Quist, 2007 based on Håkansson 1987). Moreover, activities are defined to affect resources, which, in turn can be embodied by physical, financial or human assets (Quist, 2007). Based on the interplay of all three components, the network can contribute *"…to the development of knowledge by actors"*, coordinate *"…the exchange of resources"* or contribute to the mobilization of resources (Quist, 2007).

2.2 Management of Technology

Generally, 'Management of Technology' (MOT) is concerned with the integration of technologies and business strategies (Khalil & Ezzat, 2001) and aims to provide organizations with a competitive advantage against the background of an increasingly fast changing environment (Porter et al., 2011).

A major aspect of this environment is technological development. The thesis considers *technological development* as resulting from the sum of all innovations and their quality in a sector. Doing so, technology development, can be operationalized by two aspects: its speed and its direction (Hekkert et al., 2007).By considering both aspects in the thesis, technological development is a dynamic concept that provides an insight in which direction and at what pace the Dutch gas sector develops. Moreover, technological development needs to be considered as a gradual process that evolves along technologies of a certain stage of development. By adjusting their business strategy and their own focus and pace of innovations to technological development, firms can gain a competitive advantage.

Thus, three important concepts regarding the Management of Technology are technology, innovation and the resulting competitive advantage. All three are further described in the following.

2.2.1 Technology

Suurs (2009) characterizes technologies as *"…artefacts and the material infra-structures in which they are integrated".* Furthermore, he notices that it is important to consider the technologies' socio-technical characteristics such as costs, effects of up-scaling, safety or reliability (Suurs, 2009).

2.2.2 Innovations

Emergent technologies develop and function with their related actors, functions and institutions (Hekkert & Negro, 2009). As stated by Hekkert et al. (2007), this interactional development can be named the innovation process. *"An innovation can be defined as the successful combination of hardware, software, and orgware, where orgware refers to the various components of the innovation system"* (Hekkert et al., 2007). A traditional classification of innovations is the distinction between incremental innovations that are *"…in line with the prevailing technological paradigm and often improve the performance of existing technologies…"* and radical innovation, that *"…fall outside the prevailing technological paradigm and usually involve combinations of very different concepts and technologies"* (Van Den Bergh et al., 2006). A more extensive classification of innovation is described by Freeman and Perez (1988). Next to the occurrence of incremental and radical innovations, the two authors distinguish two further magnitudes of innovation. First, 'changes of technology system', which are *"…far-reaching changes in technology, affecting several branches of the economy, as well as giving rise to entirely new sectors"* (Freeman & Perez, 1988). Moreover, changes of technology systems are described to be *"…based on a combination of radical and incremental innovations, together with organizational and managerial innovations…"* (Freeman & Perez, 1988). Second, 'changes in techno-economic paradigm', which are changes in technology systems that *"…are so far-reaching in their effects that they have a major influence on the behaviour of the entire economy. A change of this kind carries with it many clusters of radical and incremental innovations, and may eventually embody a number of new technology systems"* (Freeman & Perez, 1988). It needs to be noted, that the boundaries between the different types of innovation are typically not clear-cut and rather need to be considered as a continuum.

2.2.3 Competitive Advantage

The thesis understands competitive advantage as a favourable performance relative to a market environment, whereas continuous improvement is required to preserve this strategically beneficial position (Porter, 1990; Porter, 1998). Viewed from a national perspective, competitiveness occurs from the capability of the country's industries to innovate (M. Porter, 1990). As formulated by Hekkert et al. (2007) *"…speed of innovation is important, since innovation is a key determinant for long term economic growth and development*".

Besides, *"in international markets, innovations that yield competitive advantage anticipate both domestic and foreign needs"* and often competitors with true *"…international competitive advantage are based in only a few nations"* (Porter, 1990).

2.3 Decision Making

Decision making is a diversified theoretical field involving numerous distinct approaches. Some basic theoretical concepts that are associated with decision making are pointed out in the following. Often, decision making is classified in accordance to the fact whether a decision is carried out by an individual or a group and whether it is taken under certainty, risk or uncertainty.

The distinction whether a decision is taken by an individual or a group *"...is not a biological-social one but simply a functional one. Any decision maker – a single human being or an organization – which can be thought of as having a unitary interest motivating its decisions can be treated as an individual in the theory"* (Luce & Raiffa, 1957). However, any collection of individuals with diverging interests needs to be classified as a group in accordance to the decision making theory (Luce & Raiffa, 1957). This distinction is rather vague and thus serves as a guideline for decision making analysts with different perspectives of analysis. For example, a company can be regarded as a closed entity, thus an individual *"...or as a group composed of competing departments"* (Luce & Raiffa, 1957).

Furthermore, a decision is considered to be made under certainty "...*if each action is known to lead invariably to a specific outcome"*, under risk *"...if each action leads to one of a set of possible specific outcomes each outcome occurring with a known probability. The probabilities are assumed to be known to the decision maker"* and under uncertainty *"...if either action or both has as its consequence a set of possible specific outcomes, but where the probabilities of these outcomes are completely unknown or are not even meaningful"* (Luce & Raiffa, 1957).

Given the fact that the thesis assesses future technological options for the gas sector, which requires individual and societal decision making an involves much uncertainty regarding the future of the gas sector, the three aspects of individual decision making, group decision making and uncertainty are further elaborated in the following.

2.3.1 Individual Decisions

Individual decision making is very intuitive and can be described by a situation in which an individual *"...must order a set of alternatives, or stimuli, each of which is complex in the sense that it evokes reactions with respect to several attributes or "psychological dimensions""* (Luce & Raiffa, 1957). The latter are typically derived from the objective of the individual decision maker, his subjectivity or personal preferences. Assuming that each of these attributes or "psychological dimensions" orders the different alternatives of choice, the individual can rank the different alternatives by conglomerating all orderings (Luce & Raiffa, 1957). As a result, a decision alternative is chosen that serves the individual's preferences best, in other words has the highest utility.

More complex than individual decisions are those that are made by a group, because they involve interpersonal comparison of utility. As pointed out by (Luce & Raiffa, 1957) *"Democratic theorists, economic as well as political, have long wrestled with the intriguing ethical question of how "best" to aggregate individual choices into social preferences and choices."* Therefore, the decision making of groups is further addressed in the following.

2.3.2 Group Decision Making

"In its most general terms, the problem [of group decisions] *is to define "fair methods for amalgamating individual choices to yield a social decision"* (Luce & Raiffa, 1957). Referring to (Arrow, 2012), (Luce & Raiffa, 1957) identify this as *"...a question of "combining" individual preference patterns over various states of affairs to generate a single preference pattern for the society composed of these individuals"*.

Commonly, conventions, customs, religious codes, authority, dictatorial decree, voting, economic market institutions or other measures are used to derive preferences for a society from the preferences of individuals for different social alternatives (Luce & Raiffa, 1957). However, as pointed out by (Luce & Raiffa, 1957) these practices usually do not consider the welfare of society as a whole. Thus, to come to a decision every entity of the group is satisfied with requires further thought, which is illustrated in the following example, adapted from (Luce & Raiffa, 1957).

Given a society of two individuals and two alternatives, X and Y, each individual can prefer X over Y, can prefer Y over X or be indifferent between X and Y. *"These three cases are designated by R1, R2, and R3, respectively"* (Luce & Raiffa, 1957). This aspect is schematized in Table 2.1.

Table 2.1: Society of two individuals with two choices

	R1	R2	R3
First Choice	X	Y	x - z
Second Choice	y	X	

Assuming that individual 1 prefers X over Y, and individual 2 is indifferent between X and Y, *"...then the individual patterns of preference for this society can be summarized by the ordered pair (R1, R3)"* (Luce & Raiffa, 1957). Vice versa, a pair of RXR can be translated into order preferences of the society's individuals. Table 2.2 lists all possible combinations of order preferences for a society with two individuals and the three different choices R1, R2 and R3 as well as the social choices that can be drawn from these preferences.

Table 2.2: Possible combinations of order preferences for society with two individuals

1	2	F1	F2	F3	F4
R1	R1	R1	R1	R1	R2
R1	R2	R3	R1	R1	R3
R1	R3	R1	R1	R1	R2
R2	R1	R3	R1	R2	R3
R2	R2	R2	R1	R2	R1
R2	R3	R2	R1	R2	R2
R3	R1	R1	R1	R3	R2
R3	R2	R2	R1	R3	R3
R3	R3	R3	R1	R3	R1

Whereas the first two columns on the left of the table, headed 1 and 2, present all possible combinations of preferences, the remaining four columns represent for exemplary functions that derive social preferences from the two personal preferences. Therefore, each column *"associates to each element of RxR an element of R"* (Luce & Raiffa, 1957).

Procedure F1, for example, amalgamates the individual preferences of R3 and R1 into R1 with the reasoning that individual 1 is indifferent between X and Y whereas individual 2 prefers X over Y. Procedure F2 is an imposed procedure as it always selects R1, independent from the two individual preferences. Procedure F3 follows only individual one and neglects the choice of the second individual. *"F4 does not seem a reasonable procedure; nevertheless, it is a method of amalgamation"* (Luce & Raiffa, 1957). In total there are 3^9 = 19,683 functions of amalgamation. However, a F4 most of them are *"...more appropriately referred to as illfare rather than welfare functions"* (Luce & Raiffa, 1957). Therefore, (Luce & Raiffa, 1957) further elaborate on what can be considered as a welfare function, given these huge number of potential amalgamation functions.

The authors reason that in a society, in which all individuals have the same preference, the society should have this common preference as well. With respect to the above example, the choice of R1 by both individuals is amalgamated to R1. The same holds for the concordant choice of R2 and R3. Following this reasoning it can be assumed that (R1, R3) is not mapped into R2 but translated into a social choice of R1 because one individual is indifferent between X and Y and one prefers X over Y. Due to reasonable restrictions such as these, (Luce & Raiffa, 1957) *"...propose to eliminate many of the initially possible functions from the category of "welfare" functions"*.

Inherent to this theory are some assumptions that are made explicit by (Luce & Raiffa, 1957). First, it does not consider strategic choices of individuals but assumes *"...that the choices of the individuals are part of the data of the problem"* (Luce & Raiffa, 1957). Given that an individual is aware of the function used for amalgamation, it could adjust its personal preference to this function. In order to avoid this limitation a rule can be introduced that imposes *"...a condition on the function to the effect that it never benefits an individual to misrepresent his actual tastes; however, this idea seems to be very difficult to formalize, and no attempt will be made to use it"* (Luce & Raiffa, 1957). A theoretical example for such a rule is the toss of a coin that decides whether the personal preference of individual one or individual two is adopted as the social choice. In that case, heads up could indicate that the personal preference of individual one is adopted as the social choice and tails that the individual preference of the second individual is selected. Second, the theory assumes a nominal ranking of preferences. That is, the two individuals in the example can indicate whether they prefer X over Y but not to whether they strongly prefer X over Y or weakly. These aspects relate to subjective utility and *"...interpersonal comparison of utilities"*, two aspects that are not considered in the thesis to simplify the way of looking at the problem of social choice. Third, the theory assumes that preferences are transitive even though they might be intransitive in reality. Luce and Raiffa (1957) suggest a rank order of the different alternatives by each individual as a solution to this discrepancy.

2.3.3 Uncertainty

Decision making under uncertainty refers to a specific class of problems *"...which lie in the domain of uncertainty"* and *"...have for the most part grown up and been examined in the statistical literature, for they are very much involved in an understanding of experimental evidence and in drawing appropriate inferences from data"* (Luce & Raiffa, 1957).

Decision making under uncertainty boils down to the fact that *"...a choice must be made from among a set of acts A_1, A_2,...,A_m, but the relative desirability of each act depends upon which "state of nature" prevails, either S_1, S_2,...,S_n"* (Luce & Raiffa, 1957). What state of nature takes affect is naturally not known by the decision makers and typically the decision maker is aware of this aspect. Also the relative probability of the different future states is not known by the decision maker or, whether probabilities are applicable at all. For each act (A_i), state (S_j) pair, there is an outcome or consequence affecting the decision maker (Luce & Raiffa, 1957). *We assume that our subject's preferences among these outcomes, and among hypothetical lotteries with these outcomes as prizes, are consistent in the sense that they may be summarized by means of a utility function (see Chapter 2).*

If the consequences or outcomes of the different act-state pairs are specified by means of a utility function, the decision making problem under uncertainty can be summarized as in table 2.3. In this case the decision maker can decide for an act that is to some extent optimal or scores highest in terms of his decision making criteria (Luce & Raiffa, 1957). The totality of all states of nature listed in such tables "...*is assumed to form a mutually exclusive and exhaustive listing of those aspects of nature which are relevant to this particular choice problem and about which the decision maker is uncertain"* (Luce & Raiffa, 1957). It is thus assumed that there is one state of nature presented by a column in the table that takes effect in future.

Table 2.3: Matrix of Act-state pairs

		States					
		S_1	S_2	...	S_j	...	S_n
Acts	A_1	U_{11}	U_{12}	...	U_{1j}	...	U_{1n}
	A_2	U_{21}	U_{22}	...	U_{2j}	...	U_{2n}
	⋮	⋮	⋮		⋮		⋮
	A_i	U_{i1}	U_{i2}	...	U_{ij}	...	U_{in}
	⋮	⋮	⋮		⋮		⋮
	A_m	U_{m1}	U_{m2}	...	U_{mj}	...	U_{mn}

It needs to be n noted that the degree of uncertainty of decision making problems can be considered as a continuum. On the one end, this continuum is represented by a decision making problem with risk, in which the decision maker is fully aware of the relative probabilities with which the different states of nature occur. The other end of the continuum constitutes a decision making problem in which the decision maker is *"..."completely ignorant" as to which state of nature prevails"* (Luce & Raiffa, 1957). Especially for the latter case several decision criteria have been developed such as the Maximin criterion, the Minimax risk criterion, the pessimism-optimism index criterion of Hurwicz and the criterion based on the "principle of insufficient reason" (Luce & Raiffa, 1957), just to name a few.

2.4 Technology Assessment

This section addresses the insight of the literature review regarding the field of technology assessment, by summarizing the body of knowledge that has been developed within the last decades. Because technology assessment is the central theory of this thesis the section also highlights how technology assessment relates the other three main pillars of the literature research. Especially the connection between technology assessment and private organizations, in particular the management of technology, is often troublesome to be understood yet crucial for organizations that aim to place a bet on promising technologies. The intersection of Management of Technology and technology assessment is thus important to the thesis, which suggests the most promising technological options for further research. Similarly, the thesis establishes a relation between the theories of decision making and technology assessment because a choice must be made from different technological options. This connection is related to the theory of technology choice. Last, the section also relates technology assessment with the theories of technological development, following the idea that insights from theories of technological development can be used to prioritize the efforts of technology assessment which traditionally has been narrowed to technologies but not the bigger picture of the resulting technological development. Given this integration, technology assessment efforts can be prioritized by looking at a bigger picture.

Generally speaking, *"Technology assessment has been a growing field of management study for the last four decades... ...in both public and private domains"* (Van Den Ende et al., 1998) and "...*is concerned with the impacts of technology"* (Porter & Cunningham, 2004). However, the focus, practices and methods of technology assessment have changed and grown over time and technology assessment *"...has been inspired by – as well as inspired – a wide variety of scientific disciplines, ranging from policy analysis, science and technology studies, ethics, philosophy, social and cultural studies to communication sciences, and political sciences"* (Van Est & Brom, 2012). All of these disciplines have shaped the understanding, performing and institutionalization of technology assessment and led to multiple fields of application (Van Est & Brom, 2012). However, *"…there has been no effort made to present an overview of the methods and tools that have been cited in TA literature"* (Tran & Daim, 2008). As a result TA has developed into a large field with little integration (Van Den Ende et al., 1998). Consequently, it is not easy to grasp the body of knowledge of technology assessment, as *"…it is not a separate field of scientific research, nor is it a well-defined, clear-cut practice"* (Van Est & Brom, 2012). Moreover, *"…there are no universal tools or methods that can be applied in all TA studies"* (Tran & Daim, 2008), but the field is directly related to a variety of terms such as technology evaluation, technology selection, technology choice, technology audit, technology appraisal and indirectly related to terms such as technology forecasting, roadmapping, appropriate technology, technology scanning, adoption, and transfer (Tran &

Daim, 2008). In addition, *"…TA is an evolving area that continuously brings in new issues and challenges to the researchers and thus requires the invention of new methodologies and approaches to meet the new demands of the field"* (Tran & Daim, 2008). Despite these difficulties, the following paragraphs aim to structure the main developments in the field of technology assessment that have occurred in the last decades. To do so, three generations of TA, as presented by (Van Den Ende et al., 1998), are characterized.

2.4.1 First Generation of Technology Assessment

The first generation of TA emerged from the *forecasting* of technological trends, and found its application due to a growing interest in the negative effects of technologies that were often not intended (Van Den Ende et al., 1998). By that time, a committee of the House of Representatives perceived that the U.S. Congress *"...needed an earlier awareness, an earlier warning, and an earlier understanding of what might be the social, economic, political, ethical and other consequences of the introduction of a new technology into the society or a substantial expansion of an existing technology"* (Tran & Daim, 2008). This form of TA is called *Awareness TA* or *Early Warning TA* and attempts to incorporate values into the decision making regarding emerging technologies (Van Den Ende et al., 1998). (Tran & Daim, 2008) specify that *"...under this context the TA terminology was meant to refer to public decision making and resource allocation"* and therefore name this form public TA. According to (Van den Ende et al., 1998) it usually comprises several impact studies, such as risk and safety analyses as well as environmental impact assessments. By the time of its introduction, extensive discussions were hold whether those analyses should take a merely descriptive or normative point of view.

However, the concept of TA also raised the interest of companies and private industries, as it was perceived to be *"somewhat useful"* (Tran & Daim, 2008). However, the attempts of private industries differed in terms of objective (which was generally maximizing profit), structure, timeframes and other perceptions. Whereas public TA has looked at technological development from a social perspective, *"...the business and non-governmental TA approached the TA problem from an economic or technical viewpoint"* and tried *"...to anticipate the effects of the outside world on their own activities, rather than anticipating the effects of their activities on factors outside of themselves"* (Tran & Daim, 2008 referring to Maloney Jr, 1982). Therefore, (Coates & Fabian, 1982) suggested to refer to this TA approach as inverted TA, but no consensus has been reached (Tran & Daim, 2008). Another distinction is that *"...public TA typically employed more holistic and multifaceted research methodologies, while the private sector tended to utilize operational methods and tools"* (Tran & Daim, 2008). However, it needs to be noted that some TA methods, such as decision analysis have been applied for TA and inverted TA (Tran & Daim, 2008).

2.4.2 Second Generation of Technology Assessment

However, the oil crisis in the 1970s did not only reveal that unpredictability of sudden events makes it impossible to assess all future effects with certainty; it also *"…made many assessments (which were often hardly recognized as being related to the energy field) completely worthless"* (Van Den Ende et al., 1998). As a result, a shift towards a more narrowed objective of TA studies could be observed that began to focus on specific effects rather than the whole array of possible impacts a technology could have (Van Den Ende et al., 1998). Consequently, the second generation of TA has taken a more strategic position in the decision making process rather than a neutral input and aimed to be of consultative value in the formulation of technology strategies (Van Den Ende et al., 1998).

2.4.3 Third generation of Technology Assessment

However, it has been suggested that social and economic benefits of technology are *"...increasingly dependent on the embedding of technology in society..."* resulting in the fact that currently "...*technological potentials are underutilized in economic and in social terms"* because it arises a *"growing complexity of the context in which Science and technology develops"* and *"insights in the process of technological change and innovation itself"* have altered over time, making the integration of technology, economy and social aspects increasingly difficult (Smits et al., 1995). *As a consequence,* efforts are *"...strongly driven by the desire from policy-makers and industrial and wider stakeholders for conceptual frameworks that enable the examination of plausible future pathways in ways that will inform current decision-making",* thus allowing for the integration of social, economic and technological aspects for emerging technologies (Foxon et al., 2010). TA has been recognized as a field, capable to address these demands (Smits et al., 1995; Smits & Den Hertog, 2007). Therefore, its third generation shifts efforts towards the implementation of technologies in society (Tran & Daim, 2008; Smits & Den Hertog, 2007)and to a body of practices that strive to evaluate the impact and evolution of technologies and their characteristics against the background of future pathways and states (Porter & Cunningham, 2004; Smits & Den Hertog, 2007).*"This, however, requires that TA be more directly linked to innovation policymaking"* and the users of technologies (Smits & Den Hertog, 2007).

Table 2.4 highlights the novelties of this new TA-concept as presented in (Smits et al., 1995) compared to the older generations of TA.

Table 2.4: The conventional versus the new TA-concept (Smits et al., 1995)

Conventional TA-concept	New TA-concept
Dominant role of science	Equal role for researchers and users
High expectations of the potential of research	Modest expectations of TA-research
TA-output: study report	TA-output: study and discussions
Little attention for problem definition	Much attention for problem of definition
One TA-research organization	Multiform TA-research capacity
Instrumental use of TA-information	Conceptual use of TA-information
TA results incorporated in decision-making	"Tuning" of TA and decision-making
Autonomous technology	Technology as human creation

One TA approach that applies this new understanding is Constructive Technology Assessment (CTA). It addresses the implementation of technologies in the short- and mid-term by involving various actors in the innovation process. In doing so, CTA has the underlying notion that technological development is heavily influenced by societal processes and, more importantly, that the alignment of both can be used to influence technological development (Van Den Ende et al., 1998). In contrast to previous TA approaches, CTA takes the perspective of not only one, but several actors and strives for an alignment of all perspectives to reach at a technological development that is desirable for the collectivity of stakeholders involved (Van Den Ende et al., 1998).

Besides CTA, there are various TA approaches that address developments, further in the future. Porter et al. (2011) suggested technology futures analysis, as a field to summarize these TA approaches, conducted by public institutions as well as private actors (Porter & Cunningham, 2004). Technology future analysis distinguishes technology foresight, which *"…refers to a systematic process to identify future technology developments and their interactions with society and the environment…"* and technology forecasting that is described as a *"…systematic process of describing the emergence, performance, features, or impacts of a technology at some time in the future.* For instance, roadmapping *"...has been utilized widely in MOT as a forecasting and planning management tool"* and can therefore be considered as a form of TA (Tran & Daim, 2008) and technology futures analysis. As can be seen from this example, both approaches, technology foresight and technology forecasting, have developed in parallel within the field of TA and can be applied in both private and public sectors.

Quist (2013) classifies future related studies in three major groups. *"The first type of scenarios is about likely futures and relates to the question what will happen"* (Quist, 2013). Techniques used to create this group of scenarios are mostly quantitative extrapolations of trends (Quist, 2013). As a consequence, the scenarios are only based on present factors because unlikely developments are neglected and thus mostly represent 'Business-as-Usual' (BAU) developments (Quist, 2013).

"The second type of scenario approaches is about possible futures and relates to the question what could happen" (Quist, 2013). In contrast to the first group these scenarios typically succeed in developing distinct future visions, which account for different perspectives as well as the uncertainty related to future studies (Quist, 2013). *"Well-known examples are strategic context scenarios, as initially developed by the company Shell and the model-based scenario, as for instance developed by the IPCC and earlier in "Limits to Growth", the first report to the Club of Rome"* (Quist, 2013). Also, efforts such as the scenario planning model by Thomas (Thomas, 1996) that aims to *"...aid corporate management in planning strategic technology management, future products and competitive advantages"* need to be considered as part of this second category (Tran & Daim, 2008).

The third group of scenarios is of prescriptive nature, thus describes what future states should be achieved. Backcasting and transition management are two widely applied methods of this category. Whereas backcasting is used to build a normative future vision, formulate a transition path towards this desired future state and define milestones for the short-, mid- and long-term that 'pave' the identified transition path (Quist & Vergragt, 2006; Wangel, 2011a; Wangel, 2011b), transition management (cf. Rotmans et al., 2001; Loorbach, 2007) *"...aims to steer or modulate the dynamics of transitions through interactive, iterative engagement between networks of stakeholders"* (Foxon et al., 2010). Both methods also *"...explore the related systems innovations and transitions to sustainability"* (Quist, 2013). To do so, they involve *"...a broad range of stakeholders and actors..."*, they incorporate *"...not only the environmental component of sustainability, but also its economic and social components"* and they take *"...into account the demand side and the supply chain as well as related production and consumption systems"*, which allows for *"...getting a better understanding about the possible gains and side effects of a future vision"* (Quist, 2013). Though not explicitly referred to as backcasting,*"...other approaches like ... road mapping also use normative future visions and pathways on how to get there...",* and are classified as part of the third category in (Quist, 2013).

2.4.4 Technology Assessment & Theories of Technological Change

The intersection between the two theoretical fields of Technology Assessment and the theories of technological change has traditionally not received great attention but is of importance for the thesis.

As outlined in the previous section, TA studies have been conducted mostly from a very narrow perspective. Having said that, technologies have been assessed regarding their interaction with their environment but little attention has been paid to the bigger picture, which is the accumulative technological development a row of innovations leads to. By integrating both bodies of knowledge it can be made explicit how the characteristics of technologies relate to technological change. In turn, those technologies can be prioritized which have a desirable impact on technological change. This aspect is especially vital for TA studies, such as this thesis, which are conducted against the background of a normative concept, such as sustainable development. However, taking into consideration the social construction of technology (cf. Section 2.1.2), it needs to be considered that stakeholders differ in their personal preferences and their perception of a technology. As a result, different stakeholders consider different technologies as conducive for technological development.

This social perception of technologies can be especially helpful in future related studies as it allows *"...to explore how social and political issues, such as public acceptability of different technologies and institutional changes … and the strategies of large and small firms, interact or 'co-evolve' with present and expected future changes in technologies.*" (Foxon et al., 2010)

2.4.5 Technology Assessment & Decision Making

Given the thesis' objective to recommend technologies for continuative research, thus making a decision among several given technologies, the theoretical background presented in this chapter needs to address the intersection between technology assessment and decision making. The integration of both theories has become increasingly important and by now, "...*uncertainty in emerging technologies"* is *"...a major concern in future TA works"* because it has been concluded (Tran & Daim, 2008 referring to Grubler et al., 2007) that "...*improved system science methods and models can help to better cope with decisions under uncertainty by both better describing the cosmos of uncertainty as well as helping to improve decision making under uncertainty"* (Tran & Daim, 2008). Besides, the stronger link of TA and decision making *"...has led to increasing popularity of ... TA as a multiform research capacity with sufficient opportunities for discussion and contradictory views and findings"* (Smits et al., 1995). Given that the theoretical field of decision making is concerned how individuals or groups come to decisions and whereas technology assessment addresses the interaction between technology and society, the theoretical concept of technology choice is explained to demonstrate how the interaction of both theoretical bodies serves as a background for the thesis.

Following the definition of (Willoughby, 1990) there are four aspects around which the concept of technology choice evolves. First, *"…there is frequently a range of alternative technological means available which are suitable for the attainment of primary objectives within a given field*". Second, *"the number of alternatives in the range may be increased over time by conscious human effort*". Third, *"alternative technological means of similar suitability, for the attainment of certain primary objectives, may vary widely in their suitability for the attainment of secondary objectives*". Fourth, "*the informed selection of technological means, taking into account secondary objectives as well as primary objectives,* *combined with long term efforts to expand the range of available alternatives, is an important element of social, economic and environmental policy*".

Given that technologies have taken an increasingly important role in society to reach a diversity of different goals, also the discussion for or against technology has grown within the last decades. In his book (Willoughby, 1990) argues against this hardening of frontiers and suggests that *"...there are vital choices to be made in most fields of human endeavour – whether manufacturing, energy supply, transport, health care or food production – between different technological options with contrasting primary or secondary impacts: there is rarely, if ever, one "correct" technical solution to social, economic or environmental problems"* (Willoughby, 1990). Furthermore, he argues that the process of technology choice is also applicable to those areas which are not associated with technology at first glance (Willoughby, 1990).

Accordingly, engineers, business managers and policy makers, who increasingly impact innovation processes through their decisions should extent their decision criteria beyond those *"...under the rubrics of "efficiency" or "profit""* (Willoughby, 1990) because the choice for a technology is neither straightforward nor reducible to the technical dimension. In contrast to many traditional economic schools, the theoretical concept of technology choice highlights that technology is neither exogenous nor can it be *"...regarded as a neutral factor in social and economic policy"* (Willoughby, 1990). Thus, choice *"...from amongst technological alternatives is necessary"* (Willoughby, 1990). Willoughby (1990) argues that adhering to the concept of technology choice within technology policy *"...will help to make that field of policy more potent as a device for managing the economy, environment and social complexity of communities"* (Willoughby, 1990).

In their book (Porter et al., 1980) present several techniques related to technology assessment and impact assessment whereas some of them can be considered as carrying elements of technology choice. Most explicitly technology choice can be found in Cross-Effect Matrixes, which are a technique of impact analysis, Cost-Benefit Analysis, which is a methodology of Economic Impact Analysis, Technological, Legal, and Institutional/Political Analyses and Multi-Criteria-Analysis, which comprises a set of non-monetary based decision making methods.

Impact Analysis *"...links the identification of significant impacts with their evaluation and the formulation of policy options to deal with them"* (Porter et al., 1980). More specifically, Cross-Effect Matrixes present the effects that result from the interaction of technologies, their impacts, society and policy. Therefore, two of these four elements are selected and specified within the columns and rows of the table. Thus, each cell represents the effect that occurs from two specifications. As a result, Cross-Effect Matrixes accommodate the concept of technology choice as they can present the effects that occur from the interaction between technologies and their impacts, society or policy. Based on these results the decision maker can discriminate among different technologies.

'Cost-Benefit Analysis', being the main framework of Economic Analysis in Technology Assessment is a monetary-based technique but also assesses regarding other impacts. It *"...concerns both the potential profitability of a development and its implications for the broader economic interests of the affected public"* (Porter et al., 1980). Whereas the economic feasibility remains the major criteria for private sectors whether to further develop a technology, in the public sector one *"...is attempting to gauge the* social advantages of developing a particular technology or policy". CBA "…is a response to the need to assess such developments in the public sector" because the indirect effects of technological change *"…certainly accrue as costs or benefits"* (Porter et al., 1980). Consequently, CBA is an appropriate method to pursue the concept of technology choice.

Technological, Legal, and Institutional/Political analyses are another means to make a choice among several technological options. Whereas Technological Analyses address both *"... the "influences on" the new development by existing technologies and the "impacts of" the new development on existing technologies"* (Porter et al., 1980), Legal Analysis considers the effects of new technologies on the law and vice versa, whereas institutions and politics *"...are vital factors in the implementation of a technology..."* which *"...may be themselves drastically affected"* (Porter et al., 1980). The latter aspects are addressed in Institutional-Political analyses.

Multi-Criteria Analyses generally establish *"...preferences between options by reference to an explicit set of objectives that the decision making body has identified, and for which it has established measurable criteria to assess the extent to which the objectives have been achieved"* (Dodgson et al., 2001). To do so, all formal MCA techniques apply a scoring and rating of the options regarding the measurable criteria.

2.4.6 Technology Assessment & Management of Technology

Reflecting on the aforementioned approaches of TA and Management of Technology it becomes apparent that there is a broad interface between both fields, MOT and TA.

First, technology development is not an autonomous process and almost every decision, relating to the integration of technologies and business strategies, faces uncertainties regarding future developments. The field of TA, and particularly forecasting, can be a valuable approach to support decision making processes and to commit to long-term strategies (Hekkert et al., 2007; Porter et al., 2011). Second, innovation needs to be considered as a main enabling factor for economic growth, development and the correlated societal benefits. Moreover, the up-scaling of technological innovations has frequently revealed severe negative impacts (Hekkert et al., 2007). Consequently, *"there is a strong need to influence both speed and direction of innovation and technological change"* (Hekkert et al., 2007). This can be achieved under the application of TA.

Hence, an integration of TA and MOT can help to formulate and execute strategies for decision makers towards a desirable goal. Particularly against the background of important socio-technical trends like the emergence of a network society in which several actors depend on each other (Smits, 2002), it is crucial to regard issues, which appear to be trivial, from several perspectives. By bringing methods and tools of several perspectives into play, TA contributes to a multi-perspective, reflective management that does not only take into consideration the company's assets but also its environment (Henriksen, 1997; Van Den Ende et al., 1998).

3 Methodology of the Thesis

The following chapter elaborates on the methodology of the thesis. Its purpose is thus to link the theoretical background, outlined in the second chapter with the empirics of the following chapters. To do so, the chapter is divided into two parts. The first part describes the research approach of the thesis. Thereby, it makes explicit how the structure of the thesis serves to fulfil the thesis' objective, why the author chose this particular structure, what the underlying assumptions of this approach are and what the expected strengths and weaknesses are. Insofar, the research approach bridges the research questions with the methodology of the thesis and enables to reason in the second part of the chapter, what purpose the different methods fulfil and why they are combined in the way they are.

The second part of the chapter addresses the methods used in this thesis. For each method, a description is provided and it is explained how the method relates to the research approach as well as the theoretical background of the thesis. Furthermore, the second part defends why the author chose for the methods used in this thesis, explains how they are applied and highlights their expected strengths and weaknesses.

Together, both parts aim to answer the first research question of the thesis by developing a holistic approach that allows for the foresight of new technological options for the Dutch gas sector.

3.1 Research Approach

Recalling the objective and related research questions of the thesis, introduced in section 1.4, the following section presents the approach that is taken in answering all, apart from the first, research questions. As indicated by bracketed numbers in figure 3.1, the empirical part of the thesis is divided in four stages.

The first stage of the thesis answers the second research question by exploring the static and dynamic aspects of the Dutch gas sector. It thereby aims to provide crucial background information regarding the environment new technological options will be embedded in. Following a top-down approach it is straightforward to conduct this stage at the beginning of the thesis because it sets the stage for the following analyses. The difficulty to bring forward this analysis is, however, that the level of analysis is arbitrary. Assuming that the assessment of technological options would precede this stage, the focus of this environmental analysis could be further specified. Nevertheless, the latter order would challenge the timeframe of the thesis, which is conducted within six months, or would provide a too narrow picture on the environment. Consequently, the analysis of the Dutch gas sector is conducted at the beginning of the thesis, aims to provide a general view and - to take a pragmatic approach is therefore loosely focused on the national boundaries of the Netherlands.

The second stage of the research is addressed in the third research question. It aims to narrow down countless emerging technological options that are relevant to the Dutch gas sector to a selection that is feasible to assess within this research. Consequently, this stage involves the creation of an inventory of technological options and the subsequent selection of technologies from this inventory. In contrast, it would also be possible to assess all identified technological options in depth and to make a well informed choice for the best technologies on the base of this detailed assessment. Despite the fact that this approach might result in an outcome based on more information - because also those technologies are assessed that do not appear promising on first glance - it is not feasible within the time limitations of the thesis. However, to assure the meaningfulness of the technology selection conducted in this stage of the thesis it must be geared to the broader context of the thesis making it as relevant as possible, also against the background of a larger picture. Also, the choice for the screening criteria is made explicit in section 3.2.3 of this chapter.

The third stage of the research is partly addressed by the third and fully by the fourth research question of the thesis. Its aim is to assess those technologies in detail that are selected in the screening process of the second stage. As the third stage is thus based on the second stage of the thesis, it inherits its limitation regarding what technologies are assessed in the thesis. On top of that, the framework to assess the technological options in the third stage of the thesis is matter to the subjectivity of the author. As with the screening criteria in the second stage of the thesis, the collection of primary data from interviews could avoid this limitation but their conduction is not feasible within the timeframe of the thesis. Therefore, also the choice of criteria to assess the different technological options is made explicit in section 3.2.4.

The insights gained in the third stage of the thesis aim to provide a clear view on the characteristics, advantages and disadvantages of the technologies selected for assessment. However, in order to draw conclusions that are relevant to the context of the research, it is vital to reflect these results on the broader context of the Dutch gas sector, as explored in the first stage. Especially when looking at the research project this thesis is embedded in, it is interesting to see how the results obtained in the first three stages relate to transition paths of the gas sector and how the combination of both can be used to formulate strategies towards favoured transitions, such as sustainable development. This aspect is the core of the fourth stage of the thesis. The weakness of this approach is again the subjectivity of the author, because the number of explored future pathways as well as the description of normative measures is limited to his cognitive capacity. Especially, because the development of the future pathways is conducted at the end of the thesis, at a state at which the author has already formed an own perspective on how the gas sector could develop in future. In contrast, the exploration of future pathways at this stage allows the author to focus at specific aspects that have come out in the foregoing analyses and to demonstrate how the results obtained could be utilized to pursue a normative future development. Together, both aspects are sufficient to fulfil the objective of this stage of the thesis. A broader exploration of future pathways that precedes the assessment of the technologies and covers all thinkable outcomes or a participatory approach, including different kinds of stakeholders, would be beyond the scope of this thesis and too sophisticated for the objective of this stage.

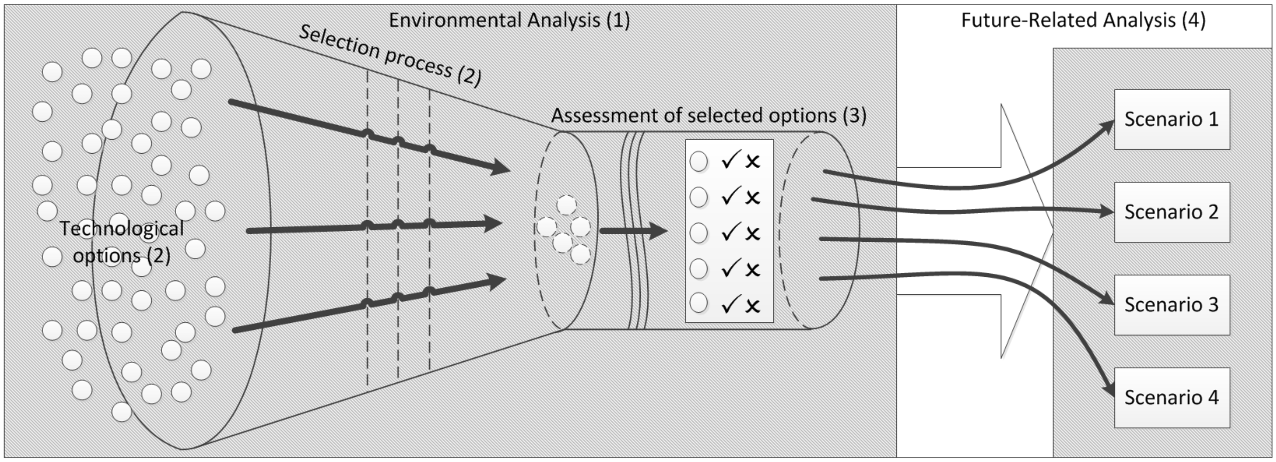


Figure 3.1: Research approach of the thesis

3.2 Methods of the Thesis

3.2.1 Socio-Technical Map

Despite the reasoning that the first stage of the thesis should explore the environment, new technological options are likely to face, it is not determined what aspects of the environment to explore.

Recalling the theories of technological change of section 2.1, two aspects of the environment appear to be especially important to the perspective of the thesis: The development of technologies as well as the interaction of this development with society. Consequently, both aspects are explored in the thesis. A method selected for the first stage of the thesis, as described in the research approach, needs to present a snapshot of the socio-technical circumstances which are currently present in the Dutch gas sector. As a method of choice, the author applies a socio-technical map in the fourth chapter.

Socio-technical maps are an important analytical tool for technology assessment (Gow, 2001 referring to Van Den Ende et al., 1998). They can be divided into two parts, a technical map and a social map, which describe technologies and actors respectively regarding a certain socio-technical regime, *"…in the current situation…"* (Marletto, 2013). Also, the insights of socio-technical maps can be related to scenarios that emerge from future transition pathways (Marletto, 2013). *"Socio-technical maps might be seen as types of checklists by which various aspects of socio-technical development are captured"* and are thus *"…a practical tool for not forgetting specific aspects of a TA study"* (Van Den Ende et al., 1998). Socio-technical maps do not have a strictly defined content but often aim to explore actors involved, their expectations and to describe technologies that form the current socio-technical regime.

Given all these aspects, the creation of a socio-technical map is highly valuable to the thesis as it allows illustrating the gas sector at the current point in time, in a very structured way. Next to that, its insights can be used to reflect the results of the Technology assessment on the transition pathways that are explored in the last stage of the thesis. Consequently, the application of a socio-technical map within the first stage of the thesis appears to be the method of choice. However, the creation of a socio-technical map, which is selected based on the paper of (Van Den Ende et al., 1998), is favoured over the study of innovation systems, the Multi-Level-Perspective and Strategic Niche Management which are other common methods applied to explore the interaction between technological development and society. The rationale for this choice is given in the following paragraph.

In contrast to a socio-technical map that focuses on the study of a socio-technical system, the study of an innovation systems, the Multi-Level-Perspective and Strategic Niche Management are all innovation centred. Put differently, they typically study the factors that enable or disable the development of a certain innovation. This perspective, however, does not align with the objective of the first stage of the thesis as it provides a too narrowed perspective and would require several analyses, for each technological option or groups of technological options. In addition the study of innovation systems, the Multi-Level-Perspective and Strategic Niche Management assume the existence of a certain structure, the technology of analysis is embedded in. However, for technologies that are of potential relevance to the gas sector, this structure is often not present yet. Furthermore, a technological innovation system is considered to be part of the socio-technical regime, depending on the diffusion of a technology (Suurs et al., 2009) and therefore can never offer the same amplitude of information about the technologies' environment as a socio-technical map which analyzes the whole socio-technical system.

Nevertheless, there are some limitations and weaknesses to the application of a socio-technical map that need to be made explicit. Next to the limitation of the socio-technical map to the geographic boundaries of the Netherlands, it is not prescribed by the method what physical artefacts and actor groups to look at. For this reason, the thesis bases its technical map on the physical assets of the Dutch gas infrastructure. However, other technologies which might be of common use for the gas sector but are not part of the gas infrastructure are thus not included. In addition, actor groups are identified as related to the market, society, research or authorities. Although market actors are not always included in technology assessment studies, and society is not necessarily a part of the three-dimensional helix structure (Leydesdorff & Etzkowitz, 2003), the thesis regards both of these groups as important and includes them in the social map. Market actors are included because the Dutch gas sector contributes a major share to the Dutch Gross Domestic Product and social actors are included due to the relevance of the energy system for society. However, this classification of actor groups might cause the neglecting of some actor groups which would become apparent in a different classification of actors. Moreover, some actors might just have been overseen by the author. All of these aspects are clear drawbacks of the method used at this state. Another major weakness is the missing insight into what dynamics affect the Dutch gas sector. To account for this drawback the third chapter integrates the creation of a socio-technical map with the procedure of a PESTE analysis, as described in the following section.

3.2.2 PESTE Analysis

The PESTE analysis needs to be considered as an extension of the socio-technical map and therefore relates in the same manner to the research approach and the theoretical background of the thesis as the socio-technical map. More specifically, it aims to identify trends that affect the Dutch gas sector and, in doing so, adds dynamics to the static picture of the socio-technical map. Thereby, the PESTE analysis focuses on trends that influence technological development and society as both aspects are identified as crucial for the environmental analysis conducted in the first stage of the thesis. It is of value to carry out the PESTE analysis after the socio-technical map because the latter pinpoints what aspects to pay attention to.

PEST is an analytical framework that analyzes macro-environmental factors and provides a 'satellite view' to assess a system in a structured manner (Peng & Nunes, 2007 referring to Ward, 2005). Generally it aims to identify political, economic, social and technical aspects. However, due to EDGaR's focus on sustainability, environmental aspects are added as a further dimension in this thesis, making it a PESTE analysis. In contrast to the application of the socio-technical map, the PESTE analysis in this thesis also consideres international developments. However, only those that have an impact on the Dutch gas sector.

Given that the PESTE anlysis is capable to provide a holistic, overview of the dynamics of the Dutch gas sector it appears to be a suitable method to expand the socio-technical map within the first stage of the thesis. Nevertheless, it needs to be recalled that the emergence of technologies can be analyzed using a Multi-Level-Perspective, comprising a landscape, regimes and niches (Geels, 2002). The socio-technical trends identified by the PESTE analysis are also understood as being created in a broader context, thus the regime or landscape, having an influence on the technologies and actors of the socio-technical system (Bergek et al., 2008; Smits, 2002). A similar perspective is taken by Strategic Niche Management. Both methods, the Multi-Level-Perspective as well as Strategic Niche Management could therefore be applied to describe the dynamic aspects of the Dutch gas sector. However, the choice of the author to combine the creation of a socio-technical map with the PESTE framework is again justified by the perspective, the first stage of the thesis aims to offer. That is, to provide a general overview of the Dutch gas sector but not to explore static and dynamic aspects that are bound to a certain innovation or group of innovations, as would result from the application of the Multi-Level-Perspective or Strategic Niche Management. Moreover, it needs to be noted that, to fulfil the current objective of this stage of the thesis, other literature often distinguishes between social, technical and economic trends (Bergek et al., 2008; Green et al., 1999; Smits, 2002) whereas this thesis adds a political and environmental perspective. The reason for the inclusion of both dimensions is the political relevance of the gas sector and the issue of sustainability related to the exploitation of fossil fuels.

Given that the PESTE framework is very comprehensive, it can include an overwhelming number of trends that can be allocated to each dimension, despite its structure of specified dimensions (Peng & Nunes, 2007). This accounts for a weakness of the method because it becomes inevitable for the author to select the most important trends based on his best judgement. This however implies that the trends presented in the PESTE framework are subject to the authors subjectivity, especially because the analysis is typically carried out as a desk study. Moreover, the researcher faces imperfect information and even under the assumption of his complete objectivity, the secondary sources he surveys can be incomplete or biased. To limit this weakness of the method, expert interviews are conducted in the frame of the thesis that serve to triangulate the findings of a broad desk study.

Another limitation of the PESTE framework is that the allocation of trends to only one dimension is often ambiguous because trends can be classified in accordance to different criteria such as their cause or their impact. Despite the fact that the thesis aims to rule out this difficulty by explicitly classifying all trends in accordance to their impact, trends often relate to several of the five PESTE dimensions. However, this limitation is not considered as imposing a difficulty on the validity of the dynamics identified because the PESTE anlysis solely serves as a measure to structure the dynamic context of the Dutch gas sector. Thus, it is considered to be of more importance to capture a complete picture of the dynamic environment than allocating all pieces of the picture to one dimension without ambiguity.

3.2.3 Technology Screening

As argued in the research approach, the second stage of the thesis requires the limitation of all potentially promising technological options to a selection that is feasible to further assess as part of the thesis. Consequently, the technology screening that is conducted in the beginning of the first stage is closely related to the second stage of the research. Moreover, the technology screening has a strong connection to the theoretical intersection of TA with Decision Making and the Theories of Technological Change. The first intersection is based on the fact that the technology screening process, as applied in this thesis, requires the selection of a limited set of technologies out of a given inventory. It is therefore related to the concept of technology choice as presented in section 2.4.5. Second, the technology screening process relates to the intersection of TA and the theories of technological change because it is geared to the objective of the thesis, the direct research context of the thesis as well as the broader interest of the EDGaR program. Thus, the technology assessment that is conducted at a later stage in the thesis is prioritized from the outset because it assesses only non-regret options that appear promising within the screening process.

The technology screening of the thesis involves the application of a checklist, which compares all technological options identified against a set of criteria. The fulfilment of all four criteria of the checklist, requiring the technological option to be '*operated potentially sustainable',* being an *'integration option',* being *'technology based'* and involving gas as a *'main energy carrier'*, determines whether a technological option is further assessed as part of the thesis.

Given, that the necessity of the technology screening is justified against the background of the research approach, the application of a checklist to screen all technological criteria is straight forward, as it is *"...the simplest scanning technique"* (Porter et al., 1980).

However, the procedure of creating an inventory and selecting technological options from this inventory has some drawbacks. First, the creation of the inventory cannot be exhaustive due to the timeframe of the thesis. Therefore, a boundary to the creation of the inventory needs to be set, which is dependent on the subjectivity of the author. Also, the selection of technologies from this inventory relates to a decision of the author and is therefore subjective. Generally, these aspects can be overcome by collecting primary data, through expert interviews for example. However, due to the timeframe of the thesis both steps are conducted as a desk study and the method applied does not overcome these weaknesses. Therefore, the boundaries for the collection and selection of technological options are made explicit in the following; enabling an evaluation by the reader.

The establishment of an inventory of technological options for the thesis is limited to the survey of documents that have been published within the research context of the thesis. This includes documents that were recommended by researchers of the sub-project 'Technology Assessment', carried out at Delft University of Technology. Given more time, it is surely beneficial to extend the inventory by other sources. However, for the purpose of the thesis, this limitation appeared to be reasonable because the technological options that are gathered in the inventory have raised the interest of the researchers but have not been assessed further.

For the screening of technologies, the four criteria of 'system integration', 'potential for sustainable operation', 'technology based' and 'gas as an energy carrier' are chosen. It needs to be emphasized that this list of four selection criteria is not exclusive but suffices for the purpose of the second stage of the thesis. Given the explorative character of the thesis and its objective to *"…identify a broad set of technological options that are relevant for further research…"* the set of screening criteria has been established in communication with the team of researchers involved in the research context. It is solely meant to pre-select potential technological options that are relevant for further research of the 'Technology Assessment' sub-project. Given other preferences of the researchers, this set of criteria could be modified which would result in a different set of technological options that passed the pre-selection. The following argumentation for the decision criteria of sustainability potential, system-integration, gas as an energy carrier and technology based, is thus meant to defend their appropriateness as selection criteria for the exploration of technological options that are of relevance for the direct research context of the thesis and the EDGaR program as wider background. Also, it aims to highlight the weaknesses and limitations of these selection criteria which, from the perspective of other researchers, might call for modification.

3.2.3.1 Potential of Sustainable Operation

Taking into account the overarching goal of EDGaR, that is to drive the Dutch gas system towards sustainability, it is straightforward to refine the obtained inventory of technologies by the criterion to be sustainable. However, the term sustainability has multiple aspects, is thus of very wide nature and also can be associated with several phases of a technologies' life cycle. Consequently, the number of technologies that have the potential of being sustainable in any way, in one of the phases of their life cycles, is too high.

Recognizing that all innovations identified are related to natural gas, bio gas or hydrogen, a further narrowing of the research on hydrogen or biogas seems straightforward. However, focusing only on technologies based on either biogas or hydrogen would not be in accordance with the research objective. First, because such a choice limits further research to either biogas or hydrogen and therefore fosters trajectories that are likely to lead to path dependency. As recognized, by (Van Den Bergh et al., 2006) the early choice for a trajectory that might lead to path dependency should be avoided in order to foster sustainable policies. Second, the choice of technologies purely based on biogas or hydrogen is not of practical relevance against the broader picture of the research. Given the fact that both biogas and hydrogen still account for only a small share of the gas market, an immediate up-scale of these technologies would be related to socio-technical difficulties that are hardly to overcome. Thus, a transitional phase that involves the simultaneous operation of both natural and renewable gas sources is indispensable in any case. Choosing for technologies that are purely based on biogas or hydrogen would implicitly neglect this transitional phase.

Instead of narrowing the inventory of technologies to only one of the two renewable gas types (hydrogen and biogas), the technologies' potential to be operated sustainably was therefore considered as a suitable criterion to set the focus of the research. The 'potential for sustainable operation' is therefore defined as the technology's capability to be fully operative solely with natural gas or solely with one of the two renewable gas sources or solely with a combination of both renewable gas sources. Given the latter two cases, the technologies' operation can be considered as almost emission-neutral, in that sense sustainable.

Furthermore, the limitation to technologies with 'potential for sustainable operation' harmonizes to a great extent with the research objective and its theoretical background of evolutionary economics due to several aspects. To begin with, technologies that have a potential for sustainable operation allow for a gradual shift from the current gas system to a sustainable energy supply and do not require a step-wise change. As stated in section 2.1, this gradual process is crucial to the theory of system innovations (Geels & Schot, 2007). Thus, including the compatibility of emerging technological options with natural gas technologies enhances the process of transition. Second, the research takes the perspective of the Dutch gas sector. A smooth transition as described above is also of more added value for the companies involved in this sector as it allows them to adapt their strategic positioning in the market and therefore to preserve their competitive advantage. Third, it can be argued that a transition in which the current gas system takes a dominating role is of more value for the society compared to a transition fully carried out by new actors of the market. Following the reasoning of Schumpeter II, actors of fewer funds are prone to be short of resources that are required to explore arising socio-technical options of the gas system and are less efficient in their operations. Furthermore, firms that have had a stake in the gas sector for years are likely to have tacit knowledge that is relevant to the transition but cannot be acquired by new market entrants. Consequently, companies entering the gas sector have less experience, thus fall back on the learning curve and are prone to carry out the energy transition less efficient than established gas companies. For all these reasons, new market entrants are more prone to failure, when taking the initiative to guide the transition towards a sustainable energy system.

3.2.3.2 System Integration

Next to the potential for sustainable operation, the thesis' aim is to focus on radical options, for the following reasoning. In his book, Mulder (2006) demonstrates that, given the fact that population is expected to grow by 50% until 2050, technology is required to be 32.4 times more efficient in terms of environmental impact than it is today. Also referring to other authors such as (Von Weizsacker et al., 1994), (Factor 10 club, 1997) and (Weaver et al., 2000), Mulder argues that incremental innovations do not appear as sufficient, but that sustainable development can only be realistically addressed by radical innovations (Mulder, 2006). As defined in section 2.2.2, radical innovations *"…fall outside the prevailing technological paradigm and usually involve combinations of very different concepts and technologies"* (Van Den Bergh et al., 2006), whereas changes of technological systems are *"...far-reaching changes in technology..." that are "…based on a combination of radical and incremental innovations, together with organizational and managerial innovations…"* (Freeman & Perez, 1988). Mulder (2006) argues similarly that *"radical innovation often implies 'system' innovation as the radical innovation can only be achieved by changing the configuration of the various elements within a technological system, instead of merely improving on a single element."* Although incremental innovations are relevant for the efficiency improvement of radical innovations, only the latter are a means to *"...create leaps in environmental efficiency..."* (Mulder, 2006).

Applying this line of thought to the Dutch gas system, it is crucial to explore radical innovations in order to foster its sustainable development. Taking into consideration the declining Dutch gas reserves, this requires the crossing of technological boundaries by integrating gas with other energy carriers than gas, such as concentrated solar power from Northern Africa (Hemmes, 2013). The options for system integration that arise from this approach are a mode of radical innovation because they combine very different concepts and technologies. Following the reasoning of (Mulder, 2006), system integration options are therefore one focus of the technology screening process because they offer great potential for sustainable development. However, system integration is often only partly related to the gas sector and offers a vast number of options. The classification of such options for the Dutch gas sector thus requires a structured manner.

Within the last decade, some work has been done on system integration, which allows for such taxonomy of integration options. A traditional view includes the usage of gas as a means to level out fluctuations in electricity supply through renewable sources. However, system integration involves more than that. According to (Aftzoglou, 2011), *"The term integration refers to the combination of energy sources, energy production methods and technologies as well as of the research and policy sectors, aiming at sustainable development*". Hemmes, et al. (2007) suggest that there are six forms of energy system integration and, after completing a global literature review, Aftzoglou (2011) added three further forms. In the following, all nine forms of integration are further described, as they are of significant potential for the Dutch gas sector (Hemmes, 2013). As suggested by (Aftzoglou, 2011), they are listed regarding their scale in a descending order.

The *integration of sustainability into energy systems design* calls for the incorporation of environmental, social and economic aspects in the development processes of technologies (Aftzoglou, 2011).

An example for the *integration of sectors* is the aforementioned usage of gas to balance out fluctuations in the generation of renewable electricity (Hemmes et al., 2007). As elaborated by Hemmes et al. (2007) the integration of sectors is often likely to result in a win-win situation across all sectors involved (Hemmes et al., 2007).

The *integration of industries into eco parks* involves the basic thought of industrial ecology, which aims for the adjustment of industrial processes in accordance with the principles of natural ecosystems (Hemmes et al., 2007). *"The aim is the transformation of open industrial loops into closed ones"* (Aftzoglou, 2011).

The *integration of sites* shares the same basic idea of industrial ecology as the integration of eco parks (Aftzoglou, 2011). However, it "...*focuses on energy conservation and heat recovery, whereas industrial ecology is a broader concept"* (Aftzoglou, 2011).

The concept to *integrate energy sources into Multi-Source-Multi-Product (MSMP) energy systems* is a logical extension of the development from linear energy systems over co-generation systems and tri-generation systems (Hemmes et al., 2007). It has the underlying definition of an energy system *"...as a system of functionally coupled components with the main task to supply energy..."* (Hemmes et al., 2007). The naming as 'Multi-Product' refers to the fact that the energy produced can be delivered to the end users in one *"...or more appropriate forms..."*, whereas the naming as 'Multi-Source' assumes the production of energy *"...based on one or more energy sources"* (Hemmes et al., 2007).

The *integration of components into a system*, the *integration of new technology into existing technology* and the *integration of functions*, as suggested by (Hemmes et al., 2007), can generally be regarded as three forms of integration that are not of distinctive scales (Aftzoglou, 2011). Instead, their absolute scale depends on their application within the socio-technical system they are embedded in (Aftzoglou, 2011). To begin with, the integration of components into a system is very important, because components *"...need to be durable, reliable and have a good performance, so that they also enhance the system's performance"* (Aftzoglou, 2011). The integration of new technology into existing technology can be either due to the dysfunction or inefficiency of old technology and usually involves the replacement of or add-on to old technologies within the system (Aftzoglou, 2011). Lastly, the integration of functions refers to products that fulfil multiple functions in order to enhance the efficient handling of key resources such as costs, space or materials (Aftzoglou, 2011).

The i*ntegration of renewable energy into products* involves the supply of power to products by photovoltaic cells, fuel cells or human power (Aftzoglou, 2011 referring to Mestre & Diehl, 2003).

3.2.3.3 Technology

The third criterion for the selection of technological options from the inventory is that the integration options assessed are on a technology level. This criterion has been chosen in order to limit the technological options selected in a way that represents the technology-oriented character of the thesis.

Table 3.1 applies this criterion to the taxonomy of integration options presented in the previous sub-section. As shown in the table, the previous mentioned integration of energy sources into MSMP energy systems, integration of components into a system, integration of new technology into existing technologies and integration of functions can be considered to be on a technology level. All other integration options, introduced in the previous sub-section are on the abstract, sector, industry or component level. Thus, they are considered not to fulfil this criterion of the technology screening.

Table 3.1: Kinds compared to levels of system integration options

Level	Integration
Abstract	Integration of sustainability into energy system design
Sector	Integration of sectors
Industry	Integration of industries into eco-parks
Technology	Integration of energy sources into MSMP energy systems
	Integration of components into a system
	Integration of new technology into existing technologies
	Integration of functions
Components	Integration of renewable energy into products

3.2.3.4 Gas as an Energy Carrier

The fourth criterion of technology screening requires that hydrogen, biogas or natural gas is an energy carrier of the technology. That is, the technology at hand involves the production, consumption or transformation of gas. This criterion assures the subject-related proximity of the Dutch gas sector to the technologies selected for assessment.

3.2.3.5 Weaknesses & Limitations of Screening Criteria

The definition of the four screening criteria faces a trade-off between selectiveness of the criteria and the timely limitation of the thesis. Despite the efforts of the author to meet this thin line, some weaknesses and limitations are inherent to the four screening criteria defined.

First, the *'potential for sustainable operation'* considers only the fuel of the technology but not its remaining environmental impacts or other related restrictions to source natural resources. To account for this limitation, attention would need to be paid to multiple aspects during the whole life cycle of the technological options. However, to apply this analysis to all technological options that are part of the inventory would go beyond the scope of the thesis. And, assuming a lifecycle analysis for every option would be feasible, limitations needed to be accepted regarding the impacts of second or higher degrees. Consequently, a limitation to the assessment of the technological options' 'sustainability potential' has to be accepted in any case; also because the term sustainability has a very broad scope.

Second, the criteria *'system integration'* is based on sources that have been published within the context of the thesis. This list might not be exhaustive and other options of integration, which are not included in this list, might therefore be neglected in the technology screening.

The third criterion limits the selection to those options, which are technologies. Against the thesis' background of Technology assessment this choice appears to be reasonable. However, it needs to be noted that suggested chemical processes that are listed in the inventory but not selected for the assessment could be turned into (multiple) technologies, which are of high interest to the gas sector and would fulfil all other screening criteria. Given a less technology oriented focus of the thesis, a change of this criterion would appear beneficial.

Fourth, it needs to be pointed out that the screening criterion of *'gas as a main energy carrier'* imposes a strong limitation on the focus of the thesis and does not accommodate sudden, radical shifts of the gas sector. For example, the mass application of passive houses or a strong increase in solar energy could make the current gas infrastructure as well as the expertise of the gas sector unnecessary. Assuming such a development would occur, a detailed TA addressing solar panels or passive houses would be far more relevant for continuative research than technological options with gas as a main energy carrier. However, the count of technological options that is not related to gas is endless and a limitation regarding this aspect had to be set. Recalling that transitions are understood as gradual processes but not sudden changes (Geels & Schot, 2007), it seems most reasonable to tighten this limitation to the usage of gas rather than a sector or a source of energy, such as solar, that is currently less related to the Dutch gas sector.

3.2.4 Multi-Criteria-Decision-Analysis (MCDA)

Recalling the second chapter, this stage of the thesis relates to the theory of decision making because it comprises the decision making process of the thesis; on the base of which the technological options are differentiated. Moreover, it relates to the intersection between the fields of TA and decision making because as well as the intersection between TA and the theories of technological change because it allows to establish a ranking among the different technological options given the decision maker's preferences for certain aspects. With reference to the research approach, this third stage of the thesis is dedicated to assess some technological options in detail.

The research approach does, however, not describe what aspects should be assessed and what method to use to discriminate between different options. Traditional methods to the theory of decision making are monetary based techniques, such as Cost-Benefit analysis, Cost-Effectiveness analysis or Financial Analysis, informal judgements and Multi-Criteria Analysis (MCA) techniques. Given that different stakeholders will be involved in the decision making process, the decision making technique used in this stage of the thesis should account for different perspectives and therefore include different dimensions of assessment to evaluate the different technological options. In turn, this implies that not all aspects which require assessed are measured in monetary units. However, the conversion of units into monetary values, for those aspects which can be measured but not valued, is not feasible to be done as part of this thesis. This aspect rules out all monetary-based techniques as a method for this stage of the thesis. Making a choice between MCA and informal decision making, the application of a MCA technique is by far more appropriate due to several reasons. To mention some of them, Multi-criteria analysis techniques are open and explicit, *"...the choice of objectives and criteria that any decision making group may make are open to analysis and to change if they are felt to be inappropriate", "scores and weights, when used, are also explicit and are developed according to established techniques. They can also be cross-referenced to other sources of information on relative values, and amended if necessary"; "can provide an important means of communication, within the decision making body and sometimes, later, between that body and the wider community; and scores and weights are used, it provides an audit trail"*

(Dodgson et al., 2001). For all these reasons MCA appears to be the most reasonable choice to discriminate among the different technological options. No matter what technique is applied in the thesis needs further specification because many MCA techniques exist with different approaches. Recalling section 2.4.5 MCA techniques establish *"...preferences between options by reference to an explicit set of objectives that the decision making body has identified, and for which it has established measurable criteria to assess the extent to which the objectives have been achieved"* (Dodgson et al., 2001). To do so, all formal MCA techniques apply a scoring and rating of the options regarding the measurable criteria. The difference between the different MCA techniques is based on their way to combine the so-obtained data into a preference among the different options. Thus, before explaining the choice for one MCA technique, the assessment framework together with its measurable criteria is presented and the scoring and weighting process is pointed out.

It also needs to be noted that MCA has its limitations compared to monetary based techniques. One of them is that *"...it cannot show that an action adds more to welfare than it detracts. Unlike CBA, there is no explicit rationale or necessity for a Pareto Improvement rule that benefits should exceed costs"* (Dodgson et al., 2001). Hence, given the results of a MCA, it could be preferable to take no action at all compared to implementing the option that ranks best in the MCA (Dodgson et al., 2001).

3.2.4.1 Development of Assessment Framework

The assessment framework of the thesis analyzes five dimensions: (1) Technical, (2) Financial, (3) Environmental, (4) Political, Economic and Social as well as (5) Dynamics of technological development. Each dimension is further divided into measurable indicators.

The establishment of the five dimensions is based on the review of several sources (Stein, 2013; Hirschberg et al., 2007; Afgan & Carvalho, 2002; Afgan & Carvalho, 2008; Doukas et al., 2006; Evans et al., 2009; Gallego Carrera & Mack, 2010; Onat & Bayar, 2010; Streimikiene et al., 2012). For example, (Stein, 2013) provides an overview of several papers applying MCA techniques. As can be concluded from the analysis of (Stein, 2013) it is common practice to assess the technical, financial and environmental characteristics of energy technologies. Moreover, the thesis integrates the assessment of the technologies' political, economic and social aspects because all three aspects directly affect society and therefore interfere with different actor groups that are concerned with the gas sector. Thus, it is not regarded as meaningful to demarcate characteristics of the options that are solely of social, economic or political nature. For this reason, the thesis aligns with the framework presented in (Stein, 2013) and assesses these three interwoven dimensions with one common group of indicators. On top of that, the thesis adopts the dimension 'dynamics of technological development'. Given the facts that the development of an assessment framework is not the sole purpose of the thesis and that the assessment provides a more extensive insight than other assessment frameworks present in literature, these five dimensions are regarded as sufficient to see into the characteristics of the different technological options.

It needs to be noted that each dimension adds to the holistic perspective of the assessment framework and cannot be left out. However, more indicators or dimensions can be added or changed for current elements of the framework if the research interest this framework is applied for, would differ significantly. The following paragraphs describe the aim of each dimension and defend its contribution to the assessment framework and the thesis. Subsequently, the indicators of each dimension are introduced, their relevance is defended and it is argued why the specification of all indicators for one option suffice to judge a technology in terms of the dimension at hand.

3.2.4.1.1 Technical Dimension

The technical dimension of assessment aims to throw light on the technical characteristics of the different technologies, from different angles. This is important regarding the objective of the thesis because it is assumed that only those technologies should be looked at in continuative research that are technically feasible to contribute considerably to the energy demand of the country. Recalling EDGaR's objective, that is to conduct research on aspects of strategic importance, technical characteristics are surely meaningful to distinguish the strategic importance of different technologies.

Average efficiency coefficient

The average efficiency coefficient is measured on a ratio scale and describes how much of the energy received by a power generating unit is transformed into its output (Stein, 2013). Given the case of technologies that are powered by fossil fuels to generate electricity, the average efficiency coefficient can be derived through the division of the fuel's heat rate (φhr = Btu/kWh) by the heat rate of electricity ($3412 \frac{Btu}{kWh}$) (Stein, 2013). For the case of cogeneration plants the sum of all outputs needs to be taken into account for the calculation of the average efficiency coefficient. As criticized by Stein (2013), the mean efficiency of all other power technologies is occasionally used to assume the average efficiency coefficient of renewable energy technologies. However, for the usage of renewable energy sources this indicator is somewhat more technology specific and is limited for example by the Betz law for wind turbines or by the reflection of sun light for solar panels.

It is important to consider the average efficiency coefficient as part of the technical dimension as it provides an insight into how suitable the technology is for the generation of energy. Assuming that a technology has a very low overall efficiency coefficient it's scaling up might not be sufficient to contribute the energy demand of a country, given a limited number of energy resources. The higher the energy coefficient, the more likely it is that it is technically feasible to convert a given amount of (sustainable) energy into sufficient energy for a country or to even obtain an overproduction of energy that can be exported.

Average capacity factor

The average capacity factor describes the ratio of the actual energy output of a plant to the potential energy output of the plant given a certain period of time (Stein, 2013). Thus, the capacity factor embodies a ratio scale whereas a higher capacity factor is advantageous.

(Eq. 3.1) $$Capacity\ factor = \frac{Actual\ power\ output\ of\ a\ plant\ [MWh]}{Potenial\ power\ output\ of\ a\ plant\ [MWh]}$$

Assuming all other characteristics equal between two options a higher capacity factor signifies an increased energy output. For this reason the capacity factor is important to assess as part of the technical dimension. Common reasons for a capacity factor below 100% are fluctuations in renewable energy sources (i.e. wind or radiation), timeslots for operation and maintenance, the specific energy policies and strategies of a country or the strategic shut down of a plant because its efficiency might not be high enough to serve low electricity or heating prices.

Flexibility of dispatch

The flexibility of dispatch is an ordinal indicator on a scale from 1 (low) to 5 (high) that describes to what extent energy production can be regulated on the basis of energy consumption (Nordel, 2000). The indicator is adopted from the SIXTH framework and classifies dispatchable and non-dispatchable technologies. The first rank higher *"…for the purpose of system control"* (Hirschberg et al., 2007). Renewable energy technologies are typically non-dispatchable (Hirschberg et al., 2007). Fuel based technologies are naturally dispatchable.

The flexibility of dispatch is important for a nation's energy system because it indicates how flexible the energy system can respond to changes in energy demand. Assuming a country implements only technologies with a low flexibility of dispatch, the country would not be able to supply sufficient energy during peak periods.

Technological availability & readiness

The availability and readiness of a technology has been suggested in (Yi, Sin, & Heo, 2011) and describes the development status of a technology. It is measured by a five-point ordinal scale and that differentiates between the conceptual stage (1), experimental stage (2), pilot stage (3), market stage (4) and mass market stage (5) of a technology.

The technological availability and readiness is important to assess against the background of the thesis' objective because certain practices of technology assessment that could be applied in continuative research, such as Constructive Technology Assessment (cf. Section 2.4.3) require a certain stage of development to involve stakeholder groups in the development.

Sufficiency of technical indicators

After reviewing the work of (Stein, 2013) that sums up the technical indicators of several papers the average efficiency coefficient, the average capacity factor, the flexibility of dispatch and the technological availability & readiness appear sufficient to the author to assess the technical aspects of the technological options. From the table provided by (Stein, 2013), it can be seen that most papers of this kind aim to assess how available a technology is at the current moment, what its capacity is throughout a year, whereas some paper assess how flexible a technology is regarding its energy production and how efficient it operates. Thus, the first two criteria mentioned represent the common practice to assess the technical characteristics of technology, whereas the latter two indicators presented are not always assessed. However, they appear to the author as a reasonable choice, given the background of the thesis. All indicators together should suffice to assess the technical characteristics of the technologies, especially in relative terms when looking at other work in this field (Stein, 2013; Hirschberg et al., 2007; Afgan & Carvalho, 2002; Afgan & Carvalho, 2008; Doukas et al., 2006; Evans et al., 2009; Gallego Carrera & Mack, 2010; Onat & Bayar, 2010; Streimikiene et al., 2012).

3.2.4.1.2 Financial Dimension

The financial dimension of the assessment framework evaluates the financial properties of the different integration options. In general, the assessment of financial indicators for emerging technologies is particularly difficult due to two reasons. First, current values of financial indicators vary greatly by source and their future development is uncertain. Second, financial performance indicators of newly developed technologies are to a great extent confidential. Yet, the analysis of financial aspects is crucial to the assessment of energy technologies, which are mostly operated by private businesses, and therefore of importance to fulfil the objective of the thesis. The thesis thus takes the perspective of (Hvelplund & Lund, 1998), later cited by (Reichert, 2012):

"We have no specific methods to use when estimating future prices of newcomer technologies, and their impacts on the technology development process in a country. Nevertheless we think that this point is one of the most important in a socioeconomic feasibility study, and we recommend that it is given a place and discussion in the structure of such studies."

In order to compare the different monetary values of the financial dimension, the price of gas is set to 0.07€/kWh for households and to 0.04€/kWh for industries (Energy.eu, 2013). Electricity prices are set to 0.21€/kWh and 0.09€/kWh, for households and industry respectively (Energy.eu, 2013). Moreover, all monetary values are adjusted to 2012 levels and are provided per kilowatt hour to enhance the comparison between options of different scales. Nevertheless, it needs to be considered that economies of scale have an effect and make larger plants typically more cost effective than options of smaller scale.

Total overnight cost

The total overnight cost account for the investment cost of a power plant as it equals the total cost for the implementation of a power plant given the assumption that all necessary operations could be carried out over night. Thereby, time-related financial aspects that are unique for different projects, such as delays in the implementation process or interest rates, are not effecting the assessment and allow the direct comparison of different options. Furthermore, total overnight costs are given in € per kilowatt (kW) in order to account for the scale of different power plants. The higher the total overnight cost per kW, the more expensive the establishment of an option is, the less this technology scores in terms of total overnight cost.

Having pointed out the importance of financial performance of energy technologies, the initial investment cots of technologies are often the main burden to the acquirer of the technology, which has to be made up for during the further life cycle of the technology. The height of the overnight cost is therefore an important factor in the decision whether to invest in a technology or not.

Operation and Maintenance (O&M) Cost

The O&M costs equal the expenses to operate and maintain a system integration option for a year. In (Stein, 2013), fixed and variable O&M costs are distinguished. However, due to the early stage of development of most options assessed, such detailed data is rarely available. Therefore, total O&M costs are used as a main indicator to compare different options. The higher the operation and maintenance costs of an option, the less appealing this option is.

Regarding the relevance of this indicator, total operation and maintenance costs is another important pillar that influences an investment decision for or against an energy technology. The relevance of assessing this aspect is therefore incontrovertible when assessing the relevance of technologies for continuative research as done in this thesis.

Cost of fuel

The cost of fuel is another important criterion that demarcates free sources of renewable power from gas driven integration options. Assuming that gas prices will increase in future, this indicator gains growing importance. In order to enhance comparison among different options, the same gas and electricity prices are used for every option. Based on the efficiency of the different options, fuel costs are subsequently presented in €/kW. Equal to the previous financial indicators discussed, the higher the cost of fuel, the lower the competitive advantage of the option is.

Particularly against the background of volatile energy prices the costs of fuel are an important factor. This holds especially because integration options make use of different fuels and can therefore build up an important advantage compared to other options, depending on their working principle.

Impact of fuel price changes

The indicator *impact of fuel price changes* serves to determine the impact of changes in the cost of fuel on the total generation costs of the integration option analyzed. As introduced by (Hirschberg et al., 2007), the impact of fuel price changes therefore equals the ratio of the fuel costs to the total operation and maintenance costs:

(Eq. 3.2) $$\text{Impact of fuel price changes} = \frac{fuel\ cost}{total\ O\&M\ cots}$$

The lower the ratio the more competitive is the option at hand, because it is less subject to increasingly volatile energy prices. Especially for integration options that require a large investment upfront, a long period is needed to achieve a return on investment. This indicator thus gives an insight into the robustness of financial planning with regard to a certain option.

Sufficiency of financial indicators

When looking at the cost structure of investments for energy technologies it appears reasonable to assume that investment costs, the operation and maintenance costs, whether fixed or variable, and the fuel costs are the main costs that appear for the investor. For the sake of a more distinct analysis the fuel costs are separated from the operation and maintenance costs, in contrast to the more common practice to include them as part of the operation and maintenance cost. The thesis aims to go one step further and also reveals the impact a change of fuel prices has on the overall cost structure of the energy technology. Other costs than those reflected in the indicators are assumed to be negligible or specific to the financial setting of a certain project. In total, the indicators presented are thus considered to sufficiently assess the financial aspects of different technological options from different angles. The fact that assessment frameworks of similar purpose assess the same or closely related indicators supports this line of reasoning (Stein, 2013; Hirschberg et al., 2007; Afgan & Carvalho, 2002; Afgan & Carvalho, 2008; Doukas et al., 2006; Evans et al., 2009; Gallego Carrera & Mack, 2010; Onat & Bayar, 2010; Streimikiene et al., 2012).

3.2.4.1.3 Environmental Dimension

The following section assesses the environmental performance of the different options from different angles. In contrast to other technology assessments in which environmental aspects are only of minor importance, a distinct dimension is dedicated to the environmental aspects for this thesis because of its relation to the EDGaR program, which explores sustainable developments for the Dutch gas sector.

Average external costs

External costs describe all those costs that have an adverse impact on society but are not represented in the market value of energy carriers. Thus, external costs allow for a very broad focus in assessing the sustainability of technological options. External costs are composed of different environmental mechanisms such as the release of harmful substances or energy such as noise, heat or radiation to the environment (ExternE, 2013). In order to quantify the external costs of different technologies in a comparable measure, data for this indicator is gathered from the ExternE program that lists external costs for many energy technologies. The higher the average external costs the less appealing is an option.

The assessment of external costs is of crucial importance for the environmental dimension of the thesis because it allows judging holistically the valuable environmental aspects of the options.

Loss of life expectancy

The loss of life expectancy (Hirschberg et al., 2007) is an indicator that represents the average loss of life expectancy, in days, as a result of all activities in the life cycle of a certain technology. Nathwani et al. (1992) describe in their book the average LLE for major energy technologies. Despite the fact that these figures are based on several assumptions (Ramanathan, 2001) they give a good indication on the overall impact of the different options assessed. The higher the loss of life expectancy, the lower is the later scoring of the technological option.

The loss of life expectancy is considered as an important indicator given the thesis' background in TA and its objective, to suggest the most relevant technological options for continuative research. As described in the second chapter, technology assessment studies the interaction between technology and society. The direct impact of an energy technology on human life is logically a vital indicator in this field of study. It is thus important to discriminate options regarding this indicator to provide recommendations continuative technology assessment studies.

Greenhouse Gas emissions

Greenhouse gas (GHG) emissions specify the contribution of a technology to global warming, whereas other gases than carbon dioxide are converted into carbon dioxide equivalents to obtain a base of comparison. Logically, the higher the emission of GHG of a technological option per kWh the lower is its scoring from an environmental perspective.

The emission of greenhouse gases is an undoubted environmental criterion that has especial priority in industrial sectors that are largely based on fossil fuels, such as the gas sector. This indicator is thus inevitable against the background of the EDGaR project and its goal of exploring sustainable development for the Dutch gas sector.

Sufficiency of environmental indicators

The selection of environmental criteria is adopted from the framework of (Stein, 2013) and (Hirschberg et al., 2007). Whereas Stein (2013) reveals in his summary of MCA papers on energy technologies that frequent aspects of assessment are greenhouse gas emissions, the impact on human life and external costs, he only applies the latter two in his paper. However, adopting the perspective of many other authors, the assessment framework of the thesis aims to emphasize the emission of greenhouse gases and therefore establishes a distinct indicator to assess the greenhouse gas emissions of the integration options, which are partly powered by fossil-fuel. In comparison with many other papers, the set of environmental indicators thus appears to be sufficient to get an insight into the environmental performance of the technological options (Stein, 2013; Hirschberg et al., 2007; Afgan & Carvalho, 2002; Afgan & Carvalho, 2008; Doukas et al., 2006; Evans et al., 2009; Gallego Carrera & Mack, 2010; Onat & Bayar, 2010; Streimikiene et al., 2012).

3.2.4.1.4 Political, Economic, Social (PES) Dimension

The following section analyses the social, economic and political aspects of the technological options in an integrative manner. Due to the fact that the boundaries between the dimensions can be regarded as a blurry, most indicators are long on one or two of the three dimensions.

Nevertheless, recalling the insights of the second chapter, the assessment of PES indicators as one distinct dimension is important given the thesis' background of Technology Assessment that studies the interaction between technology and society.

Autonomy of generation

The autonomy of generation is adopted from the framework of Hirschberg et al. (2007). It aims to evaluate the autonomy of a state in terms of its energy production because countries, their industries and societies *"…may be vulnerable to interruptions in service if imported fuels are unavailable due to economic or political problems related to energy resource availability."* The indicator is measured on an ordinal scale that ranks from 0 to 10 in accordance to table 3.2.

Table 3.2: I*ndependence from foreign energy sources* (Hirschberg et al., 2007)

Group name	Value	Description
Imported energy carrier	0	Technologies that rely on fuels or energy resources that must be imported
Domestic oil	2	For oil-fired technologies in countries where domestic oil resources are available
Domestic gas	3	For gas-fired technologies in countries where domestic gas resources are available
Domestic coal	6	For coal-fired technologies in countries where domestic coal resources are available
Domestic uranium	8	For nuclear technologies in countries where domestic uranium resources are available (includes extraction from seawater)
Domestic renewable energy resource	10	For technologies which rely on renewable energy fluxes present in a given country (e.g. hydro, solar, wind, wave and geothermal)

The evaluation of the autonomy of generation is important to assess as part of the PES dimension, because the EDGaR program aims to build up knowledge of strategic importance for the gas sector. Given trends presented in the following chapter, such as a changing power position among gas producing countries, the continuative research on energy technologies, which assure autonomy of generation surely generates knowledge of strategic importance.

Job creation

The indicator of job creation indicates how many jobs are directly created during the life cycle of a power plant from its design to its operating state. Therefore, the indicator is measured on a ratio-scale of job-years per GWh. In his framework Stein (2013) points to Wei et al. (2010), who compare *"…several power plant technologies in their ability to generate jobs in the U.S.A"* and normalize *"…jobs data to average employment … per unit of energy (GWh) produced over the lifetime of a plant"* (Stein, 2013).

Also for the objective of the thesis, the job creation is considered as an important indicator because the energy sector can be, but is not necessarily, a labour intensive sector of a country's economy. Again, the importance of this indicator can be stressed by means of the purpose of the EDGaR project, which aims to research gas-related topics in the interest of the Dutch economy. Employment takes a substantial share of this aspect. Also from a TA perspective, job creation is an important factor regarding the interaction of technology and society.

Potential of energy system induced conflicts

The *potential of energy system induced conflicts* is measured on an ordinal scale (Hirschberg et al., 2007). On a five-level Likert scale it ranks technologies regarding their potential for conflicts as *very low, low, middle, high or very high,* based on experiences from historic events. The assessment in terms of this indicator needs to be done on a component level because many of the options have not reached mass application yet and therefore no conclusion can be drawn for the integration option based on historic experiences. Thus, if applicable, noticeable components such as fuel cells or wind turbines are assessed.

The indicator is important given the thesis' research context of technology assessment. As can be told from experience, some energy technologies, such as nuclear power, can cause massive conflict within the society of countries, which can be very destructive for the political arena, the energy system or even the economy of a country.

Necessity of participative decision making process

The *necessity of participative decision making process* is an indicator that is ranked on an ordinal scale from 0 to 10. A low ranking in this indicator means that the decision for a particular technology does not require a public, participative decision-making process, whereas a high ranking indicates the contrary and that permissions or licenses are required for the construction or operation of a certain technology (Hirschberg et al., 2007).

Generally, it can be said that a higher necessity of participative decision making process translates into more difficulties regarding the implementation of a technology. All other characteristics being equal, an energy technology with a higher necessity of participative decision making is thus less attractive to a country than a technology with a low necessity for a participative decision making process.

Consequently, the first option would be of less strategic importance for a country and is thus not as interesting as the latter for continuative research within the EDGaR program.

Sufficiency of PES indicators

The overview of MCA frameworks presented in (Stein, 2013) addresses the PES dimension mainly in terms of the interaction between the society, economy and technology. Therefore, the securing of energy supply in the long term as well as the impact of technology on the employment of the country are two indicators which are frequently assessed. However, the author of this thesis perceives that this approach disregards the political aspect of this dimension, which relates to the decision making process that is involved in the implementation of new energy technologies as well as the tensions that are created by a technology within the political landscape of a country. Therefore, the thesis adopts the latter two of the indicators presented above from the framework of (Hirschberg et al., 2007). Given that many other papers neglect this aspect, it is assumed that this dimension sufficiently reflects the PES characteristics of the different technological options.

3.2.4.1.5 Dynamics of Technological Development Dimension

The dimension 'Dynamics of technological development' assesses dynamics in the development of the different integration options. More specifically, it aims to quantify actors' activities that are related to the technological development of the different options assessed. To do so, 'Tech Mining' as described in the book by Porter & Cunningham (2004) is conducted[1].

The dynamics of technological development are important to assess the relevance of technological options for continuative research because the dimension provides an insight on how acute certain topics are. This dynamic view is important to assess, especially because the EDGaR program aims to build up knowledge of strategic importance. Consequently, it should be known whether the technologies assessed are currently a common subject of research, not yet or not anymore.

Numbers & trend of publications

This indicator counts the *total number of publications* of each integration option. Given the fact that every publication requires a foregoing research, it indicates an interest for the subject of publication. Thus, the number of publications over time on each technological option and the associated trend give an indication how the interest on the different options has developed during the last years. Hence, after a trend has been derived from the number of publications over time it is translated into an ordinal scale that ranks from 1 to 5 and indicates whether the interest in an option is strongly decreasing (1), decreasing (2), constant (3), increasing (4) or strongly increasing (5).

Sufficiency of Dynamics of Development Indicators

This two-fold indicator fully represents the insights that are sought to be obtained by the dimension and is therefore of unique importance for the dimension. In contrast, it can be argued that this discrete indicator is also sufficient to assess the dynamics of technological development because it assesses how

[1] Given that 'Tech Mining' is a method itself it is further explained in a distinct section (cf. section 3.2.5). In the following paragraphs, attention is paid only to the reasoning why the dynamics of technological development and its underlying indicators are relevant for the MCA.

much interest technological options attracted in the past, how much they attract and how this development is likely to develop in future.

3.2.4.2 Scoring of Technologies

To discriminate the different technological options from each other, MCA techniques allocate numerical values to every technological option addressed, by scoring and weighting. In the scoring process, *"…the expected consequences of each option are assigned a numerical score on a strength of preference scale for each option for each..."* indicator (Dodgson et al., 2001). In practice, the score of options often ranges from 0 to 100 whereas a score of 100 represents the most preferable score and 0 the least preferable score. Moreover, the transfer of quantitative data to the strength of preference scale depends on the sense of direction, on the definition of the minimum and maximum and on the target function. Typically, higher natural values of options represent higher scores on the strength of preference scale. For example, a higher efficiency has a higher score than a lower efficiency. However, some cases require the sense of direction to be changed. For instance, lower costs are typically preferred over higher costs and therefore rank higher. If applicable, the change of direction is therefore indicated in the MCDA procedure of the thesis. Moreover, the minimum and maximum of the natural values of technologies can be defined locally or globally (Dodgson et al., 2001). In the case of a local minimum and maximum, the highest and lowest natural value of the technologies represents a scoring of 0 and 100. In the case of a global minimum and maximum, values for a score of 0 and 100 are set externally that have a range wide enough to allow for the subsequent ranking of all options. The thesis applies a global ranking in its MCA procedure to accommodate further options to be assessed with the framework. The transfer of natural values that characterize an option into a score from 0 to 100 is usually done by the usage of a target function (Dodgson et al., 2001). Next to the usage of a linear function that assumes constant marginal returns and assumes risk neutrality of the decision maker, the target function can have the shape of an exponential or root function. Figure 3.2 illustrates these different target functions. For practical purposes the MCA procedure of the thesis assumes a linear target function.

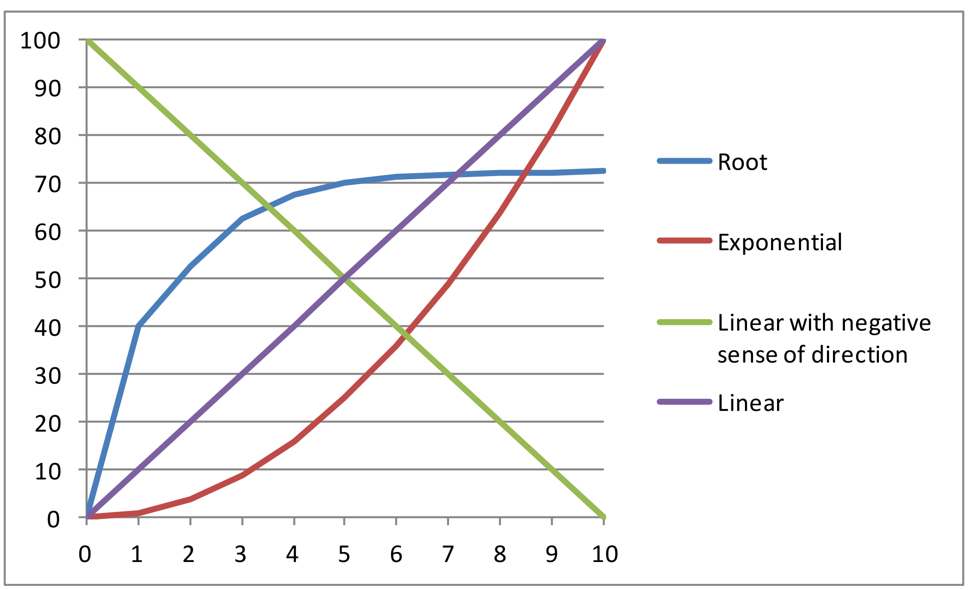


Figure 3.2: Target functions for scoring

Given that X represents the natural value at hand, for all indicators that are translated from their natural value to a normal linear target function, equation 3.3 applies.

$$\text{(Eq. 3.3)} \qquad \text{Score (X)} = (\text{X} - \text{Global Min}) \cdot \left(\frac{100}{Global\ Max - Global\ Min}\right)$$

For all indicators that are translated from their natural value to a reversed normal linear target function, equation 3.4 applies.

$$\text{(Eq. 3.4)} \qquad \text{Score (X)} = (\text{Global Max} - \text{X}) \cdot \left(\frac{100}{Global\ Max - Global\ Min}\right)$$

3.2.4.3 Weighting of Indicators

The weighting process of MCA techniques allocates relative weights to the dimensions and their underlying indicators used, in order to highlight their importance. Thus, the sum of all weights typically adds up to 100 percent. Having said that, the thesis assumes for its MCA procedure the same weight of 20 percent for each of the five dimensions assessed. It is therefore assumed that the decision maker has no preference for one of the five dimensions. The table below indicates the resulting global weights for all dimensions and indicators.

Table 3.3: Global weights of dimensions and criteria

Global dimensions and indicators weights																	
Financial evaluation				Technological evaluation				Environmental evaluation			PES evaluation				Development Dynamics	
20,00%				20,00%				20,00%			20,00%				20,00%	
Total overnight cost [$/kW]	Operation & Maintenance €/kWh	Cost of fuel €/kWh	Impact of fuel price changes %	Average efficiency coefficient	Average capacity factor	Flexibility of dispatch	Technological availability & readiness	Average external costs [€cents/kWh]	Loss of Life Expectancy	GHG emission g/kWh	Autonomy of electricity generation	Job creation/ direct employment	Potential of conflicts induced	Necessity of participative decision making processes	Number of publications	Trend of publications
5 %	5 %	5 %	5 %	5 %	5 %	5%	5%	6,67%	6,67%	6,67%	5 %	5 %	5 %	5 %	10%	10%

3.2.4.4 The Application of MCA in the Thesis

As discussed in the beginning of the section there are different techniques to apply MCA. After developing the assessment framework and pointing out the weighting and scoring process, the following section specifies what technique is applied to conduct the MCA in the thesis. As mentioned above, these techniques differ mainly in the way they process the scoring and weighting into an overall score to discriminate between different options. Next to a direct comparison of the scoring, (Dodgson et al., 2001) name multi-attribute utility theory, the analytic hierarchy process, outranking methods, fuzzy set theory and multi-criteria decision analysis (MCDA) as the most common techniques of MCA. The thesis applies MCDA in the fifth chapter to rank the different technological options. It is thus important to make explicit why the author chose to apply MCDA instead of the other MCA techniques.

To begin with, the direct analysis of the performance matrix offers only a limited insight into the relative advantages of the options assessed. These advantages can cause dominance of one option over others or require trade-offs from decision makers (Dodgson et al., 2001). *"Dominance occurs when one option performs at least as well as another on all criteria and strictly better than the other on at least one criterion… Once any dominance analysis has been concluded, the next stage is for the decision-making team to determine whether trade-offs between different criteria are acceptable, so that good performance on one criterion can in principle compensate for weaker performance on another"* (Dodgson et al., 2001). However, in order to aggregate *"…each option's performance across all the criteria to form an overall assessment of each option, on the basis of which the set of options can be compared"* one of the following MCA techniques is required (Dodgson et al., 2001). Therefore, the direct analysis of the performance matrix should be rather considered as a technique for preliminary analysis and cannot serve the objective of the thesis to come to an overall ranking among the different technological options.

The Multi-Attribute Utility Theory combines the weighting and ranking into an overall assessment of each option by *"…estimating the parameters in a mathematical function which allow the estimation of a single number index, U, to express the decision maker's overall valuation of an option in terms of the value of its performance on each of the separate criteria."* (Dodgson et al., 2001). This approach is based on the work of Keeney and Raiffa (1993) and "…*allows attributes to interact with each other in other than a simple, additive fashion",* while dealing with uncertainty in a formal manner (Dodgson et al., 2001). However, it also causes this MCA technique to be very complex and, despite its *"…powerful theoretical insights, it does not directly help decision makers in undertaking complex multi-criteria decision tasks"* (Dodgson et al., 2001). As recommended by (Dodgson et al., 2001), this MCA technique is *"…best implemented by specialists on major projects where time and expertise are both necessary and available"*. Given that both aspects are limited in the development of this master thesis, Multi-Attribute Utility Theory does not appear as the right choice to apply MCA.

The Analytical Hierarchy Process (AHP) typically *"…uses procedures for deriving the weights and the scores achieved by alternatives which are based, respectively, on pair wise comparisons between criteria and between options"*. However, the indicators that are developed in the assessment framework of the thesis are quantitative. A qualitative comparison of this data by means of the AHP would thus unnecessarily harm the preciseness of this data. As pointed out by (Dodgson et al., 2001) *"…it is a fair generalization that the less precise the data inputs to any decision support procedure, the less precise and reliable will be the outputs that it generates".* From a theoretical point of view *"…serious doubts have been raised about the theoretical foundations of the AHP and about some of its properties"* (Dodgson et al., 2001). For both reasons, the author chose not to apply AHP as the MCA technique of the thesis.

Outranking methods are most frequently applied in France and are based on the idea that one option can *"…outrank another if it outperforms the other on enough criteria of sufficient importance… and is not outperformed by the other option in the sense of recording a significantly inferior performance on any criterion"* (Dodgson et al., 2001). The main weakness of this approach is *"…that it is dependent on some rather arbitrary definitions of what precisely constitutes outranking and how the threshold parameters are set and later manipulated by the decision maker"* (Dodgson et al., 2001). Apart from that the technology screening that is applied before the MCA in the thesis selects only those technological options that appear most promising, given the criteria of the researcher. Thus, all options that are assessed as part of the MCA are non-regret options because they fulfilled the technology screening. Therefore, no further selection should occur as part of the MCA process but options should only be ranked among each other. For these reasons, the thesis does not apply an outranking method.

"Fuzzy sets attempt to capture the idea that our natural language in discussing issues is not precise" (Dodgson et al., 2001). Options which are named as expensive in our natural language can thus further be classified as 'fairly expensive' or 'rather expensive'. Fuzzy arithmetic *"…tries to capture these qualified assessments using the idea of a membership function, through which an option would belong to the set of, say, 'attractive' options with a given degree of membership, lying between 0 and 1"* (Dodgson et al., 2001). These fuzzy performance levels are subsequently further aggregated. However, the application of fuzzy sets has not been proven to be of critical advantage in comparison with conventional models, is difficult to understand for non-specialists and has no *"…clear theoretical foundations from the perspective of modelling decision makers' preferences"* (Dodgson et al., 2001). Due to all these drawbacks, fuzzy sets are not applied in the thesis.

Instead of the above introduced methods, the thesis applies MCDA which is *"...both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option"* (Dodgson et al., 2001). When comparing different options to address a problem, one of them is rarely best regarding every objective and tradeoffs occur from the different scoring of the options in terms of different objectives (Dodgson et al., 2001). For instance, costs and benefits often diverge because options of higher quality have an increased price (Dodgson et al., 2001). MCDA addresses this problem by breaking one problem *"…into more manageable pieces to allow data and judgments to be brought to bear on the pieces, and then of reassembling the pieces to present a coherent overall picture to decision makers"* (Dodgson et al., 2001). Thus, MCDA is not a tool to make a decision among several options but serves as an aid to the decision maker (Dodgson et al., 2001). To do so, objectives of the decision maker are divided into dimensions of decision making, subordinated decision criteria and indicators.

To consolidate these pieces, MCDA is based on linear additive models. The latter assume that the measurable indicators are preferentially independent of each other, which can be reasonably assumed, and it requires that uncertainty is not build into the MCA model. Also the latter aspect is given, which makes linear additive models applicable for the thesis. The application of linear additive models is well proven to provide *"...robust and effective support to decision-makers"* and widely applied as an MCA technique (Dodgson et al., 2001). It combines *"...many criteria into one overall value... by multiplying the value score on each criterion by the weight of that criterion, and then adding all those weighted scores together"*(Dodgson et al., 2001).

Equation 3.5 shows the linear additive model as applied in the thesis, whereas ω_i equals the weight of indicator *i* and x_i the scoring of a technological option regarding indicator *i*.

$$\text{(Eq. 3.5)} \qquad \bar{x} = \sum_{i=1}^{n} w_i x_i$$

After entering the weighted scoring of the different options into a performance matrix, the last step of a MCDA procedure is typically a sensitivity analysis that tests for the robustness of the results. This step is also conducted at the end of the MCDA procedure of the thesis. It accounts for the limitation of MCDA which is assumed to be conducted under certainty. Through the usage of *"risk analysis package 'add-ins' to standard spreadsheet programmes, profiles of possible overall performance level outputs..." are created, which* reflect *"...estimates of the uncertainties surrounding key inputs"* (Dodgson et al., 2001). For the sensitivity analysis of this thesis 'Risk Solver Platform' was applied. To do so, the scoring of all indicators is presented for a low, high and base case to demarcate the lower and upper boundary for the technologies' scoring in terms of every indicator. This is especially crucial to account for the occurrence of ordinal and interval scaled criteria within the framework. That is to say, their translation in a ratio-scaled target function poses the biggest threat to the preciseness of the MCDA results.

However, the sensitivity analysis does not account for the assumption of MCDA of being carried out by one single decision maker with no equal preference for every dimension. As a result, all dimensions remain to be weighted equally.

3.2.5 Tech Mining

Given that the MCA dimension 'Dynamics of technological development' aims to *"quantify actors' activities that are related to the technological development of the different options*", on a global level, a qualitative analysis of this dimension does not seem to be appropriate. Instead, a quantitative technique should be used that is capable of capturing the aforementioned actors' activities in a broad fashion. Tech mining analyzes *"what is happening now and likely to happen in the future with regard to development of particular technologies"* (Porter & Cunningham, 2004). Moreover, it is a form of data mining, thus capable to deal with large quantities of data and therefore appears as a suitable technique to gather information for this dimension.

The latter aspect also relates to the theoretical background of the thesis. As pointed out in the section on evolutionary economics, technological options are often bound to a regime, whereas new technological options develop in niches and their existence is therefore often difficult to track in a qualitative manner. The quantitative collection of data on emerging technological options from databases related to research and development and innovations, as applied in Tech Mining, appears thus as a logical step.

In general terms, Tech Mining gathers data in the form of search results of databases. After cleaning this data, information can be derived and analyzed that is contained in the entities of the search result. For example, tech mining can be used to identify the number of scientific publications on a topic or trends, actors, institutions, cities or countries that are related to these publications. The basic assumption of tech mining is that the interest of actors within socio-technical systems is difficult to quantify but is represented by indicators such as patents and publications. Given the assumption that the number of publications on a certain topic is related to the interest actors have in this subject, publications reflect the pattern of present and future developments of technologies and make their development quantifiable. The process of tech mining is more fruitful, if a reasonable amount of search results (around 2000) are obtained on an object that is researched. Therefore, a search query is formed with a Boolean expression, which can be improved iteratively, based on the preliminary search results that are obtained and based on the purpose of tech mining as part of the study (cf. Mogoutov & Kahane, 2007). Figure 3.3 illustrates the most common Boolean expressions that are applied to form a search query.

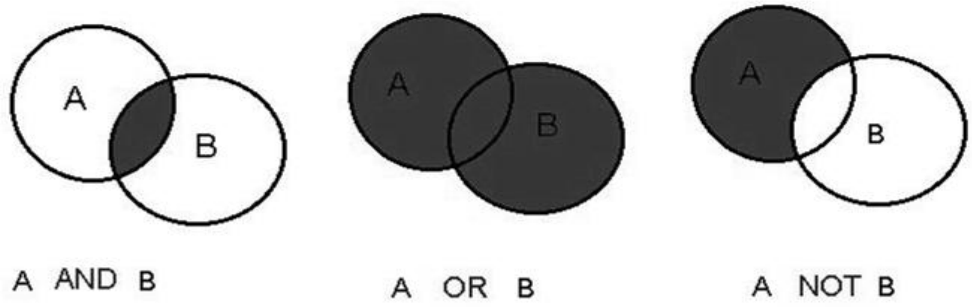


Figure 3.3: Introduction to Boolean operators (Guides, 2013)

The application of Tech Mining in the thesis is two-fold because of the following line of reasoning: The number of publications related to emerging technological options is limited. As a result it is not reasonable to conclude on the dynamics of development of the technological options, based on the results of one database. However, the data that can be extracted from different sources is only partly complementary and therefore cannot be pooled. As a consequence, the largest data set obtained from the scientific database Science Direct is used as an input for the MCDA whereas the results from other sources, that are the Web of Science, Scopus and the Derwent Patent Index, are used to reflect on the information obtained through Science Direct.

Next to the insights on the dynamics of technological development that are used for the MCDA, the Tech Mining of the thesis is used to explore the main actors and institutions that are concerned with the development of the different options. This additional analysis, which is not a direct input for the MCDA, is interesting for the thesis and based on the idea that authors and their affiliations are likely to make technological progress regarding subjects they publish academic articles on. As explained in the second chapter, a result of this progress is competitive advantage. Consequently, the more publications an author and his affiliation have on an integration option assessed in this chapter, the more likely it is for them to be more knowledgeable on this subject compared to other authors and affiliations. Recalling the fact that this thesis is written for the EDGaR program that seeks to improve the competitive advantage of the Dutch gas sector, an author or affiliation is considered to have more strategic knowledge on an option the more articles he or it has published on this option. Furthermore, the analysis of publishing actors and affiliations allows pointing out networks that have formed around emerging technologies through common authors and institutions. However, both of these aspects are not included in the MCDA of the thesis, because their evaluation as positive or negative is strongly dependent on the innovation strategy of the decision maker, thus the EDGaR program and its subordinate research projects.

Appendix B illustrates the development of the search queries for the technological options assessed in this thesis, based on a Boolean expression. Due to the fact that the queries are specific to the technologies under assessment, they are not presented in this methodology section.

3.2.6 Field Anomaly Relaxation (FAR)

As described in the research approach in section 3.1, the fourth stage of the thesis aims to reflect the results of the MCDA again on the bigger picture of the gas sector by bringing it in context with its transition paths. Subsequently, the stage aims to reflect the so gained insight in order to formulate strategies towards favoured transitions. It is argued that the fourth stage of the thesis requires a two-step approach as it combines the exploration of future pathways with normative analyses, whereas it was pointed out in section 2.4.3 that future related studies can typically be classified as belonging to one of these two categories. The thesis applies Field Anomaly Relaxation (FAR) to explore different future pathways. The following paragraphs give an introduction to the method and explain why it appears to be the most suitable method for the objective of the thesis, from the perspective of the author. The subsequent section on backcasting addresses the normative part of the fourth stage of the thesis.

FAR aims to explore conceivable forms of future development regarding certain aspects and is based on Lewin's social field theory (Coyle, 2003). The latter suggests that people live in fields of infinitely detailed components, all of which have several conceivable conditions (Coyle, 2003). Equally, FAR makes use of these fields, their components and their conditions in order to structure potential developments in the future (Coyle, 2003). For instance, economic growth constitutes one conceivable component of future development and a combination of its direction and magnitude, such as 'high growth' or 'slight decline' embodies its condition. However, for the description of a conceivable future development several component/ condition pairs need to be combined. Thereby, it is crucial to the process of FAR that inconsistent combinations of component-condition pairs, so called anomalies, are ruled out. As a result it remains a set of plausible future states that can be further explored and combined to create possible pathways to the future. *"Like all simplifications of reality it [FAR] is a model, the intention of which is to give a tool for rational and systematic thought about the future's possibilities".* Having said that, *"FAR aims to provide a backdrop of internally consistent futures as contexts for policy formulation and decision making"* (Coyle, 2003). Thereby its objective is to highlight questions of strategic importance but not to answer them (Coyle, 2003).

Due to the fact that a full-cycle FAR requires a considerable amount of time by a research team, the thesis applies a simplified FAR as suggested in (Coyle, 2003). To do so, a matrix of component/condition pairs is created as in the process of a regular FAR. Second, a consistent configuration representing the current situation and some consistent configurations representing the end of the time horizon are selected. Third, consistent configurations are selected that embody potential intermediate states. Last, potential pathways are explored by connecting the intermediate and end future states.

In addition, the thesis investigates conceivable actor coalitions and their preferences that could occur in the frame of the different future pathways. Accordingly, the FAR conducted has a great value in the bigger picture of the thesis as it allows to analyze potential changes in weights of the MCDA dimensions and to relate them to potential pathways of future development. As a consequence, the technological options can be rated against the background of future uncertainty and measures that foster sustainable development can be defined. All these aspects make FAR appear as a suitable method to explore future transitions of the gas sector and to subsequently link these results to the insights of the MCDA. However, it also needs to be highlighted why not other future oriented methods of analysis such as trend extrapolation or strategic context scenarios, are applied in the thesis.

In accordance to the classification of (Quist, 2013), mentioned in section 2.4.3, the application of FAR in the thesis relates to the second type of future oriented studies that aim to explore what future developments could happen. Given the research context of the thesis as part of the sub-project 'The next fifty years: developing robust strategies for the gas transition', it cannot be the objective of the thesis to predict future developments or to pursue a normative future vision without having identified what potential future developments are possible. Consequently, those future related studies that are classified in (Quist, 2013) as belonging to the first or third category of 'predicting the future' or 'pursuing normative future visions' would not fulfil the same purpose as FAR at this point in the thesis. It remains to defend why not other methods of the second category as presented in (Quist, 2013) are applied, that aim to explore potential future pathways.

The advantage of FAR in comparison to strategic context scenarios or model-based scenarios is that it recognizes the fact that *"…a planner's world view tends to dominate his assumptions and judgments…"* (Coyle, 2003). FAR aims to limit this fact by making the composition of future states transparent and being explicit on the reasons of neglecting certain states. This is particularly important because within the research approach, the subjectivity of the author is identified as the major weakness of this stage of the thesis. Thus, making transparent how the author concludes the plausibility of different future states is of high value.

Another reason for the suitability of FAR for this thesis is that it offers these advantages despite its simplified application in this thesis, making it a very time effective technique. Moreover, input for the FAR can be used from (Weidenaar et al., 2012) in order to improve the validity of the future pathways identified. The creation of strategic context scenarios or model-based scenarios from scratch would have been a daunting task which, next to the other stages, would have exceeded the capacity of this thesis. Next, many *"...scenario exercises give clues about the possible nature of future energy systems but ...* [do] *not offer much insight in the way paths towards these futures may unfold"* (Hofman & Elzen, 2010). Through the definition of intermediate and final states as part of the FAR analysis and the subsequent analysis of actors' perception, this stage of the thesis addresses this aspect. Besides, the combination also accounts for the fact that actor perceptions play an important role regarding future developments and are often more important than technological developments (Hofman & Elzen, 2010; Foxon et al., 2010). This important insight is often neglected by traditional scenario techniques, like *"...modelling based approaches* that assume a high level of economic rationality of actors. *Despite its useful insights, such work does not illuminate how technological changes arise through the dynamic interactions between a range of actors with different perspectives and goals*" (Foxon et al., 2010). Nevertheless, in order to complement the results of the MCDA by the insight of the fourth stage, this aspect is vital to obtain from the future-related analysis of the thesis.

As mentioned above there are however some limitations to the application of FAR in this thesis because it cannot explain how to foster favourable scenarios, such as sustainable development. To account for this aspect the thesis integrates a backcasting analysis with the application of FAR. Moreover, the application of FAR does not provide an insight into the perception of different stakeholder groups regarding certain future pathways and the related effect on technologies. The following section explains the approach taken by the thesis to account for this aspect.

3.2.7 Societal Perception of Technology

As explained in the research approach, it is the objective of the fourth stage of the thesis to reflect the results obtained by the MCDA on the *"broader context of the Dutch gas sector, as explored in the first stage"*. Given the thesis' background in TA, an important aspect of this reflection is how society potentially perceives emerging technological options, what would be the implied reactions and what future pathways are likely to be taken due to different potential preferences. These aspects relate to the social construction of technology, which addresses the varying perception of technologies by different actors and to the intersection between the field of TA and the theories of technological change because it provides an insight how different perceptions of technologies would varyingly prioritize the results of this TA study. Moreover, this section of the thesis also relates to the concept of group decision as introduced in section 2.3.2 because it needs to involve different actor groups as decision makers.

Having a further look at the research approach of the thesis, all of these aspects are necessary insights in order to be able to define strategic actions for a favoured future pathway, because they show how actors related to the gas system can influence what future pathway is pursued and how, in turn, the perception related to technological options changes. All these aspects therefore need to be developed in the fourth stage of the thesis.

It is important to highlight, again, that MCDA, even though often treated differently in literature, assumes that a decision is taken by a single decision maker. Consequently, the third stage of the thesis is not sufficient to consider several decision makers as required for the fourth stage of the thesis. Yet, in order to integrate the results of the MCDA with the ambitions of the fourth stage the potential coalitions formed by actor groups identified in the fourth chapter of the thesis is combined with the weights given for the different dimensions of the MCDA. This approach follows the thought that different social configurations change the weights for the different dimensions assessed. Thereby, the scoring of the different options remains constant during this process, because it is considered as being objectively determined by the natural characteristics and related natural values of the technologies.

Furthermore, it is assumed that the technical dimension takes a differentiated position and has a constant weight. The reason is that technical feasibility is indispensable for every scenario, and thus independent of the decision maker's preferences. To account yet for the fact that a different weighting of the technical dimension results in a modified ranking among the options assessed, the weight of the technical dimension is alternated for every analysis conducted. Most importantly, this approach of the thesis does not take into account the dimension *dynamics of development* because it assesses the general interest for a certain technology. In contrast to the MCDA of chapter five, this analysis explores the preferences of plausible actor coalitions for one of the five options. These preferences are however assumed not to be attached to the fact how much interest has been dedicated to a certain technology in the past.

Starting from the equal weighting of 25 percent for each dimension, this step of the thesis reallocates the weights among the different dimensions, according to the identified preferences of actor coalitions.

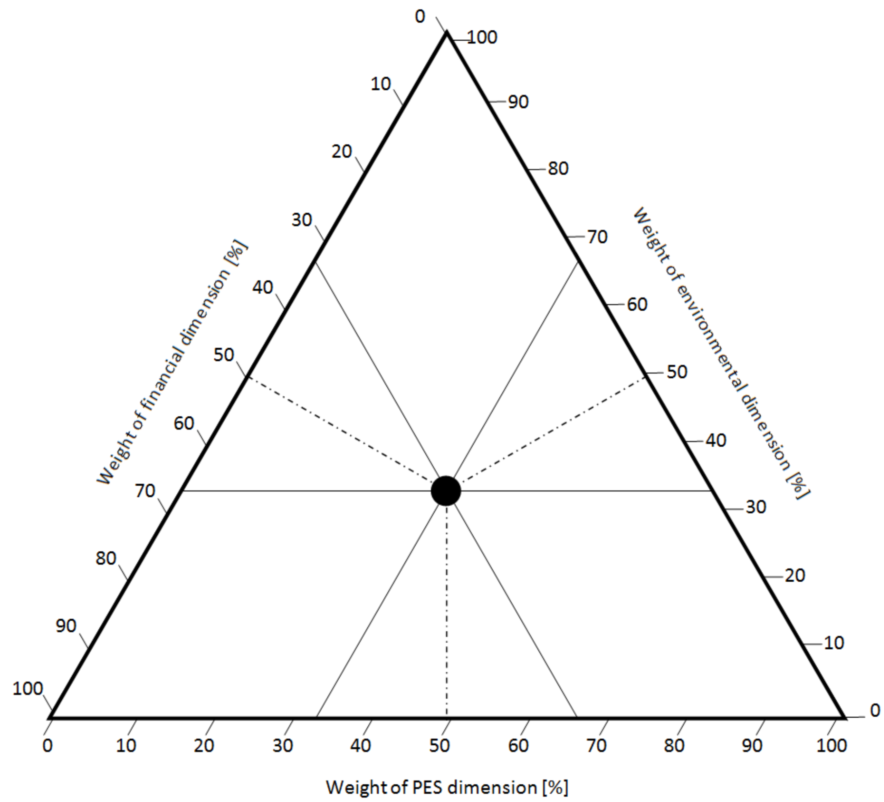


Figure 3.4: Major directions of development and related preferences of weighting

A triangular diagram as illustrated in Figure 3.4 is used to explore this context. It shows different compositions of weight which add up to 100 percent at every point in the triangle. Because the technical dimension is left out, the 75 percent of the three remaining dimensions constitute 100 percent in every distribution illustrated by the triangular diagram. Thus, 50 percent in the diagram equal a global weight of 37.5 percent, if all four dimensions are considered.

As indicated by the angle of the gauge marks, every point in the diagram is measured by parallels of the outer edges. The weight of the environmental dimension, labelled at the right side of the triangle is measured by parallels of the bottom line. The weight of the PES dimension, labelled at the bottom line is measured by parallels of the left outer edge. The weight of the financial dimension is measured by parallels of the right outer edge of the diagram. According to this mechanism, the black point plotted in the centre of the diagram represents an equal weighting of all three dimensions of 33.33 percent. When taking into account the technical dimension, this value refers to a weight of 25 %, expressed in global weights.

When moving from the point of equal weights in the centre of the triangle towards its corners, the weight of one dimension increases whereas the weight of the other two dimensions decreases. Thus, within the three rhombi, the weight of the respective dimension is at every point higher than the weight of the other two dimensions. In other words, each of the three, solid coloured rhombi favours one of the three dimensions. When leaving a rhomb by moving away from a corner of the triangle along one of its outer edges, the preference for a certain dimension becomes blurred. The cusp of this gray area, which is indicated by a chain line, represents a series of points at which the local weight of two dimensions is the same whereas the third dimension is rated lower. Thus, the grey areas as well as the rhombi embody a weighting that can represent the preference of an actor coalition. In turn, to each of the weight distribution of the triangles relates a ranking of the technological options assessed. Thus, it can be indicated which technological option is preferred by which actor coalition. Furthermore, each of the actor coalitions is related to one of the future pathways explored. As a result, it is possible to determine which of the technological options appears to be most suitable for the different future pathways.

At first glance, this approach appears to violate the limitation of MCDA which is conceptualized explicitly for a single decision maker. However, keeping in mind the goal of this thesis, that is to point out technologies that are worth to be assessed in further detail by the research project, the assumption of a single decision maker is not violated because the final decision remains with the project. Besides, future notions such as an increasing urgency for sustainable development, which are likely to be created by potential actor coalitions, not only need to be taken into account in order to decide for a technology that fulfils the criteria of the decision maker and also faces promising future prospects. Given the fact that the research project is eager to focus its efforts on the most promising technologies that are currently developing in the Dutch gas sector, the exploration of future preferences and subsequent search for the most robust decision is even indispensable to find the optimal choice of a single decision maker. Moreover, the exploration of potential actor coalitions and their associated preferences is important in order to steer future development towards a direction that is preferred by the decision maker, such as sustainable development. This approach is further pursued in section 6.4.

The drawback of the thesis' approach is that the border between different regimes of stakeholder coalitions cannot be determined precisely. For example, one stakeholder coalition might be more tolerant than another and therefore occupy a larger share of the triangle. Additionally, in reality, the difference between the stakeholder coalitions and the future pathways needs to be considered as gradual, thus blurry and not clear cut. Nevertheless, in return this analysis offers a comprehensive insight in the roles of different actor groups in the transition and how future paths and the preferences for certain technological options can change given that actor groups can collaborate potentially in different manners.

3.2.8 Backcasting

As mentioned in the previous section, the research approach developed for the thesis requires the pursuit of favourable pathways for the gas sector because it allows reflecting on the results of the MCDA conducted earlier. Besides, it is explained that the sole exploration of future pathways does not suffice this purpose, but that the pathways need to be brought in context with the development of technologies. Backcasting aims to develop normative future scenarios and to formulate pathways that steer towards these scenarios. It results a broad applicability of backcasting as a tool to develop future visions, desirable normative scenarios, R&D agendas and pathways that allow backcasting also to be used for defining next steps for the short-, mid- and long-term (Quist, 2013). Therefore, it appears to be an appropriate method to round off the fourth stage of the thesis. Backcasting has been applied to a broad range of sectors and different problem settings. Studies can be distinguished in terms of their degree of stakeholder participation, number of steps involved, nature and scale of system analyzed, or the number and scopes of visions developed for the study. As a consequence, different approaches for backcasting have been developed (Quist, 2013; Wangel, 2011b). For example, Quist (2013) distinguishes the backcasting approach of Robinson (1990), Holmberg and Robèrt (Holmberg, 1998; Holmberg & Robèrt, 2000), the Dutch STD program (Weaver et al. 2000; Vergragt, 2005) and the international sustainable households project (Quist et al., 2001; Green & Vergragt, 2002; Vergragt, 2005). Based on all four approaches Quist and Vergragt (2006) developed a comprehensive methodological framework for backcasting that also serves as the foundation for the backcasting efforts of this thesis. This methodological framework, as illustrated in (Quist, 2007) is illustrated in figure 3.5. It accounts for different types of demands, different goals and tools and methods.

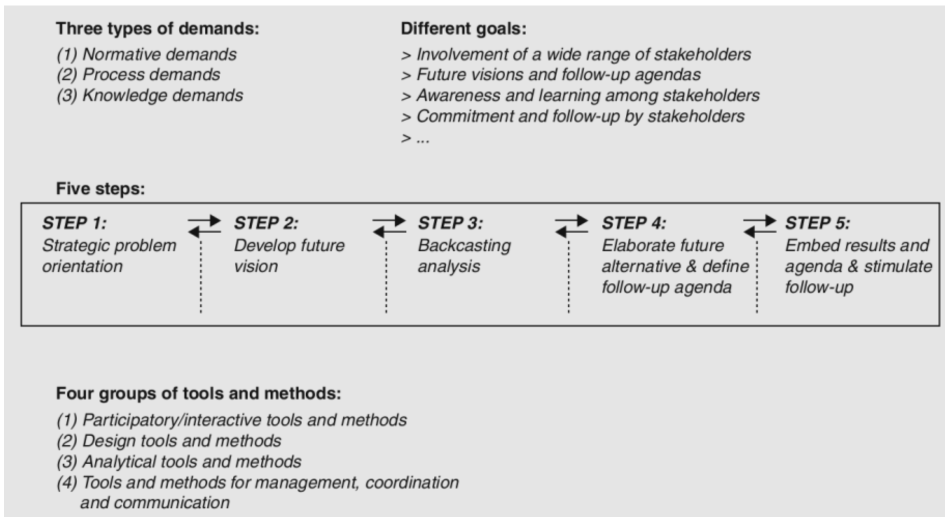


Figure 3.5: methodological framework for participatory backcasting (Quist, 2007)

As can be seen in figure 3.5, the framework is divided in five steps. Based on a strategic problem orientation and the subsequent development of a normative future vision that comprises a structural, socio-cultural, technical and organizational perspective, a transition path is formulated to transit to the desired future state. Subsequently, milestones for the short-, mid- and long-term are defined that 'pave' the identified transition path (Quist & Vergragt, 2006). Last, the results are embedded and a follow-up agenda is defined. It needs to be noted that, despite the linear outline in figure 3.5, the framework developed by Quist (2007) assumes the iterative development of the five steps, which influence each other mutually (Quist, 2013).

As mentioned earlier, the thesis aims to integrate the development of transition pathways by FAR with backcasting. The purpose of this integration is to demonstrate how, from a set of potential pathways, favourable pathways can be pursued by means of a preferred technology. Given the thesis' background in sustainability it applies backcasting to suggest measures to pursue the most sustainable pathway identified by FAR. Therefore, the thesis picks up the methodological framework developed in (Quist & Vergragt, 2006), from the third step, the backcasting analysis. Following the argument of Dreborg (1996), *"...backcasting is particularly useful in case of complex societal problems, when there is a need for major change, when dominant trends are part of the problems, when there are side effects or externalities that cannot be satisfactorily solved in markets, and when long-time horizons allow for future alternatives that need several decades to develop.*" All of these conditions are fulfilled looking at the Dutch gas sectors' problem setting to transit from its current state towards sustainability, which confirms the hypothesis of

Dreborg that *"most sustainability problems are obvious examples of such complex problems"* (Quist, 2013) referring to Dreborg, 1996). Therefore, backcasting appears to be particularly suited to be applied within the fourth stage of the thesis.

As identified in the section 2.4.3 transition management is another normative future related analysis which aims *"…to steer or modulate the dynamics of transitions"* (Foxon et al., 2010) and therefore also appears promising as a potential technique. However, it is based on *"…interactive, iterative engagement between networks of stakeholders…"*, which *"…involves involves creating shared visions and goals, mobilizing change through transition experiments, and learning and evaluation of the relative success of these experiments"* (Foxon et al., 2010 referring to Kemp & Rotmans, 2005; Loorbach, 2007). *"A key element of this process is the creation of a 'transition arena', in which a relatively small group of innovation-oriented stakeholders can come together to engage in social learning about future possibilities and opportunities"* (Foxon et al., 2010). Both of these aspects indicate that the application of transition management would not correspond with the objective of the thesis that aims to identify the most promising technological options for continuative research. Based on the results of this thesis, the application of transition management would be surely beneficial at a later stage in the research context. However, at this point in time, the application of a solely participatory technique, such as transition management seems to be too early.

In contrast, the major weakness that results from the application of backcasting in the thesis, solely based on secondary data is the author's limited cognitive capacity. Strictly speaking, the measures defined in the backcasting cannot be considered as exhaustive but more as a brainstorming to foster sustainable development. Moreover, the future transition of the Dutch gas sector is in any case a highly dynamic development. Thus, the measures and milestones defined in this thesis cannot be seen as a fixed future route for sustainable development but are likely to require some adoption or addendum in future.

3.3 Conclusion

The foregoing chapter lays down the methodology of the thesis. Therefore, it first presents the approach of the thesis and subsequently explains in detail every method used in the stages of the research approach. In the chapter it is explained how every of the methods used benefits the fulfilment of the thesis' objective, why no other method is used and what are the expected merits and drawbacks of every method used. It is argued that in combination all methods add up to the overall objective of the thesis and that none of the methods can be left out in order to fulfil the objective of the thesis. Figure 3.6 repeats the research approach presented in the beginning of the chapter. The bracketed numbers indicate the stages of the research. Whereas other technology assessment usually only address one or two of these stages this thesis aims to provide a more holistic framework, which accounts for all aspects that need to be considered when choosing from a multitude of technological options.

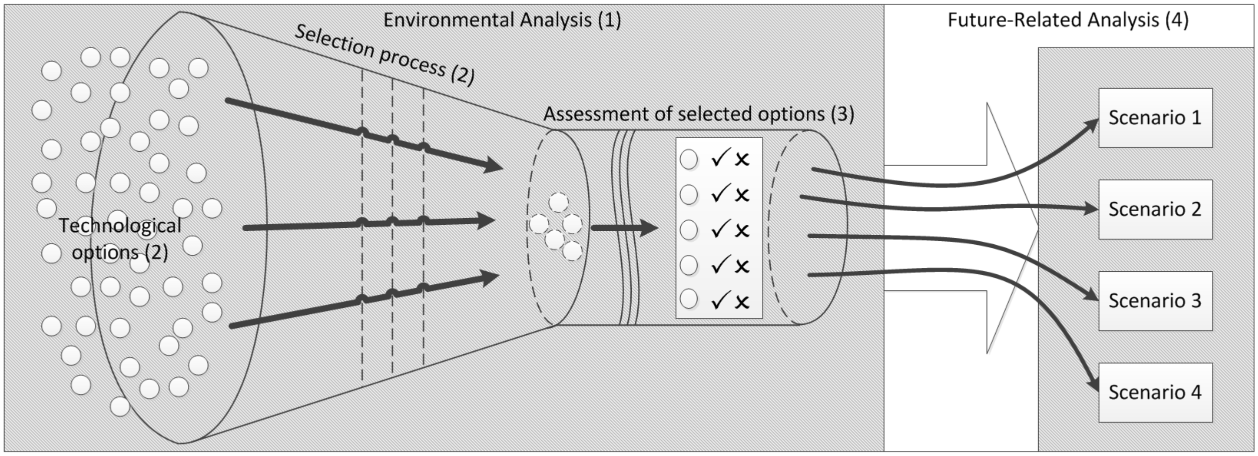


Figure 3.6: The research approach of the thesis

In the first stage, the thesis conducts an environmental analysis that analyzes the static and dynamic aspects of the Dutch gas sector. For this purpose a socio-technical map, researching the present physical and social assets of the gas sector in the Netherlands, is combined with a PESTE analysis which explores current trends affecting the Dutch gas sector. Next to the provision of vital background information, the insights gained in this step serve as an input for the fourth stage of the thesis. The second stage of the thesis creates an inventory of technological options from the research context of the thesis and applies a checklist to select those options which appear to be most suitable against the background of the thesis' objective and the problem setting of the EDGaR program. The third stage of the thesis applies a broad assessment, applying a multi-criteria decision analysis (MCDA). To do so, a framework is developed containing (1) Technical, (2) Financial, (3) Environmental, (4) Political, Economic and Social as well as (5) Dynamics of Development indicator. Fourth, the thesis reflects the insights of the MCDA on a set of explored future pathways. Therefore, it is analyzed how the formation of actor coalitions changes the perception of the different technological options and how these actor coalitions relate to a set of future pathways explored by Field Anomaly Relaxation (FAR). Based on this insight backcasting is applied to demonstrate how favourable pathways can be pursued through the development of a technology which is preferred in these pathways.

Through the combination of all four stages the thesis applies a methodology that integrates the foresight of new technological options for the Dutch gas sector in a holistic approach, as demanded by the first research question. Nevertheless, next to the drawbacks of the different methods, pointed out in the chapter, there are some expected drawbacks of the methodology developed for this thesis. First, the connection between the environmental analysis and the following stages of the thesis is to some extent tacit and could be made more explicit. This holds especially for the technical map created in section 4.1. Second, the broadness of the thesis' analysis sacrifices some of its depth. Thus, in accordance to the objective of the thesis, the refined methodology requires further, subsequent assessments which research in-depth more specific aspects of the technological options assessed.

4 Socio-technical Map

The following chapter starts the analytical part of the thesis. Therefore, it begins with an analysis of the Dutch, socio-technical gas system. This step is divided into two sub-parts. First, the technical map describes and draws a boundary around the technologies that are considered by the thesis to be part of the Dutch gas sector. Second, the social map involves the analysis of actors and their relations that are of importance to the Dutch gas sector. The second section of the chapter points out trends that affect the incumbent system.

4.1 Technical Map

The following section describes the technical specifications of the Dutch gas sector. Due to the fact that the usage of gas other than natural gas is almost negligible, solely the technologies related to natural gas will be regarded as the incumbent system. Another design choice of the technical map is the limitation to the national boundaries of the Netherlands. Thus, the technical artefacts that are described in the context of this chapter are represented in figure 4.1 that outlines the main Dutch infrastructure for natural gas. For the reason of simplicity the technical system of the Dutch gas sector, as introduced above, is referred to in the following as the 'technical system'.

Figure 4.1: The Dutch transmission network (Gasunie, 2013b)

For the comprehensiveness of the section, the description of the technical system is structured in accordance to the value chain of gas, into up-, mid- and down-stream. Figure 4.2 summarizes this classification.

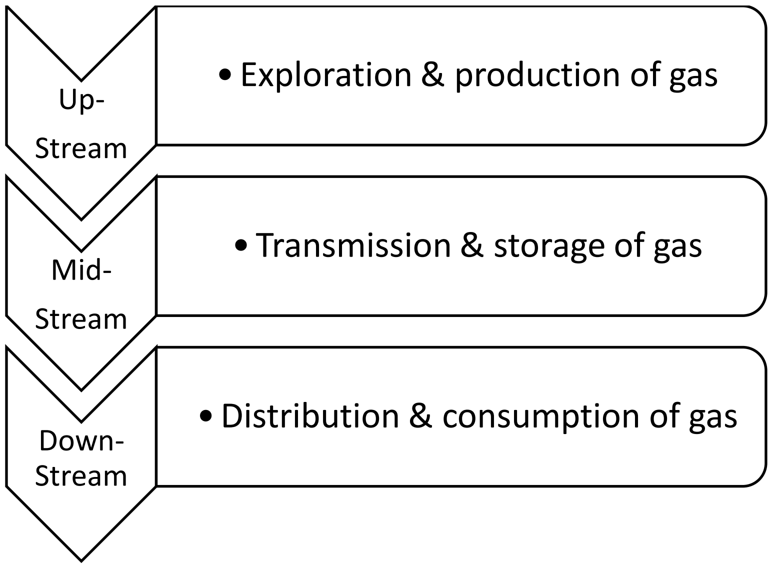


Figure 4.2: The gas value chain (Kema, 2012)

4.1.1 Up-Stream

The Up-stream of the technical system involves all activities before gas is fed into the transmission system. This involves exploration and production of natural gas as well as the import of gas from international suppliers. Figure 4.3 schematizes the up-stream of a gas system.

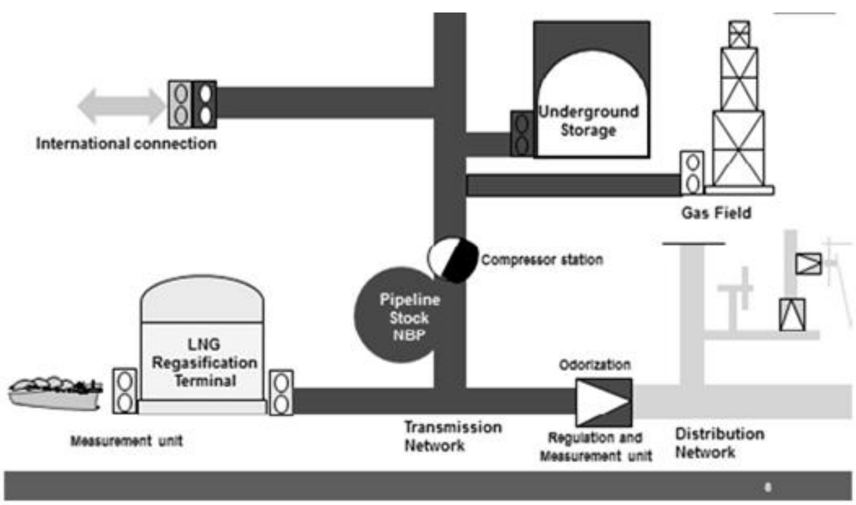


Figure 4.3: The natural gas chain (Prieto, 2012)

After the exploration, that is the mapping of new gas resources from the surface and the verification of those resources with a test drill, the production and subsequent processing of gas take place. Both are crucial technical processes in the up-stream of the gas system and are thus further described in the following.

4.1.1.1 Production of natural gas

The production of natural gas comprises the completion of drilling activities and subsequent lifting of gas from reserves below the surface. Once, the existence of gas is verified, its production requires the "…strengthening of the well hole with casing, evaluating the pressure and temperature of the formation, and then installing the proper equipment to ensure an efficient flow of natural gas out of the well" (Prieto et al., 2012). All of these steps are further elaborated in the following.

The process of well casing aims to strengthen the drill hole. It includes the implementation of a series of tubes into the plain drill hole, which ensure its impermeability. Due to the well case, no leakage of fossil resources occurs during their lifting from the underground and no liquids can penetrate the walls of the drill hole (Prieto et al., 2012). Each well needs to be adapted to the unique characteristics of the drilling location, whereas it needs to be distinguished between conductor casing, surface casing, intermediate casing, linter strings and production casing (Prieto et al., 2012).

"Well completion commonly refers to the process of finishing a well so that it is ready to produce oil or natural gas" (Prieto et al., 2012). Like the well casing, the method of well completion is strongly dependent on the physical and chemical characteristics of the well. It can be distinguished between open hole completions, conventional perforated completions, sand exclusion completions, permanent completions, multiple zone completions and drain hole completions (Prieto et al., 2012).

"The wellhead consists of the pieces of equipment mounted at the opening of the well to manage the extraction of hydrocarbons from the underground formation" (Prieto et al., 2012). It consists of the casing head, the tubing head, and the 'Christmas tree' (Prieto et al., 2012).

Due to the fact that natural gas is lighter than air, most gas wells do not require lifting equipment (Prieto et al., 2012). After the well is drilled, the gas will rise through the well casing to the surface. This holds particularly for time periods after a new well is completed because the gas field is usually under pressure. However, by the time, the 'decline rate' takes effect and pressure of the gas field decreases. As a result, lifting by pumps or well stimulation, that is the injection of water, gas or acid to ease the gas flow, might become necessary to increase the production rate of the field (Prieto et al., 2012).

4.1.1.2 Processing of natural gas

After its production, natural gas needs to be processed in order to adapt it to the quality standards of the distribution network. This step is essential for the gas value chain in order to account for varying gas qualities from different gas fields. The processing of gas makes it *"…. the clean burning and environmentally sound energy choice"* (Prieto et al., 2012).

In contrast to the gas that is used by consumers and consists almost completely of methane, the gas that rises through the well also contains other hydrocarbons, water vapour, hydrogen sulphide, carbon dioxide, helium, nitrogen and further compounds (Prieto et al., 2012). To turn the gas produced into dry natural gas of 'pipeline quality' (Prieto et al., 2012), it must pass an oil and condensate removal, a water removal, a separation from natural gas liquids, that are associated hydrocarbons such as ethane, propane, butane and pentane, as well as a sulphur and carbon dioxide removal (Prieto et al., 2012). It needs to be noted that the natural gas passing these steps additionally needs to experience some heating in order to avoid the formation of hydrates. Therefore, *"…small natural gas-fired heating units are typically installed along the gathering pipe"* that transports raw gas from the well to the processing plant (Prieto et al., 2012). Subsequent to these processing steps, the gas can be transported to its consumers (Prieto et al., 2012).

4.1.2 Mid-Stream

The mid-stream of the gas system involves the transportation of natural gas within and across the borders of the Netherlands. For this purpose an extensive network is required (Prieto et al., 2012). More specifically, the mid-stream involves the transmission, distribution, storage and trading of natural gas. *"While transmission gas pipelines transport natural gas from the processing regions to the consuming regions and may serve large wholesale users such as industrial or power generation customers directly, it is the distribution system that actually delivers natural gas to most retail customer, including residential natural gas users"* (Prieto et al., 2012). Figure 4.4 summarizes the different types of pipelines that are part of the technical system. As discussed in the previous section, gathering pipelines are used to transport gas from the wellhead to the processing station. In this section, transmission pipelines are further discussed. The section on the Down-stream of the technical system addresses the distribution system.

Figure 4.4: Types of Pipelines in the Gas system (Based on: (Prieto et al., 2012))

4.1.2.1 Transmission

The transmission network transports gas from areas of production to locations with high natural gas demand (Prieto et al., 2012). Transmission pipelines are under a pressure of approximately 80 bar which significantly *"…reduces the volume of the natural gas being transported (up to 80 times), as well as propelling natural gas through the pipeline"* (Prieto et al., 2012). The transmission network consists of a number of components among which the most important ones are addressed in the following.

Transmission pipes range from 6 to 48 inches of diameter whereas the 'line pipe', that is the actual pipeline itself, are made of strong carbon steel material, *"…engineered to meet international standards"* (Prieto et al., 2012). The line pipe is coated in order to prevent it from moisture and to avoid corrosion and rusting (Prieto et al., 2012).

Compressor stations are placed all over the gas network, every 100 to 200 kilometres along the gas lines, to maintain the high pressure within the network. After entering a compressor station, the gas is led through a turbine, motor or engine that is in operation to increase the pressure (Prieto et al., 2012). On the one hand, compressor stations require very high gas purity. On the other hand, some liquids contained in the gas only dissolve with its transmission. Consequently, compressor stations typically filter gas before its compression. This process accounts for their second function within the gas network (Prieto et al., 2012).

Metering stations are installed frequently along the gas network in order to follow the gas flow within the pipelines without impeding it (Prieto et al., 2012).

Valves are embedded in the transmission network along its entire length at a frequency of around 20 kilometres (Prieto et al., 2012). They operate as gateways that can stop the gas flow within a certain area in order to prepare the associate pipelines for maintenance or replacement (Prieto et al., 2012).

"Centralized gas control stations collect, assimilate, and manage data received from monitoring and compressor stations all along the pipeline" (Prieto et al., 2012). The data that is processed by the control stations is usually collected by Supervisory Control and Data Acquisition (SCADA) systems that are *"…essentially sophisticated communications systems that take measurements and collect data along the pipeline…",* at key points of the gas transmission network (Prieto et al., 2012).

4.1.2.2 Storage

The *"transportation of natural gas is closely linked to its storage: should the natural gas being transported not be immediately required, it can be put into storage facilities for when it is needed"* (Prieto et al., 2012). These storage facilities are logically located closely to market centres that do not have an own production of natural gas (Prieto et al., 2012). This geographic proximity eases the up-scaling of gas supply for certain areas whenever it is exceeded by gas demand (Prieto et al., 2012). As described by Correljé (2012), *"…natural gas has been a seasonal fuel…"* that faces overproduction in summer and underproduction in winter, when it is used as a main source for heating (Prieto et al., 2012). This function of storage that serves the base load of energy demand to fulfil seasonal increases in demand is mainly served by depleted gas reservoirs that are refilled with processed gas (Prieto et al., 2012). Logically, the turnover rate of these facilities is usually one year, their capacity is very high and their delivery rate is low. Given these characteristics, depleted gas reservoirs, filled in summer, can be used to add to the constant but insufficient gas supply provided in winter (Prieto et al., 2012).

Moreover, natural gas storages serve *"… as insurance against any unforeseen accidents, natural disasters, or other occurrences that may affect the production or delivery of natural gas"* (Prieto et al., 2012). In this function, gas storages seek to support the peak load of the gas system by meeting *"…sudden, short-term demand increases"* and are mostly embodied by salt caverns but also aquifers (Prieto et al., 2012). These types of underground storages have a lower capacity, thus can be replenished quickly and have higher delivery rates than depleted gas fields (Prieto et al., 2012). Thus, they can scale up gas supply for a short period of time and often have a turnover rate *"…as short as a few days or weeks"* (Prieto et al., 2012).

A more recent development is the usage of gas storage for economic reasons. Due to the de-regulation of the gas market, gas prices fluctuate more significantly (Prieto et al., 2012). Thus, *"…storing gas when* *prices are low, and withdrawing and selling it when prices are high…"* is a relatively new purpose of gas storages used by industry participants (Prieto et al., 2012).

4.1.3 Down-Stream

The down-stream, as described in this section, involves the distribution and consumption of natural gas within the Netherlands that is not used as a propellant for energy transformation processes in centralized heat plants, oil refineries or electricity plants.

4.1.3.1 Distribution

"Distribution is the final step in delivering natural gas to customers" (Prieto et al., 2012). Even though large scale customers (e.g. for electricity production) typically obtain gas directly from the transmission pipeline, consumers of smaller scale such as households are supplied with gas by utility companies , also referred to as local distribution companies (LDC). LDCs are designated to a certain geographic area and can be classified as owned by the local government or private investors (Prieto et al., 2012). As illustrated in figure 4.5, the associated distribution networks originate from an interconnection point nearby which is fed from a transmission line and split up into a dense network of small-diameter distribution lines. Due to this highly dense network that only supplies relatively low amounts of gas per customer, *"…distribution costs typically make up about half of natural gas costs for households and small volume customers"* (Prieto et al., 2012). In contrast, the foregoing transportation of gas via transmission lines faces fewer fixed costs per unit of gas due to the high capacity of pipelines (Prieto et al., 2012).

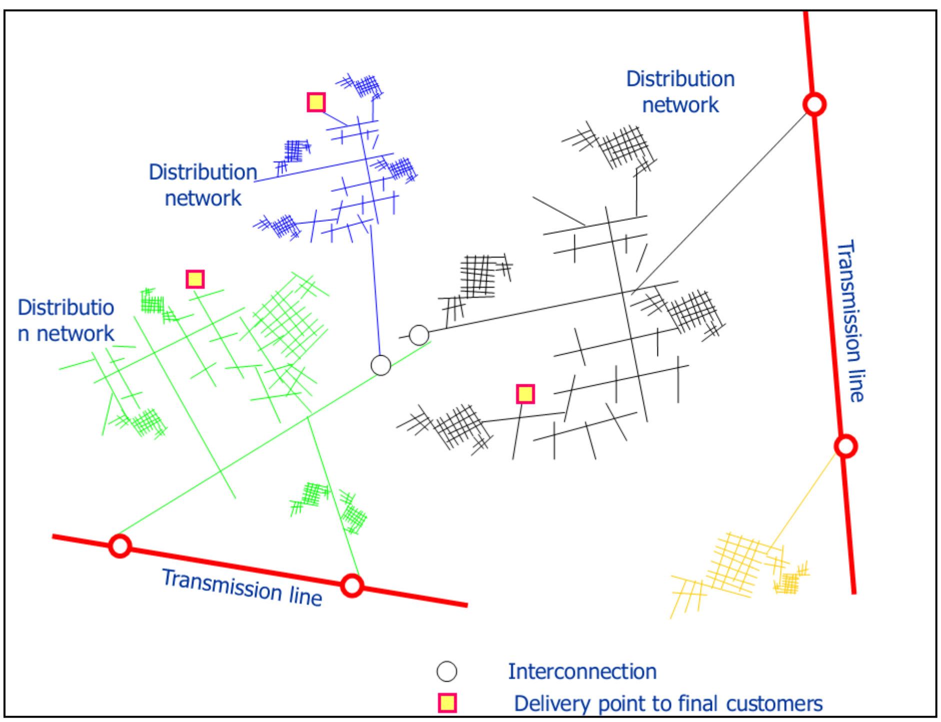


Figure 4.5: Transmission and Distribution pipelines (Prieto, 2012)

Apart from that, the technical set-up of the gas distribution network equals the transmission of gas to a large extent. As with the transmission of gas, meters, SCADAs and valves are implemented to monitor and control gas supply. However, the distribution pipelines require a much lower pressure (around a few mbar) to meet the low gas consumption of small scale customers (Prieto et al., 2012). Moreover, gas needs to be odorized to enable the detection of gas leaks in urban areas. Next to the depressurization of gas, an odorant thus needs to be added before the gas is delivered to the final customers (Prieto et al., 2012).

4.1.3.2 Consumption

As shown in figure 7, the usage of natural gas in the Netherlands can be classified by end usage into industry, transport, residential, commercial and public service, agriculture and forestry and purposes not related to energy (IEA, 2013).

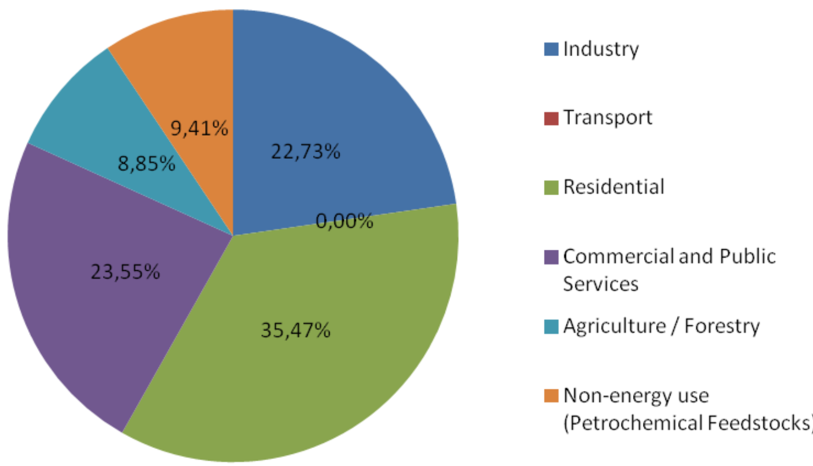


Figure 4.6: Natural gas consumption in the Netherlands by end user in 2009 (Based on: (IEA, 2013))

As illustrated, the highest share of gas is used by (the heating of) residential areas. Next to that, industry as well as commercial and public services account for a major share of gas consumption in the downstream. According to KEMA (2012), particularly the gas consumption by industry is likely to increase in future whereas the gas consumption by households decreases on average.

4.2 Social Map

The following section addresses the social system that underlies the gas sector. Therefore, it addresses the stakeholder groups that have an influence on the development of the Dutch gas system and vice versa. They are classified as related to market, authorities or society. The following subsections address all actor groups in detail. Figure 4.7, summarizes the stakeholder groups identified.

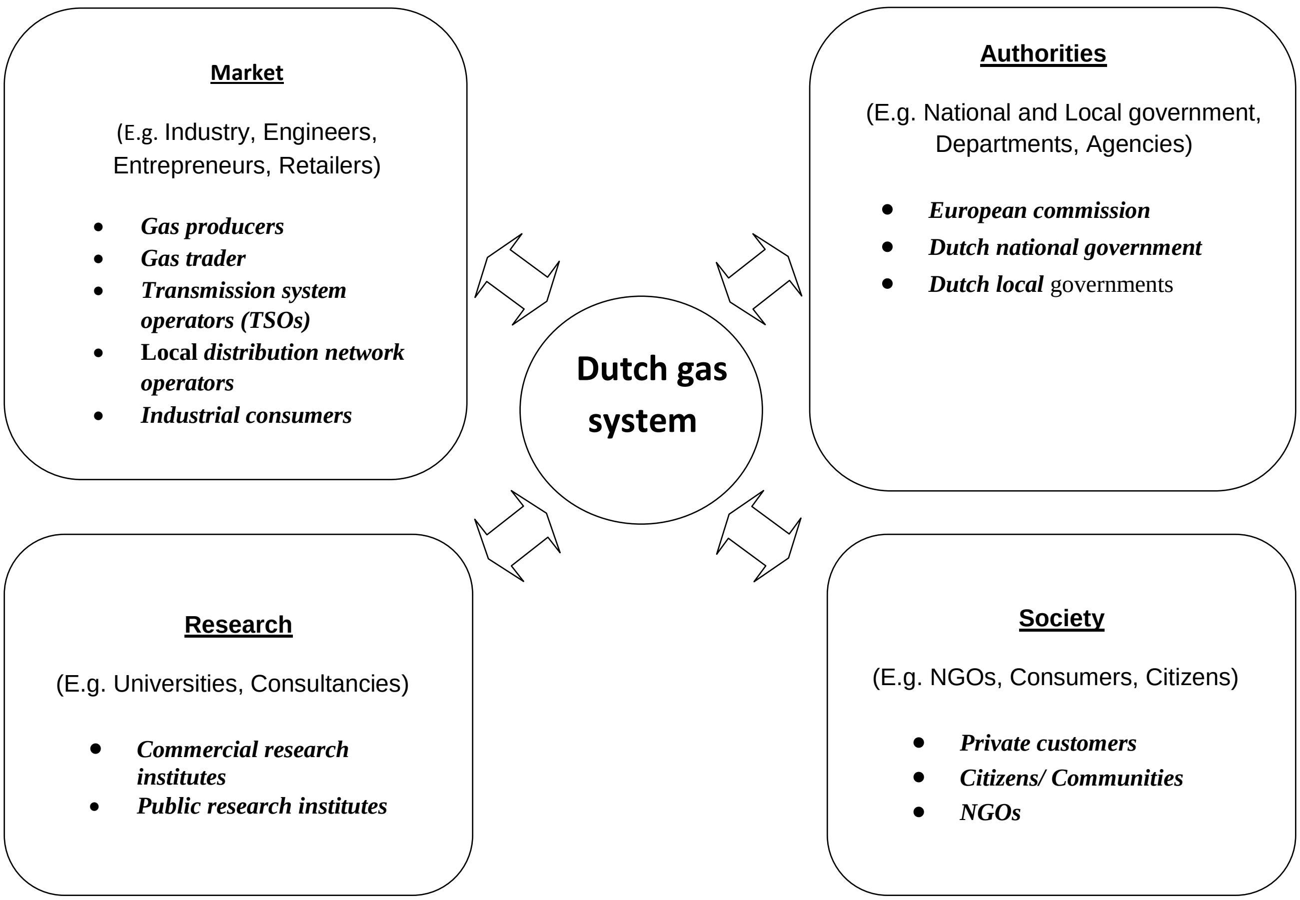


Figure 4.7: Classification of Actor groups (Based on: (Figueroa, Groot, Paassen, Lee, & Regett, 2013))

4.2.1 Market

Market actors are those that are involved in the gas sector for professional reasons. Therefore, they typically pursue an objective that is related to their business.

Market actors include gas producers, gas traders, transmission system operators, distribution network operators, industrial consumers of gas as well as research centres and consultancies, summarized as research institutes.

4.2.1.1 Gas producers

Gas producers are situated in the very up-stream of the gas value chain exploring gas reservoirs and producing gas from the subsurface (EBN, 2013; NAM, 2013). In the Netherlands there are several gas producing companies, Nederlandse Aardolie Maatschappij BV (NAM) and Energie Beheer Nederland B.V.

(EBN) being the largest of them. The interest of these two companies is to explore and produce gas in a way that adds to a sustainable energy mix (EBN, 2013; NAM, 2013).

EBN is a fully state owned company whereas NAM constitutes a joint venture of Royal Shell and Exxon Mobile (EBN, 2013; NAM, 2013). Given this legal set-up of both companies and taking into account that their production meets the Dutch energy demand to a large extent, both companies have a high power position. Moreover, they are bound to the paradigm that natural gas serves as a major share of the Dutch energy supply. As expected by EBN *"...there is a substantial amount of potentially producible gas in Northwest Europe"* (EBN, 2013). Consequently, if these expectations are not fulfilled anymore the companies' power positions, which are largely dependent on their expertise and revenues related to natural gas production, are likely to decrease.

4.2.1.2 Gas trader

Gas trading companies are located in the mid-stream of the gas-value chain and sell gas to national as well as international actors. For the Netherlands, GasTerra carries out all gas trading activities. Being active in the European gas market the company's objective is *"...to forge sustainable relationships with market parties and to set up commercially viable sales agreements"* (GasTerra, 2013a). Before and after its legal separation from Gasunie in 2005, the company has accumulated 40 years of expertise regarding the trading of gas and has therefore a strong competitive position in the market (GasTerra, 2013a). In contrast to the gas producers described above, the company is less threatened by the depletion of natural gas. Radically speaking, it can also hold up its operations if the Netherlands become a net importer of natural gas or shift towards renewable gas sources by trading bio gas. In that sense, GasTerra is less dependent on the incumbent paradigm associated with natural gas. Particularly, the implementation of the Dutch 'gas round-about', as described in section 4.2.4, would heavily increase the Dutch gas trade and naturally improve the power position of GasTerra.

4.2.1.3 Transmission System Operators (TSOs)

Transmission system operators are located in the mid-stream of the gas value chain and enable the long-distance transportation of natural gas through their gas infrastructure. In the case of the Netherlands, the transmission system with a length of 15.000 kilometres belongs to Gasunie. The company is fully state owned, with the Ministry of Economic Affairs as its sole shareholder, serves international gas demands and strives *"...to achieve the highest standards in relation to safety, reliability, efficiency and sustainability."* (Gasunie, 2013a).

Since its establishment in 1963 the company has built up a good international reputation and *"...has the resources, manpower and ambition to play a key role in the transport of gas in northwest Europe"* (Gasunie, 2013a). Key to the high power position of the company are its gas network and the associated infrastructure with several international connection points that play a key role in ensuring security of Northwest Europe's natural gas supply (Gasunie, 2013a).

Given the planned realization of the Dutch 'gas round-about', described in section 4.2.4, the power position of Gasunie is likely to improve further as it requires a significant increase in the capacity of the Dutch, thus Gasunie's, gas infrastructure (Figueroa et al., 2013 referring to Hoeven, 2009). The company's bound to the government requires it to assume this future condition, which involves a centralized gas supply and thus requires the transmission of gas in the first place. Given however, a decentralized production of gas, high capacity for long-distance gas transports would not be required. Consequently, Gasunie's power position based on its current resources would decrease.

4.2.1.4 Local distribution network operators

Gas distribution companies are located in the down-stream of the gas-value chain and supply gas from the transmission network to private customers. Thus, this stakeholder group does not serve large-scale industries that are directly connected to the transmission pipelines. In the Netherlands there are *"...around 30 companies operating on the Dutch gas retail market, including NEM, E.ON, DONG, Electrabel, Eneco, RWE (formerly Essent), Vattenfall (formerly Nuon), and Delta"* (IEA, 2012). Local gas distributors traditionally hold a regional monopoly in the Netherlands and are therefore regulated by the government in terms of their selling prices (Correljé et al., 2003). Consequently, the power position of gas distribution companies is limited. However, as gas trading companies, gas distribution companies are not affected by the type of gas they supply, which awards them a stable stake in the future of the Dutch gas market. Due to both aspects, local gas distributors aim to diversify their services and improve their power position by striving towards other commodities, such as electricity (Prieto et al., 2012; TPM, 2011). Thereby, local gas distributors loosen up the conventional natural gas paradigm and target towards an integration of systems on household level. In doing so, local gas distributors have high capabilities as most of them are multinational enterprises that can apply a lot of experience they have gained in the past, from their operation in other countries, to the Netherlands.

4.2.1.5 Industrial consumers

The group of industrial consumers involves those actors that are directly connected to the transmission lines of the gas network. In contrast to private customers that are classified as being part of society, industrial consumers use gas for their business operations and are thus listed as market actors. In addition, these industries embody end consumers of gas. Thus, they are regarded to be located in the down-stream of the gas-value chain. Industrial consumers can be further classified as associated with the chemical sector, power sector, agricultural sector or others and typically pursue their own business operations, which require the secure supply of large gas quantities.

The expectations of industrial consumers are determined by an affordable gas price that ensures the profitability of their business. The gas they require needs to be of high calorific value but, given the emergence of new gases as described in section 4.4.4.1, does not need to be conventional natural gas. This flexibility grants industrial consumers a certain power position which is fostered by their industry-specific allies they often relate to and which could initiate a common action of the industry. However, as industrial consumers are typical experts in terms of their core business, their know-how related to gas is limited. Therefore, the aforementioned change of their stake by adopting self-sustaining gas supplies would require a radical change of their expectations concerning the gas sector.

4.2.2 Research

Research actor groups are those institutions that conduct research on problem statements of the Dutch gas sector. They operate apart from the gas value-chain by contributing to its holistic improvement. Research actors can group up and form research programs such as EDGaR but are thereby dependent on the award of contract from actors situated in the gas value chain or the government. Thus, despite their distinct expertise related to gas, they have only a limited power position in the gas market. In fulfilling their objective that aims to generating unique expertise, research institutes and consultancies follow the paradigm that the gas sector is dynamic whereas its change can be expected and is addressed by their research. Given that some research actors address more relevant developments than others, they create competitive advantage compared to other actors and have the potential to increase their power position through their exclusive knowledge. Based on their source of funding, research actor groups can be classified as public and commercial. It needs to be noted that this distinction is not clear-cut as research can be funded partly by the government and market actors.

4.2.2.1 Commercial Research

Commercial research is typically conducted by commercial research centres and consultancies which sell the expertise they generate to other actors of the social system. Also, the research and development departments of other actor groups are considered as commercial research as they act in the direct interest of these actor groups. Main commercial research, addressing gas-related topics, in the Netherlands appears to be conducted by DNV-Kema, ECN, TNO, and the R&D departments of Gasunie, Kiwa, and Shell.

4.2.2.2 Public Research

Public research is conducted by actors that are not motivated to generate profit but to increase public knowledge and to serve the overall welfare of society. Such institutes include universities of the Netherlands, related to gas research, namely Delft University of Technology, Energy Delta Institute, Hanze University of Groningen but also non-profit research foundations such as the EDGaR program or the North Sea Power to Gas Platform.

4.2.3 Society

Society actor groups are those that have a stake in the socio-technical system of the Dutch gas sector, which is not based on a financial but on a social interest that relates to them or others. The actors groups that are classified as social actors have a much higher overlap than market actor groups. This proximity enhances their formation of alliances with each other, which result in a significant increase of their low individual power position.

4.2.3.1 Private Customers

Private costumers are located in the down-stream of the gas-value chain and use gas for their daily living. Major applications for private consumption involve the usage of gas for residential purposes as well as for transportation. The actor group of private customers has by far the largest number of members since it includes all private persons in the Netherlands that are connected to the Dutch gas infrastructure or use transportation that is powered by natural gas. Generally, private customers are only seldom concerned with natural gas and pursue their own personal objective. Nevertheless, all of them desire a secure and safe, and some of them an affordable or sustainable, gas supply for their purposes.

Most private customers follow the conventional paradigm of the natural gas system which involves a centralized energy supply. This entrenchment can be explained by their convenient connection to the gas infrastructure on household level. However, technological advancements offer private customers the opportunity to change towards a self-sustaining, decentralized energy supply as applied in Dongen

(Brabant) (Hemmes, 2013). This example shows that, given a determining event, private customers are willing to shift to other energy resources than a centralized gas supply and thereby change their position significantly. Besides, due to their relations to non-governmental organizations as well as citizens and communities, the ties among private customers are usually strong. This allows for a snowball effect of customer migration from natural gas in the case of very controversial events and grants a high power position to the group of private customers, although each individual of the group has only limited capabilities.

4.2.3.2 Citizens& Communities

Citizens and their associated communities are often, but not necessarily, private customers of natural gas. Therefore, they are listed as a distinct social actor group and cannot be classified as related to a certain part of the gas-value chain. Citizens and communities typical live close to and are triggered by an operation that is associated with the natural gas system. Motivated by the objective to maintain their living environment in the current state they aim to influence this operation in several ways. In doing so, initiatives of citizens or communities are rarely in favour of operations which are related to the natural gas regime. For example, the obviation of the Carbon Capture and Storage (CCS) site in Barendrecht resulted from an organized protest of citizens and communities that involved demonstrations as well as the collection of signatures for a petition (Feenstra et al., 2010). As with the group private customers, individual citizens rarely have a high power position on their own but easily activate their whole community together with other social actors. Thereby, they can raise their power position greatly.

4.2.3.3 Non-governmental Organizations (NGOs)

Non-governmental organizations are formations of individuals that centre on a certain subject, often related to ecological sustainability. In that sense, NGOs are a form of network as outlined in chapter two. In accordance to the article of Van de Poel, NGOs can be classified as outsiders to the system that do not share the same paradigm or vision as the incumbent regime (Van de Poel, 2000). As citizens and communities, NGOs are not related to a certain part of the gas-value chain and have the objective to prevent an acute operation by actors of the natural gas system. An example of an NGO, related to the Dutch gas sector is ‘Milieudefensie’ which collaborates with several communities and citizen groups in the foundation ‘Schaliegasvrij Nederland’ to counteract the exploration and exploitation of shale gas in the country (Milieudefensie, 2011; SchaliegasvrijNederland, 2013). In contrast to private customers or citizens and communities, the members of NGOs are not necessarily personally affected by operations but rather act for idealistic reasons. In doing so, NGOs acquire capabilities in terms of power, resources and know-how from their members. In addition, given the occurrence of contradictory events, private customers as well as citizens and communities can ally with NGOs, raising their power position and capabilities.

4.2.4 Authority

Authority actors belong to governmental institutions that regulate the activities of market and social actors directly or indirectly by legislation. Actor groups presented in this section have high capabilities and high authority power and therefore do not depend on allies. However, authority actors require re-election to maintain their high stake and are therefore dependent on social and market actor groups to a certain extent. Furthermore, authority actor groups can be classified in accordance to their scale of authority. The European Union being the highest it is followed by the Dutch national government as well as provincial and municipal governments.

4.2.4.1 European Commission

The commission, council and parliament of the European Union set the international framework of Dutch policies related to gas. Therefore, the European Union acts as an overarching body that brings forward new and controls existing legislation of its member countries. It thereby aims to foster a secure and sustainable energy supply in the interest of all its countries, acting under the paradigm of a unified Europe. As the highest instance in Europe it has very high capabilities.

4.2.4.2 Dutch national government

The Dutch national government represents the interests of the Netherlands as a whole. Nevertheless, in its political measures, the Dutch national government has to take into account the legislations as suggested by the European Union. The Dutch national government is divided in several ministries involving foreign affairs, economic affairs, finance, infrastructure and the environment, to mention a few. All of these ministries represent the interests of the country against the background of their particular subject. For example, the Ministry of Economic Affairs seeks to improve the prosperity of the country by means of the countries natural gas resources.

An overarching goal of the Dutch government, which has been pursued since 2005, is the establishment of the Dutch gas-roundabout. It accounts for a depletion of Dutch gas resources and involves a shift in the core business of the Dutch gas sector from a producing to a trading state. By 2022, when *"…the Netherlands can no longer cover domestic gas consumption from its domestic production…"* this establishment aims to import significant quantities of gas from abroad, store and partly use them within the country and re-distribute them around Europe. Figure 4.8 illustrates the principle of this strategy.

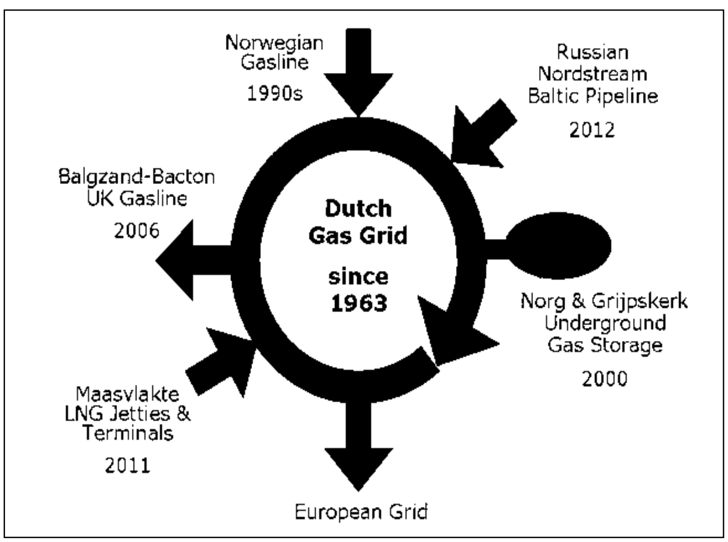


Figure4.8: The Dutch gas system as a round-about (Weijermars & Luthi, 2011)

Dutch provincial and municipal governments

Next to the national government, 12 provinces and 408 municipalities play a crucial role in the political landscape of the Netherlands. Thereby, the provincial governments act as a link between municipalities and the national government. On the one hand, provinces execute national policies. On the other hand they design provincial policies that are executed on a municipal level. Generally, provincial and municipal governments represent the interest of their region and are not necessarily affected by the Dutch paradigm of natural gas. Triggered by predominant motivations, this independence can result in the autarkic energy supply of single municipalities such as in Dongen (Hemmes, 2013).

4.2.5 Potential Coalitions among Actors

The following paragraph describes the further accumulation of actor groups based on the above analysis and explains the underlying assumptions and restrictions that are associated with the configuration of their coalitions. Based on this analysis actor coalitions can be explored for potential future pathways of the energy sector in the last stage of the thesis.

The regrouping of the actor groups identified above results in seven actor groups that are considered for the configuration of stakeholder coalitions. Figure 4.9 illustrates the changes made in the regrouping process. First, the classification into market, research, authority and society actors is mostly neglected because it served the progress of inventorying actor groups. However, no new actors are added at this point. Second, gas producers and transmission system operators are merged in one main actor group because the central production of natural gas, as in the current state, requires a transmission system for gas and vice versa. Therefore, both actor groups follow the same rational. In contrast, local distribution network operators fall apart in terms of their interest because their network is denser and requires a decentralized distribution or production of gas. Gas traders and research institutes are not considered in the exploration of actor coalitions as they do not represent physical assets of the gas sector and adjust their focus and goals to the objectives of their customer and their environment. Therefore, they are rather independent and are considered not to have a preference for any future path of development. Together with industrial consumers, private customers add up to the main actor group of customers because they are considered to be more economically oriented than other society actors. The latter are consolidated in the main actor group of citizens, communities and NGOs and act mainly for reasons related to environmental protection. Last to be mentioned, all authority actors are considered as discrete main actor groups because their interests are related to their area of accountability. Hence their formulated policies often diverge and they have different preferences for different future pathways.

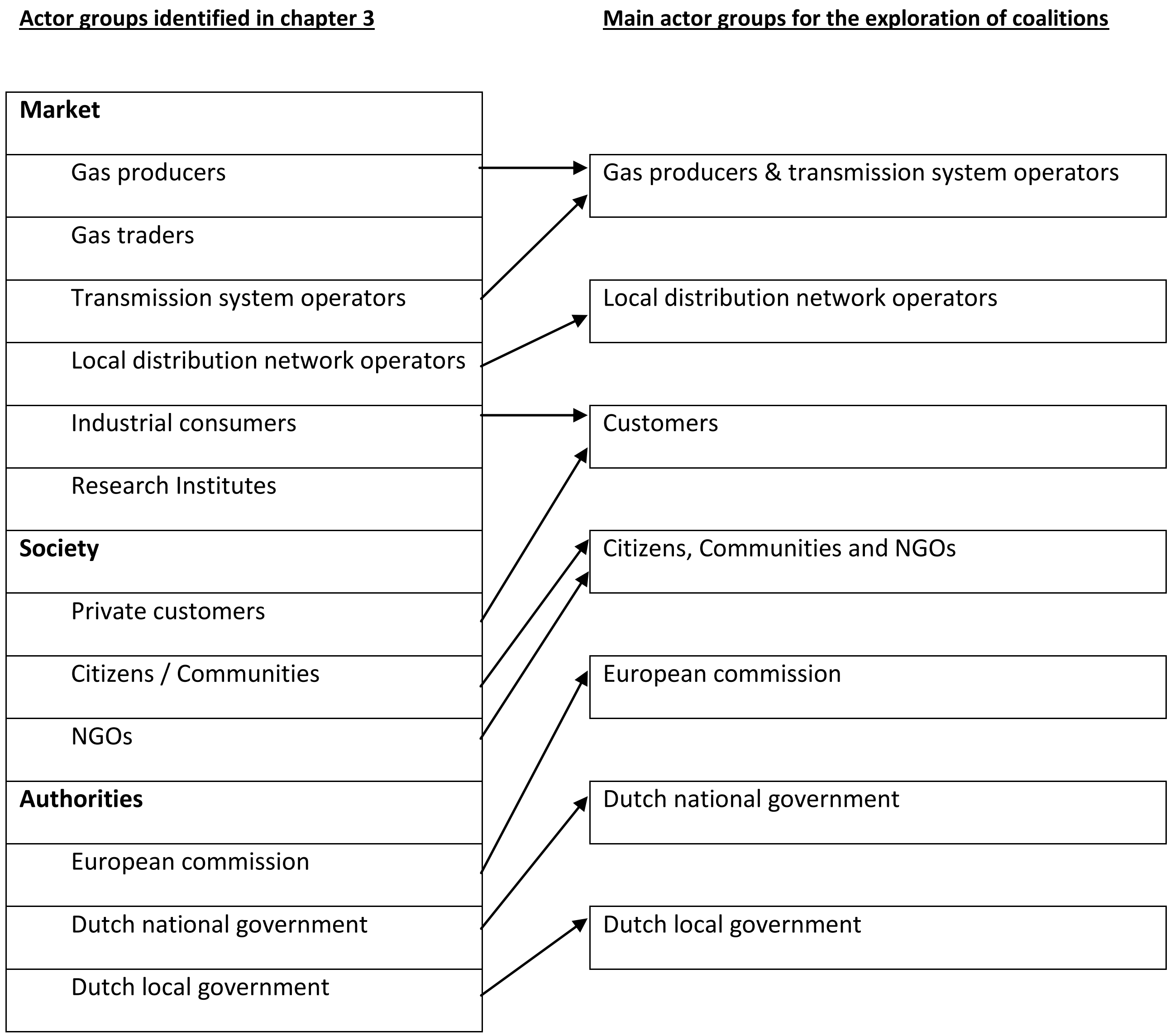


Figure 4.9: Regrouping of identified actor groups

4.3 Historical Development of the Dutch Gas System

In their book 'Natural Gas in the Netherlands – From Cooperation to Competition', Correljé et al. (2003) provide a systematic overview of the development of the Dutch gas sector (Correljé et al., 2003). In doing so, the authors distinguish three main periods since the beginning of gas exploration in the Netherlands that *"…are distinguished on the basis of the specific perspectives of policy-makers, industry, and consumers on the role of natural gas in energy supply"* (Correljé et al., 2003). To describe the first of these periods, an additional insight into the historic analysis of Kaijser (1999) is provided which illustrates the transition towards the new gas regime after the field in Slochteren was found.

The first period commenced with the discovery of the gas field in Slochteren and ended in the 1970s, when the socio-technical system was already well-established (Correljé et al., 2003). Whereas, gas was previously regarded as a clean energy carrier to avoid the transportation of petroleum or coal, the resources of Groningen elevated gas to the main energy carrier of the Netherlands (Kaijser, 1999). As described by Kaijser (1999), the set up of related rules and institutions, which allowed for the connection of a new national gas grid with existing local and regional infrastructure, took only two and a half years. Together with these new physical and institutional assets of the Netherlands, lucrative marketing strategies for the gas assured huge incomes for the state and *"...paved the way for the rapid arrival of Groningen gas on the European market..."* (Kaijser, 1999). An important milestone in this transition was the adoption of the '*Nota inzake het aardgas'*, which declared the distribution of responsibilities and functions among the main players of the Dutch gas system and was negotiated among NAM, as a venture of Esso and Shell, J.W. De Pous (the former Minister of Economic Affairs), the Dutch State Mines, SGG (a company operating local and regional gas grid by that time) and the Social Democratic Party (PvdA) (Correljé & Odell, 2000; Kaijser, 1999).

> According to the 'Nota inzake het aardgas', *"...NAM would hold the concession and a new financial entity (Maatschap) would be created. Transport and wholesales of gas would be handled by a new company, Gasunie, with a 50/50 state-private ownership. Approximately 70 per cent of the total revenue of gas sales would accrue to the state. In addition the bill proposed that the Minister for Economic Affairs would have important powers regarding nominations to the board of directors of Maatschap and Gasunie, gas tariffs, export and domestic shares in gas sales and discriminatory prices..."* (Kaijser, 1999).

Based on these changes the first period continued with a perception of *"…energy abundance, low oil prices, economic growth a relatively closed process of political decision-making, and a rapidly increasing share of natural gas in Dutch energy supply…*" (Correljé et al., 2003).

The second period of the Dutch gas system initiated during the first oil crisis. The latter gave rise to an increasing concern on the capacity of the Dutch gas field and its future performance of supply (Correljé et al., 2003). Due to the immense increase in gas production since the discovery of Slochteren, the importance of gas to the country had increased manifold by this time. As a result, the supply of gas was much more embedded in the political landscape of The Netherlands. Consequently, viewpoints had coagulated and their divergence became more apparent (Correljé et al., 2003). This side-development was fuelled by the economic recession in 1973 and 1974 (Correljé et al., 2003). By the end of the second period, policy makers decided to shift the supply of gas to a higher number of smaller gas fields (Correljé et al., 2003). Simultaneously, Groningen's gas field was determined to be used as a 'swing supply' (Correljé et al., 2003) in order to balance out fluctuations in the gas production from smaller gas fields. Even though this approach was less cost efficient, gas companies were encouraged to exploit smaller gas fields and, given a predetermined rate of depletion, were granted a reasonable price from Gasunie that held the right of first refusal (Correljé et al., 2003).

The third period started in the 1980s with an increasing liberalization of the European energy markets (Correljé et al., 2003). After a period of development the European Union adopted therefore *"...three consecutive legislative packages..."* that aimed at the liberalization and harmonization of its internal energy market (Europa, 2009). All three packages addressed the improvement of market access, transparency and regulation, consumer protection, supporting interconnections and adequate levels of supply (Europa, 2009). As an outcome of this process, *"...industrial clients and domestic customers have had the freedom to choose their gas supplier since July 1st of 2004 and July 1st of 2007 respectively"* (Europa, 2009). Moreover, new gas and electricity suppliers can freely enter the European markets of today (Europa, 2009). During the liberalization process of the EU's energy market, the Netherlands took an opposing position until the white paper on Energy in 1995 *"...indicated that fundamental changes to the traditional organization and the operation of the Dutch gas industry were under way"* (Correljé et al., 2003). Despite the fact that this contemplated changes did not seek to change the key roles of Gasunie and De Maatschap/NAM, guidelines published by the Dutch Energy Market Regulator (DTe) initiated the radical separation of GasTerra from Gasunie in 2005 (Correljé et al., 2003). Since then, transport and trading activities of Dutch gas have been carried out by these two different institutions.

4.4 PESTE Analysis

Even though the book of Correljé et al. (2003) provides a very detailed overview of the dynamics of the Dutch gas sector for the last five decades, it cannot provide an input for the most recent and future trends of the Dutch gas sector. In this thesis, a trend is understood as the development towards a certain direction that fosters or limits the development of technological options that are relevant to the gas sector. To identify current trends, the following section carries out a PESTE analysis that is build on a desk study as well as expert interviews. The expert interviews aim to confirm the relevance of trends that are mentioned in literature or to add other trends which are not adressed. It needs to be noted that the efforts of this chapter are not an attempt to foresee the future but a way to map developments that are likely to affect the Dutch gas sector in future in any conceivable way. To make this qualitative analysis as solid as possible, the section on triangulation at the end of the chapter compares explicitly the results of the interviews with those of the desk study.

4.4.1 Political Trends

Political trends are those that are caused within the 'decision making landscape' of the Dutch gas system.

4.4.1.1 Changing international power position of gas producing countries

One political trend affecting the Dutch gas system is related to the power position of countries that comes with the production of fossil fuels such as natural gas (TPM, 2011). Given the fact that only few European countries have experienced the same richness in natural resources as the Netherlands and that almost all economies in Europe are dependent on and locked-into natural gas, the Dutch gas system has had an important position regarding the gas supply of Western Europe, meeting up to 20 percent of its natural gas demand (MinistryEconomicAffairs, 2008; TPM, 2011). However, as the Dutch production of natural gas declines (cf. section 4.4.5), political power is likely to shift to other countries that have major gas resources (TPM, 2011). Moreover, gas demand of EU-15 countries is expected to rise from 187 bcm in 2000 to 632 bcm in 2030 (cf. figure 4.10) (MinistryEconomicAffairs, 2008). Consequently, the aspect of energy security that is subject to the growing power of gas supplying countries is becoming more and more important (MinistryEconomicAffairs, 2008; TPM, 2011). Besides, the sources of international gas supply are shifting over time and it is worth noting that "more than half of the world's existing gas reserves are located in only two countries: Russia and Iran" (MinistryEconomicAffairs, 2008). To remain an important player within the international gas market and to secure its own as well as European needs for energy, the Netherlands needs to account for this political trend.

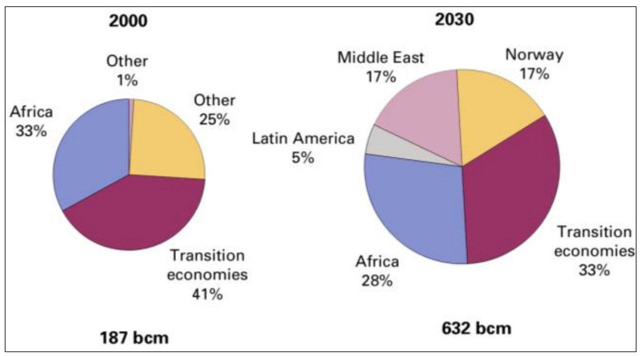


Figure 4.10: Import of natural gas into the EU-15, by source (in billion m3) (MinistryEconomicAffairs, 2008)

4.4.1.2 Increasing power of society

Another political trend is that collective groups of individuals increasingly take initiative in order to affect decision making and are becoming more powerful than they used to be in the past (TPM, 2011). Next to local proximity as a reason for grouping of these individuals, in communities for example, initiatives can evolve around certain topics and be embodied in the form of NGOs for instance. Two recent examples for this trend have been the movement against nuclear energy in Germany that contributed to a large extent to the banishment of nuclear power plants (Economist, 2011) and the activities of 'Schliegasvrij Nederlands' as described in section 4.2.3 (SchaliegasvrijNederland, 2013).

Relatively speaking this trend of public involvement is significant for the gas sector because its setting was traditionally controlled by the government and utility companies, whereas society did not intervene. However, due to the dynamics of the Dutch gas system, other trends such as the emergence of alternative gas sources (see section 4.4.4.1) put tension on the incumbent system. For the case of biomass, as a source for biogas, farmers can rise to significant producers and are thus likely to take an important role in future (TPM, 2011). For the case of other energies, examples such as Dongen in Brabant indicate that energy provision via energy communities is on the rise and might play a crucial role in future *(TPM, 2011)* (Hemmes, 2013). As a consequence, political settings within the gas sector are also likely to become more complex because the network of important actors is becoming increasingly dense. Public and private gas producers (E&P) *"…are becoming increasingly aware of the importance of embedding its activities in society"* (EBN, 2012).

4.4.2 Economic Trends

Economic trends are those that affect the income or expenses of the Dutch gas sector or the Dutch economy.

4.4.2.1 Gas exports & imports

A major economic trend that will affect the Dutch gas system in the coming decades is a decrease in production of gas (see section 4.4.5) and a resulting decline of income from gas. Since the production of gas in the Netherlands picked up, the Dutch gas sector has generated 220 billion Euro of total revenue for the state until January 2010 (Weijermars & Luthi, 2011). This accounted for an annual contribution to the Dutch GDP of 1 to 3 percent, or €4.5 to €14.8 billion per year, during the last decade (Weijermars & Luthi, 2011). This strong fluctuation, illustrated in figure 4.11 has occurred mainly due to wide variations in energy prices (Weijermars & Luthi, 2011).

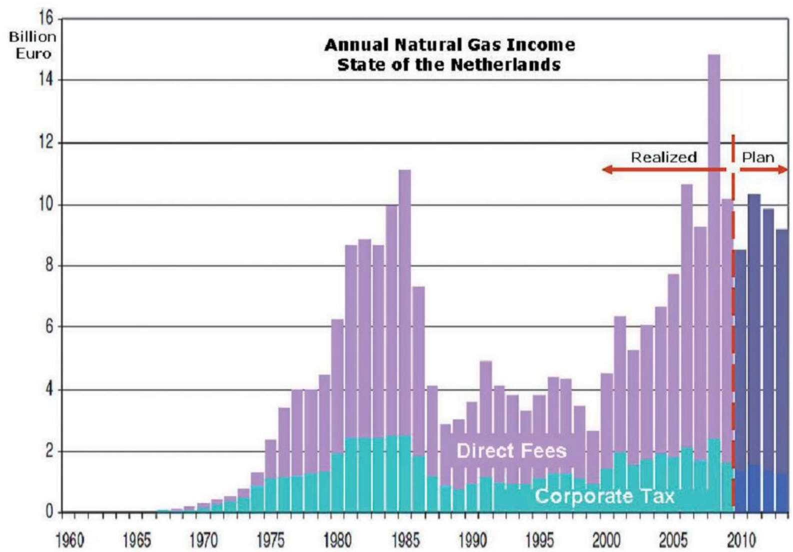


Figure 4.11: Annual net income for the Dutch State from natural gas business operations (Weijermars & Luthi, 2011)

Particularly the last decade *"…has seen a recovery (if not explosion) of global energy prices, which explains the steep rise in state income from natural gas over the past decade …, in spite of a more or less steady production output…"* around 72 bcm (Weijermars & Luthi, 2011). However, in future the Dutch gas fields are predicted to produce significantly less gas and as a consequence the gas income of the Dutch state will fall by € 250 million per year. This trend can result in a compounded loss in state earnings of €13.75 by 2020 and € 81.25 billion by 2035 due to *"…lower corporate tax from gas business, fewer exploration and production licenses, and fewer participations by the State (via EBN)"* (Weijermars & Luthi, 2011). It is worth noting that the above calculations do not account for variations in future energy prices (Weijermars & Luthi, 2011). Thus, decreases in state income due to a reduction in gas production can turn out to be more or less drastic, dependent on the future development of gas prices.

4.4.2.2 Gas price

"Gas is becoming more important as a global energy source, with an annual growth rate of 1.7 percent" (Oswald et al., 2011). However, after a slowdown due to the economic crisis, gas demand in Europe is

expected to grow only by 0.4 percent per year until 2020 (Oswald et al., 2011). This relatively stable gas demand is predicted in the context of two counterworking mechanisms. First, the usage of gas for heating purposes is going to lose ground which leads to a decrease in gas consumption (Oswald et al., 2011). Second, due to the nuclear disaster of Fukushima, the nuclear development of the EU27 countries is expected to decline. Next to the resulting shutdown of 11 nuclear power plants in Germany in 2011 and the closure of all remaining power plants until 2020, the number of newly built power plants is expected to decline by 20 to 30 percent (Oswald et al., 2011). Both factors account for an increasing use of combined-cycle gas turbine power plants for the production of electricity in Europe and level off the estimated increase of gas consumption in Europe until 2020 at 0.4 percent (Oswald et al., 2011).
In contrast, the Dutch and British gas production is declining. As a result, European gas imports are expected to increase from around 327 to 413 bcm in 2020 (Oswald et al., 2011). This number holds despite the relatively flat consumption curve and a few years ago future gas imports to Europe were expected to grow even further (Oswald et al., 2011). As a consequence, *"…the gas import infrastructure is undergoing massive expansion in both pipeline gas and LNG"* and import infrastructure projects are estimated to account for a 65% increase in pipeline import capacity and a 100% increase in liquefied natural gas (LNG) capacity, leading to an overcapacity of supply facilities of around 77 bcm (Oswald et al., 2011). This development is expected to lead to a harsh competition between pipeline and LNG terminal operators, driving down gas prices in the next years. Figure 4.12, illustrates the expected development for the EU27 countries until 2020 (Oswald et al., 2011).

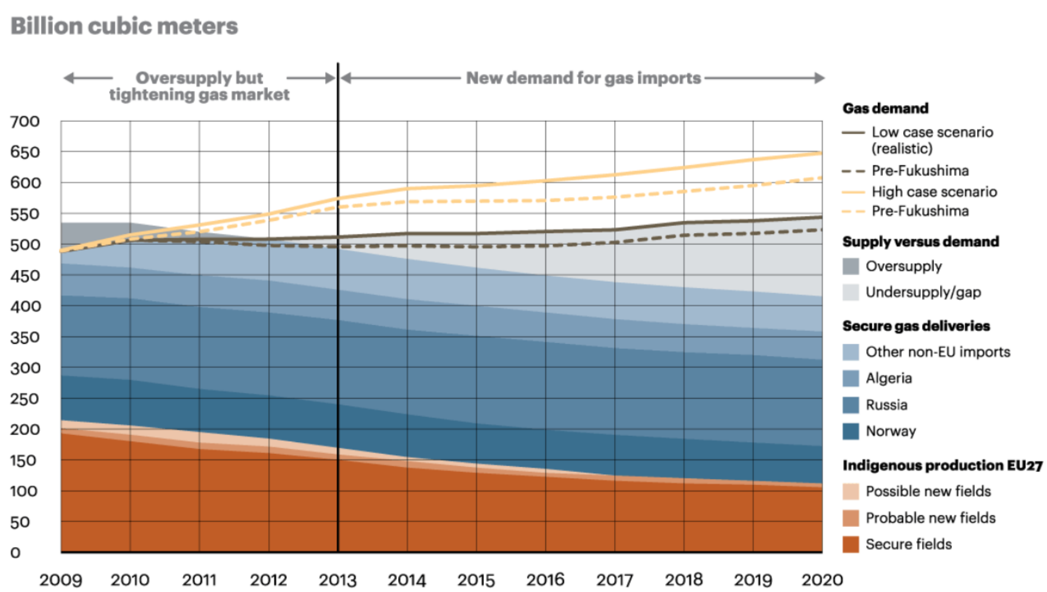


Figure 4.12: Gas demand versus production in EU27 until 2020 (Oswald, Dörler, & Seth, 2011)

For the long term it needs to be considered that gas is produced to a degree that exceeds its reformation. Consequently, gas resources are not infinite. Together with a demand for gas that increases around 1.7 percent annually (Oswald et al., 2011), it is thus likely that energy prices of fossil fuels experience an increase in the mid-term future. With reference to the previous sections, this trend interrelates with the power position of gas producing countries, the depletion of the Dutch gas resources and the vulnerable position of the European Union regarding gas supply (Weijermars & Luthi, 2011). Logically, gas prices in the Netherlands are likely to rise in the longer term.

4.4.2.3 Liberalization

The deregulation of the European gas market since the late 1990s has strongly affected the Dutch gas sector (TPM, 2011). Most significantly, the Netherlands has *"...fully unbundled the midstream and downstream gas distribution networks from the gas trading and sales companies..."* (Weijermars & Luthi, 2011). Whereas the mid-stream of the technical system remains fully state owned through Gasunie, gas trading and sales are partly privatised by GasTerra (TPM, 2011; Weijermars & Luthi, 2011). As a result, *"...a complex market has emerged in which ... providers and purchasers of natural gas are free to enter into contracts with each other"* (TPM, 2011). However, the process of market liberalisation *"...has only just begun in Europe"* (Weijermars & Luthi, 2011) and is thus likely to take further effect in future.

4.4.3 Social Trends

Social trends emerge from the mutual dependency of the Dutch society and the gas system as described in section 4.1.

4.4.3.1 Increase in households

One trend affecting many Western European countries, including the Netherlands, is that an increasing number of people live in single households (Weidenaar et al., 2012). Compared to 2003, when 2.3 million people lived in a single household, by 2035 3.4 million Dutch are expected to live in a single-household (Van Nimwegen et al., 2003). Also, couples will remain a dominant living arrangement and are expected to increase from 4.1 million in 2003 to 4.5 in 2035 (Van Nimwegen et al., 2003). As a result, the number of households that need to be supplied by any form of energy is expected to grow from 6.8 million in 2003 to 8.3 million in the year 2035 and then level off (Van Nimwegen et al., 2003). Besides, the average energy consumption per household has been decreasing during the last 30 years (Energie-Nederland & Netbeheer-Nederland, 2011). Hence, it needs to be feasible to spread forms of emerging technologies wider and simultaneously denser along the country.

4.4.3.2 Environmental awareness

Another social trend that is likely to put pressure on the Dutch gas system is an increasing environmental awareness in Europe (Weidenaar et al., 2012) (TPM, 2011). The German initiative, 'Atomkraft, Nein Danke', that was reinitiated after Fukushima needs to be regarded as an indicator of this trend (Economist, 2011).

4.4.3.3 Demography

Further, the demography of countries has been changing during the last decades. For Western European countries, such as the Netherlands, this trend involves the development of a reverse age pyramid, as a result of which the mean age of population increases. In the Dutch population, the percentage of older adults (65 years and over) is expected to increase from 14 per cent in 2003 to 23 percent in 2025 (Van Nimwegen et al., 2003). Given this trend, and also due to an increasing average level of education (Van Nimwegen et al., 2003), the Dutch gas sector is likely to face a bottleneck of specialized workers in future who can maintain and modify the Dutch gas infrastructure (Weidenaar et al., 2012). As a consequence, a higher automation for the Dutch gas system might be required in future.

4.4.4 Technical Trends

Technical trends are those that affect the gas value chain as described in section 4.1. Thereby, it needs to be emphasized that single technological developments are not regarded as technical trends because the description of all new innovations regarding the gas value chain is beyond the scope of this chapter and would cloud the 'satellite view' of the gas sector this chapter aims to provide. Instead, several technological innovations are considered to form one trend. These clusters are presented in the following. Nevertheless, the technical dimension of the PESTE analysis has a particular weight because of the technological focus of the thesis. Therefore more attention is devoted to this section than to the remaining dimensions by further structuring it into up-, mid- and down- stream, as introduced in section 4.1.

4.4.4.1 Up-stream

In accordance to the definition of section 4.1.1, trends in the up-stream of the gas sector are caused in the context of activities that take place before gas is fed into the transmission system. Given this definition, the following trends affect the up-stream of the Dutch gas system.

4.4.4.1.1 Diversification of gas types

One trend that potentially affects the up-stream of the Dutch gas supply is the emergence of new gas sources (TPM, 2011). First, this includes the exploration of unconventional gases such as tight gas, shale gas and coal bed methane (Kema, 2012). Second, new gases, like hydrogen, biogas, green gas and synthetic natural gas might gain a growing importance for the Dutch energy supply. Also, gas hydrates are becoming increasingly important but are left out in the further discussion due to the high geographic distance of these resources from the Netherlands.

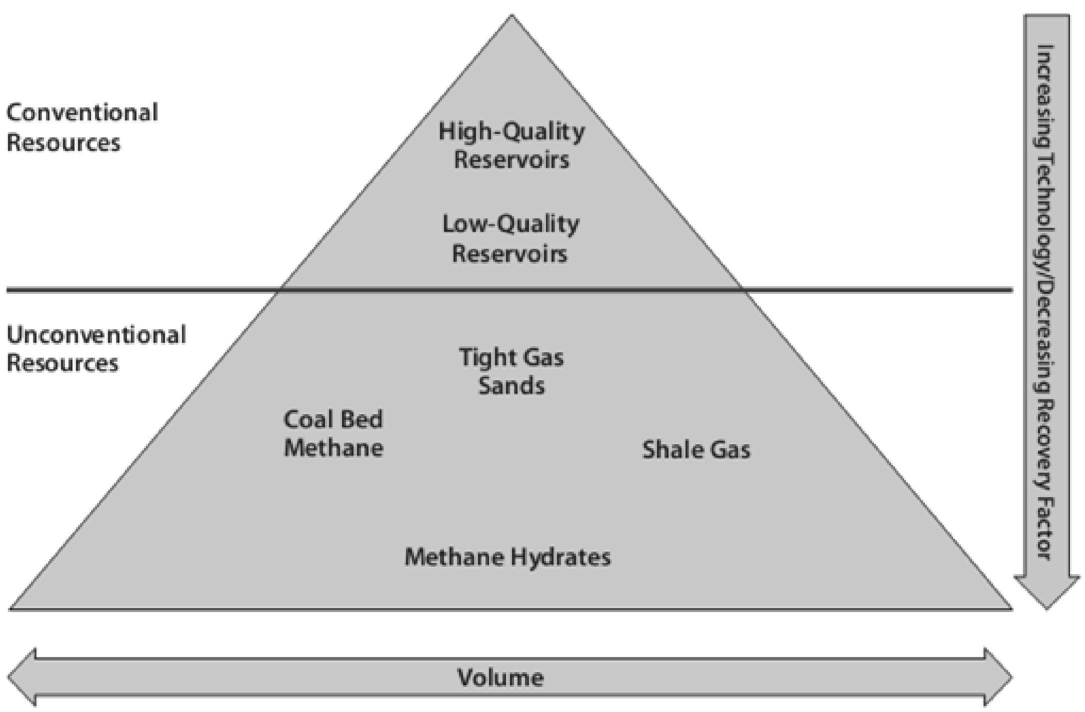


Figure 4.13: Resource triangle for natural gas (Holditch, 2006))

Unconventional Gases

Unconventional gases are natural gases that are located in *"...relatively impermeable rock formations"* (Kema, 2012). Techniques such as horizontal drilling and hydraulic fracturing are particularly common in the United States to access these sources. However, their application is still controversial in Europe. Horizontal drilling involves the creation of a well that, with an increasing depth, changes its direction from vertical to horizontal. Hydraulic fracturing involves the injection of water, sand and some chemical additives under high pressure in the well, which results in the broadening of pores in underground rock formations. As a consequence, trapped gases can freely flow to the drilling well.

Tight gas is a form of natural gas that accumulates in small, weakly connected voids underground, mostly bordered by sandstone, at a depth of below 3.500 metres (ExxonMobil, 2013; Wintershall, 2013b). In contrast to conventional natural gas, tight gas cannot flow freely to the well because of the low permeability of the sand stone (Wintershall, 2013b). For this reason, the exploitation of tight gas requires hydraulic fracturing. However, due to the high porosity of the sandstone only small amounts of fracturing liquids are required. Therefore, and also because of the large depth of tight gas reservoirs, the environmental impact of this gas' production is regarded to be low (ExxonMobil, 2013; Wintershall, 2013b). With respect to global scale, the exploitation of tight gas has been pursued for decades, it accounts for 40% of the United States' gas production and it is also applied in the Netherlands (Petzet, 2012).

Shale is one of the most frequent stratified rocks of the world (ExxonMobil, 2013). Shale gas is a natural gas which can form in this rock and remains at its place of formation due to the impermeability of shale (Wintershall, 2013b). Put differently, shale goes does not accumulate in voids but is bound to the surface of its host rock (Wintershall, 2013b) and can be produced given the existence of certain geologic characteristics. However, it requires more effort to produce shale gas than tight gas because shale is denser and less porous than sand rock. Thus, more production steps and fracturing liquids are required for the production of shale gas, which is also located in much lower depths than tight gas (Wintershall, 2013b). For these reasons the production of shale gas is riskier in environmental terms, particularly regarding the quality of fresh water reservoirs, than the production of tight gas. It supervenes that the production of tight gas is well matured whereas the production of shell gas still requires significant research (Wintershall, 2013a). However, potential shale gas resources are huge and are likely to have a tremendous impact on the gas market in future. First studies identified around 700 shale gas reservoirs spread over 142 regions worldwide (ExxonMobil, 2013). Especially in the United States production of shale gas has experienced a significant boom that made gas imports of the country unnecessary. Solely in 2009, the share of shale gas of the United States' gas production increased from 1% to 20% (ExxonMobil, 2013). By 2035, shale gas production in the United States is expected to grow to up to 50% (ExxonMobil, 2013). Given the fact that this trend continues and shale gas is also exploited in other countries, it might constitute one of the most relevant trends for the Dutch gas sector (Hemmes, 2013).

Coal bed methane forms as a by-product during the natural transformation of plant material into coal (DMT, 2013). However, it does not accumulate as a free gas in the pores of the coal bed but is bound closely to the surface of the coal bed, which allows for its production exclusively under the existence of certain geological characteristics, such as a certain gas pressure or permeability (DMT, 2013). Given the absence of these conditions, hydraulic fracturing or horizontal drilling needs to be applied, raising the controversies described previously. Worldwide, the production of coal bed methane has been pursued since the middle of the last century and has increased significantly within the last decades (Thielemann, 2008). Particularly in China and Russia huge resources of coal bed methane are present that are likely to trigger an increased production of coal bed methane in these countries in future (Thielemann, 2002).

New gases

New gases are those that do not build up under the surface like natural gas but their production can be industrialized.

Biogas is obtained from the anaerobic fermentation of biomass and can be classified as obtained from landfill, manure, crops or sewage (CBS, 2010). *"Direct injection of biogas into the gas grid is not possible because its caloric value is much lower"* (CBS, 2010). Therefore, it needs to be upgraded to 'green gas' before it is injected into the gas infrastructure. Despite the fact that this energy source contributes with 0.025 percent only a small share to the gas production of the Netherlands, there is a high interest in its production since the total consumption of biogas has increased from 2376 TJ in 1990 to 12286 TJ in 2010 and for the future *"...there are plans to realise a significant share of the gas supply through green gas"* (CBS, 2010). This development could be significantly fuelled by the process of gasification, further addressed in the next paragraph (Kema, 2012).

Synthetic natural gas is a *"...artificially produced version of natural gas"* (Chandel & Williams, 2009). It can be obtained through the gasification of coal, biomass, petroleum coke or solid waste and, like biogas, requires a further upgrade before it injection to the gas grid (Kema, 2012). The gasification process of coal has been applied for decades and is promising for the Netherlands due to two reasons (Hemmes, 2013). First, the country has proven its potential for decentralized gas production in form of city gas before the gas field in Slochteren was discovered (Correljé et al., 2003). Second, the coalmines in the South of the country were closed before their complete depletion. An underground gasification process of coal would thus be possible in that region (Hemmes, 2013). However, the gasification of coal is problematic due to its high emissions of green house gases and can only be pursued in an emission neutral way by combining it with Carbon Capture and storage (CCS) (Chandel & Williams, 2009). In contrast, the production of SNG from biomass is particularly interesting from an environmental perspective because the usage of biomass is carbon neutral and, in combination with CCS could even have negative carbon emissions (Chandel & Williams, 2009).

Hydrogen has been suggested multiple times as the solution towards an emission neutral economy. Though, it is a secondary energy carrier, which requires its production through a primary energy carrier such as renewable power or fossil fuels (Wengenmayr & Thomas, 2011). This implies that hydrogen is not a direct substitute for fossil fuels (Wengenmayr & Thomas, 2011). However, *"the future energy provisioning is ... threatened not only by a crisis of scarcity on the supply side, but also by a crisis in the disposal of the waste products from energy consumption"* (Wengenmayr & Thomas, 2011). If hydrogen is generated by means of renewable electricity the involved disposal of waste products is negligible and it offers a promising, sustainable alternative to batteries for the storage of electricity (Wengenmayr & Thomas, 2011). This application is particularly relevant as a fuel for the transportation sector or as a swing supply for the generation of energy (Wengenmayr & Thomas, 2011). Nevertheless, for this goal, particularly the production and handling of hydrogen need to be improved. With energy losses of around 25% electrolysis currently seems to be the most promising process to produce hydrogen (Wengenmayr & Thomas, 2011). Considering the fact that its subsequent conversion to electricity and heat faces further losses, the total efficiency of hydrogen as an electricity storage is too low in the current stage (Wengenmayr & Thomas, 2011). Regarding the transportation of hydrogen, particularly its volatility imposes an issue to its handling because it causes leakages of hydrogen to the atmosphere. In that case it would act as a green house gas itself.

4.4.4.2 Mid-stream

As defined in section 4.1.2, the mid stream of the Dutch gas sector comprises the storage and transportation of gas.

Storage technology

Storage technologies are applied to use a former energy surplus at a point in time when energy demand exceeds energy production. The usage of stored energy is particularly relevant with an increasing share of renewable energy sources that can have a high fluctuation of energy generation (Lenz, 2012). Moreover, the demand for energy varies over time, as described in the following section. Therefore, peaks and lows of energy production and demand need to be aligned over time. Figure 4.14 illustrates several storage technologies that fulfil the need for energy storage with different characteristics.

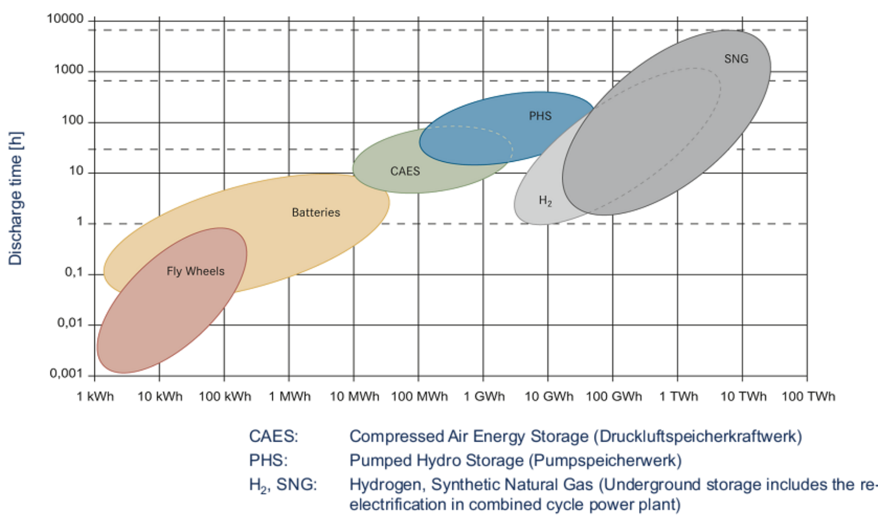


Figure 4.14: types of energy storage (Lenz, 2012 referring to research centre Jülich)

Regarding the different storage technologies, presented as bubbles in the diagram, the vertical axis displays the maximal discharge time of the energy stored whereas the horizontal axis indicates the amount of energy that can be stored by means of the different technologies presented. A particular difficulty is the storage of large amounts of energy (Lenz, 2012). Therefore, the storage of energy in form of gas such as H_2 or synthetic natural gas (SNG) is particularly promising.

Aging gas grid

Another trend, affecting the transportation of the Dutch gas is the growing age of the Dutch gas grid. After the establishment of the high-pressure network in the 1960s, major parts of the Dutch gas infrastructure require a renovation within the coming decades (IEA, 2012; Weidenaar et al., 2012). Given other trends, described in this chapter, such as the emergence of new gas sources, investments in Dutch gas infrastructure need to be well-considered, in order to accommodate possible parallel developments (TPM, 2011). For example, the gas infrastructure of the future might have to accommodate a two-way transmission of gas due to an increase of gas imports (TPM, 2011). Moreover, the transportation of different types of gases, with different physical and chemical characteristics, at arbitrary concentrations seems to be indispensible in future (TPM, 2011) *and needs to be served by the gas infrastructure*.

4.4.4.3 Down-stream

Trends in the down-stream of the system reflect changes in the consumption patterns of energy as well as the resulting dynamics between energy demand and supply.

Difficulty to match demand and supply

Bringing together the facts that energy in the Netherlands has been mainly used for heating purposes and that the isolation of new buildings is improving the average energy consumption per household decreases, because houses are likely to remain warm passively. However, in case of exceptional weather conditions, the isolation of houses is not sufficient alone. Consequently, at those times, relative peaks in energy consumption are likely to become even more drastic than they have used to be (Weidenaar et al., 2012). This trend implies that future gas systems need to be capable of performing a rapid scale up of gas production, given the case of peaks in energy demand (Weidenaar et al., 2012).

Restructuring of gas demand

Another trend in the downstream of the Dutch gas system is a reallocation of gas demand. On the one hand, average household gas consumption decreased from 3,000 to 1,617 m^3 within the last 30 year, mostly due to a fall in required space heating because of the introduction of high-efficiency boilers and improved homes' heat isolation (Energie-Nederland & Netbeheer-Nederland, 2011). On the other hand, gas is used more and more for the production of electricity and for the industry sector (cf. Section on climate change).

4.4.5 Environmental Trends

This section analyzes environmental trends that have an influence on the Dutch gas system and the emerging technological options that are relevant to it.

4.4.5.1 Climate Change

Climate change, together with the increasing environmental awareness, and other trends described in the previous sections, has a strong impact on the future development of the Dutch gas sector. At the current state, the Dutch electricity and gas sectors are responsible for annual emissions of 51 million tons of CO_2, which accounts for 25% of total CO_2 emissions of the Dutch economy (Rossum & Schenau, 2010). However, these statistics also include other fossil fuels than gas. Compared to coal, the combustion of natural gas emits only half as much CO_2, whereas the combustion of crude oil results in CO_2 emissions that lie between the figures of natural gas and coal. On top of that, the combustion of gas is very flexibly and can therefore be operated easily as a swing source of energy to level out fluctuations in renewable energy production (TPM, 2011). These differences are not only an advantage *"...during the transition period to a more sustainable energy supply"* (MinistryEconomicAffairs, 2008) but also play a significant role in terms of air pollution. Therefore, gas is likely to be the only source of fossil fuel that allows for a sufficient air quality at a time of growing population and is estimated by the European Commission to grow as a means of electricity production from less than 20 percent in the year 2000 to 37 percent in 2020 (MinistryEconomicAffairs, 2008). For the same reasons, it is argued that gas is likely to experience a golden age and will rise steeply in its significance in the upcoming decades, especially at the expense of coal (Birol et al., 2011) (MinistryEconomicAffairs, 2008).

On the downside, the increasing dependence of the Netherlands on gas imports potentially increases the global environmental impact of its gas system due to three reasons. First, the gas production in other countries is not as strictly regulated as in the Netherlands and therefore more harmful to the environment (MinistryEconomicAffairs, 2008). Second, gas transports over large distances involve leakages that release approximately two to five percent of the gas volume transported to the atmosphere (MinistryEconomicAffairs, 2008). Third, *"...powering the compressors that are needed to transport the gas* [over continental distances] *consumes a lot of energy"* (MinistryEconomicAffairs, 2008).

4.4.5.2 Sensitive areas

Another environmental trend that affects the gas sector and is invigorated by the political trends described in section 4.4.1 is the production of gas in environmental sensitive areas (MinistryEconomicAffairs, 2008). These areas are subject to the strict 'birds and habitat directives', whereas they are expected to cover *"...approximately one third of the gas futures in the Netherlands..."* (MinistryEconomicAffairs, 2008). Even though scientific studies can be concordantly summarized that the environmental impact from gas production can be negligible given the adherence to narrow policies, *"...natural processes cannot be predicted with one hundred percent accuracy"* (MinistryEconomicAffairs, 2008). Thus, should *"...natural processes show a significant deviation from the expected trend, intervention is basically possible, following the 'hands-on-the-tap' principle"* (MinistryEconomicAffairs, 2008). However, this uncertainty also signifies an uncertainty for gas producing companies that expect only relatively small gas fields under these sensitive areas, compared to those gas fields of other countries, influencing the investment climate in the Netherlands for the production of natural gas.

4.4.5.3 Depletion of resources

Another environmental trend that is of particular importance is an expected increasing resource scarcity in future (Smith et al., 2012). First, this trend holds for the consumption of fossil fuels and, for the Dutch case, particularly for the gas field in Groningen *"...that will become depleted in the coming decades"* (TPM, 2011). As illustrated in figure 4.15, the production of gas from Groningen's gas field has continuously decreased within the last years. Despite technological advancement in gas production technologies or the conversation of gas resources by policy measures, it is thus likely that in 2022, "...*the projected domestic demand of about 50bcm in the Netherlands can no longer be covered by the declined domestic gas production"* (Weijermars & Luthi, 2011).

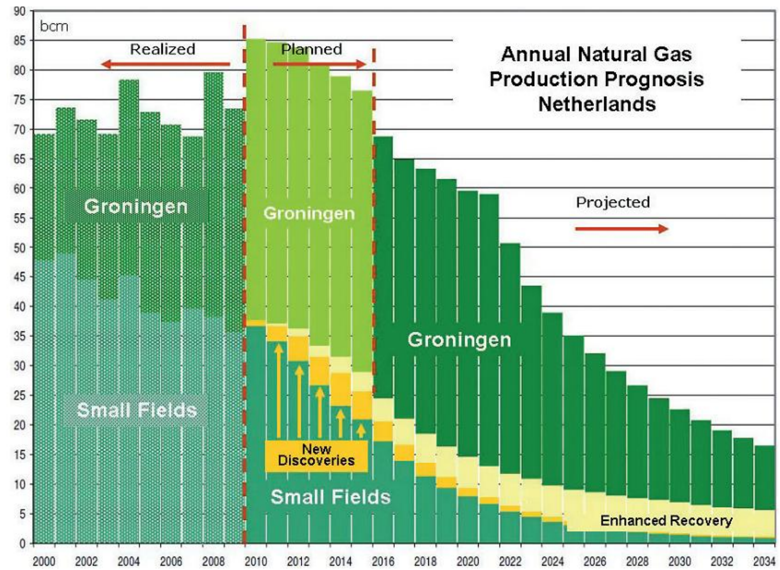


Figure 4.15: Annual Natural Gas Production Prognosis Netherlands (Weijermars & Luthi, 2011 referring to MinistryEconomicAffairs, 2010)

Second, the trend of depletion also holds for resources that are indirectly related to the Dutch gas system but are influential for its development in future though. As an example, steel, necessary to build gas infrastructure, again requires fossil fuels such as coal for its production process.

4.4.6 Triangulation of Results

The following section aims to triangulate the results of the desk study presented above with the insights gained by the expert interviews. Table 4.1 summarizes the results of this process for each of the trends mentioned above. As the legend below the table shows, a tick indicates that a trend is perceived by the expert as presented above. A cross means that the expert refused to acknowledge a trend. The combination of a tick and a cross was used to mark trends the experts partially agreed on. The letters 'NC' indicate that the expert did not comment explicitly on a trend for different reasons.

From table 4.1 it can be drawn that the 'changing international power position', 'the increasing power position of society', the 'ratio of gas exports to imports', the 'increase in households', and the 'diversification of gas types' could be found in literature and were independently confirmed by the two experts interviewed. Hence, it can be suggested that these five trends are most likely to have a significant effect on the Dutch gas sector in future. Among those, the diversification of gas types and the related globalization of the gas market via LNG were highlighted by the expert to be especially important.

Next, some trends that were suggested by literature to become apparent in the few years were refused to be commented by the experts because they were regarded as too complex to be predicted accurately. One example for this circumstance in which both experts did not comment is the development of the gas price as outlined in section 4.4.2.

Furthermore, some developments were refused to be acknowledged by the experts. For example, the trend that demographic development in the Netherlands might have an adverse affect on the pool of skilled labour for the gas sector (cf. Section 4.4.3) was not accepted by both experts. The consistent argument is that labour can be sourced from other countries and knowledge is very unlikely to get lost.

Table 4.1: Triangulation of desk study and expert interviews

Dimension	Trend		Literature	Dr. Kas Hemmes	Floris van Foreest
Political	Changing international power position		✓	✓	✓
	Increasing power position of society		✓	✓	✓
Economic	Gas exports & imports		✓	✓	✓
	Gas price		✓	NC	NC
	Liberalization		✓	NC	✓
Social	Increase in households		✓	✓	✓
	Environmental awareness		✓	×	NC
	Demography		✓	×	×
Technical	Up-stream	Diversification of gas types	✓	✓	✓
	Mid-stream	Importance of storage technology	✓	NC	✓
		Aging gas grid	✓	NC	×
	Down-stream	Difficulty to match demand and supply	✓	✓	×
		Restructuring of gas demand	✓	NC	✓
Environmental	Climate Change		✓	NC	✓
	Sensitive areas		✓	×	✓
	Depletion of resources		✓	NC	✓

✓ = Agree × = Disagree NC = no comment

In general, the triangulation of the results reflected that the ideas on the dynamics of the gas sector, gained by the literature study were mostly familiar to the interviewees. Moreover, most of them appeared to the experts to have a sound reasoning, but experts refused to agree fully with them because they were aware of a counterworking mechanism. Nevertheless, given the bigger picture of the thesis, the PESTE analysis aims to provide an understanding of the dynamics of the Dutch gas sector but not to predict future development. Given the fact that the experts could name the change of international power positions and the diversification of gas types as the most important trends, instead of other trends not mentioned in the chapter, the desk study can be considered to give a relevant overview on the trends that are likely to affect the Dutch gas sector in future.

4.5 Conclusion

To conclude, the foregoing chapter serves a broad collection of background information that helps to understand and assess the technological options, addressed in the following chapters. To do so, the chapter first presents a static overview of the socio-technical system that emergent technological options, relevant to the gas sector, are likely to face. Subsequently, trends that affect this socio-technical system are explored using the PESTE framework, which give an impression of the dynamics of the socio-technical system. Insights of both parts are concluded in the following.

The socio-technical system is described by means of a socio-technical map that is divided into a technical map, describing main technologies of the gas sector, and a social map, analyzing the main actor groups associated with the gas sector. The technical map divides the technologies of the gas sector in accordance to their position in the gas value chain as belonging to the up-stream, mid-stream or down-stream. The exploration and production and cleaning of gas are further described as major parts of the Up-stream. The Mid-stream is further specified by elaborating on the transmission as well as the storage of gas. The distribution and consumption of gas are the core elements of the Down-stream and thus also described in further detail. The social map portrays main actor groups that are concerned with the gas sector and classifies them as related to the market, research, society or authorities. Furthermore, the power positions, expectations and alliances of all actor groups are explained. In total 13 actor groups are identified. Gas producers, gas traders, transmission system operators (TSOs), local distribution network operators and industrial consumers are considered as market actor groups. Research actor groups are divided into public research and private research. The European commission, the Dutch national government and Dutch local governments are identified as authorities. Private customers, NGOs as well as citizens and communities account for the entity of social actor groups. Subsequently, these thirteen actor groups are further condensed, in accordance to their preferences for future developments.

The PESTE analysis that is conducted in the second part of the chapter categorizes trends in accordance to their impact as political, economic, social, technical and environmental. It takes a ‘satellite perspective’ to investigate trends which influence the Dutch gas sector and emerging technologies that are relevant to it. Next to a desk study, two expert interviews were conducted the insights of which are used to reflect on the results of the desk study. The latter identified a total of 16 trends. Changing international power positions and an increasing power position of society are classified as political trends. The decreasing ratio of gas exports to imports, the development of the gas price and the liberalization of the European gas market are classified as economic trends. An increasing number of households and rising environmental awareness as well as demographic changes are considered as social trends. Climate change, an increasing interference of the gas sector with sensitive areas and the depletion of resources are categorized as environmental trends. Due to the technological focus of the thesis, technical trends are further classified as related to the up-stream, mid-stream or down-stream of the gas value chain. In doing so, the diversification of gas types is identified as a trend related to the up-stream. The increasing importance of gas storages and the aging process of the gas grid are trends related to the mid-stream. Last the increasing difficulty to match demand supply of gas as well as the restructuring of gas demand are trends associated with the down-stream of the gas value chain.

The insights of the expert interviews that were conducted in the frame of the PESTE analysis are presented in the last subsection of the chapter. It becomes apparent that both political trends, the change of international power positions and the increasing power position of social stakeholders are acknowledged by both experts. Besides, the diversification of gas types, as described in the chapter was emphasized by both experts to be of particular importance. Finally, an increase in the number of households that needs to be served by the gas sector appeared was confirmed by both experts.

The remaining trends that are identified by the desk study were either refused to be commented or challenged by one of the two experts. However, the interviewees were familiar with all trends presented to them. It can therefore be argued that all trends contribute to some extent to the discussion on the dynamics of the gas sector, whether they have an actual effect or not.

From the perspective of the EDGaR program this chapter provides an overview over the static and dynamics aspects of the Dutch gas sector and can therefore be brought in context with the second research question of the thesis. At large, the chapter demonstrates a structured way for policy makers to collect relevant background information of the environment of emerging technological options. Thus, it can give close guidance to analysts who have difficulties to define a starting point for their analyses.

5 Technology Assessment

This chapter carries out the assessment procedure of the thesis. Therefore, it is divided in four parts. The first part explores a set of 54 technological options from the research context of the thesis and applies the four screening criteria developed in section 3.23 to them. Thus, each technological options is evaluated in terms of its potential to be operated sustainably, system integration, technology base and whether it uses gas as a main energy carrier. Based on this screening process, the second part of the chapter describes the selected technological options, their working principal and their basic characteristics in detail.

In the third part, the MCDA framework of section 3.2.4.1 is applied to those technological options which passed the screening process. In this context, quantified results regarding the (1) financial, (2) technical, (3) environmental, (4) political, social and economic as well as (5) dynamics of technological development dimension are assessed, by specifying the indicators of each dimension for every option. To do so, secondary data was collected from company, governmental and research reports. In order to assure the correctness of this data to a certain degree, the search followed the principal of decreasing marginal returns: The searching of a certain indicator regarding an option was continued until no additional sources were found anymore. Subsequently data was compared and a range, based on a lower case, base case and higher case, was defined. In some instances, no appropriate data was found on the characteristics of certain options and assumptions had to be made. In order to make this process transparent, section 5.3 specifies what data or assumptions were chosen regarding each technology, and for what reason. At the end of the chapter, an MCDA is conducted which ranks the different options assessed (cf. section 3.2.4). Basic insofar, as it distributes equal weights to the different dimensions of assessment and their subordinate indicators. Subsequently, a sensitivity analysis tests for the impact of single indicators on the final ranking of the technologies by varying the specification of indicators between lower cases and higher cases for every technological option.

5.1 Technology Screening of Technological Options

This section presents the integration options identified in the documents that served as an input to the thesis and applies to them the four screening criteria discussed above. In total, 54 options are identified, whereas five of them fulfil all four screening criteria.

Table 5.1 makes the screening process transparent. The first column from the left embodies all options identified in the documents scanned. The second column from the left lists the literature sources the associated option stems from. The remaining columns indicate the fulfilment of the screening criteria with reference to each option. A filled circle stands for the fulfilment of the screening criteria by the row’s option whereas an empty circle means that the option in the row does not fulfil the screening criteria.

As can be seen in table 5.1 the different technological options that have been mentioned in the research context are overlapping and on different levels of aggregation. Nevertheless, five technological options can be discriminated because they fulfilling all four screening criteria. Those options are the solar reforming of methane, the Superwind concept, mini/micro combine heat power units, hybrid gas turbine fuel cell systems and the power-to-gas concept. These four options are in bold letters in the table and further assessed in the following chapters.

Table 5.1: Technology screening

		Screening criteria			
Option	Source	Integration option	Potential of sustainable operation	Technology based	Gas as energy carrier
Agriculture and transport	(Aftzoglou, 2011)	●	●	○	●
Anaerobic digestion of biomass	(Roelse, 2012)	●	●	○	●
Biomass gasification	(Roelse, 2012)	●	●	○	●
CCS for oil recovery	(Veringa et al., 2008)	○	●	●	○
Chemical looping	(Veringa et al., 2008)	○	●	○	●
Coal gasification	(Hemmes, 2013)	○	○	●	●
Combined cold power	(Veringa et al., 2008)	●	●	●	○
Concentrated solar power and thermo-electric materials	(Veringa et al., 2008)	●	●	●	○
Construction of solar antennas from nanotubes	(Aftzoglou, 2011)	●	●	○	○
Direct carbon fuel cell	(Veringa et al., 2008)	○	●	●	●
Direct Combustion of biomass	(Roelse, 2012)	●	●	○	○
Direct Expansion solar heat pump	(Aftzoglou, 2011)	●	●	●	○
Ecolution	(Aftzoglou, 2011)	●	●	●	○
Electric batteries	(Veringa et al., 2008; Lenz, 2012)	○	●	●	○
Energy and Building	(Aftzoglou, 2011)	●	●	○	●
Energy generating clothing	(Aftzoglou, 2011; Elango, 2012)	●	●	●	○

Energy, Transport and Building	(Aftzoglou, 2011; Elango, 2012)	●	●	○	●
Extraction of oilseeds	(Roelse, 2012)	●	●	○	○
Fermentation of biomass	(Roelse, 2012)	●	●	○	○
Hybrid gas turbine fuel cell system	(Veringa et al., 2008)	●	●	●	●
ICT and Energy	(Aftzoglou, 2011; Elango, 2012)	●	●	○	●
Integration of CSP and photovoltaic	(Veringa et al., 2008)	●	●	●	○
Integration of Industries into Ecoparks	(Aftzoglou, 2011; Elango, 2012)	●	●	○	●
Integration of production sites	(Aftzoglou, 2011; Elango, 2012)	●	●	○	●
Integration of sustainability gals into energy systems design	(Aftzoglou, 2011; Elango, 2012)	●	●	○	●
Kalina Cycle	(Veringa et al., 2008)	●	●	●	○
Mechanical watches	(Aftzoglou, 2011)	●	●	○	○
Membranes	(Veringa et al., 2008; Aftzoglou, 2011)	○	●	●	●
Micro/ Mini Combined Heat and Power (CHP)	(Kema, 2012)	●	●	●	●
Night Wind	(Veringa et al., 2008)	●	●	●	○
Osmosis for electricity production	(Veringa et al., 2008; Aftzoglou, 2011;	○	●	●	○
Photosynthetic paint	(Aftzoglou, 2011)	●	●	●	○
Photovoltaic Noise barrier	(Elango, 2012)	●	●	●	○
Piezo-electric materials	(Aftzoglou, 2011; Elango, 2012)	●	●	○	○
Plug-in hybrids	(Veringa et al., 2008)	●	●	●	○
Polymer fuel cell	(Veringa et al., 2008)	○	●	●	●
Portable fuel cells	(Aftzoglou, 2011; Elango, 2012)	○	●	○	●
Portable solar shelter	(Aftzoglou, 2011)	●	●	○	○
Power-to-gas	(Lenz, 2012)	●	●	●	●

PV roof for housing	(Aftzoglou, 2011)	●	●	○	○
Pyrolysis	(Veringa et al., 2008)	●	●	○	●
Quantum dot solar cells in solar panels	(Aftzoglou, 2011; Elango, 2012)	●	●	○	○
Regenerative breaks	(Aftzoglou, 2011)	●	●	○	○
Renewable Energy & conventional energy	(Aftzoglou, 2011)	●	○	○	●
Solar cracking of methane	(Veringa et al., 2008; Cinti & Hemmes,	●	●	●	●
Solar panels for products	(Aftzoglou, 2011; Elango, 2012)	●	●	○	○
Superheating	(Hemmes, 2007)	●	●	○	●
Superwind	(Veringa et al., 2008)	●	●	●	●
Thermo electric materials	(Veringa et al., 2008)	○	●	●	○
Transparent thin films for transparent solar panels or windows	(Aftzoglou, 2011; Elango, 2012)	●	●	○	○
Tri-Generation (as an addition to CHP)	(Veringa et al., 2008; Aftzoglou, 2011)	●	●	●	○
Valorisation of biomass	(Veringa et al., 2008)	○	●	○	○
Waste and Energy	(Aftzoglou, 2011)	●	●	○	●
Wave energy	(Veringa et al., 2008; Aftzoglou, 2011)	●	●	●	○

5.2 Description of Technologies

5.2.1 Solar Reforming of Methane

The solar reforming of methane as addressed in Cinti and Hemmes (2011) is a Multi-Source Multi-Product system that uses concentrated solar power and natural gas to produce hydrogen and Carbon. The two authors consider the concept to have the potential to *"…play an important role in the future world energy supply when it comes to the problem of finiteness of raw materials and fossil energy resources"* (Cinti & Hemmes, 2011).

The decomposition of Methane (CH_4) into C and H_2 is of particular value for a future economy that is largely based on hydrogen and carbon. However, the decomposition is highly endothermic and therefore traditionally requires large amounts of fossil fuels or electricity. In contrast to these conventional processes, the application of a solar reactor does not require any additional fuel. Solar reactors, *"…collect energy from the sun light and redirect, via high reflecting mirrors, the solar rays in one point* *where the flux of energy reaches considerable levels"* (Cinti & Hemmes, 2011). These temperatures, reached by solar radiation, are used for the cracking of methane (Cinti & Hemmes, 2011). Promising locations for such a system are countries of North Africa, especially Algeria and Egypt, because of their huge potential for solar power, existing natural gas reserves and large *"…land area that is or can be made suitable for biomass production"* (Cinti & Hemmes, 2011). Moreover, the extension of the energy sector in those countries could have a positive effect on the countries' employment and, due to their proximity, accommodate a supply of hydrogen or electricity to Europe (Cinti & Hemmes, 2011).

Figure 5.1 shows the design of the concept as suggested by Cinti and Hemmes (2011). It consists of a sun cracking unit, a separation and storage unit and a direct carbon fuel cell that, supplied with natural gas, can produce additional hydrogen and electricity in a very efficient manner (Cinti & Hemmes, 2011). Common to other publications in this field is the usage of concentrated solar power and a solar reactor for the reforming of methane (Kaucic & Sattler, 2004). The subsequent production of electricity and pure CO_2 by means of a direct carbon fuel cell is however specific to this source. Similarly, the obtained hydrogen could be used for the propulsion of a gas turbine. Therefore, only the solar reforming of methane is assessed as an option in this paper but not the subsequent steps of integration because they offer too many degrees of freedom and are not homogeneous among literature. On the left side of figure 5.1 it is illustrates how methane is fed into the system by a blower (Cinti & Hemmes, 2011). After it is heated by a heat exchanger, it enters the solar reactor[2] where each methane molecule is split up into two hydrogen molecules and one solid carbon molecule.

(Eq. 5.1) $CH_4 = C + 2H_2$

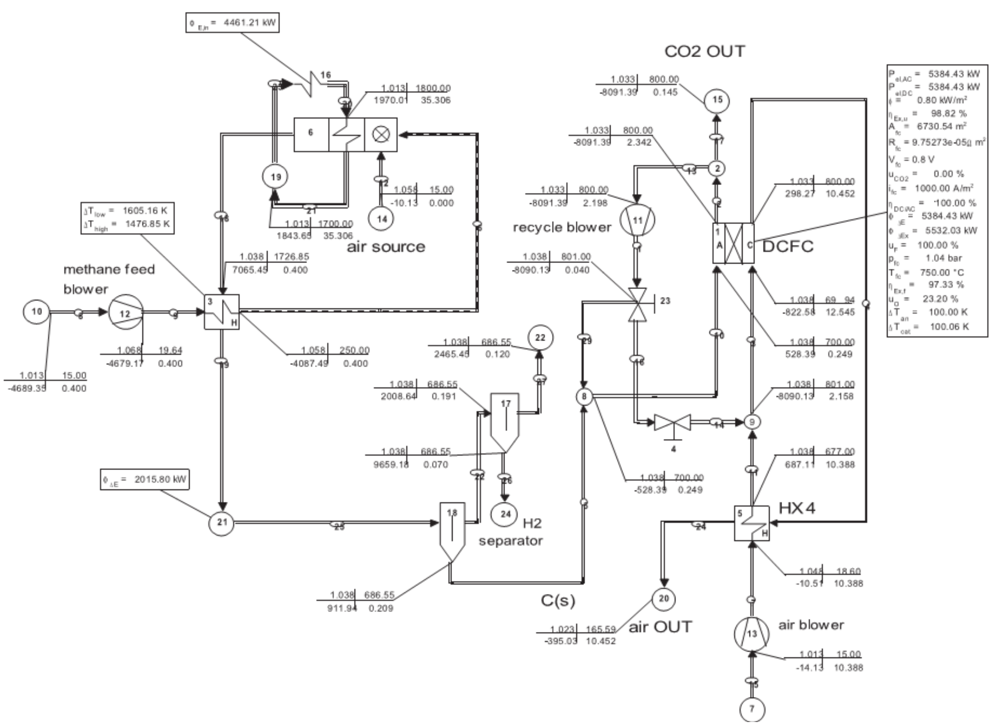


Figure 5.1: Cycle-Tempo model of the CSP-DCFC concept

[2] As pointed out by (Cinti & Hemmes, 2011) the solar reactor in figure 5.2 is depicted as a standard gasifier component due to limitations of the simulation software used. Therefore, the external air supply is set to zero.

Because this reaction is endothermic, temperatures of more than 1500 K are required to achieve full decomposition of the methane. Figure 5.2 illustrates the equilibrium of this reaction (Cinti & Hemmes, 2011).

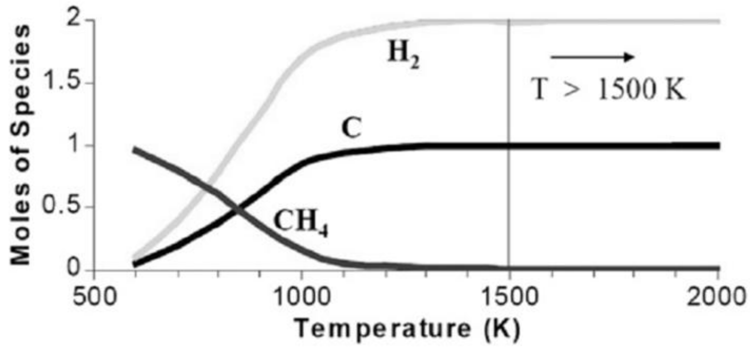


Figure 5.2: Primary methane decomposition equilibrium products P= 0.1 MPa (Cinti & Hemmes, 2011)

5.2.2 Superwind

The Superwind concept involves the integration of a wind turbine with an internal reforming fuel cell in order to produce hydrogen and electricity at flexible shares (Hemmes et al., 2007). Alternatively to the wind turbine, other power sources, such as photovoltaic panels can be used to generate the electricity required. Besides, heat can be withdrawn from the fuel cell and supplied to residential or industrial customers.

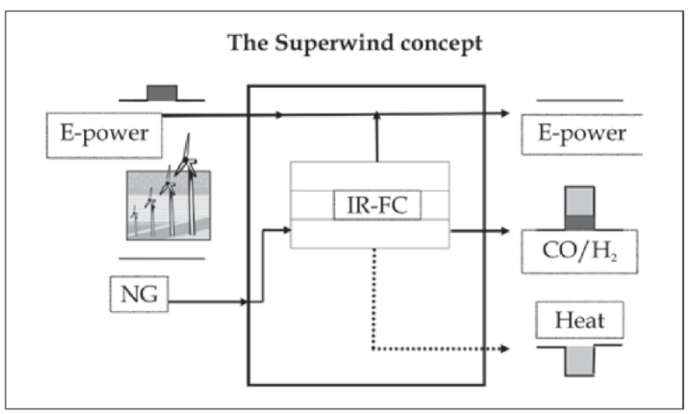


Figure 5.3: The Superwind concept (Hemmes et al., 2007)

Especially for renewable energy scenarios, the levelling of peaks and gaps that result from an increased share of wind and solar power plays a crucial role. Other concepts such as power-to-gas (introduced in section 5.2.4) aim to handle peaks in power production, through the conversion of electricity to gas, and consider a conversion from gas to power at a later point in time when electricity generated by renewable sources is low. The Superwind concept aims to directly fill in the gaps in renewable power production (Hemmes et al., 2007). As illustrated in figure 5.3 the upper part of the box that illustrates the boundary of the Superwind concept involves the generation of electricity from a wind turbine. As long as this power generation is sufficient, the 'E-power' at the right side of figure 5.3 equals largely the 'E-power' generated at its left side. However, as the generation of renewable electricity drops, the internal reforming fuel cell (IR-FC) ,that runs continuously on natural gas or biogas, shifts its operation from

CO/H_2 production to the generation of electricity (Hemmes et al., 2007). This way, the output 'E-power', depicted at the right side of figure 5.3 remains constant over time. Moreover, the hydrogen produced from the fuel cell is especially useful as a sustainable energy supply for transport and industrial applications in a hydrogen economy (Hemmes et al., 2007). For the realization of the Superwind concept the application of a molten carbonate fuel cell or solid oxide fuel cell appears most suitable (Vernay et al., 2008). A distinct characteristic of both types is their high temperature and pressure of operation that enable the internal reforming of fossil fuels. That means that both types can create hydrogen from carbonates and are not prone to poisoning by carbon monoxide or dioxide. Table 5.2 compares both fuel cells regarding their characteristics.

Table 5.2: Comparison of MCFC and SOFC (Brouwer, 2002; NFCRC, 2007a; NFCRC, 2007b)

Feature	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
Electrolyte	Immobilized Molten Carbonate	Ceramic
Typical operating Temperature	600 – 650°C	600 – 1000°C
Charge Carrier	$CO_3^{=}$	$O^{=}$
Prime Cell components	Stainless Steel, nickel, carbonate salts	Ceramics, high temperature metals
Catalyst	Nickel	Nickel, Perovskites
Product Water Management	Gaseous Product	Gaseous Product
Product Heat Management	Internal reforming + Process gas	Internal Reforming + Process gas
Anode	$H_2 + CO_3 \rightarrow H_2O + CO_2 + 2e^-$	$½ O_2 + 2e^- = O$
Cathode	$½ O_2 + CO_2 + 2e^- \rightarrow CO_3$	$H_2 + ½ O = H_2O + 2e^-$
Net reaction	$H_2 + ½ O_2 + CO_2 \rightarrow H_2O + CO_2$	$½ O_2 + H_2 \rightarrow H_2O$
Water-shift reaction	$CO + H_2O = H_2 + CO_2$	
Internal reforming reaction	$CH_4 + H_2O \rightarrow 3H_2 + CO$	

Based on a feasibility study of the Superwind concept (Vernay et al., 2008) that suggests the capacity ratio of the fuel cell to the wind turbine to equal 1 to 4, the following assessment assumes a 500 kW fuel cell to serve a 2 MW onshore wind turbine. Moreover, the assessment looks particularly at SOFC fuel cells because their realization is easier. However, a MCFC could have been chosen for the assessment as well.

5.2.3 Micro Combined Heat Power

"Combined generation of heat and power (CHP), also known as cogeneration, means that electricity and heat are generated simultaneously" (Meijer et al., 2007). Whereas large-scale CHP plants are common practice, cogeneration on household level has hardly reached mass application. As illustrated in figure 2, small scale CHP units are typically fed by gas that is mainly converted to heat (>70%) but also electricity (10-25%). Through a storage tank, heat is preserved and can be used at a later point in time. As a result, the CHP unit can be operated at economically beneficial times, when gas prices are low. In order to meet peaks in electricity demand, the housing is also connected to the grid. In contrast to traditional households, this connection is twofold and also serves for the fed in of electricity from the CHP unit to the grid, at times of low electricity demand in the house. During this state, the house owner earns money back at the established fed-in tariff for electricity.

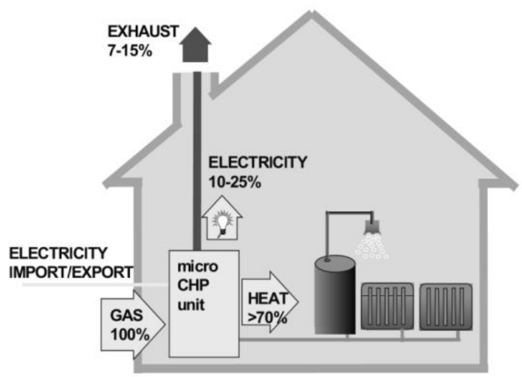


Figure 5.4: Energy inputs and outputs of a micro CHP Unit (Harrison, 2012c)

Micro CHP units can be realized in different forms. Figure 5.5 summarizes them and shows their state of development (Jong, 2011).

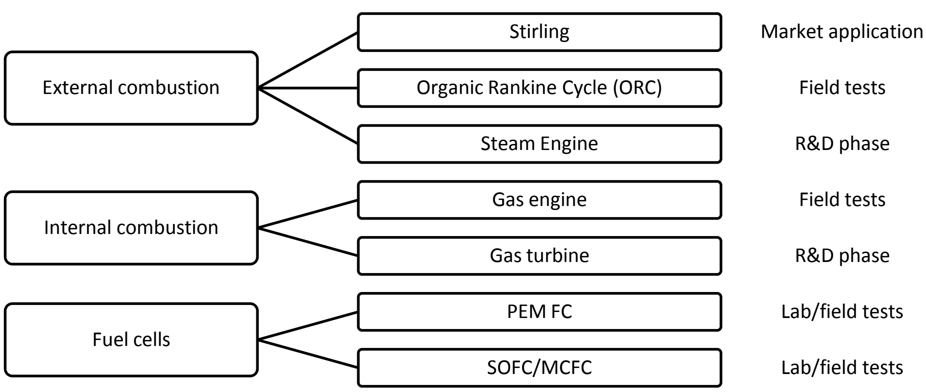


Figure 5.5: Micro CHP concepts (Jong, 2011)

External combustion engines are well suited for stationary, constant running applications such as micro CHP. Therefore, most micro CHP units that have been realized are based on external combustion engines (Microchp.dk, 2009). *"External combustion engines separate the combustion process (which is the energy input to the engine) from the working gas, which undergoes pressure fluctuations and hence does useful work"* (Harrison, 2012c). More specifically, the majority of micro CHP units operate a stirling engine *"…in* *which a working gas is alternately heated and cooled to create pressure changes which in turn drive a power piston"* (Microchp.dk, 2009). Another common external combustion used for CHP purposes is "*…the Rankine engine in which a fluid is heated to evaporate and expand against a piston or turbine, and then cooled and condensed prior to the next heating and cooling cycle"* (Microchp.dk, 2009). Being another format of external combustion engines for micro CHP purposes, steam engines are still in the R&D phase (Jong, 2011).

"Internal combustion engines inject fuel and air into the cylinders where combustion occurs. The resulting temperature and pressure changes of the fuel/air mixture (which is also the working gas) act on the piston to produce useful work" (Harrison, 2012c). Internal combustion engines are not as common as external combustion engines for the application of micro-CHP due to their working principle. The latter is cyclical and therefore causes more noise and vibration than external combustion engines (Harrison, 2012c). Moreover, internal combustion engines tend to burn fuel not as complete as external combustion engines and thus create more pollution (Harrison, 2012c). All these aspects make internal combustion engines less advantageous for home applications compared to external combustion engines or fuel cells. Nowadays, internal combustion engines for micro-CHP purposes are available as gas engines (Jong, 2011). Compared to early products that were based on automotive internal combustion engine technology, these product are specifically developed for home applications and therefore have significantly less operating and service costs than their predecessors as well as higher product life times (Harrison, 2012b). Gas turbines for micro-CHP applications are still under development (Jong, 2011).

Fuel cells have massive potential for their application as micro- CHP units as they generate electricity and heat solely based on a chemical reaction and therefore do not create any noise or vibrations (Harrison, 2012c). *"In a fuel cell, the chemical energy within the fuel is converted directly into electricity (with by-products of heat and water) without any mechanical drive or generator"* (Harrison, 2012c). In theory, the application of fuel cells as micro-CHP units *"…can result in high electrical conversion efficiencies and low emissions. However, numerous additional components are required to condition the fuel and to convert the DC electrical output into AC suitable for domestic installations; their theoretical potential has yet to be realised in any commercially viable domestic product."* (Harrison, 2012c). Next to small formats of internal reforming fuel cells as discussed in section 5.22, Proton Exchange Membrane (PEM) fuel cells are suggested for application (Harrison, 2012a). The latter have proven their application for transportation and portable power purposes (Brouwer, 2002). Table 5.3 summarizes their characteristics.

Table 5.3: Description of PEM fuel cell (Brouwer, 2002; NFCRC; NFCRC, 2007b)

Feature	Proton Exchange Membrane (PEM)
Electrolyte	Ion Exchange Membrane
Typical operating Temperature	80°C
Charge Carrier	H^+
Prime Cell components	Carbon, plastics, special polymers

Catalyst	Platinum
Product Water Management	Evaporative
Product Heat Management	Process gas + Independent Cooling Medium
Anode	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Net reaction	$\frac{1}{2} O_2 + H_2 = H_2O$

In the following assessment of micro CHP units, particular attention is paid to Stirling engines. Given the fact that this technology is the only Micro CHP technology that has reached market application yet, most data can be obtained regarding its application.

5.2.4 Power-to-Gas

The power-to-gas concept has been suggested frequently, especially for renewable energy scenarios. It can be divided into two sub-processes, electrolysis and methanation, which are described in the following. Both of these concepts have been known for a long time, their integration and common application in the power-to-gas concept is yet, innovative (Reichert, 2012).

5.2.4.1 Electrolysis

First, electricity is converted to gas by means of electrolysis, as illustrated in figure 5.6 (Dena, 2013). Thereby, peaks in the fluctuating generation of electricity generation can be 'cut off' and stored permanently in the form of gas. The underlying chemical reaction of electrolysis can be described as follows.

$$\text{(Eq. 5.2)} \qquad 2H_2O\ (l) \rightarrow 2H_2\ (g) + O_2\ (g) \qquad \Delta H_R^0 = +\ 572\ \text{kJ/mol}$$

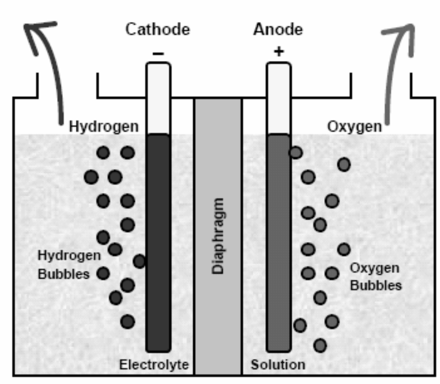


Figure 5.6: Standard electrolysis (Dena, 2013)

Currently, there are at least three types of electrolysis. First, alkaline electrolysis, that is based on a basic electrolyte and has been applied in large industrial scales for decades (Dena, 2013). Second, electrolysis based on a proton exchange membrane (PEM), with a polymer solid electrolyte (PEMEL). This type has reached commercialization in small scales and current activities aim at the scale-up of its related membrane-electrode units (Dena, 2013). Third, the application of high temperature electrolysis in combination with a solid oxide electrolyte (HTEL) is still in the stage of basic research (Dena, 2013).

Furthermore, (Dena, 2013) identifies three different ways to integrate electrolyzers into the existing grid: Through their direct coupling with renewable power technologies, through their integration in autarkic electricity grids or through their connection to traditional power transmission or distribution lines. However, only the latter of these approaches offers a constant supply of electricity. Given an intermitted application of electrolysis, life-time and efficiency of electrolyzers are largely dependent on its peripherals. That is to say, in contrast to the chemical reaction which can adapt quickly to different loads, the mechanical parts of those components are subject to abrasion. In this context, the further development of PEM electrolyzers is promising as they offer advantages in their intermitted operation compared to alkaline electrolyzers. Next to a quicker adoption to changes in load, PEM electrolyzers offer a higher efficiency at lower load rates and can start up quicker (Dena, 2013).

5.2.4.2 Methanation

Methanation is the second crucial process of the power-to-gas concept. It processes hydrogen (H_2) and carbon oxide (CO) or carbon dioxide (CO_2) to synthetic methane (CH_4) and can be described as follows:

$$\text{(Eq. 5.3)} \quad 3H_2 + CO \rightarrow CH_4 + H_2O\ (g) \quad \Delta H_R^0 = -206\ \text{kJ/mol}$$

$$\text{(Eq. 5.4)} \quad 4H_2 + CO \rightarrow CH_4 + 2H_2O\ (g) \quad \Delta H_R^0 = -165\ \text{kJ/mol}$$

The Methanation from CO_2 is also referred to as the Sabatier process. The CO_2 required for this process can be collected from fossil energy carriers, such as coal powered plants, in combination with carbon capture and storage (CCS) or from regenerative sources such as biogas plants (Dena, 2013).

Methanation has been developed in the 1970s for the gasification of coal. However, due to the increasing interest in renewable energy technologies and the associated shift of focus towards the gasification of biomass, significantly smaller methanation plants are required nowadays. Unfortunately, the economic and technical difficulties that arise from this difference do not allow for a direct technology transfer from past technologies (Bajohr et al., 2011). Besides, the fulfilment of high quality standards, which is indispensable to make methanation a feed-in process of the gas infrastructure, requires further research and optimization of existing technologies (Bajohr et al., 2011). Thereby, it has been most challenging to obtain a constant heat transport from the process because it is strongly exothermic. To do so, 2-phase systems and 3-phase systems are suggested (Bajohr et al., 2011). 2-phase systems have gaseous educts and solid catalysts. They can be classified as fixed-bed reactors, fluidized-bed reactor and coated honeycomb reactors. 2-phase systems are commercialized as fluidized-bed reactors but mostly as fixed-bed reactors (Dena, 2013). In contrast, the application of 2-phase reactors with a coated honeycomb structure has not reached large-scale commercial application yet. The 3-phase system has gaseous educts, a heat transfer fluid, and a solid catalyst. It has been realized with a bubble column but its application is still in the experimental stage (Bajohr et al., 2011). The potential advantage of 3-phase systems is their improved adaptability to fluctuations in loads, compared to 2-phase systems (Dena, 2013). All four applications of two- and three-phase Methanation processes are illustrated in figure 5.7 to 5.10.

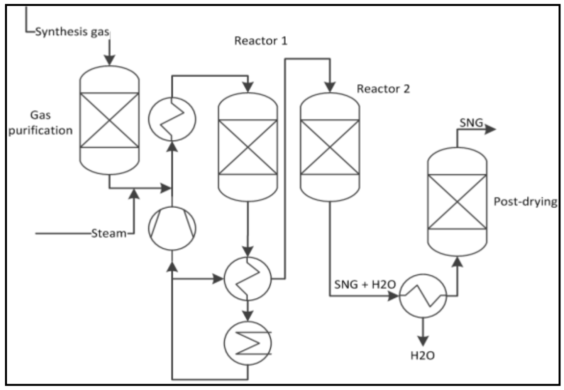


Figure 5.7: Solid bed methanation on basis of the Lurgi process (Dena, 2013)

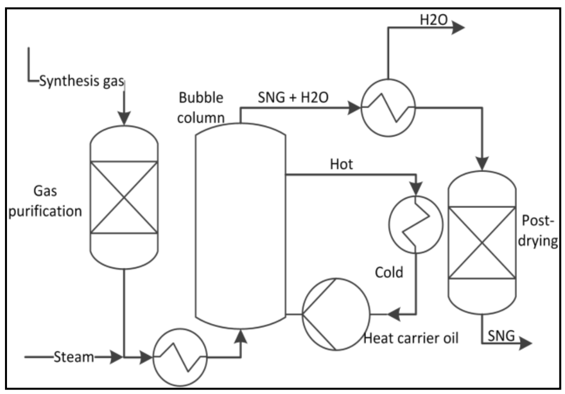


Figure 5.8: Bubble column methanation (Dena, 2013)

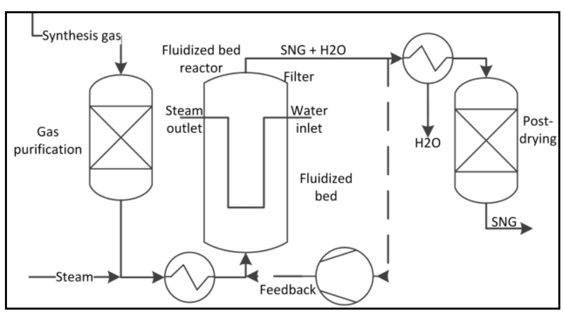


Figure 5.9: Solid bed methanation (Dena, 2013)

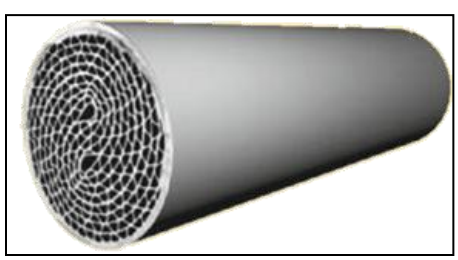


Figure 5.10: Metallic honeycomb reactor (Dena, 2013)

5.2.5 Hybrid Gas Turbine Fuel Cell Systems

"A highly efficient and low emitting concept that has been considered for the future is the hybrid gas turbine high temperature fuel cell concept" (Brouwer, 2002). *"These types of hybrid systems have been developed and proposed for operation on natural gas, coal, biomass and other fossil fuels"* and involve *"…two major components, a high temperature fuel cell and a gas turbine engine"* (Brouwer, 2002).

Through the creation of synergies that emerge from the conversion of fuel cell exhausts into additional energy through a heat engine, hybrid gas turbine fuel cell systems are expected to approach higher cost and technical efficiencies than gas turbines or fuel cells on their own (Brouwer, 2002). More specifically, hybrid gas turbine fuel cell systems aim to (1) *"convert most of the fuel by electro-oxidation in the fuel cell leading to low emissions … and relatively high fuel-to-electricity conversion efficiency", (2) "use fuel cell heat and turbine exhaust heat elsewhere in the system … in a manner in which overall efficiency is enhanced",*(4) *"use the high pressure produced by the gas turbine in a manner that improves fuel cell output and efficiency (if possible)"* and (5) *"use the separated fuel and oxidant streams of the fuel cell to enhance other features … of the hybrid cycle (if possible)"* (Brouwer, 2002).

To fulfil these design concepts, numerous ways for the configurations have been suggested that can be divided into a tremendous number of possible cycle configurations (Brouwer, 2002). Brouwer (2002) defined the 'fuel cell topping cycle', 'fuel cell bottoming cycle', 'direct hybrid cycle' and 'indirect hybrid cycle' as four basic parameters that help to categorize most of the different alternatives suggested. The 'fuel cell topping cycle', which will be addressed in the following assessment, *"…is one in which the gas turbine is considered the balance of plant (BOP) with the turbo-machinery placed downstream of the fuel cell in the cycle"* (Brouwer, 2002). A 'fuel cell bottoming cycle' *"…is one in which the gas turbine turbo-machinery resides upstream of the fuel cell"* (Brouwer, 2002). A 'direct hybrid cycle' *"…flow from upstream elements is directly used in downstream elements of the cycle"* (Brouwer, 2002). Finally, an 'indirect hybrid cycle' *"…uses devices (usually heat exchangers) to de-couple the gas turbine and fuel cell components of the system so that flow from upstream components does not enter downstream components* (Brouwer, 2002).

Recent developments in fuel cell technology have indicated the fulfilment of sophisticated characteristics by high temperature fuel cells in terms of technological and commercial aspects that would enable these integrations in future (Brouwer, 2002). However, according to (Brouwer, 2002), the technical feasibility of these hybrid systems is still limited in the current stage. *"As fuel cells advance and scale-up and pressurization of MCFC and/or SOFC technology becomes viable, larger and more sophisticated gas turbine engines will be required"*, increasing overall efficiency of the hybrid systems (Brouwer, 2002). Despite the immense potential of hybrid gas turbine fuel cell systems in terms of different scales and applications, *"…the front-end risk associated with developing this technology is considerable"* and *"broad investment in industry, at national laboratories, and in university research and development is required to advance hybrid gas turbine fuel cell technology"* (Brouwer, 2002).

5.3 Assessment

The following section specifies the performance of the different options assessed regarding each dimension and their subordinated indicators. For this purpose the assessment of each dimension is divided into three subsections. First, indicators are introduced that add up to an option's overall rating with respect to a certain dimension. Second, the values of all indicators are specified for the different options at hand. In this step it is also reasoned what data has been chosen to assess an option and for what specifications assumptions have been made. Third, a preliminary comparison of the different options regarding the dimension at hand is made. At the end of the chapter it follows a more sophisticated assessment, using an MCDA approach.

5.3.1 Technical Performance

The following section evaluates the technical performance of the different options at hand. As with the following dimensions discussed, most options show dynamics regarding their technical characteristics because they have not reached mass market application yet.

In order to assess the technical performance of the different options, four indicators have been selected that are illustrated in figure 5.11.

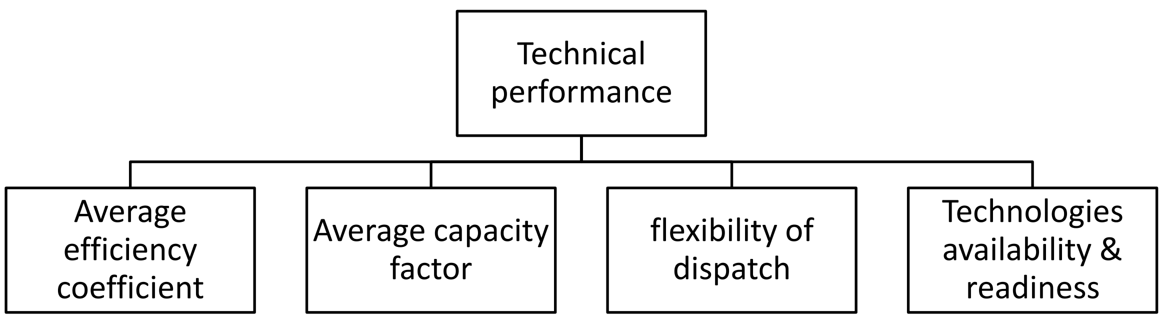


Figure 5.11: Technical indicators

5.3.1.1 Specification of Technical Indicators

5.3.1.1.1 Solar cracking of methane

As indicated in (Kaucic & Sattler, 2004), the overall efficiency of the solar cracking of methane ranges from 86 to 87 percent. Its capacity factor is limited to the capacity factor of solar CSP because the propulsion by gas typically has a higher capacity factor (Stein, 2013). Depending on the site of the solar plant, the capacity factor can vary greatly and is named in some sources to be as low as 23 percent (Kaucic & Sattler, 2004) or to be as high as 73 percent (Price, 2003). For the base case the lower value of 23 percent is assumed.

In terms of its flexibility of dispatch, the solar reforming of methane is ranked as lowest of all options assessed because it creates only a secondary energy carrier and is dependent on strong solar radiation. Furthermore, as mentioned in several sources (cf. Cinti & Hemmes, 2011; Kaucic & Sattler, 2004) the solar reforming of methane is still in the pilot project phase. Being more conservative, the current state could be regarded as the experimental stage. In the best case, the current technological applications of the solar methane reforming could be regarded as its first market applications.

Table 5.4: Technical characteristics of solar reforming of methane

Overall efficiency coefficient [%]			Capacity factor [%]			Flexibility of dispatch [rank]			Technological status		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0,86	0,865	0,87	0,23	0,23	0,73	5	5	5	2	3	4

5.3.1.1.2 Superwind

For the evaluation of the Superwind concept, the high efficiency mode with intermediate fuel utilization was chosen as a base case because it represents an appropriate distribution of electricity output to gas output, given that today's electricity consumption is still significantly higher than hydrogen consumption. However, it needs to be noted that a shift in the ratio of electricity production to hydrogen production by the SOFC fuel cell is at the heart of the Superwind concept. It does not only determine its high flexibility of dispatch, by filling out gaps in wind energy production, but also causes variations in the option's overall efficiency, which can range from 52 to 94 percent (Vernay et al., 2008). The capacity factor of the Superwind concept is very high as it continuously produces hydrogen or electricity. It is determined by the fuel cell's capacity factor that is mentioned concordantly by literature to be around 90 percent (Braun et al., 2001; scwd[2], 2011). Therefore, the capacity factor of the Superwind concept was set to 90 percent for the low case, 92.5 percent for the base case and 95 percent for the best case. So far, the Superwind concept has not been realized in practice and is therefore considered to be in the conceptual or experimental phase of its technological development.

Table 5.5: Technical characteristics of the Superwind concept

Overall efficiency coefficient [%]			Capacity factor [%]			Flexibility of dispatch [rank]			Technological status		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0,52	0,79	0,94	0,9	0,925	0,95	2	2	2	1	1	2

5.3.1.1.3 Micro CHP

As described by Nordel (2000), micro CHP units are a non-dispatchable form of energy generation since they can hardly adapt to peaks in energy demand. However, as micro CHP units can be switched on or off on demand, they need to be rated higher regarding their flexibility of dispatch than the solar reforming of methane. The overall efficiency that is mentioned for Micro CHP units varies across literature between 70 and 90 percent (CarbonTrust, 2011; Orr et al., 2011), whereas an efficiency of 77 to 82 percent is often mentioned as the mean. Thus, for the base case an overall efficiency of 80 percent is assumed. In (CarbonTrust, 2011) a micro CHP unit is specified to run around 6000 hours per year, which equals a capacity factor of 68 percent and is assumed to be the base case. The low case, assumes 5000 running hours per year and the high case 7000 running hours per year.

Carbon Trust (2011) also acknowledges that especially Stirling engines have reached market application. Thus the rating of the technological status ranges from 3 to 5 whereas market application is assumed to be the base case.

Table 5.6: Technical characteristics of a Stirling CHP

Overall efficiency coefficient [%]			Capacity factor [%]			Flexibility of dispatch [rank]			Technological status		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0.7	0.8	0.9	0.57	0.68	0.8	4	4	4	3	4	5

5.3.1.1.4 Power-to-gas

For the concept of power-to-gas, a capacity factor of 41% has been assumed which is based on (Kroposki et al., 2006) who estimated the cost for hydrogen in dependence of the electricity price for capacity factors of 30, 41 and 55 percent. The overall efficiency of the two-phased power-to-gas process is described by literature to vary between 0,52 and 0,75 (Reichert, 2012 referring to Jentsch et al., 2011; Specht, 2011; Trost et al., 2011). Following the assumption of Reichert (2012), an efficiency of 62 percent is assumed for the base case. The concept’s flexibility of dispatch is ranked on place three as it creates a secondary energy carrier (hydrogen) but can be operated in accordance to the demand for hydrogen. Given the fact that there are currently three power-to-gas pilot plants on the world, the technological availability and readiness of this option is considered to be in the pilot or early market phase.

Table 5.7: Technical characteristics of power-to-gas

Overall efficiency coefficient [%]			Capacity factor [%]			Flexibility of dispatch [rank]			Technological status		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0,52	0.62	0,75	0.3	0.41	0.55	3	3	3	3	3	4

5.3.1.1.5 Hybrid gas turbine fuel cell systems

The assessment of technical performance characteristics of hybrid gas turbine fuel cell systems is based on several studies. Alsup (2002) suggests an overall efficiency of 52 percent, which *"…is approximately equal to that which others have found in performing such studies"* (Alsup, 2002). Indeed, also (Zhang, 2006) and (Ghezel-Ayagh, n.d.) suggest ranges of overall efficiency from 45 to 70 percent. However, it is also stated that the higher end of possible efficiencies has not been reached (Ghezel-Ayagh, n.d.). Therefore, a figure of 60 percent is suggested as the base case for the assessment.

Furthermore, figures regarding the capacity factor of are based on studies by (Alsup, 2002), suggesting 8400 operation hours per year (96%); (Zhang, 2006), assuming 8000 hours of operation per year (91%) and the figure of Stein (2013), according to whom the capacity factor of gas power plants equals 92 percent. These numbers coincide approximately with the numbers of fuel cells – the other component of the system – and therefore determine the capacity factor of the whole option. Furthermore, the fuel cell topping cycle of a gas power plant is ranked first in terms of its flexibility of dispatch as it is the only option that can adapt its maximum output as a response to the demand pattern at any point in time. Currently, the fuel cell topping cycle is only demonstrated by some pilot projects (Brouwer, 2002) and therefore considered to be between the experimental stage and the market stage of technological availability and readiness, the pilot stage being the base case.

Table 5.8: Technical characteristics of fuel cell topping cycle

Overall efficiency coefficient [%]			Capacity factor [%]			Flexibility of dispatch [rank]			Technological status		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0.45	0.60	0.75	0.91	0.93	0.96	1	1	1	2	3	4

5.3.1.2 Technical Comparison of Different Options

As can be seen in figure 5.12, the Superwind concept and the fuel cell topping cycle have the highest capacity factors in the base case, followed by micro CHP units, the POWER-TO-GAS concept and lastly the solar reforming of methane. It is interesting to note that the solar reforming of methane has a significantly lower capacity factor than efficiency whereas the FC topping cycle has a low efficiency compared to its capacity factor. In other words, the plan for the solar reforming of methane and the power-to-gas concept operate only few hours a day but at high efficiencies. In contrast, the fuel cell topping cycle operates more than 90 percent of the year at lower efficiencies.

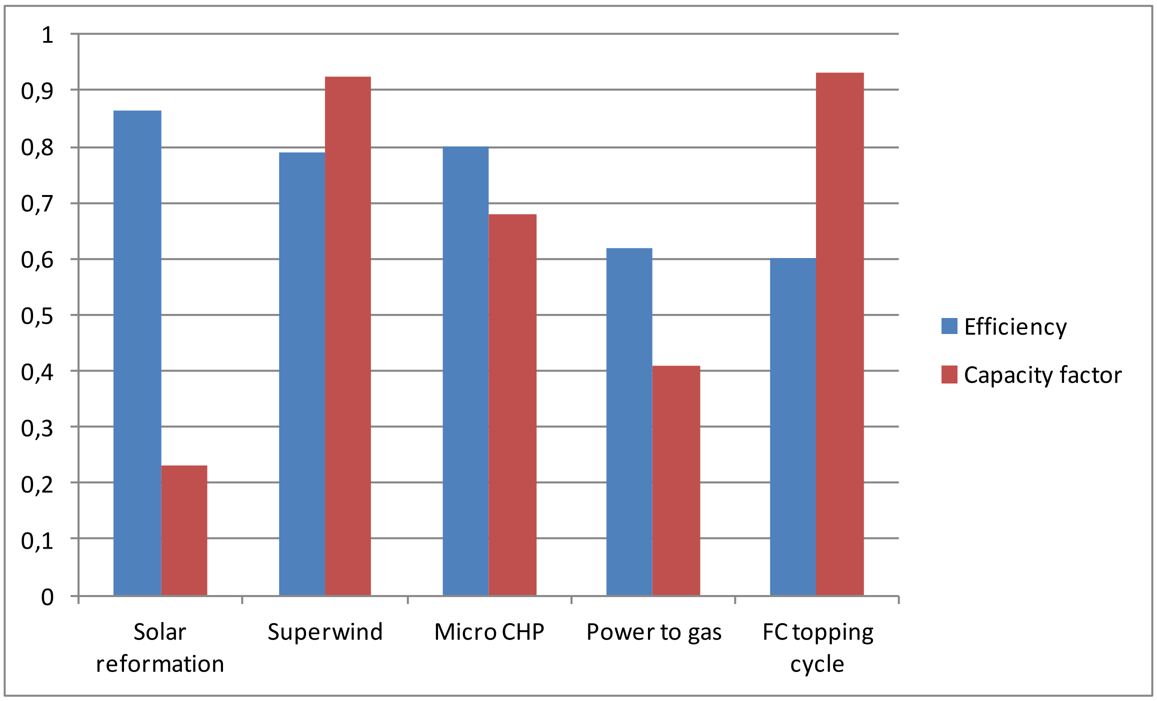


Figure 5.12: Efficiency and typical capacity factor of different options

5.3.2 Financial Performance

Figure 5.13 illustrates the different financial indicators that are used for assessment.

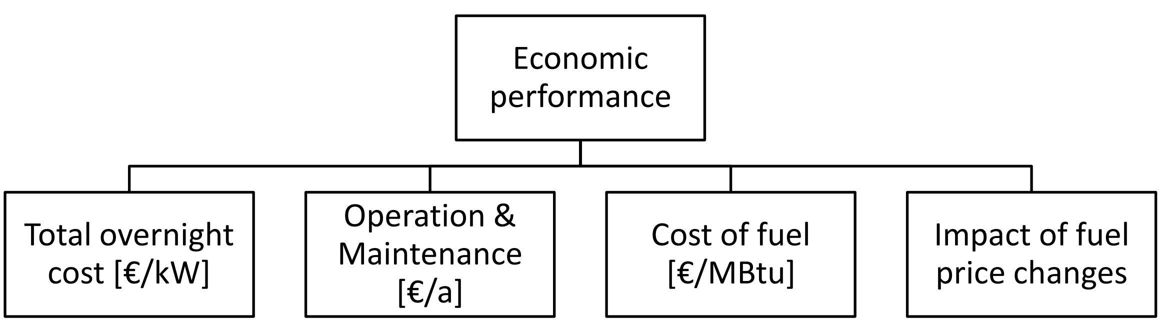


Figure 5.13: Financial indicators

5.3.2.1 Specification of Financial Indicators

5.3.2.1.1 Solar cracking of methane

The assessment of the financial properties of the solar cracking of methane is based on a study of the German Aerospace Centre in collaboration with the University of Flensburg (Kaucic & Sattler, 2004). More specifically, the data of table 5.9 represents the specifications of two design alternatives assessed, the concept *steam methane reforming* (SMR) 1.5 and 3.0, which differentiate in terms of their steam to methane ratio as well as their cooling mechanisms. As a result they yield different economic specifications that are considered to be the high and low case. The average of SMR 1.5 and 3.0 is considered to be the base case for the technology assessment of this paper. The SMR 1.5 is described in the document as being more efficient and cost effective (Kaucic & Sattler, 2004) and therefore accounts for the low case. The cost of fuel and the impact of fuel price changes are rated as zero because the system is propelled solely by sun radiation.

Table 5.9: Financial indicators of solar reforming of methane

Total overnight cost [€/kW]			Operation & Maintenance cost [€/kWh]			Cost of fuel [€/kWh]			Impact of fuel price changes [%]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
1225.34	1268.548	1311.756	0.093	0.094	0.095	0	0	0	0	0	0

5.3.2.1.2 Superwind

The financial assessment of the Superwind concept is conducted in two steps. First, the financial assessment of a SOFC is carried out. Second, the financial aspects of a wind turbine are analyzed. The so obtained costs are cumulated to obtain the financial characteristics of the Superwind concept as a whole. To estimate the financials of a wind turbine, data is gathered from the European Wind Energy Association (Krohn et al., 2009). For the SOFC analysis several studies were reviewed. As mentioned in the technical description of the Bloom Box (Light, 2010) and by the U.S. department of energy (DOE, 2013), the SECA program successfully aimed to develop SOFCs at a price of €567/ kW ($700/ kW). With an accelerating progress in the field of fuel cells, the base case of total overnight cost for the SOFC component of Superwind are therefore assumed to equal this number Besides, $400/kW is considered as the low case and $1000/kW as the high case, following the assumptions provided by (Lipman et al., 2004). Regarding the wind turbine, average overnight costs of €1198 were derived from (Krohn et al., 2009). Corrected from 2006 to 2012 levels and accounting for a some variance in overnight costs are generally good to predict due to the high experience regarding the construction of wind turbines, the low case for the wind turbine was determined to be €1300, the base case €1355 and the high case €1400.

The Operation and maintenance costs are derived on the one side from a range of c€ 0,3 per kWh to c€ 2,5 per kWh for wind turbines, whereas the base case for the TA is assumed to be c€ 1 per kWh because the O&M costs for wind turbines in the 2MW range is typically lower. On the other side, maintenance costs for fuel cells range from €0.0757 to € 0.086 per kWh, including the costs for SOFC that are typically on the lower end (Ramage & Agrawal, 2004), and costs for operation are assumed to be fixed at € 0.0557 per kWh, given the gas price specified in the beginning of section 3.2.4.1.2 and the base case of the technical efficiency specified in table 5.5. The cumulated values that account for the overall O&M costs of the Superwind concept are specified in table 5.10. The costs of fuel of the concept depend on its mode of operation. Given the case that the wind turbine provides enough power, the costs of fuel as well as the impact of fuel price changes are negligible. This mode resembles the low case of both indicators. If no wind is present and the fuel cell is the only component that supplies energy, the costs of fuel increase to c€5.6 per kWh and the impact of fuel price changes rises to 65 percent. For the mode of operation that requires a partial provision of power from the fuel cell and the wind turbine, the mean value of the low and high case is assumed.

Table 5.10: Financial indicators of the Superwind concept

Total overnight cost [€/kW]			Operation & Maintenance cost [€/kWh]			Cost of fuel [€/kWh]			Impact of fuel price changes [%]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
1624.42	1922.74	2211.06	0.079	0.086	0.11	0	0.028	0.056	0	0.368	0.65

5.3.2.1.3 Micro CHP

The assessment of the overnight costs of a micro CHP is based on a study of the sustainable energy authority of Ireland (Orr et al., 2011), a research report for the US Department of Energy (De Valve & Olsommer, 2006) as well as a discussion paper by several organizations (Pehnt et al., 2004). In (De Valve & Olsommer, 2006) and (Pehnt et al., 2004), investment costs for micro CHP units are mentioned to range from \$ 1604/kW$_e$ to €4689 /kW$_e$. Corrected to 2012 levels, the lower and higher case of total overnight costs for a micro CHP unit on household level were assumed to be €1403/kW (1600\$/kW) and € 5548,3/kW (€4689/kW). The base case is derived from the mean of both values.

The operation and maintenance cost shown in table 5.11 are derived on the one hand from the operation and maintenance cost that are mentioned in (Pehnt et al., 2004), and range from € 0.01 to

0.02 /kW. On the other hand they are derived from the cost of fuel presented in the table, which are in turn derived from the efficiency range of micro CHP units, presented in table 5.6 and the cost of gas for households.

Table 5.11: Financial indicators of a CHP unit

Total overnight cost [€/kW]			Operation & Maintenance cost [€/kWh]			Cost of fuel [€/kWh]			Impact of fuel price changes [%]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
140 3.6	347 6	554 8.3	0.08 78	0,10 2	0.12	0.07 78	0.08 7	0.1	0.83 3	0.85 3	0.88 6

5.3.2.1.4 Power-to-gas

The financial characteristics of power-to-gas illustrated in table 5.12 are derived from a thesis on the financial feasibility of the power-to-gas concept (Reichert, 2012). As unveiled by the author of that thesis *"…there is no fixed state of the art factsheet"* and *"even among leading experts and different articles of same experts, there are different assumptions, especially for investment cost"* (Reichert, 2012). The author presents different scenarios, in which investment costs mostly add up to €1750/kW but are assumed in one scenario to reach only 1250€/kW. Thus, the low case of table 5.12 is assumed to be €1250/kW and the base case and high case €1750/kW. The operation and maintenance cost of the power-to-gas concept comprise 3 percent of its investment cost. Translated to kW/h the O&M costs therefore depend primarily on the operating hours of the power-to-gas concept. As argued by Reichert (2012), only power-to-gas facilities that operate more than 4000 hours a year are likely to run profitably. For this reason, the low case of O&M costs presented in table 5.12 assumes 4500 operating hours. Moreover, Reichert (2012) states that *"…the majority of power-to-gas capacity is operating in less than 2000 hours. Between 2000 and 3000 hours are rare, while only a minority of capacity is used for more than 3000 hour"*. Hence, for table 5.12 1500 and 1000 operating hours per year are assumed for the base and high case respectively. All three cases additionally consider the industrial price of electricity presented in the beginning of the section as well as a price for water of water of 0.001€ per kWh (cf. Reichert, 2012).

The cost of fuel also consider the water price of 0.01 € per kWh, the electricity price for industrial applications, mentioned in the beginning of the section as well as the three different efficiencies of the power-to-gas concept illustrated in table 5.7

Table 5.12: Financial indicators of the power-to-gas concept

Total overnight cost [€/kW]			Operation & Maintenance cost [€/kWh]			Cost of fuel [€/kWh]			Impact of fuel price changes [%]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
1250	1750	1750	0.14	0.184	0.23	0.132	0.149	0.1777	0.772	0.821	0.94

5.3.2.1.5 Fuel cell topping cycle

The total overnight cost of the hybrid gas turbine fuel cell system are rated with 650 €/kW for the low case, €800/kW for the base case and €950/kW for the high case. This rating is based on two simulations that suggest investment costs of €949.4/kW ($43.25834M/ 43.795MW) (Alsup, 2002) and €699.19/kW ($32M/37MW) (Cheddie, 2010). Both numbers appear to be reasonable given that *"…major studies by Siemens, Rolls Royce, FuelCell Energy, the University of California, Irvine, Genoa University, and others have concluded that hybrid fuel cell gas turbine systems may cost less than the corresponding atmospheric pressure fuel cell systems"* (Brouwer, 2009). The operation and maintenance costs that are presented in table 5.13 are adopted from (Alsup, 2002) for the low case and from (Singhal, 2003) for the high case. The base case is formed by averaging the low and high case because it is also stated in (Singhal, 2003) that the O&M costs for atmospheric systems tend to be lower than $0.45/kW. The costs of fuel are calculated in accordance to the industrial gas price and the different efficiencies listed in table 5.8.

Table 5.13: Financial indicators of a hybrid gas turbine fuel cell system

Total overnight cost [€/kW]			Operation & Maintenance cost [€/kWh]			Cost of fuel [€/kWh]			Impact of fuel price changes [%]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
800	950	1000	0.22	0.39	0.56	0.0591	0,0739	0.0985	0.1496	0.1593	0.2118

5.3.2.2 Financial Comparison of Different Options

In order compare the financial performance of the different options, the amount of full operating hours was set to 2000h and to 8400h. As a result, the O&M costs as well as their subordinated cost of fuel can be compared with the total costs of each option. Thereby, the amount of operating hours was set on the basis of an annual operation but needs to be considered as arbitrary. Thus, the following analysis does not claim validity in terms of absolute figures but only in terms of its relative outcomes. Figure 5.14 and 5.15 depict the cost structure of all options for 2000 hours and 8400 hours respectively.

Given the case of 2000 working hours, have the highest total costs followed by power-to-gas, the Superwind concept, the hybrid gas turbine fuel cell system and the solar reforming of methane. The main determents of this ranking are overnight costs which are decreasing in a similar order. Only the operation and maintenance cost of the hybrid gas turbine fuel cell system and the power-to-gas concept poke out and make them in total more expensive than the solar reforming of methane and the Superwind concept respectively. However, at a number of 2000 operating hours, the cost of operation and maintenance and the underlying cost of fuel generally do not account for a high share of total cost.

Thus, the construction of a large plant such as the solar reforming of methane or a hybrid gas turbine fuel cell system is the least expensive option because it involves economies of scale. Moreover, the hybrid gas turbine fuel cell system includes the construction of a gas turbine, which has a very advanced position on the learning curve, and is therefore the cheapest option in terms of overnight costs. In contrast, the construction of less experienced integration options such as the power-to-gas concept or Superwind is not as cost-effective regarding their installation yet. Furthermore, the concepts of Superwind and power-to-gas lose ground in this comparison as they require the installation of a wind turbine and a SOFC or of an electrolysis and methanation plant respectively. Most tremendously emerge the overnight costs of Micro CHPs. This aspect is straightforward because a Micro CHP unit is usually sold to single households, therefore generates much less power and has no economies of scale. However, due to the experience in the production of Stirling engines, the cost of fuel as well as the operation and maintenance costs associated with micro CHPs stand out less.

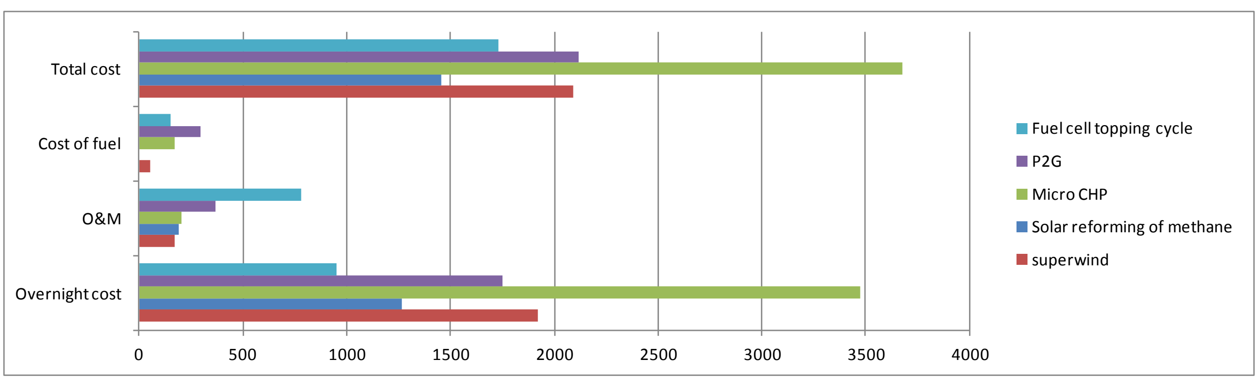


Figure 5.14: Cost structure of options at 2000 working hours

Given the case that all options operate for 8400 hours, micro CHPs remain the most expensive option and the ranking among the hybrid gas turbine fuel cell system and the power-to-gas concept changes. The power-to-gas concept that used to be the second most expensive option for 2000 operating hours is now the third most expensive option by being overtaken by the hybrid gas turbine fuel cell concept. The solar reforming of methane as well as the Superwind concept remains to have lowest and second lowest costs respectively.

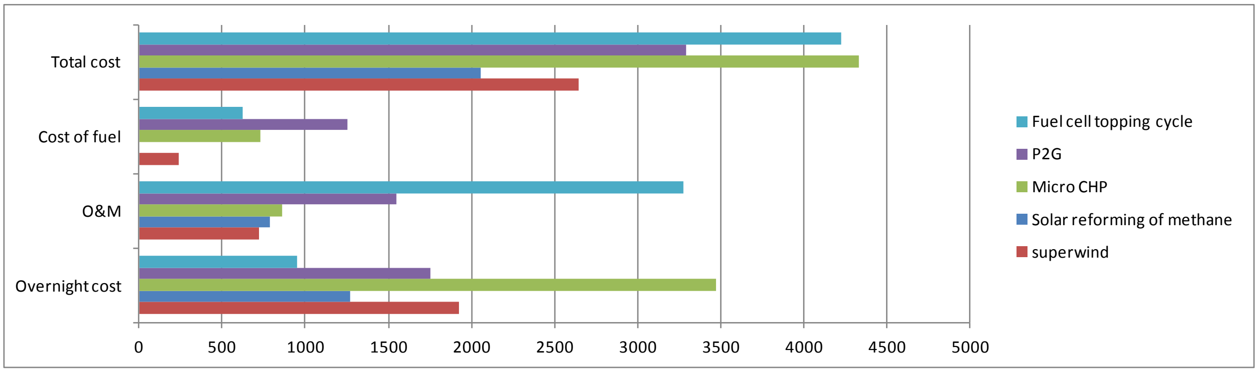


Figure 5.15: Cost structure of options at 8400 working hours per year

The main reason for this change is the increase of fuel costs and operation and maintenance costs as a share of total cost. In the case of 2000 operating hours, the overnight cost account for the main cost share of the integration options. However, given 8400 operating hours, as illustrated in figure 5.15, operation and maintenance cost as well as fuel costs become a major determent of total costs.

5.3.3 Environmental Performance

Figure 5.16 illustrates the three indicators that are applied to assess environmental performance.

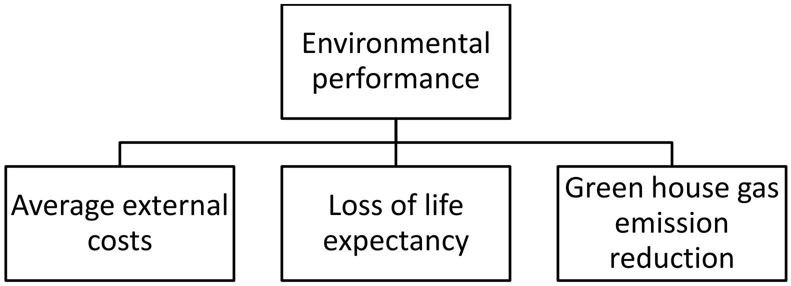


Figure 5.16: Environmental indicators

5.3.3.1 Specification of Environmental Indicators

5.3.3.1.1 Solar reforming of natural gas

The data presented in table 5.14 indicates the environmental performance of the solar reforming of methane. Due to the fact that this option is still in its pilot phase, data regarding this aspect is limited. To estimate the options' average external costs the characteristics of a concentrated solar power plant are used for approximation. In Sixth (2009), external costs of CSP are specified as 0.13€cent per kWH,whereas (Edkins et al., 2010) assume them to be around 0,06 € cent per kWh. For the high case, external costs of photovoltaic are adopted, specified by the ExternE project (European Commission, 2003). However, the later stick out compared to the previous two etimates and are therfore not used to calculate the base case. Instead the data provided by (Sixth, 2009) is considered as the base case. In accordance to the information available on wind turbines and solar photovoltaic, the loss of life expectancy is assumed to be negligible and is therefore assumed to be 0,1 as presented in (Stein, 2013). Last, the greenhouse gas emissions of the solar reforming of methane are zero since the technology is fully powered by solar radiation.

Table 5.14: Environmental indicators of solar reforming of methane

Average external costs [€ cent/kWh]			Loss of life expectancy [days]			Greenhouse gas emissions [g/kWh]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values								
0.06	0.13	0.6	0.1	0.1	0.1	0	0	0

5.3.3.1.2 Superwind

The external costs of the are determined by the external costs caused by the wind turbine (0,167€) and by the fuel cell, which is in turn rated at the external costs of gas powered technologies (1,167€). The external costs of the wind turbine are derived from the lower's bound average of external costs in

European countries that have been determined by the ExternE project (European Commission, 2003). Given that the Superwind concept operates fully by wind, its external costs equal those of the wind turbine. If no wind is present, the Superwind concept is operated solely by gas but the wind turbine remains in place. Thus, for this 'high case' the external costs equal the cumulated external costs of the wind turbine and the fuel cell. As stated previously, the ratio of wind turbine capacity to fuel cell capacity equals 1 to 4. Thus, the base case of average costs equals the figure for the high case divided by 5, 0.266 € cent per kWh. The loss of life expectancy from the Superwind project is at least as high as the loss of life expectancy caused by the wind turbine and at most as high as the cumulated loss of life expectancy of the wind turbine and the fuel cell. The base case is approximated by the average of the LLE caused by the wind turbine and the LLE caused by the fuel cell, which is assumed to cause the same LLE as other gas powered technologies (Stein, 2013). The greenhouse gases emitted by the Superwind concept are solely determined by the emissions of the fuel cell. Those are very low and stated in literature to range from 294 g/kWh to 392 g/kWh (Kreuer, 2013). For the base case 340 g/kWh as stated by Thijssen (2009) appears to be a solid assumption.

Table 5.15: Environmental indicators of the Superwind concept

Average external costs [€cent/kWh]			Loss of life expectancy [days]			Greenhouse gas emissions [g/kWh]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values								
0.17	0.27	1.33	0.1	0.45	0.8	294	340	392

5.3.3.1.3 Micro CHP

Given the fact that gas producing technologies are frequently stated to cause 1 to 2 €cents of external costs (CarbonTrust, 2011; Chatzimouratidis & Pilavachi, 2009), micro CHP units are due to their high efficiency assumed to operate at external costs of 1 Eurocent per kWh. Also their LLE is expected to be slightly below traditional gas technologies and therefore rated at 0.6 days for the base case, 0.4 for the low case and 0.8 for the high case. According to (CarbonTrust, 2011), greenhouse gas emissions of micro CHP units are equal to 129 g/kWh. This figure is considered as the low case. According to (Roads2HyCom, 2007), emissions add up to 295 g/kWh, embodying the base case of the assessment. The high case is rated with 510 g/kWh as stated by (Pehnt et al., 2004).

Table 5.16: Environmental indicators of a Micro CHP unit

Average external costs [€cent/kWh]			Loss of life expectancy [days]			Greenhouse gas emissions [g/kWh]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values								
1	1	2	0.4	0.6	0.8	129	295	510

5.3.3.1.4 Power-to-gas

For the high case, the power-to gas-concept is rated with external costs of 4.23 € cents per kWh (Sixth, 2009). This figure is higher than for the sole production of hydrogen and embodies a conservative estimate that also accounts for the process of methanation after the generation of hydrogen. Sixth (2009), indicates that average external costs for the same process decrease to 0.54 €cents by 2025. This figure is assumed to be the lowest case of today. Assuming a linear decrease of average external costs over the years, today's average external costs are assumed to equal 3.3 €cent per kWh in the base case.
Due to a lack of data, the loss of life expectancy is assumed to be 0.5 days lower, equal to or 0.5 days higher than the LLE of regular gas technologies, presented in Stein (2013). Last, there are no emissions of greenhouse gases associated with the power-to-gas concept. The low, base and high case for this indicator, for this technology are thus rated as zero.

Table 5.17: Environmental indicators of Power-to-gas

Average external costs [€cent/kWh]			Loss of life expectancy [days]			Greenhouse gas emissions [g/kWh]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values								
0.54	3.3	4.23	0.3	0.8	1.3	0	0	0

5.3.3.1.5 Hybrid gas turbine fuel cell system

In (Chatzimouratidis & Pilavachi, 2009) gas power plants with a combined cycle are listed with 1.33 € cents of external costs per kWh. Given the fact that external costs of gas power plants in the Netherlands range from 1 to 2 cent per kWh and gas turbine, fuel cell hybrid plants have typically less emissions, the figure presented by Chatzimouratidis and Pilavachi (2009) apperas to be a resonable base case. However, the loss of life expectancy is rated as less in the low case, slightly lower in the base case and higher in the high case compared to conventional gas technologies. The greenhouse gas emissions of the concept are derived from the figures of a traditional combined cycle plant and a SOFC and are adopted from the data of a combined cycle plant as 398.2 gram per kWh for the high case (Klara & Winner, 2007), averaged from both technologies to 369 gram per kWh for the base case and adopted from the base case of an SOFC for the low case.

Table 5.18: Environmental indicators of a fuel cell topping cycle

Average external costs [€cent/kWh]			Loss of life expectancy [days]			Greenhouse gas emissions [g/kWh]		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values								
1	1.33	1.85	0.2	0.7	1.2	340	369	398,29

5.3.3.2 Environmental Comparison of Different Options

Figure 5.17 compares the different options in terms of their environmental characteristics. It is most notable that the option power-to-gas does not emit much green house gases but has by far the highest average external costs. The reason for this discrepancy is that greenhouse gas emissions are only counted as a by-product of generation and are thus not created during electrolysis or methanation. However, hydrogen has global warming potential when it is released to the atmosphere. Due to its volatility, the accidental discharge of hydrogen is hardly to avoid when handling it in the context of the power-to-gas concept. Apart from that, the environmental impact of solar methane reforming is by far the lowest and appears to be preferable against the background of sustainable development.

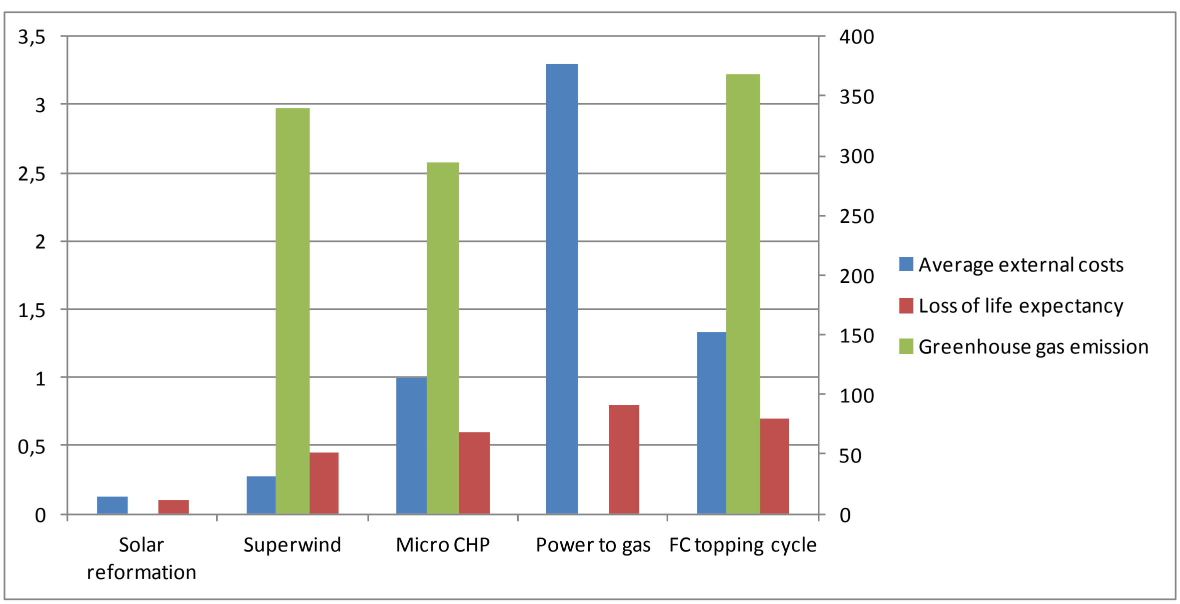


Figure 5.17: Environmental comparison of options

5.3.4 Political, Economic, Social (PES) Performance

Figure 5.18 shows the different indicators applied to assess the PES performance of the different integration options.

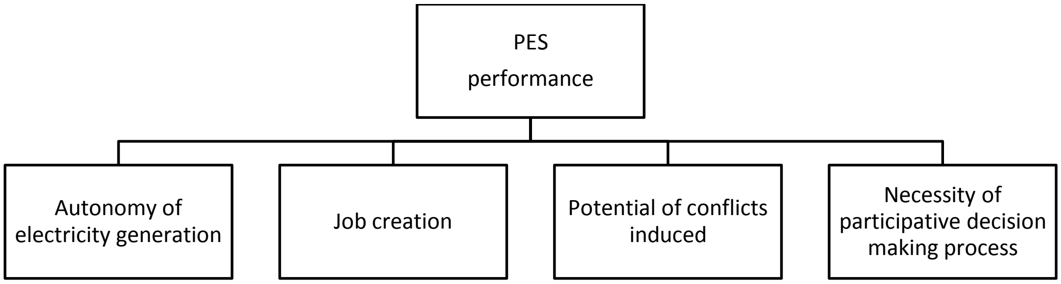


Figure 5.18: PES indicators

5.3.4.1 Specification of PES Indicators

5.3.4.1.1 Solar reforming of natural gas

The solar reforming of natural gas is a technology "that relies on fuels or energy resources that must be imported" as it requires a sun radiation that is far higher than in the Netherlands. Moreover, this option needs an input of natural gas or biogas which is likely to be supplied by its "hosting" country rather than the Netherlands. Regarding table 3.2, the option is therefore rated as 0 for the low, base and high case, given that it relies strongly on imported energy carriers. The figures on job creation are derived from the data on concentrated solar power as presented in (Wei et al., 2010). In terms of the potential of conflicts induced, solar reforming of natural gas is ranked as middle for the base case because it has not been subject to many conflicts in the past. However, experience of recent years indicate that the establishment of this option in countries of North Africa, as often suggested (cf. Cinti & Hemmes, 2011), involve a politically less stable environment compared to options located in Western Europe. The low case and high case are consequently ranked with low and high respectively. The option's necessity of participative decision making is ranked as very high for all three cases due to a similar reasoning: agreement is not only needed among the states of the European Union but, beyond that, also with participating countries in Northern Africa.

Table 5.19: PES characteristics of solar reforming of Methane

Autonomy of generation			Job creation [job-year/GWh]			Potential of conflicts induced			Necessity of participative decision making		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0	0	0	0.13	0.23	0.4	low	mid dle	high	Very high	Very high	Very high

5.3.4.1.2 Superwind

In terms of its related autonomy of generation, the Superwind's base case is rated as 6.5. This number is determined by the averaged autonomy of generation due to the wind turbine and the SOFC. Whereas the wind turbine scores a ten in the rating of table 3.2, the SOFC is a gas based technology and therefore ranks as three. According to the base case, the total job creation of the Superwind concept equals 1.04 job-years per GWh. This figure is derived from the sum of average jobs created through the life cycle of the wind turbine, that is 0.17 (Wei et al., 2010), and the fuel cell. However, due to the fact that the fuel cell industry has not reached mass market application yet, no hard data is available on the jobs created throughout the life cycle of a fuel cell (Heavner & Del Chiaro, 2003). However, it is estimated by (Heavner & Del Chiaro, 2003) that the direct employment of fuel cells approximately equals that of solar photovoltaic technology, on average 0.87 job-years per GWh (Wei et al., 2010). For the high and low case, the maximum and minimum reported numbers of job creation through wind turbine technology and solar technology as stated by (Wei et al., 2010) are cumulated. The potential of conflicts induced through the Superwind concept is determined by the construction of the necessary wind turbine because the SOFC is of low potential for conflict. In contrast, wind turbines can be subject to public protest in the Netherlands and further constructions have been banned in some parts of the country because protests of local stakeholders increased significantly (EPAW, 2013). Thus, the Superwind concept is rated with 'low' for the low case 'middle' for the base case and 'high' for the high case regarding its potential of conflicts induced. Similarly, the necessity of participative decision making is also rated from low to high and solely caused by the wind turbine as it affects several (local) stakeholder groups. However, it is not rated as very high because the setting up of wind turbines usually does not involve international agreements among several countries.

Table 5.20: PES characteristics of the Superwind concept

Autonomy of generation			Job creation [job-year/GWh]			Potential of conflicts induced			Necessity of participative decision making		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
3	6.5	10	0.33	1.04	1.68	low	mid dle	high	low	mid dle	high

5.3.4.1.3 Micro CHP

In accordance with table 3.2, micro CHPs are rated as a three because they fall into the category of *"gas fired technologies in countries where domestic gas resources are available"*. In order to determine the number of job-years created during the life cycle of a Micro CHP, data was gathered from (ECOTEC, 1999). As described in the report, that analyses the impact of the production of Micro CHP units on job creation, 260 fulltime employees are necessary for the instalment of 350GWh and 21 fulltime employees for their maintenance. This equals the creation of 0.8 jobs per GWh per year. It is also mentioned that due to the decentralized power generation of micro CHPs, the number of potential installations together with its job creation can increase by a factor of ten (ECOTEC, 1999). This number presents the high case. To determine a minimum regarding micro CHP for the indicator 'job creation', the lowest figure of solar PV as presented in (Wei et al., 2010) was chosen, because micro CHP are similarly labor intensive as compared to solar pv systems. The potential of conflicts induced is rated as low for the low and base case because Micro CHP units are sold to private customers. If those do not agree with the concept of Micro CHP units they might not buy the product, but would also not cause a conflict. For the same reason, the necessity of participative decision making is rated as low. It is however not rated as 'very low' as past experience has shown that policies and their related subsidy schemes have had a major impact on the market introduction of Micro CHP units in the Netherlands (Meijer et al., 2007).

Table 5.21: PES characteristics of Micro CHP

Autonomy of generation			Job creation [job-year/GWh]			Potential of conflicts induced			Necessity of participative decision making		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
3	3	3	0.23	0.8	8	Very low	Very low	low	Very low	low	low

5.3.4.1.4 Power-to-gas

The ranking of the power-to-gas concept in terms of its autonomy of generation depends on the reasoning. For the high case, the power-to-gas concept is ranked as ten in terms of its autonomy of generation since it can be fuelled by the most preferable source of electricity, also renewable energy technologies. However, hydrogen is only a secondary energy carrier and thus does not contribute to the energy autonomy of a country if no electricity is generated in excess of its demand. Therefore, the low case is rated as zero. For the base case, it is assumed that some excess electricity is generated in the country, which can be transformed into gas and store until it is required. Hence, for the base case the power-to-gas concept is rated with a three, like all other gas technologies. The job creation of the power-to-gas concept is based on an estimate because no data is available on this aspect. Based on the number of job years created by fuel cells, which are in a similar state of development, but taking into account the economies of scale that occur from the larger scale of power-to-gas units, 0,52 job-years per GWh appear to be a solid figure for the base case. This is an average of the mean job creation by solar PV technology (0.87) and wind turbine technology (0.17). The latter numbers are assumed to be representative for the high and low case. The potential of conflicts from the power-to-gas concept is ranked as very low because it does not have any drastic influences on the landscape it is embedded in and because many experts consider power-to-gas as the most promising solution for long term storage of energy. Due to its integration of three energy carriers, that are electricity, hydrogen and methane, the power-to-gas option is ranked as 'high' regarding its necessity of participative decision making for the base and high case.

Table 5.22: PES characteristics of Power-to-gas

Autonomy of generation			Job creation [job-year/GWh]			Potential of conflicts induced			Necessity of participative decision making		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
0	3	10	0.17	0.52	0.87	Very low	Very low	low	mid dle	high	High

5.3.4.1.5 Fuel cell topping cycle

The fuel cell topping cycle is a gas powered integration option and therefore ranked as 3 in any case with reference to its autonomy of generation. Moreover, it is assumed to create a slightly higher number of employment-years than conventional gas power plants as it has not reached mass application yet. Taking a conservative estimate for the low case, it is assumed to create the same number of job-years per GWh as conventional gas powered plants, presented in (Wei et al., 2010). For the high case, the low case (0.11) and the base case of fuel cell technology (0.87) are added. This is likely to be the absolute maximum because the technology is very centralized and involves huge economies of scale in terms of its operation. The actual figure is likely to be somewhere in between the high and low case and thus assumed to be 0.49 for the base case. Similarly, the *potential of conflicts induced* by a fuel cell topping cycle is considered to be low because traditional gas powered plants are relatively clean compared to other plants powered by fossil fuel and the efficiency of combined cycle plants is even used by some companies for marketing purposes. Last, the *necessity of participative decision making* for power plants with a fuel cell topping cycle is rated as low because it does not require public acceptance. However, they typically include the coordination of gas and electricity distributors, several companies and regional governments for their construction. Thus, the high case is considered to be 'middle'

Table 5.23: PES characteristics of the Fuel Cell Topping Cycle

Autonomy of generation			Job creation [job-year/GWh]			Potential of conflicts induced			Necessity of participative decision making		
Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case	Low case	Base case	High case
Natural values											
3	3	3	0.11	0.49	0.98	Very low	low	low	Very low	low	mid dle

5.3.4.2 PES Comparison of Different Options

Table 5.24 compares the ordinal PES indicators of all five options. It can be seen that Micro CHPs score highest with respect to two indicators whereas the solar reforming methane scores the last rank regarding every indicators. The FC topping cycle, the power-to-gas concept and Superwind have a scattered performance. The results of this analysis can be explained by the nature of the technologies. Whereas the implementation of the solar reforming of methane is huge, centralized undertaking that requires the collaboration of a multitude of stakeholders, Micro CHPs are a very decentralized option, available on the market and therefore do not cause much attention.

Table 5.24: Comparison of PES indicators

<table>
<tr><th>Rank</th><th colspan="3">Autonomy of electricity generation</th><th colspan="2">Potential of conflicts induced</th><th colspan="2">Necessity of participative decision making</th></tr>
<tr><td>1</td><td colspan="3">Superwind</td><td rowspan="2">Power-to-gas</td><td rowspan="2">Micro CHP</td><td rowspan="2">Micro CHP</td><td rowspan="2">FC topping cycle</td></tr>
<tr><td>2</td><td rowspan="3">FC topping cycle</td><td rowspan="3">Micro CHP</td><td rowspan="3">Power-to-gas</td></tr>
<tr><td>3</td><td colspan="2">FC topping cycle</td><td colspan="2">Superwind</td></tr>
<tr><td>4</td><td rowspan="2">Superwind</td><td rowspan="2">Solar reforming of methane</td><td colspan="2">Power-to-gas</td></tr>
<tr><td>5</td><td colspan="3">Solar reforming of Methane</td><td colspan="2">Solar reforming of methane</td></tr>
</table>

The last PES indicator, job creation, is illustrated separately in figure 5.19 as it is measured on a ratio scale and the performance of the different options can therefore be compared directly with each other. According to the figure, the Superwind concept scores highest in terms of job creation. This aspect can be explained by the fact that it requires jobs to accommodate the lifecycle of a wind turbine but also a

SOFC. Next, Micro CHP units create around 0.8 job-years per kWh as they are a form of decentralized power generation which decreases economies of scales in terms of their maintenance. With a lower value of created job-years, due to the same logic, gas turbine, fuel cell hybrid systems, the power-to-gas concept and the solar reforming of methane require less labour during their life cycle.

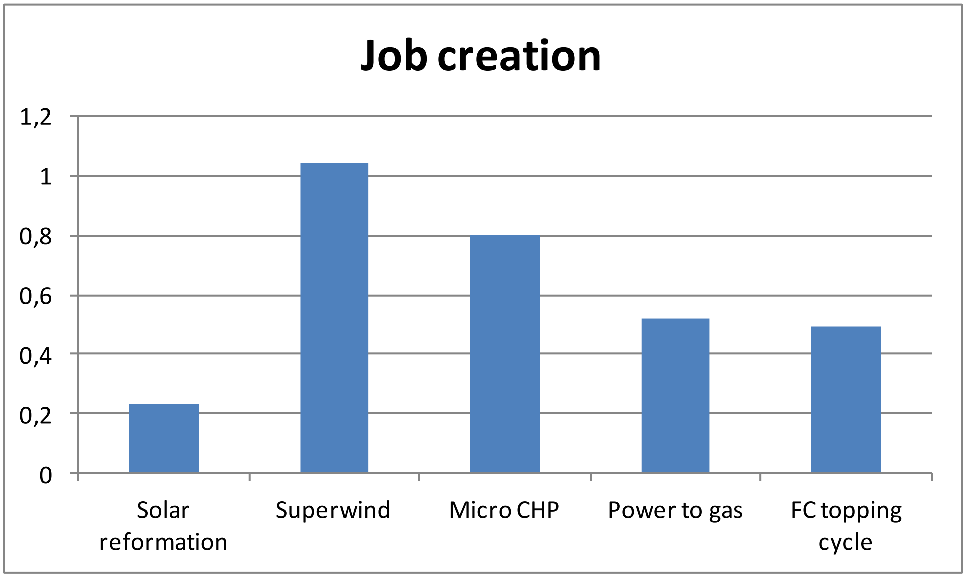


Figure 5.19: Job creation of different options

5.3.5 Dynamics of Technological Development

The two indicators that are derived from this analysis are illustrated in figure 5.20.

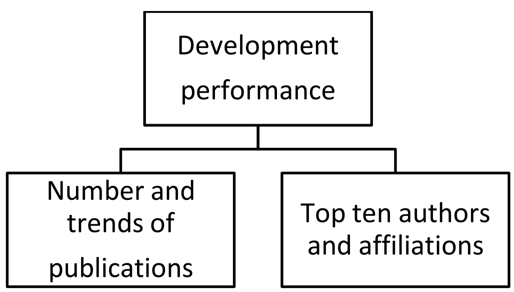


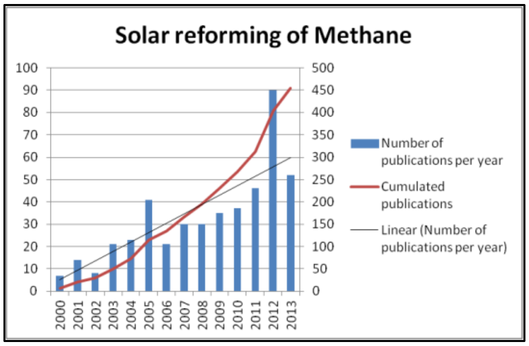
Figure 5.20: Indicators of technological development

5.3.5.1 Insights from Science Direct

The database Science Direct contains a sufficient number of publications that address the five integration options. However, the data that can be retrieved from these results is limited because only the authors' names and number of publications per year can be extracted. Related affiliations were thus searched manually for the top ten authors.

5.3.5.1.1 Solar reforming of natural gas

Regarding the solar reforming of methane 455 publications where downloaded whereas the trend line indicates that there is an increasing interest for this option. Except for 2002 and 2006 the number of publications has not dropped from one year to another. Obviously, no conclusion can be made yet regarding the publications of 2013. So far, Aldo Steinfeld has published most papers on the solar reforming of natural gas, which can be explained with his participation in the EU-project SOLREF that explores this option. Moreover, it can be noted that only the University of Rome is associated with more than one author of the list and therefore the top third publication affiliation on the solar reforming of natural gas.

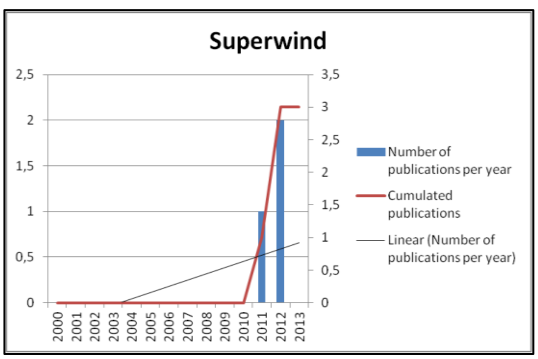


Place	Number of publications	Top Ten Authors	Related Affiliation
1	19	Steinfeld, Aldo	ETH Zürich
2	17	Mannan, Sam	Texas A&M University
3	11	Law, Chung K.	Princeton University
4	11	Lu, Tianfeng	University of Connecticut
5	6	De Falco, Marcello	University Roma
6	6	Schurig, Volker	Universität Tübingen
7	6	Valorani, Mauro	University Roma
8	6	Weimer, Alan W.	University of Colorado Boulder
9	5	Goussis, Dimitris A.	National Technical University of Athens
10	5	Sattler, Christian	German Aerospace Center

Figure 5.21: Information from Science Direct on solar reforming of methane

5.3.5.1.2 Superwind

The Superwind concept is the only option that is related to top ten authors from the Netherlands and TU Delft. The latter is associated with 75 percent of all top ten publications. However, it needs to be kept in mind that the number of publications on the Superwind concept is far from representative because only three publications have been made. Thus, future years of publications are more crucial than for any other option assessed to evaluate the development of the Superwind concept.

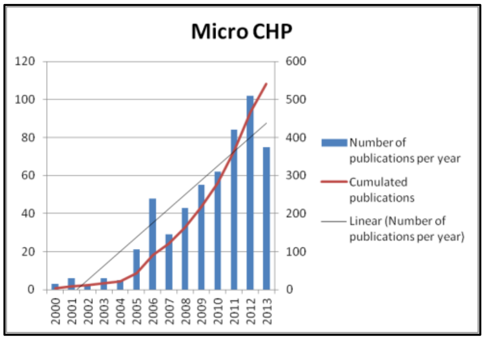


Place	Number of publications	Top Ten Authors	Related Affiliation
1	3	Hemmes, Kas	TU Delft
2	1	Barbieri, Giuseppe	TU Delft
3	1	de Werk, G.	TU Delft
4	1	De Wit, Hans (J. H. W.)	TU delft
5	1	Drioli, Enrico	ITM-CNR, Italy
6	1	Guerrero, Josep M.	Aalborg University
7	1	Kamp, L. M.	TU Delft
8	1	Lee, Young Moo	Hanyang University
9	1	Vernay, A. B. H.	TU Delft
10	1	Zhelev, Toshko	University of Limerick

Figure 5.22: Information from Science Direct on Superwind

5.3.5.1.3 Micro CHP

From 2000 to 2013 541 publications have appeared in Science Direct. Especially in the last five years the number of publications has increased significantly on a yearly basis. This development indicates a strong interest for the application on a micro-scale. The top ten authors are mostly related to Canadian and Italian affiliations whereas the University of Perugia and the Politechnico di Milano have the highest number of total publications, as they are both associated with two authors.

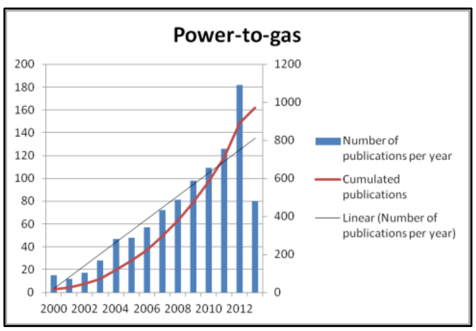


Place	Number of publications	Top Ten Authors	Related Affiliation
1	8	Beausoleil-Morrison, Ian	Carleton University
2	8	Dincer, Ibrahim	University of Ontario Institute of Technology
3	8	Sibilio, Sergio	University of Neaples
4	7	Manzolini, Giampaolo	Politechnico di Milano
5	6	Alanne, Kari	Aalto University
6	6	Bidini, Gianni	Universita' di Perugia
7	6	Klemeš, Jiří Jaromír	University of Pannonia
8	6	Sasso, Maurizio	Università degli Studi del Sannio in Benevento
9	5	Barelli, L.	Universita' di Perugia
10	5	Campanari, Stefano	Politechnico di Milano

Figure 5.23: Information from Science Direct on Micro CHP

5.3.5.1.4 Power-to-Gas

With 972 total publications, the power-to-gas concept is by far the most popular option assessed. In addition the number of publications per year has been increasing significantly since 2002. Among the top ten authors two are affiliated to the Ontario Institute of Technology, which accounts for the major share of publications related to Power-to-gas. Besides, it is worth noting that general Motors has contributed considerably to the list of publications.

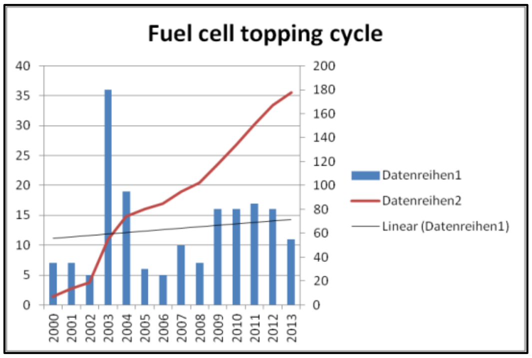


Place	Number of publications	Top Ten Authors	Related Affiliation
1	39	Dincer, Ibrahim	University of Ontario Institute of Technology
2	17	Nejat Veziroglu, T.	University of Miami
3	14	Rosen, Marc A.	University of Ontario Institute of Technology
4	13	Sørensen, Bent	Roskilde University
5	11	Barbir, Frano	University of Split
6	10	Hepbasli, Arif	Yasar University
7	9	Lund, Henrik	Aalborg Unviersity
8	8	Kelly, Nelson A.	General Motors Research and Development Center
9	8	Mathiesen, Brian Vad	Aalborg Unviersity
10	7	Contreras, Alfonso	Universidad Nacional de Educación a Distancia

Figure 5.24: Information from Science Direct on Power-to-gas

5.3.5.1.5 Hybrid gas turbine fuel cell system

The yearly number of publications on gas turbine, fuel cell hybrid plants has been not, and if only slightly, increasing over time. This indicates that the interest on this option has not increased significantly during the last year. However, it is interesting to identify that the authors with the most publications is the same as for the power-to-gas concept and that the University of Ontario Institute of Technology as plays a major role for this option as it is related to three of the top ten authors.



Place	Number of publications	Top Ten Authors	Related Affiliation
1	6	Dincer, Ibrahim	University of Ontario Institute of Technology
2	5	Chacartegui, R.	Universidad de Sevilla
3	5	Muñoz de Escalona, J. M.	Escuela Técnica Superior de Ingenieros de Sevilla
4	5	Rosen, Marc A.	University of Ontario Institute of Technology
5	5	Samuelsen, G. Scott	University of California Irvine
6	5	Sánchez, D.	Escuela Técnica Superior de Ingenieros de Sevilla
7	4	Ahmadi, Pouria	University of Ontario Institute of Technology
8	4	Brouwer, Jacob	University of California Irvine
9	4	Rao, Ashok D.	University of California Irvine
10	4	Sánchez, T.	University of Seville

Figure 5.25: Information from Science Direct on Hybrid gas turbine fuel cell system

5.3.5.1.6 Network of options' development

Figure 5.26 indicates the ties between different options by authors of publications. The only network that could be detected among the leading ten authors exists between Micro CHPs, the power-to-gas concept and the FC-topping cycle. Both researchers that have published on these topics are of the Ontario Institute and Technology. From picture it can be assumed that there is a co-development within this university among all three options.

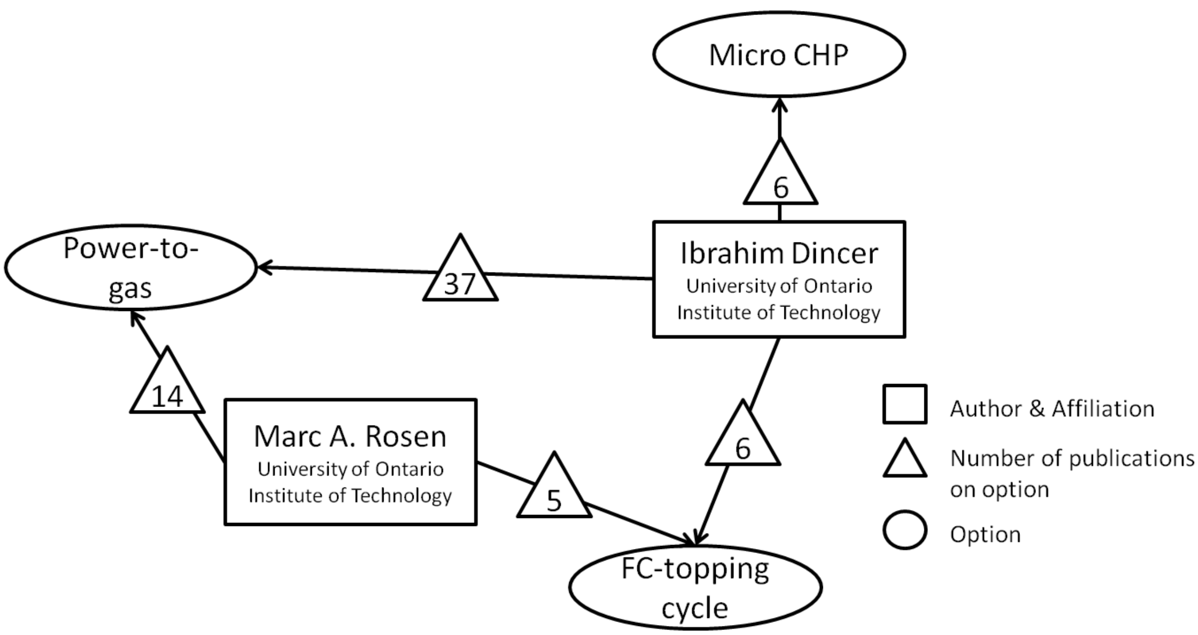


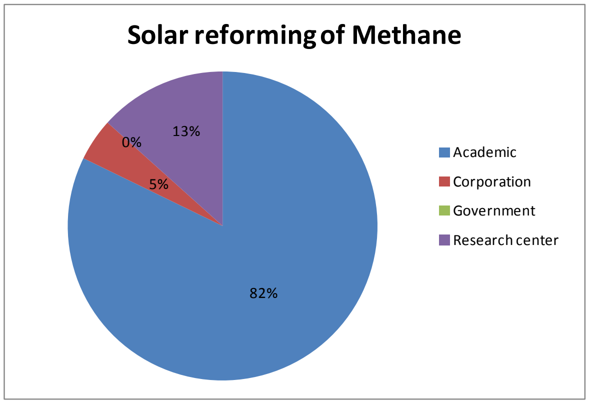
Figure 5.26: Network of Publications

5.3.5.2 Insights from Web of Science

The database Web of Science has only a very limited number of publications that address the five integration options. On the other hand, the data that can be retrieved from these results is more complete as it also includes the authors' affiliations and countries. Thus, this section is used to present the data that was retrieved from Web of Science.

5.3.5.2.1 Solar reforming of natural gas

The solar reforming of natural gas is addressed by 45 articles in Web of Science, 82% of which is published by academic institutions, 13% by research centres and 5 % by corporations. The top ten countries in terms of publications are led by the USA, Italy and China.

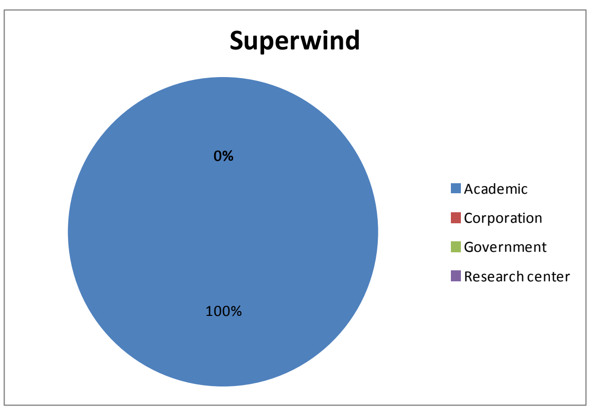


Place	Number of publications	Top Ten Countries
1	14	USA
2	13	Italy
3	6	China
4	4	Switzerland
5	2	Netherlands
6	2	Portugal
7	2	Spain
8	1	Greece
9	1	UK

Figure 5.27: Information from Web of Science on solar reforming of methane

5.3.5.2.2 Superwind

The Superwind concept is solely addressed by publications of academic institutions of the Netherlands, Italy, South Korea and Switzerland. In total three publications are available on Web of Science on the Superwind concept from the Netherlands, Italy, South Korea and Switzerland.

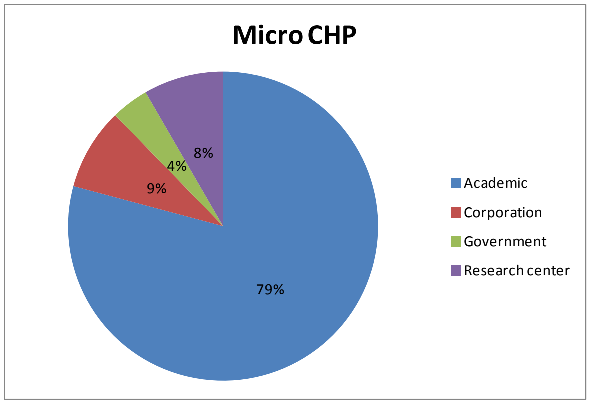


Place	Number of publications	Top Ten Countries
1	4	Netherlands
2	2	Italy
3	1	South Korea
4	1	Switzerland

Figure 5.28: Information from Web of Science on Superwind

5.3.5.2.3 Micro CHP

Micro CHPs are a topic of academic institutions, corporations, governments as well as research centres, whereas most publications stem from the UK, Italy and the Netherlands.

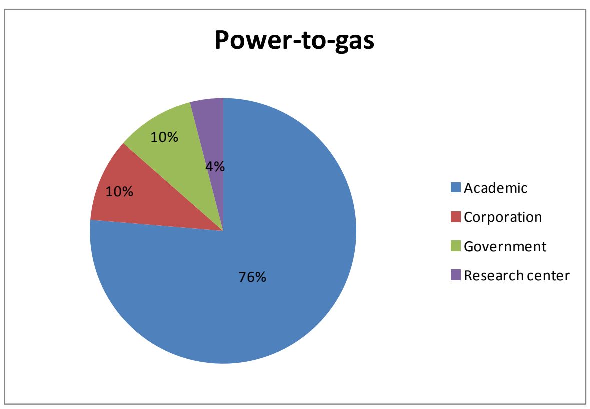


Place	Number of publications	Top Ten Countries
1	90	UK
2	65	Italy
3	38	Netherlands
4	32	Canada
5	20	Germany
6	18	France
7	16	Denmark
8	14	USA
9	12	Poland
10	11	Finland

Figure 5.29: Information from Web of Science on Micro CHP

5.3.5.2.4 Power-to-gas

The Power-to-gas concept has the highest percentage of non-academic publications, which reflects a high interest of corporations, governments and research centres. The USA, China and Japan are by far the leading countries regarding this technological option.

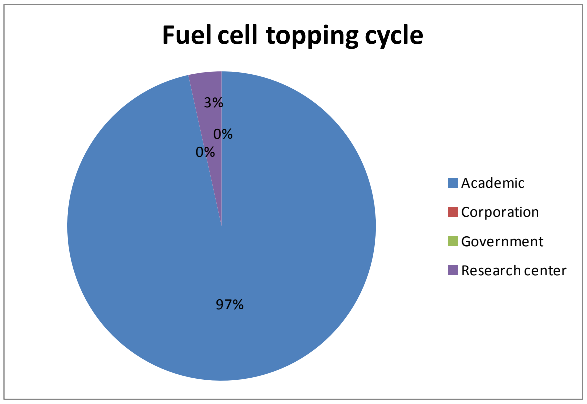


Place	Number of publications	Top Ten Countries
1	124	USA
2	103	China
3	90	Japan
4	65	South Korea
5	37	Germany
6	32	Italy
7	32	France
8	19	Australia
9	21	Russia
10	18	Spain

Figure 5.30: Information from Web of Science on Power-to-gas

5.3.5.2.5 Hybrid gas turbine fuel cell system

The hybrid gas turbine fuel cells system is represented in Web of Science by 29 publications that stem from 9 countries, led by USA, Japan and India.



Place	Number of publications	Top Ten Countries
1	6	USA
2	6	Japan
3	6	India
4	4	Italy
5	2	China
6	2	Denmark
7	1	South Korea
8	1	Spain
9	1	UK

Figure 5.31: Information from Web of Science on Hybrid gas turbine fuel cell system

5.3.5.3 Triangulation

As can be seen in figure 5.32 the ranking of total publications across Science Direct and Web of Science remains the same, whereas the total number of publications differs. Taking into account this commonality and difference, the following section specifies the MCDA indicators for the dimension "Dynamics of technological development".

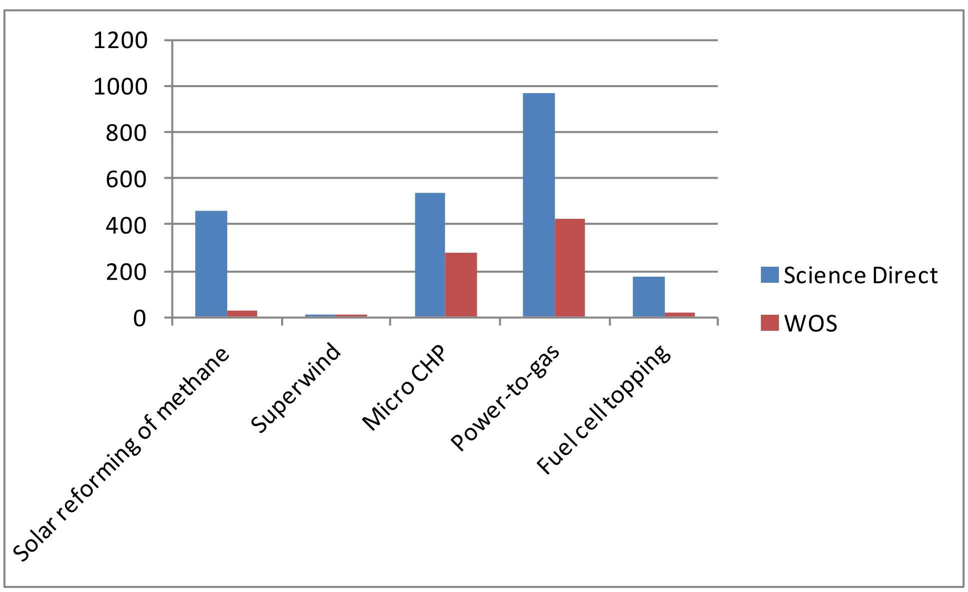


Figure 5.32: Tech Mining total publications of Science Direct and Web of Science

In order to test the validity of the Tech Mining results which were obtained from Science Direct and Web of Science the Scientific Database Scopus and the Derwent Patent Index were searched and the results were compared with those from the other two databases.

Scopus has a different collection of journals and the total number of publications found regarding the technological options was always in-between those of the other two databases. However, it provides insights that are very similar to those of Science Direct and Web of Science. As illustrated in figure 5.33, the ranking of total number of publications is the same as for the other two databases except for the fact that Micro-CHP units have a higher number of publications than the power-to-gas concept. Furthermore, the sources of publications, whether geographically or classified by type of organization appeared to be overall the same. It can be concluded that the brief scan of Scopus supports the results that have been found in the other two scientific databases.

The insights provided by the Derwent Patent Index are also of similar nature. In terms of total number of patents, the five technological options have the same ranking as in Science Direct and Web of Science, except for the fact that the solar reforming of methane is ranked slightly higher than micro CHPs. Also, the power-to-gas concept has a significantly larger surplus to the other options compared to the results of the scientific databases. This might be a validation of the finding that the power-to-gas concept attracts the highest number of corporations, which seek to secure their competitive advantage through the protection of their intellectual property by patents.

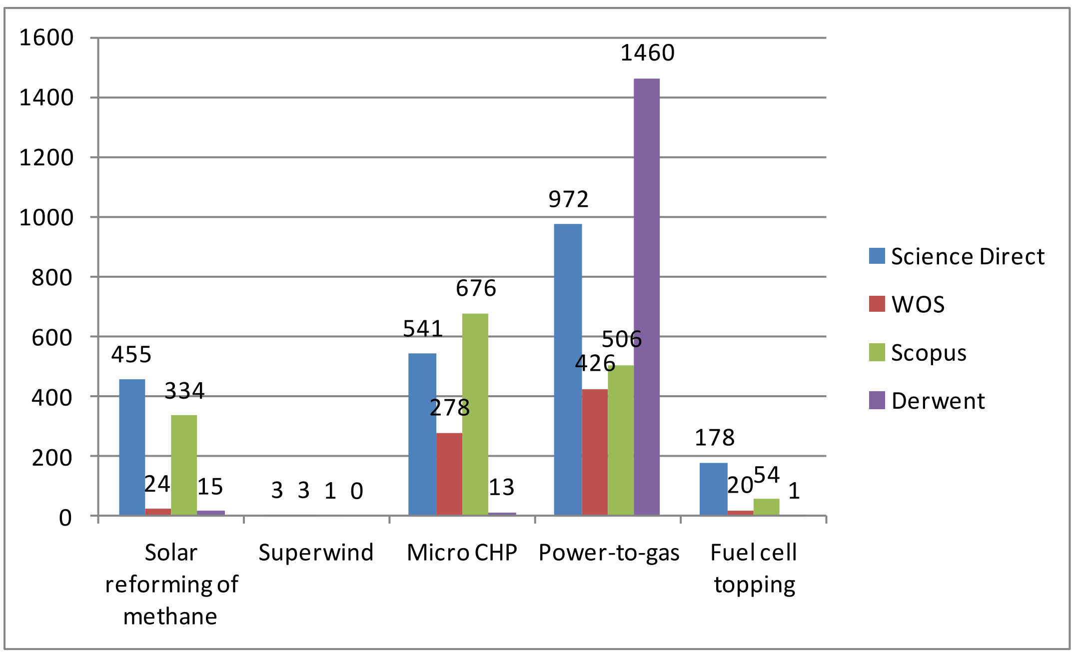


Figure 5.33: Tech Mining total publications of Science Direct, Web of Science, Scopus and Derwent Patent Index

5.3.5.4 Specification of Different Options

5.3.5.4.1 Solar reforming of natural gas

The solar reforming of natural gas has the third highest number of publications in both databases, demonstrates an increasing trend in terms of publications per year. The German aerospace centre is the only non-academic institutions that among the top ten publishing affiliations which indicates that this option is still in a phase of basic research. The insights gained through web of science show that 18% of all publications are non-academic. Compared with the other options, this percentage can be considered as intermediate. Taking into account the insight of other dimensions, this result might be a consequence of the general characteristics o the technology: Given the fact that the technology has promising characteristics but is difficult to implement in an international political settings, current research might be focusing on its technical feasibility whereas not much governmental research is dedicated to its implementation. Moreover, the top locations of research that were found in both scientific databases coincide with the technologies characteristics. Most efforts are spend in the USA and across Europe, mainly among the same countries. From this overall picture the solar reforming of methane is rated with its total number of publications as well as a growing potential regarding its future development

Table 5.25: Dynamics of development characteristics of solar reforming of methane

Number of publications			Future Development		
Low case	Base case	High case	Low case	Base case	High case
Natural values					
455			growing		

5.3.5.4.2 Superwind

The Superwind concept has the same three publications in Science Direct and Web of Science, whereas two of them were published in 2012. Thus, the attention of the concept is still limited but likely to grow further.

Table 5.26: Dynamics of development characteristics of Superwind

Number of publications			Future Development		
Low case	Base case	High case	Low case	Base case	High case
Natural values					
3			growing		

5.3.5.4.3 Micro CHP

In both databases the number of publications on micro CHP units is the second highest, whereas Italy, Canada and Finland appear in both as related to the top ten publishing authors/ countries. Moreover, the UK are represented in Web of Science as the country with the highest numbers of publications, which coincides with the insights the Desk study that was carried out for the other MCDA dimensions and frequently refers to British sources. Being the technological options with the second highest number of publications it has also the second highest percentage of non-academic publications, which indicates an existing potential of companies and governmental organizations. Besides, the insights from Science Direct show a steep increasing number of publications per year. Table 5.27 summarizes these specifications of Micro CHPs in terms of number of publications and future development.

Table 5.27: Dynamics of development characteristics of Micro CHP

Number of publications			Future Development		
Low case	Base case	High case	Low case	Base case	High case
Natural values					
541			Strongly growing		

5.3.5.4.4 Power-to-gas

The Power-to-gas concept has the highest number of publications, the highest percentage of non-academic publications and, together with Micro CHPs, the strongest growth of publications per year. Publishing authors and affiliations are mostly located in the USA, China and Japan.

Table 5.28: Dynamics of development characteristics of Power-to-gas

Number of publications			Future Development		
Low case	Base case	High case	Low case	Base case	High case
Natural values					
972			Strongly growing		

5.3.5.4.5 Hybrid gas turbine fuel cell system

The fuel cell topping cycle is the only technology that has a stagnant number of publications over the years. Moreover, no corporations have published on this option. As a result it is rated with a stagnant growth rate. When intersecting the insights of Science Direct and Web of Science, the USA, China, India, Spain and Canada seem to be the main publishing countries on this technology.

Table 5.29: Dynamics of development characteristics of hybrid gas turbine fuel cell system

Number of publications			Future Development		
Low case	Base case	High case	Low case	Base case	High case
Natural values					
178			stagnant		

5.4 MCDA

The following section carries out an MCDA analysis that creates an overall ranking among the five options assessed. At this point it is therefore assumes that all indicators and dimensions have the same weight.

Table 5.30: Scoring of technological options

Indicator		Global Minimum	Global Maximum	Score Reversed?	Value	Solar reforming of methane	Superwind	Micro CHP	Power-to-gas	Hybrid gas turbine fuel cell system
Financial	Total overnight cost [$/kW]	0	6000	Y	Natural	1268,55	1922,74	3476	1750	950
					MCDA	68,28625	51,9315	13,1	56,25	76,25
	Operation & Maintenance €/kWh	0	1	Y	Natural	0,094	0,086	0,102	0,184	0,39
					MCDA	90,6	91,4	89,8	81,6	61
	Cost of fuel €/kWh	0	1	Y	Natural	0	0,028	0,087	0,149	0,0739
					MCDA	100	97,2	91,3	85,1	92,61
	Impact of fuel price changes %	0	1	Y	Natural	0	0,368	0,853	0,821	0,1593
					MCDA	100	63,2	14,7	17,9	84,07
Technical	Average efficiency coefficient	0	1	N	Natural	0,865	0,79	0,8	0,62	0,6
					MCDA	86,5	79	80	62	60
	Average capacity factor	0	1	N	Natural	0,23	0,925	0,68	0,41	0,93
					MCDA	23	92,5	68	41	93
	Flexibility of dispatch	1	5	Y	Natural	5	2	4	3	1
					MCDA	0	75	25	50	100
	Technological availability & readiness	1	5	N	Natural	3	1	4	3	3
					MCDA	50	0	75	50	50
Environmental	Average external costs [€cents/kWh]	0	4	Y	Natural	0,13	0,27	1	3,3	1,33
					MCDA	96,75	93,25	75	17,5	66,75
	Loss of Life Expectancy	0	1.5	Y	Natural	0,1	0,45	0,6	0,8	0,7
					MCDA	90	55	40	20	30
	GHG emission g/kWh	0	1000	Y	Natural	0	340	295	0	369
					MCDA	100	66	70,5	100	63,1
PES	Autonomy of electricity generation	0	10	N	Natural	0	6,5	3	0	3
					MCDA	0	65	30	0	30
	Job creation/ direct employment	0	2	N	Natural	0,23	1,04	0,8	0,52	0,49
					MCDA	11,5	52	40	26	24,5
	Potential of conflicts induced	1	5	Y	Natural	3	3	1	1	2
					MCDA	50	50	100	100	2
	Necessity of participative decision making processes	1	5	Y	Natural	5	3	2	4	2
					MCDA	0	50	75	25	75
Development Dynamics	Number of publications	0	1000	N	Natural	455	3	541	972	178
					MCDA	45,5	0,3	54,1	97,2	17,8
	Trend of publications	1	5	N	Natural	4	4	5	5	3
					MCDA	75	75	100	100	50

5.4.1 Results

By multiplying the scores of table 3.3 with the weights of table 5.30, table 5.31 indicates the weighted scoring of each option with respect to every dimension as well as the total, accumulated score of every option. Figure 5.34 illustrates the data of table 5.31. The options' scores related to a dimension as well as the total score of all options indicate to what extent the option full fills the objective of being relevant to future research, measured by the indicators introduced previously.

Given that all dimensions are ranked equally, micro CHPs and the power-to-gas concept appear to be the best options to focus future research on, even though they score best only in the PES dimension and dynamics of development dimension respectively. The solar reforming of methane and the Superwind concept also appear to be equally promising and follow closely up to Micro CHPs and the power-to-gas concept. The gas-turbine fuel cell hybrid system falls slightly behind in its total scoring, mainly due to its relatively low ratings in terms of the PES dimension and its dynamics of development. It needs to be noted that none of the option dominates another in all dimensions. Thus, it is difficult to value the MCDA results based on this analysis. However, depending on the strategy of the research project the weights of indicators and dimensions need to be modified what results in different outcomes. The following chapter does so by introducing different pathways the research project can pursue to contribute to a sustainable energy scenario. In addition, it is important to test how the results change given that the technologies' specifications regarding the different indicators change in accordance to their low, base and high case, as specified in table 5.4 to 5.23.

Table 5.31: Overall ranking of assessed options

	Financial	Technical	Environmental	PES	Development	Total
Solar reforming of methane	18,47	7,98	19,50	3,08	12,05	61,08
Superwind	15,99	12,33	15,88	10,85	7,53	62,57
Micro CHP	11,89	12,40	14,71	12,25	15,41	66,66
Power-to-gas	12,77	12,77	12,94	9,05	19,72	67,25
Gas-turbine, fuel cell hybrid plant	16,09	15,15	13,44	6,58	6,78	58,04

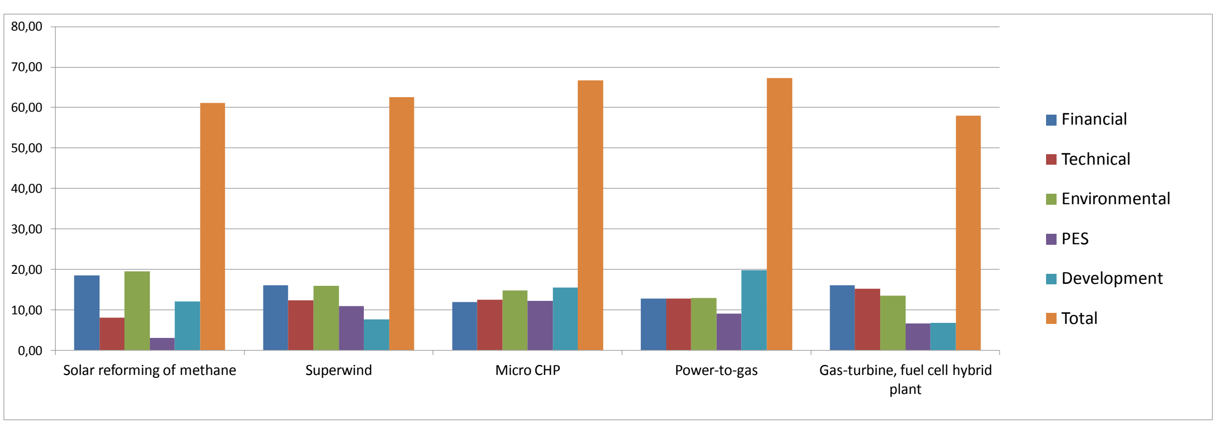


Figure 5.34: Overall ranking of assessed options

5.4.2 Sensitivity Analysis

The following section conducts a sensitivity analysis of the MCDA results. This process is crucial because the data gathered during the desk study has been collected from secondary sources and despite all efforts can have flaws, which change the overall ranking of the technologies. Thus, the sensitivity analysis changes the scores between the highest case and lowest case of all indicators in order to test for the stability of the result. To do so, a Monte-Carlo simulation with 10000 trials was conducted that underplayed all specifications of indicators in terms for technology with a uniform distribution. The latter assumes a continuous specification of an indicator within the low and high case defined in table 5.4 to 5.23 with equal likely hood. As can be seen in figure 5.35, either the power-to-gas concept or Micro CHP units were rated best with regarding each of the 10000 random indicator specifications.

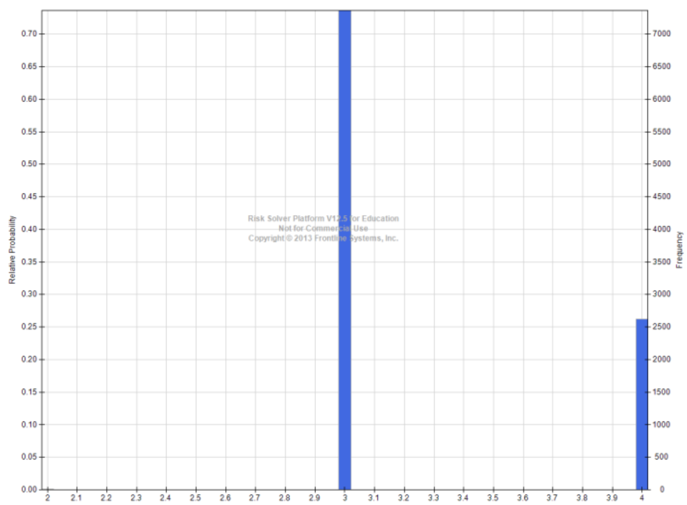


Figure 5.35: Results of Monte Carlo Simulation

When having a look at the sensitivity analysis of this result, it can be seen that the job creation by Micro CHP units is by far the most critical indicator, driving down the overall ranking towards three, whereas only the specifications of Micro-CHP indicators and power-to-gas indicators have an influence on the first ranking. Therefore, a closer look is paid in the following two sections on the specifications of Micro CHP and Power-to-gas.

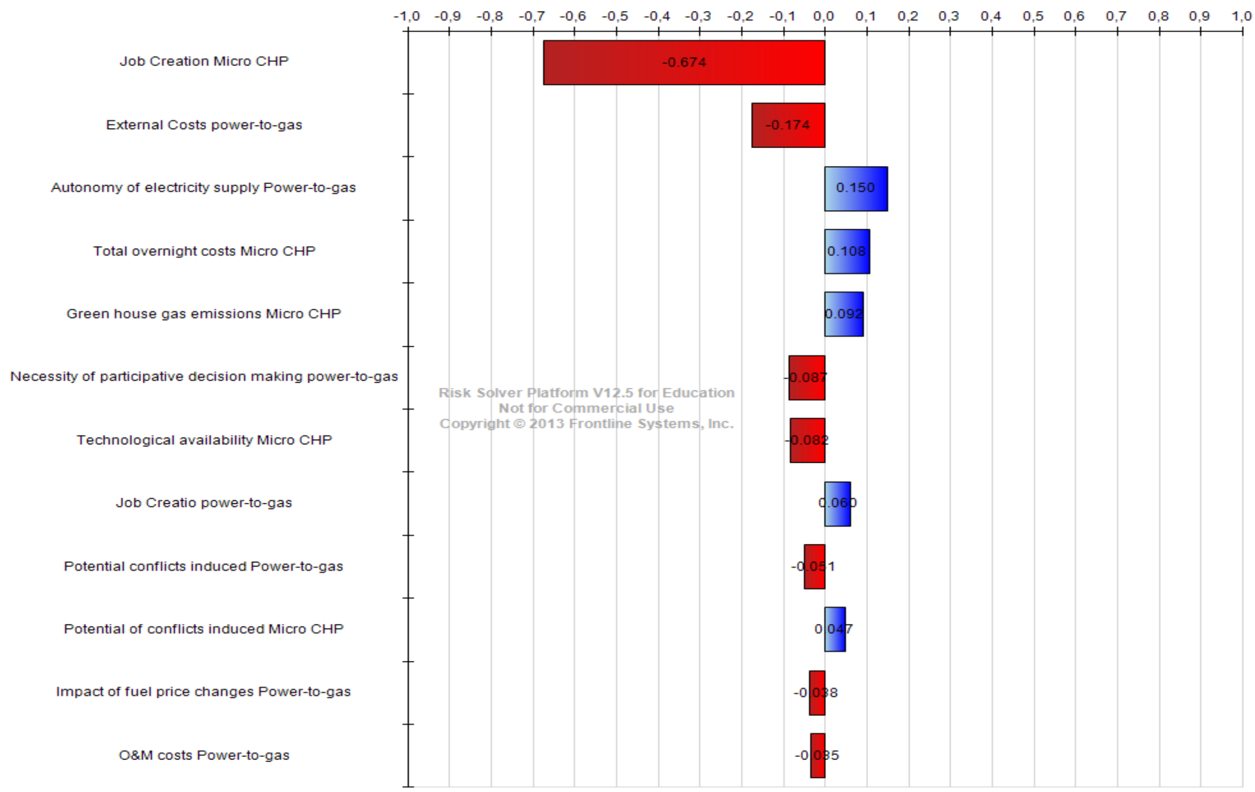


Figure 5.36: Sensitivity analysis Monte Carlo analysis

5.4.2.1 Micro CHP

The distribution of the Micro CHP scores varies between 63 and 90 within the 10,000 trials, whereas values between 69 and 84 have a likelihood of close to 7 percent. Moreover, the mean score is around 76.

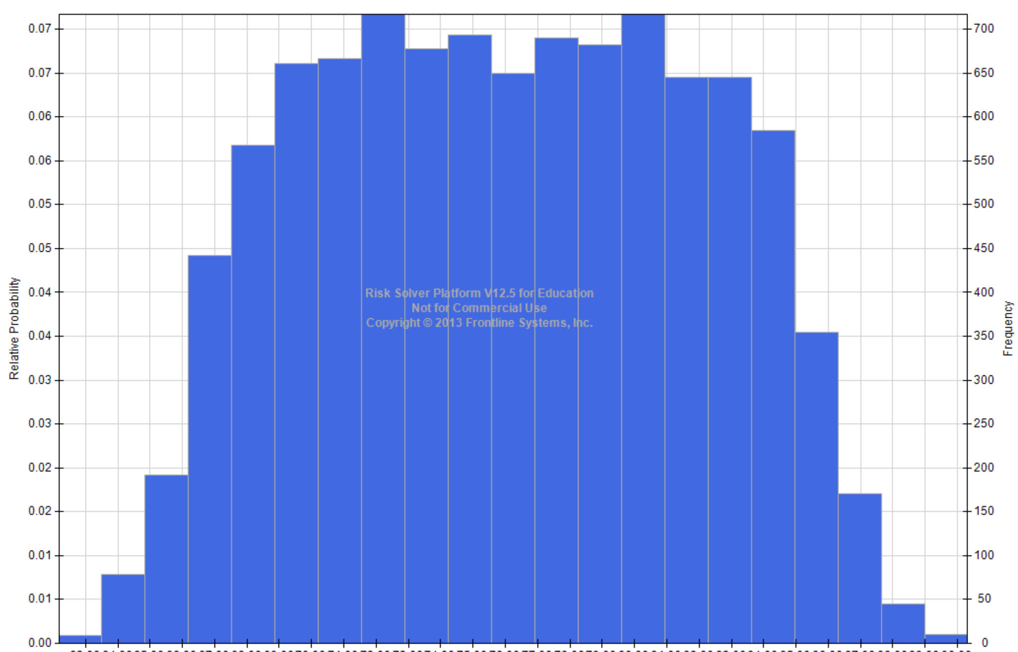


Figure 5.37: Distribution of Micro CHP score

From the tornado chart of figure 5.36 it can be seen that the specification of the indicator Job creation has a high positive impact on the score of Micro CHP. Strictly speaking, as long as the job creation of Micro CHP units is rated as 3.95 or higher, it is ranked higher than 78.5 and therefore the technological option ranked first. For scores lower than 3.95, the overall ranking depends on the specifications of the remaining indicators. Thus, it is crucial for further research to analyze the social impacts of Micro CHP units in order to further this broad range. Next, the total overnight costs, green house gas emissions as well as the specification of technological availability of Micro CHP has a smaller impact on the score of Micro CHP. The specification of all other variables is neglected in this analysis because their impact on the overall score of Micro CHP accounts for less than 0.1.

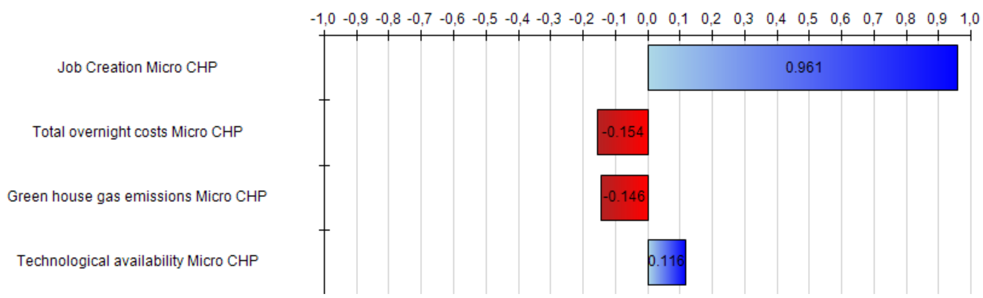


Figure 5.38: Sensitivity analysis of Micro CHP score

5.4.2.2 Power-to-gas

The distribution of scores of the power-to-gas concept within the 10,000 trials has a higher kurtosis than the scores of Micro CHP. As a consequence, there is a likelihood of around 30 percent that the overall scoring of the power-to-gas concept is between70.50 and 72.50 percent.

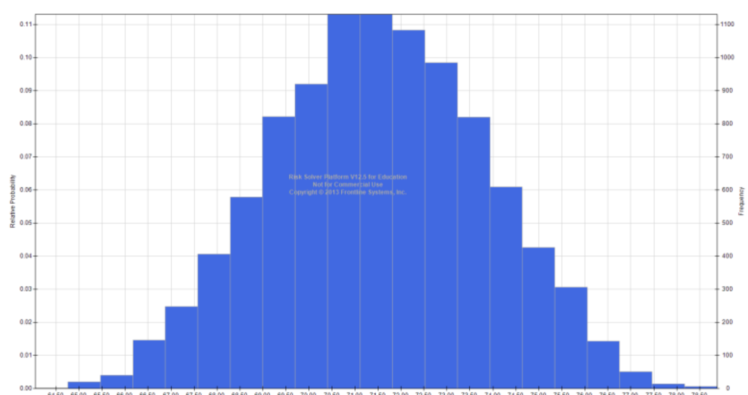


Figure 5.39: Distributed scores of power-to-gas

Figure 5.39 shows that the specification of the autonomy of electricity supply impacts the overall score of the power-to-gas concept most. Also the rating of its external costs has a heavy negative impact on its score. With reference to the process of the desk study conducted for this thesis, this result makes sense because for both aspects assumptions had to be made that need to be further narrowed in future research.

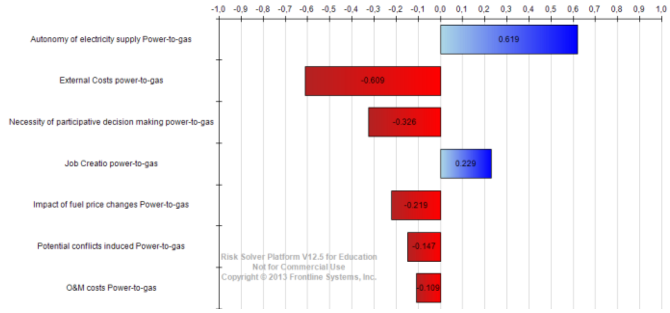


Figure 5.40: Sensitivity analysis of power-to-gas indicators

5.5 Conclusion

The foregoing chapter comprises a technology assessment of the thesis. Therefore, a technology screening is conducted that selects five technologies out of all technological options that have been suggested in the context of the thesis. To do so, the four screening criteria developed in section 3.2.3 are applied: the potential of sustainable operation, system integration, the selection of a technology and gas as an energy carrier.

The technology screening process is shown in table 5.1. It discriminates five technological options: (1) The solar reforming of methane, (2) Superwind, (3) Mini/Micro CHPs, (4) Power-to-gas and (5) Hybrid gas turbine fuel cell systems. These five technologies are further assessed in the following steps of the chapter in order to test their relevance for further research.

To do so, the second step of the chapter begins with a description of all technologies that addresses their working principle, points out different formats of these options, one of which is chosen for the assessment framework, and generally serves to gather information that enables the rating of the technologies in the assessment process. The second section of the chapter applies the MCDA framework which aims to rate the five technological options in terms of their technical, financial, environmental and political, economic, social (PES) criteria as well as their dynamics of development. To do so, every dimension is divided in a set of indicators that are elaborated and specified for each technology (cf. section 3.2.4.1). In doing so, the underlying desk study identified a low case, base case and high case for the specification of each indicator in order to account for inaccuracy of the secondary data that has been reviewed. Thereby, the dimension 'dynamics of development' differs from the other dimensions assessed as it involves the conduction of Tech Mining based on the content of scientific databases and the Derwent Patent Index as a means to collect primary data. Subsequently, to the specification of one dimension regarding each technology, a preliminary, qualitative analysis of results is conducted.

Based on the first three sections it can be concluded on the nature of the different technologies analyzed. The solar reforming of methane is a large scale, thus centralized mean of hydrogen production. It has a high efficiency but only a limited capacity factor due to its dependence on sunlight. Moreover, it involves some difficulties of implementation since it requires an international consensus. In doing so, the solar reforming of methane has large economic advantages due to its non-existent fuel requirements. The solar reforming of methane still primarily attracts the attention of academic institutions but the increasing number of publications per year that are associated with this options indicate a growing related interest, despite the upcoming difficulties of implementation. Superwind is still in its concept phase of development which is indicated by the low number of scientific articles that have been filed on this option. More specifically, Superwind has been suggested mostly by scientists of TU Delft and has not raised the attention of governmental or corporate parties. However, this aspect does not impact its feasibility, especially with respect to its good technical, environmental, financial and PES characteristics. The Superwind concept is a decentralized option that suggests the combination of a wind turbine with a SOFC, which allows to increase its capacity factor tremendously and to improve the overall efficiency of the system. However, it also involves some drawbacks such as that are bound to the characteristics of the wind turbine such as impacts on the landscape and the associate resistance from local stakeholders. The implementation of Micro CHP units has experienced market application in some countries, such as the United Kingdom, but has not grown significantly in the Netherlands yet, which has been reasoned by instable policies and related subsidy schemes (cf. Meijer et al., 2007). Micro CHP units have a great potential in terms of environmental and technical criteria, whereas their nature of being a much decentralized technology is two sided. On the one hand, micro CHP units are above-average expensive because they serve only single households and thus do not involve economies of scale regarding their power generation. On the other hand, this offers relatively large employment opportunities for regions that produce Micro CHP units for an international context. Academic as well as governmental and corporate institutions are aware of these benefits, which has led to a growing number of publications on Micro CHPs during the last decade. The power-to-gas concept is by far the most popular solution to a renewable energy scenario that requires the long-term storage of energy due to fluctuations in renewable electricity generation. Moreover, the power-to-gas concept is relevant for stationary as well as transportation purposes which results in a big interest by large corporations, such as General Motors. This is likely to result in a feedback loop that enables the strong increase in publications per year, in different databases, on the power-to-gas concept. It needs to be noted that the power-to-gas concept is only of lower average regarding its technical, financial and PES performance. A main factor is that it is dependent on the generation of electricity to be operated. However, given the difficulty of long-term energy storage that sustainable energy technologies implicate, the power-to-gas concept is the only solution that is currently at hand. The hybrid gas turbine fuel cell system is a centralized technology that involves the expansion of a regular gas power-plant by an internal reforming fuel cell to increase its efficiency. As such, this hybrid is promising in terms of its financial and technical characteristics. In contrast, its environmental impact is rather high and it is alarming that the annual number of publications regarding this option has stagnated during the last years.

The fourth section of the chapter comprises a multi-criteria-decision-analysis (MCDA) that is carried out in two steps. First, the natural values that are identified as the base cases, in the third part of the chapter, are translated into scores based on a linear target function and the definition of global minima and maxima (cf. Section 3.2.4.2). After calculating the weighted average for each technology, based on the global weights outlined in table 3.3, it can be seen in table 5.31 that the power-to-gas concept is the most beneficial option, followed closely by Micro CHPs. Nevertheless, this result is only of limited validity due to the fact that the ranking of the weighted scores for the different technological options can change when other natural values than the base cases are considered. To test for the stability of the first rank among all technologies, which is associated with differing weighted scores of all technologies, the fourth section of the chapter conducts a sensitivity analysis. The latter is based on a Monte-Carlo-Simulation that involves 10,000 trials, each of which assigns a random specification for each indicator regarding every technology, within the predefined range between low and high case. As a consequence, the weighted scores of all technologies are varied randomly within their possible limitations and for each trial it is recorded what technology scores best. It is very interesting to note that during all 10,000 trials either Micro CHPs or the power-to-gas concept score best. Moreover, it is determined that the specification of the indicators 'job creation of Micro CHP units', 'external costs of power-to-gas' and 'necessity of participative decision making' are the top three impacting variables that determine whether Micro CHPs or the power-to-gas concept ranks first. Especially, the job creation by Micro CHPs has a huge impact and can determine on its own whether Micro CHP should be chosen or not, given that all other indicators of Micro CHPs are rated as the low case.

From all these insights it can be concluded that, given equal weights for all five dimensions, Micro CHPs and the power-to-gas concept are the most promising options. Thus, the decision can be limited to focus future research either on Micro CHPs or the power-to-gas concept, whereas the first scores better in the majority of cases. Nevertheless, to be able to make this decision, further research needs to investigate the specification of indicators, especially the three most determining ones, mentioned above. Finally, it needs to be highlighted that this decision neglects normative preferences of the decision maker as it assigns the same weight to all five dimensions. This aspect is further investigated in the following chapter.

From the perspective of the EDGaR program the foregoing chapter provides a reasonable inventory of technological options and suggests screening criteria which could be applied in other decisions of the EDGaR program. Moreover, the chapter analyses five technological options in more detail, the results of which can serve as an input for further research projects.

For policy makers in general, this chapter demonstrates a procedure how to select some out of several technological options. Even though the screening criteria applied in this chapter might be uninteresting for other selections, a similar selection procedure based on a modified set of screening criteria is easy and straight forward to conduct, based on this chapter of the thesis. The same insights can be drawn from the MCDA framework applied.

6 Pathway Analysis

The following chapter tests the results of chapter 5 given that the weights of the different dimensions are alternated. Moreover, the chapter bridges these potential weights to different scenarios in order to demonstrate potential dimensions that can be observed by the decision maker and translated into different weights to come to a decision. The chapter is divided in five sections. In the first section different potential developments for the gas sector are introduced by means of table 6.1. The development of the table is based on the methodology of field anomaly relaxation (FAR) but conducted in a simplified manner, as suggested in (Coyle, 2003). For every sector, potential states are described and related to the trends identified in the third chapter. Moreover the technologies' ranking is illustrated, given that the weight of the associated assessment criterion changes. The second step involves the construction of potential scenarios from a combination of different sector states. In order to assure the plausibility of the scenarios selected, the second section is based on the paper of (Weidenaar et al., 2012) which was written in the frame of the research project and describes four scenarios of for the Dutch gas sector. As part of this step, weights for the four assessment dimensions are allocated regarding each scenario and it is analyzed how different technologies would perform as part of these scenarios. At last, the options' performance is analyzed against the background of different pathways that lead to the end-state scenarios.

6.1 Sectors and Factors of Development

In order to construct different possibilities of development for the Dutch gas sector, scenarios written by (Weidenaar et al., 2012) served as an input to identify different sectors that determine potential development for the Dutch gas sector. In short, the concern about sustainability, countries' energy strategies, economic efficiency and the source of energy were identified as sectors that can be used to describe a future state. In the following, all sectors as well as the sector-factor combinations are described. In doing so, relevant trends of the third chapter are utilized to describe the different combinations as specific as possible. Table 6.1 summarizes all possible sector-factor combinations.

Table 6.1: Sector factor matrix

	Sectors			
	Sustainability	Countries' energy collaboration	Economic efficiency	Source of energy:
Factors	S1: Low concern	C1: Market	E1: Dominant	SoE1: Fossil fuel only (and some nuclear)
	S2: Middle concern	C2: EU-collaboration	E2: Existing	SoE2: Diversified energy supply
	S3: High concern	C3: Isolationism	E3: Not important	SoE3: Renewable energy supply

6.1.1 Sustainability

In their paper, (Weidenaar et al., 2012) identify the ability and willingness to mitigate greenhouse gases as one of the main characteristics of a future scenario of the Dutch gas sector. By adopting the sustainability concern as a key sector of a future energy scenario, this characteristic is a broadened and also accounts for other environmental impacts than greenhouse gases that influence sustainable development.

6.1.1.1 S1: Low Concern

In the case of a low concern for sustainability, environmental aspects are very low on the political agenda because other priorities prevail. In this sector-factor combination, climate change loses attention, because of other overruling aspects of development. Also the concerns about other environmental threats, such as those caused by fracking, do not contribute to public decision making. Thus, resources are depleted with hardly any limitation, also in sensitive areas. The environmental awareness within society has decreased significantly as well. For those actions, environmental impacts are proven to exist but are not taken into account if other factors object sustainable development.

6.1.1.2 S2: Middle Concern

Given that there is a middle concern for sustainability, environmental aspects form a part of the political agenda. More specifically, environmental aspects such as climate change, resource depletion and the potential damage of sensitive areas are a permanent background of decision making but are not a solely determent criteria of decision making. As a result, environmental aspects are considered in several situations to a varying extent.

6.1.1.3 S3: High Concern

In the case of a high concern for sustainability, environmental aspects are high on the political agenda. Therefore, they rule public decision making day by day and are considered to some extent in every decision of the Dutch gas sector. In this case the precautionary principle is applied and technologies which are not proven to be sustainable are applied only on a very limited scale. For the same reason, the exploitation of unconventional gases (i.e. CBM and shale gas) faces severe restrictions. Furthermore, policy frameworks consisting of rules and incentives support this development and prohibit for example the local combustion of natural gas at household level and the compulsory capture and storage of greenhouse gases at centralized power plants. As a consequence of the latter, the gas system undergoes significant changes.

6.1.2 Countries' Energy Collaboration

The sector *countries' energy collaboration* is derived from the scenario characteristic of *perceived scarcity of energy resources* as presented in (Weidenaar et al., 2012). However, given recent developments such as Europe's economic crisis, countries might decide for several rationales on their energy strategy. For this reason, and to take a more descriptive perspective, this sector was not directly adopted from (Weidenaar et al., 2012) but further particularized.

6.1.2.1 C1: Market

In this state, energy is not perceived to be scarce but treated as a commodity and subject to increasing globalization. In Europe, gas from pipelines competes with other sources such as LNG and fracking. The liberalization among institutions progresses and energy generation scatters around the globe so that the investment climate of countries takes a subordinated role. Gas pipelines from Russia and Norway are further sophisticated whereas the power position of these countries remains moderate. Also societal actors involved in the energy sectors, such as farmers that generate biogas, have a limited stake in the Dutch gas sector because cheap gas can be imported from abroad, thus energy provision is centralized. Demographic developments do not impose a problem to the free trade of gas.

6.1.2.2 C2: EU-Collaboration

In the sector-factor combination of EU collaboration, the finiteness of energy is acknowledged but not feared to be present soon. Until then, the European countries aim to obtain a high strategic position by collaboration. Therefore, gas pipelines are aimed to be substituted by domestic resources and LNG terminals. The liberalization in this scenario does not further progress, to not endanger stability, but also does not step backwards. Instead, countries aim to obtain an attractive investment climate and energy security for the EU as a whole, and therefore increase pipeline connections among European countries. The power position of countries with gas resources is higher in comparison with the sector-factor combination C1 and the EU aims to counteract this power position by partitioning itself from other countries. The power position of society is higher than for C1 as this state requires a more decentralized power production to ensure an increased self-sufficiency of the EU. Moreover, demographic developments are feared to impose a problem to the situation at hand and therefore decision making is taking likely developments regarding this aspect into account.

6.1.2.3 C3: Isolationism

In this state, energy is regarded as very scarce and to be a main determent for a country’s welfare. Gas pipelines have only very limited capacity as the power position by the gas supplying country is too high. Moreover, liberalization regresses because the security of supply is considered to be more important than a liberalized market. Also, countries compete harshly in terms of their investment climate because the attraction of energy companies allows them to be ahead of other countries, in terms of their self-sufficiency, whereas the power position of energy producing countries is undisputable. Compared to other scenarios, the collaboration of energy policy with societal actors is necessary in order to increase domestic energy production to a self-sustaining level. Demographic developments are feared to impose a problem to this state because it might involve a change in domestic energy demand that cannot be covered by national resources.

6.1.3 Economic Efficiency

The economic efficiency is mentioned explicitly only once in the narrative scenarios of (Weidenaar et al., 2012). Nevertheless, it is an important sector that determines to what extent financial aspects of a technological solution influence its adoption as part of the energy system. In the following, three different factors are distinguished regarding economic efficiency.

6.1.3.1 E1: Dominant

Given a state in which energy companies dominate the energy mix of a country and policies do or do not aim to strengthen the financial competitiveness of financially less beneficial options, the economic efficiency of new technologies is likely to be prevailing, thus dominating the selection of technologies in the energy mix.

6.1.3.2 E2: Existing
The sector-factor combination in which economic efficiency is an existing, but not the sole decision making criterion, represents a situation in which social or political developments raise the importance of other decision making criteria. For example the need for sustainable development or the adherence to emission goals might reduce the importance of economic efficiency as a decision making criterion.

6.1.3.3 E3: Not Important
Third, there is a sector-factor combination in which economic efficiency might not be a decision making criterion. In this state, the urgency of other aspects and their associated decision making criteria largely outweigh the financial characteristics of a technology. Given this state, other than financial benefits are expected from newly introduced technologies.

6.1.4 Source of Energy
The source of energy is specified in all scenarios that are constructed in (Weidenaar et al., 2012) and therefore decided to form a distinctive sector in the FAR analysis. Next, to the primary energy sources, this sector determines also to some degree the usage of the gas system or its components respectively.

6.1.4.1 SoE1: Fossil Fuel only (and some nuclear)
This sector-factor combination represents a state in which only fossil fuels and potentially nuclear power contribute to the energy supply of the Dutch energy system. Because renewable energy sources compete directly with these technologies, their share is limited. The gas system in this state coincides to a large extent with the current gas system as described in chapter 3, mainly distributing conventional and unconventional natural gas but bio methane only to a very limited extent. An infrastructure for hydrogen is also not existent.

6.1.4.2 SoE2: Diversified Energy Supply
In this state, primary energy sources are highly diversified. Therefore, fossil fuels and nuclear power as well as renewable energy sources have a significant share in the energy mix. Storage is built up as part of the gas infrastructure to enable its adoption to fluctuations in renewable power generation.

6.1.4.3 SoE3: Renewable Energy Supply
In this sector-factor combination, renewable sources of energy account for a major share of energy supply. In rural areas the gas distribution network is fed with bio methane whereas urban areas are served by electricity and heat networks. The current gas transmission system is used to propel centralized gas power plants or to level out fluctuations of renewable power production. In addition, separate infrastructures are set up for carbon dioxide and hydrogen, with hydrogen distribution pipelines broken down to a household level.

6.2 Potential Pathways for the next 50 Years
The following section addresses potential pathways towards the future by translating the current state and future scenarios into sector-factor combinations, presented in the previous section. Subsequently, potential intermediate states are identified that allow pinpointing pathways from the current state to future states of the gas sector.

6.2.1 Current State

The current state can be expressed as the sector-factor array *S2C1E1SoE1*. Following the sector-factor combinations introduced in the previous section, sustainability is currently of middle concern, energy is treated in a market environment, economic efficiency is dominant in decision making processes and the primary sources of energy are fossil fuels and some nuclear power.

6.2.2 Final States

Given the thesis' background as being part of the project 'The next fifty years: developing robust strategies for the gas transition', it is aimed to identify developments of the gas sector within this time frame. Therefore, this subsection describes final states in accordance with future scenarios as identified by (Weidenaar et al., 2012), which could take place in fifty years. Subsequently, these final states are used as an input to identify pathways from the current state to the future.

6.2.2.1 Business as Usual (BAU)

The BAU scenario as identified in (Weidenaar et al., 2012) outlines a future case in which sustainability still plays a minor role as a decision making criterion. Instead economic efficiency is pursued which leads to a high share of fossil fuels and a gas infrastructure that mostly coincides with today's gas system (Weidenaar et al., 2012). In accordance to the sector-factor combinations this scenario is represented by an array of *S2C1E1SoE1*.

6.2.2.2 Carbon Constraints (CC)

The CC scenario as described in (Weidenaar et al., 2012) involves a high concern about sustainability, especially greenhouse gases, and shape actions to a large extent. Therefore emissions from centralized gas power plants are fed into a CO_2 infrastructure and renewables take a share in the energy mix. This state is described by the sector, factor array of *S3C1E2SoE2*.

6.2.2.3 Tight Market (TM)

The TM scenario outlines a future state that has a diversified energy supply in order to secure energy supply of the European Union. Also, economic efficiency and sustainability play a subordinated role. In sum, this energy scenario can be described with the sector-factor array of S1C2E3SoE3.

6.2.2.4 Renewable Energy (RE)

The renewable energy scenario in (Weidenaar et al., 2012) is dominated by a high concern about sustainability. As a result, renewable energy technologies dominate the energy mix and the gas infrastructure changes considerably to level out fluctuations of renewable power production. Therefore, separate pipelines for hydrogen and carbon dioxide are established. In the RE scenario economic efficiency is existent but not dominant, and every country aims to achieve self-sustainability on its own. The RE scenario can be described by the sector, factor array of *S3C3E2SoE3.*

6.2.3 Intermediate States

The definition of intermediate states is described in (Coyle, 2003) as carried out subsequent to the description of future scenarios by exploring states that are in the middle of the current state and the final states. Thereby, it needs to be pointed out that intermediate states do not necessarily embody a gradual intermediate step of sector-factor combinations from the current state to a future state but rather need to be considered as a logical part of the pathway, which is not necessarily of gradual nature

(Coyle, 2003). In the following, three potential intermediate states are described that could be part of those pathways which could lead to the end-states identified.

6.2.3.1 Shale Gas Exploitation

The intermediate state of shale gas exploitation is very similar to the current state. However, it involves worldwide scale-up of shale gas production and an associated development of shale gas capacity. Because of the abundance of gas on the market, gas prices drop notably, accelerating other industrial sectors. As a consequence, the concern for sustainability drops below current levels and is not taken into account as a criterion for decision making anymore. Instead, economic efficiency remains dominant and the energy mix will remain mostly based on fossil fuels. It results a sector-factor array of *S1C1E1SoE1.*

6.2.3.2 Fear of Energy Crisis

The fear of an energy crisis is another potential intermediate state in the future development of the gas sector. It is a state in which industrial and domestic consumers fear the exhaustive usage of gas as a primary energy carrier due to impacts or forecasts regarding the economics or reservoirs of gas or political tensions for example. As a result, the energy strategy of European countries turns against traditional means of gas transport because they are perceived as not reliable, depending only on one supplying countries. Although renewable power generation and the supply of LNG are considered as robust elements of the energy mix, especially for the former, a significant timeframe is required to build up sufficient capacity of energy supply. In doing so, the Dutch gas sector would leave this intermediate state and its associated sector-factor array of *S1C2E2SoE1* again.

6.2.3.3 Sustainable Rethinking

The intermediate state of sustainable rethinking is similar to the fear of energy crisis, as described before, but highlights sustainable development instead of rationales for energy security. However, as for the fear of an energy crisis, this intermediate state lacks the infrastructure for a sustainable energy mix.

6.2.4 Pathways

Figure 6.1 illustrates potential pathways from the current, over the intermediate, to the four final states. According to (Coyle, 2003), the pathways are ordered from least to most preferable from left to right. Besides, the letter-cipher chains next to each state of the pathways express arrays constructed from the distinct sector-factor combinations presented in table 6.1. Furthermore, Figure 6.2 groups the different pathways into three major courses of development, classified in accordance to the outcome of their end-state. As with the pathways, these major courses are ordered from least preferable to most preferable from left to right. Given the background of this thesis in sustainable development, the preferences of the decision maker shifts from economically to environmentally driven from left to right.

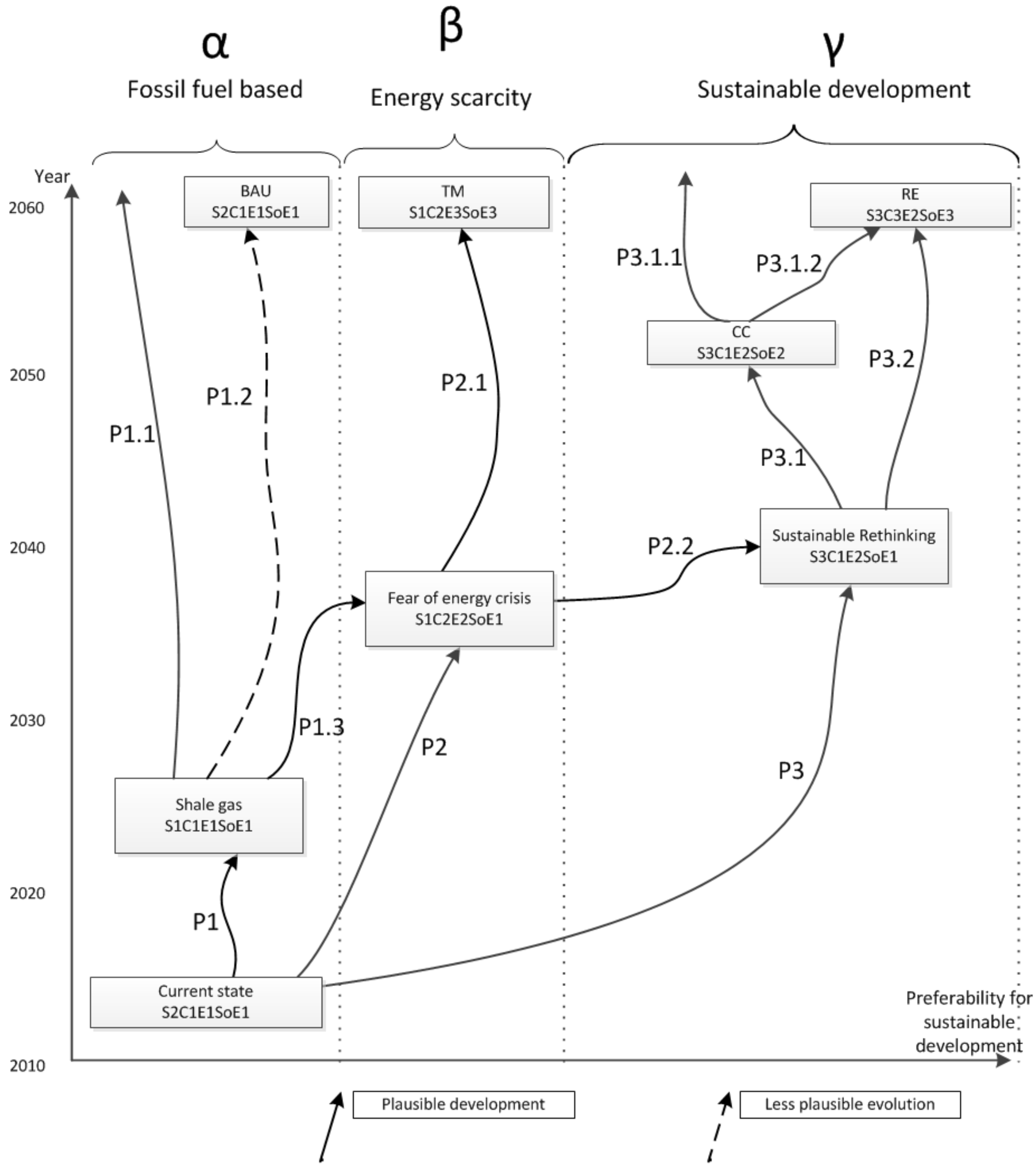


Figure 6.1: Pathways

6.3 Social Reconfiguration

The following section addresses different social configurations that potentially develop as part of the major courses of development, from the current states to the potential future states. Additionally, it elaborates how those configurations affect the preference for different technological options. Whereas the last chapter included a sensitivity analysis that varied the scores of the different options, this chapter follows the underlying thought that different social configurations change preferences of society and therefore the weights for the different dimensions assessed. As discussed in section 3.2.7, the scoring of the different options remains constant during this process. In order to present the outcome of this analysis, three steps are taken in the further progress of this section. First, the major courses of development are translated into preferences for the different dimensions of the MCDA framework. Second, potential coalitions among the condensed actor groups, presented in the third chapter, are described for each major course of development. Third, the ranking among the technological options are related to different preferences for weighting and the three major courses of development.

6.3.1 Translating Preferences into Weighting

Table 6.2 summarizes how the major courses of development are related to the dimensions of assessment, introduced in the fifth chapter. Starting from the equal weighting of 25 percent for each dimension, the table illustrates how the actor coalitions of each of the three main courses of development would reallocate weights, according to their preferences, among the four dimensions. As introduced in section 3.2.7, it is assumed for all three major courses of development that the technical dimension takes a differentiated position and has a constant weight.

Table 6.2: Preference of weights in relation to main courses of development

Weight (%)	Dimension	Explanation	Main courses of development		
			Sustainable Development	Energy Scarcity	Fossil fuel based
25	Financial	The higher the weight of financial criteria the more important the financial performance of options in the decision making	↓	↓	↑
25	Technical	Technical criteria remain important in every scenario for one or the other reason. However, they are also not pivotal to the decision making. Therefore, they are considered with the same weight for every scenario	→	→	→
25	Environmental	The more important sustainability in the decision making, the higher weighted these criteria	↑	↓	↓
25	PES	The PES dimension is particularly important in an energy scarcity as it indicates the contribution of an option to the competitiveness of the country	↓	↑	↓

Given the course of sustainable development, the environmental dimension is clearly weighted as most important, whereas financial and PES indicators are considered as secondary. Thus, an increased weight for environmental indicators lead to a decreased weight of the financial and, or the PES dimension. In a course that is concerned with energy scarcity, the PES dimension is chosen over the environmental and the financial dimension because the PES dimension represents the effect an option has on the competitive advantage of a country and its energy system. In the case of a fossil fuel based course of development, financial indicators are considered as most important and thus valued higher at the cost of environmental and PES indicators. However, the difference between the three major courses of development is gradual and it is difficult to border each major course development with a specific allocation of weights to each dimension.

Figure 6.2 illustrates this context. It specifies the triangular diagram as introduced in figure 3.4., in which each rhombus favours one of the three dimensions. Taking into account the insight of table 6.2, each rhombus embodies a weighting that aims distinctively towards one of the major courses of development. When leaving a rhomb by moving away from a corner of the triangle along one of its outer edges, this relation to one major course of development becomes blurred.

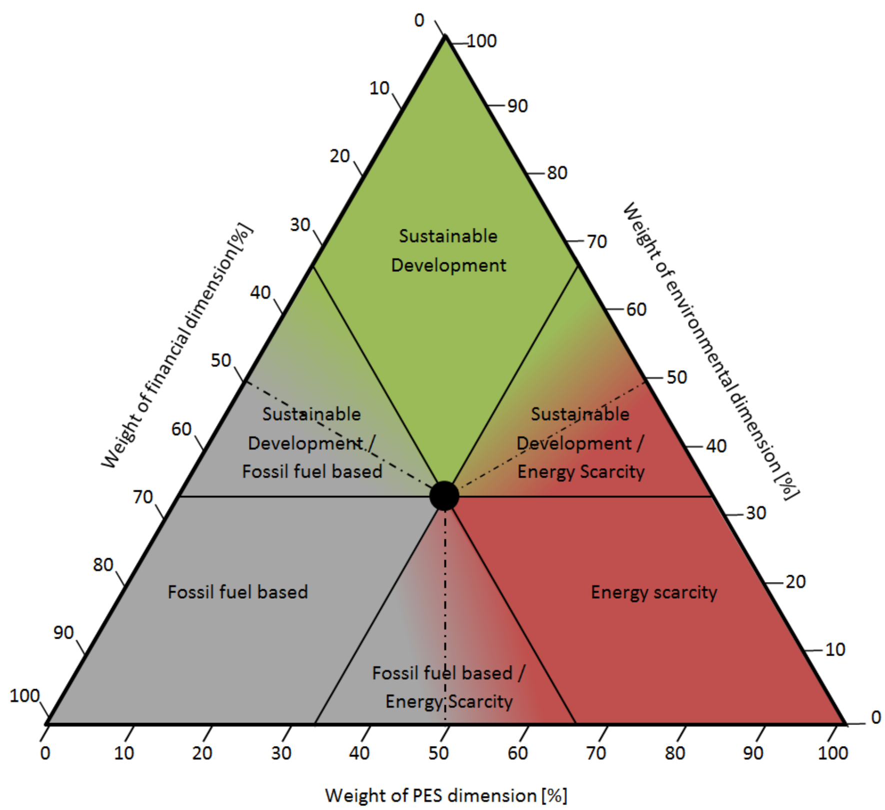


Figure 6.2: Major directions of development and related preferences of weighting

In the following three subsections the insights of table 6.1, 6.2 and figure 6.2 are combined and it is analyzed what coalitions of main actor groups are most likely to form and represent most closely the three major directions of development.

6.3.2 Major Courses of Development & Related Actor Coalitions

In the following, each major course of development is described and it is outlined how different actor groups shift regarding their power position and their relations among each other. In this sense, some stakeholder groups converge and others diverge during the transition from one state to another. The condensed actor groups identified and described in chapter 3 serve as an input for this section. Based on the preferences of converged or diverged actor groups, different weights are assigned to the dimensions of the MCDA procedure in chapter five.

6.3.2.1 Aiming towards Fossil Fuel Based Future

Given that the course of a fossil fuel based future is taken, the actor groups of gas producers and transmission system operators and local distribution network operators remain as powerful as they are nowadays, or even increase their power position. An exemplary but not indispensable external event that could foster this development is the worldwide, large-scale exploitation of unconventional gases that drives down of gas prices. Because market actors form the centre of the actor coalition in this course of development, financial aspects are considered as very important. As a result, gas remains the main energy carrier in the Netherlands because it is much more cost effective than renewable energy technologies or other fossil fuels. Also, the actors associated with these energy sources, such as NGOs, citizens and communities, are therefore overruled and less powerful despite their protests. Furthermore, gas producers, transmission system operators and local distribution network operators have a strong tie to the customers of gas who appreciate the economic advantage that results from the falling gas prices. Authority actors diverge regarding their policies in this course of development. Whereas the European Commission can support or counteract the development, the Dutch national government sees a huge potential opportunity in the course of development and therefore fears to hamper the development of the Dutch economy by interfering with the ongoing inertia. Only some Dutch local governments oppose the course of development and potentially team up with social actors to avoid for instance environmental pollutions in their region. However, the received opinion highlights that unconventional gas drives more polluting fossil fuels out of the market and therefore benefits environmental sustainability.

Figure 6.3 depicts the above described position of the actor groups, given a fossil fuel based course of development. Based on the illustration it can be argued that the strongest coalition for a fossil fuel based course of development would include the Dutch national government, gas producers and transmission system operators, local distribution network operators and customers, whereas the European Commission and the Dutch local government pursue a policy strategy that behaves neutral. Only NGOs, communities and citizens oppose the development. This case is illustrated by the arrows labelled with a plus. The weakest coalition that represents the course of fossil fuel based development is indicated by the arrows that are labelled with a minus. In this case, only gas producers, transmission system operators and local distribution network operators are considered as core actors. The Dutch national government, customers and European commission hardly prefer a fossil fuel based development whereas Citizens, communities and NGOs oppose a future course that is based on fossil fuels.

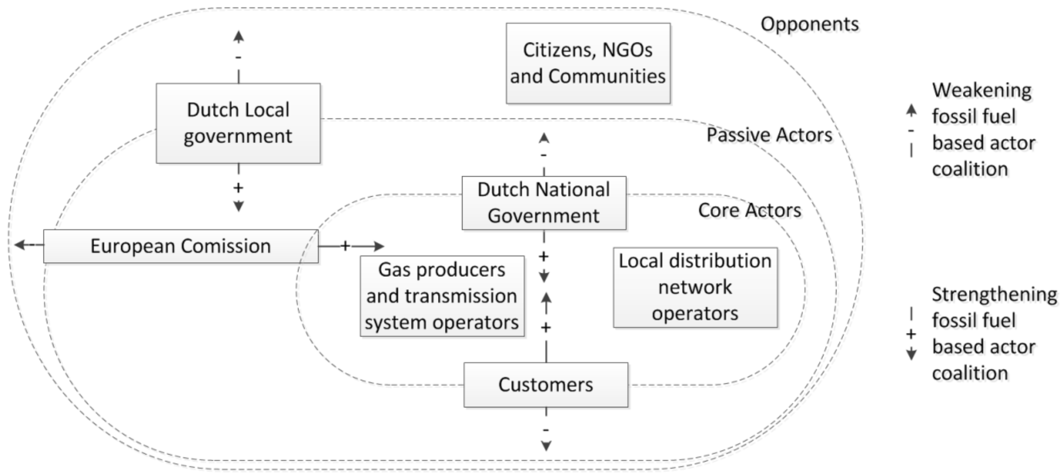


Figure 6.3: Actor position given a fossil fuel based course of development

6.3.2.2 Aiming toward Security of Energy Supply

The preparation for an energy crisis and the foregoing change of mindsets that is represented by a fear of energy scarcity is the second major course of future development. As illustrated in figure 6.1 this course can be entered from the current state or an intermediate state of the future. It can be initiated, for example, by the disillusion that fossil fuels, and especially unconventional gas, will not last as long as initially predicted. As a result, European governments converge and unite to preserve their power position against gas producing countries. Likewise, the European commission and the Dutch national government approximate. Moreover, the fear of an energy crisis causes increasing gas prices and a diversification of the energy supply, which is supported by policies of the Dutch national government. The resulting built-up of sustainable energy sources is appreciated by citizens, communities and NGOs that support renewable energy sources and experience an increase in their voice, thus power position. Nevertheless, those actors still criticize the combustion of gas as a common practice. Thus, they are considered in figure 6.4 to have a neutral to positive attitude towards this course of development. Besides, renewable power sources still have a limited market share because they are only one of the means to secure energy supply. Customers of gas and local governments have a negative to passive attitude towards the securing of energy supply because they are or are not convinced by its reality but oppose its implications. For example, customers of gas are concerned by a potential increase in gas prices. Local governments might withstand the increase of renewable power production due to the implied increase of wind turbines in their province, causing social unrest. Gas producers and transmission system operators are likely to regard an increasing concern about energy security as negative because it decreases their market share due to an increased decentralization of energy production. As a result, they are prone to lobby against this development. In contrast, distribution network operators are less affected by a course towards the securing of energy supply because houses will remain connected to the gas distribution network. Thus, they are considered to have a neutral attitude towards this major course of development.

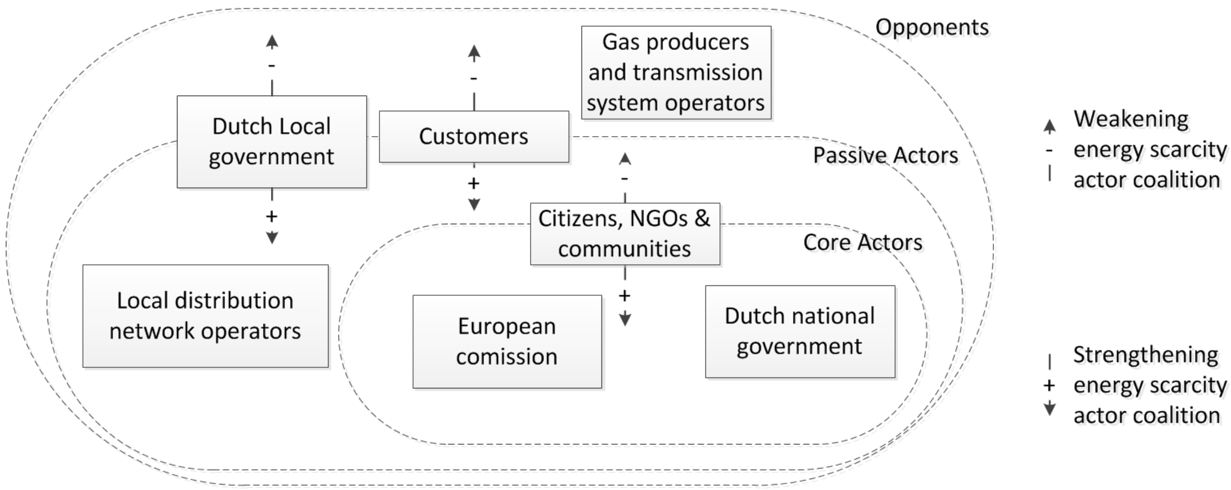


Figure 6.4: Actor positions for the major development of energy scarcity

6.3.2.3 *Aiming towards Sustainable Development*

When aiming towards sustainable development, consumers are likely to play a crucial role by producing their own energy, thus becoming self-sufficient. As a result, they do not connect their houses or industry to the gas grid anymore but produce gas or electricity locally. Citizens, communities and NGOs accord with this development to a large extent and support the initiative of gas consumers by lobbying. Gas producers and transmission system operators are assumed to have a neutral to negative perception of sustainable development, depending on the strictness of policies regarding the combustion of natural gas. However, in accordance to (Weidenaar et al., 2012) it is assumed that the centralized combustion of natural gas in combination with CCS is permitted. In contrast, local distribution system operators are likely to oppose sustainable development for two reasons. First, many consumers become self-sufficient and their connections to a local gas grid are not necessary anymore. Second, policies are likely to forbid the local combustion of natural gas in order to meet emission targets. For both reasons the local distribution gas grid is becoming unnecessary. The authority actors are likely to act in concert given the case of sustainable development. Therefore, the European commission introduces policies that impose emission targets for countries. The Dutch national government has a neutral to positive attitude towards sustainable development as it needs to meet these targets and is likely to approach them by penalties for fossil fuel based technologies and subsidies for renewable energy technology. On the other hand however, it fears to damage the competitive advantage of the companies of the Dutch national gas sector and the impact on the Dutch economy. Dutch local governments are neutral but can take a positive or negative attitude towards sustainable development, based on their local circumstances. In this analysis local governments are yet considered as one actor group, which represents the general notion of local governments, likely to favour sustainable development.

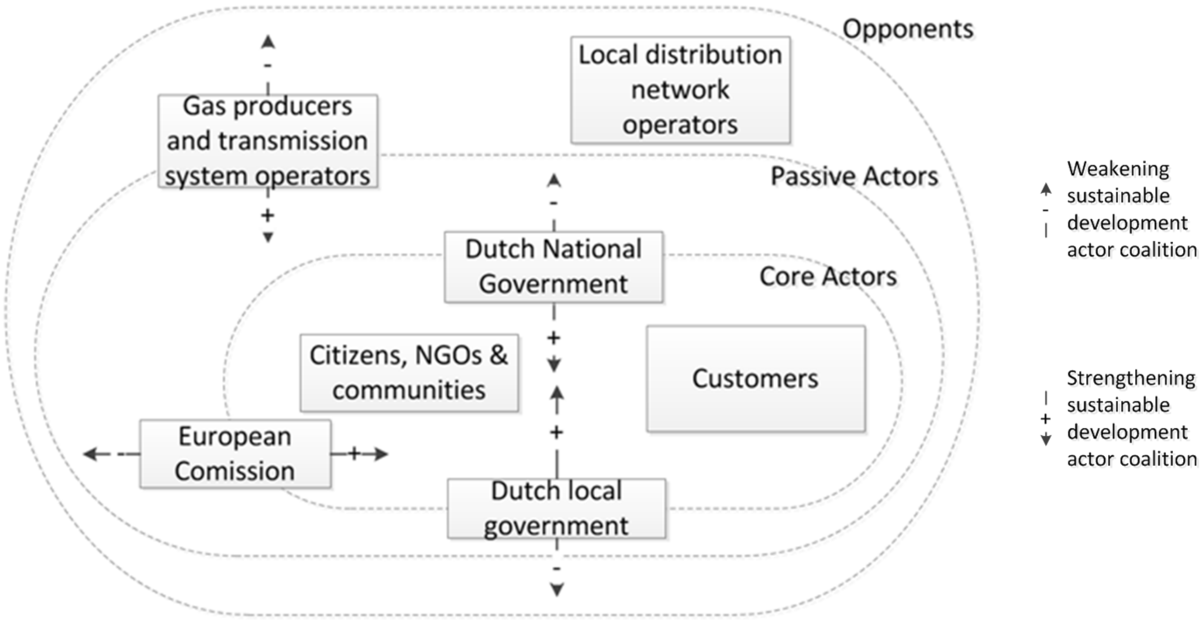


Figure 6.5: Actor positions for the major development of sustainable development

6.3.2.4 Systematic Variation of Variables

The following subsection analyzes the performance of the different integration options in terms of varying weights. Therefore a diagram, equal to figure 3.4 is set up with Microsoft Excel and Visual Basic. With an accuracy of 0.5 the diagram incorporates all possible distributions of weight, adding up to a total of 100 percent. As for figure 3.4 and 6.2, the weight for the technical dimension is fixed for every triangular diagram. In order to account for changes in weight of technical indicators, the weight for the technical dimension was gradually raised from 5 to 70 percent. Thus, 14 triangular diagrams were created. In the following, a selection of 6 diagrams is described that represents the most significant effects of incremental changes in the technical weight.

When increasing the technical weight from 5 to 15 percent the solar reforming of methane, the Superwind concept and Micro CHPs occupy the first ranks, at all possible weighted distributions. When the technical dimension is weighted with five percent solar reforming of methane ranks first in the majority of all potential distributions. The Superwind concept comes more and more into play as soon as the PES weight overcomes 20 percent. This breaking point rises with an increasing environmental weight. As soon as the environmental weight is above 70 %, the solar reforming of methane scores best, for any possible distribution of the remaining weights. When the PES dimension is weighted between 30% and 55% the Superwind concept occupies the first rank. At any weight for the PES dimension that exceeds 55%, Micro CHPs gain increasing importance with a decreasing weight of the environmental dimension.

Given that the weight for the technical dimension increases to 15 percent, the aforementioned boundaries between solar reforming of methane and Superwind shift slightly, whereas the regime of Micro CHPs remains the same. The Superwind concept crowds out some share of the solar reforming of methane at distributions where local PES weight is above 18 percent and environmental weight is below 75 %. At a technical weight of 15% the majority of distributions results in a first ranking of the Superwind concept. Figure 6.6 illustrates these developments in highest rankings among the three options when increasing the technical weight from 5 to 15 percent.

Most interesting for a decision maker are the boundaries between the differently coloured areas. Also, it is important to keep in mind the insight provided by figure 6.2. According to that illustration, an actor coalition of sustainable development, in the gray area to fossil fuel, or even a fossil fuel based regime would select the solar reforming of methane or the Superwind concept. A slightly different coalition that aims towards a fossil fuel based development but is rather oriented towards energy scarcity would prefer the Superwind concept. An actor coalition that is concerned with the security of energy supply would select Micro CHPs, and in its bordering gray areas the Superwind concept, or Micro CHPs.

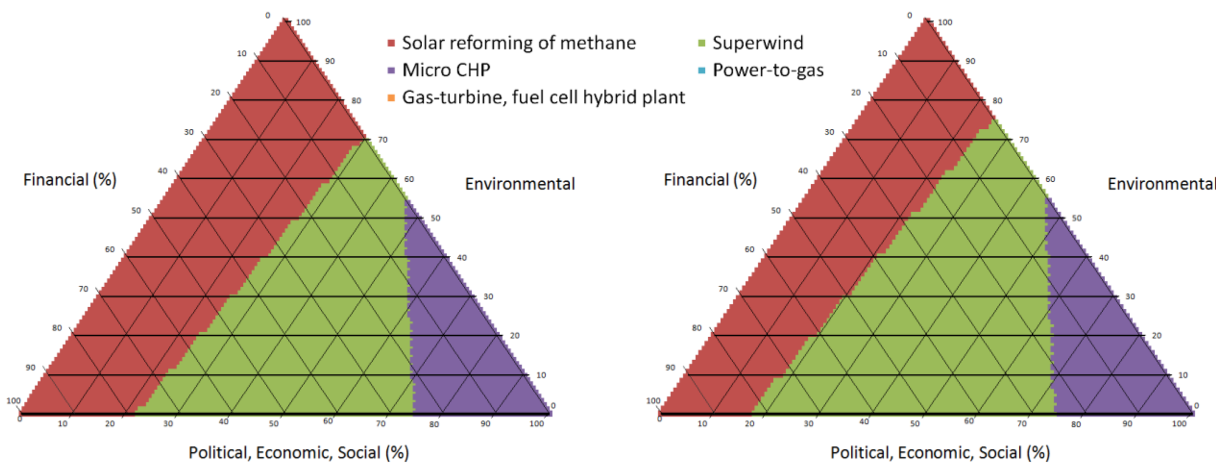


Figure 6.6: Increase of technical weight from 5% to 15%

The next phase starts at a weight of technical indicators of 20 percent, ends at a technical weight of 45 percent and is illustrated in figure 6.7. At a weight of 20% for the technical dimension, the effects that broaden the area of the Superwind concept progress further, whereas the regime of Micro CHPs remains almost constant. Besides that, the gas turbine, fuel cell hybrid plants occupies an area at the left corner of the triangle. This is illustrated by the small yellow area within the left diagram of figure 6.7. With an increasing technical weight, all described effects carry on.

First, the gas turbine, fuel cell hybrid plant grows in importance from the left corner to the right side and top of the triangle, where only a small area remains occupied by the solar reforming of methane. The Superwind concept remains at the first rank with a decreasing importance for PES and an increasing importance for environmental aspects. Micro CHPs remains top scored around the right corner of the triangle, where the PES dimension is rated high, the financial dimension is rated low and the environmental dimension's weight varies. After this transition the next phase begins.

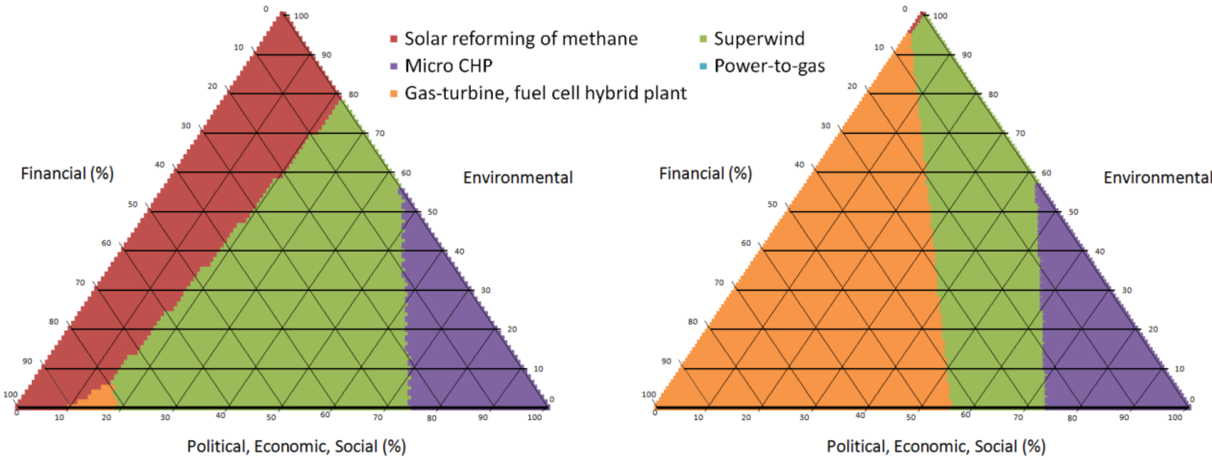


Figure 6.7: Increase of technical weight from 20% to 45%

At a technical weight of 50 percent, the solar reforming of methane is crowded out completely by the gas turbine, fuel cell hybrid plant. With a further increase of the technical weight by 5%, to 55% in total, also the Superwind concept is crowded out. Both states are depicted in figure 6.8. Progressing from the state as illustrated in the right triangle of figure 6.8 to the right outer edge of the pyramid, the gas turbine, fuel cell hybrid plant is best at every potential distribution if the technical dimension is weighted with 70 %. It is necessary to recognize that the increase of the technical weight from 45% to 55% has a much more critical impact on the first rank among all technologies than the previous rise from 20% to 30% or 30% to 40%.

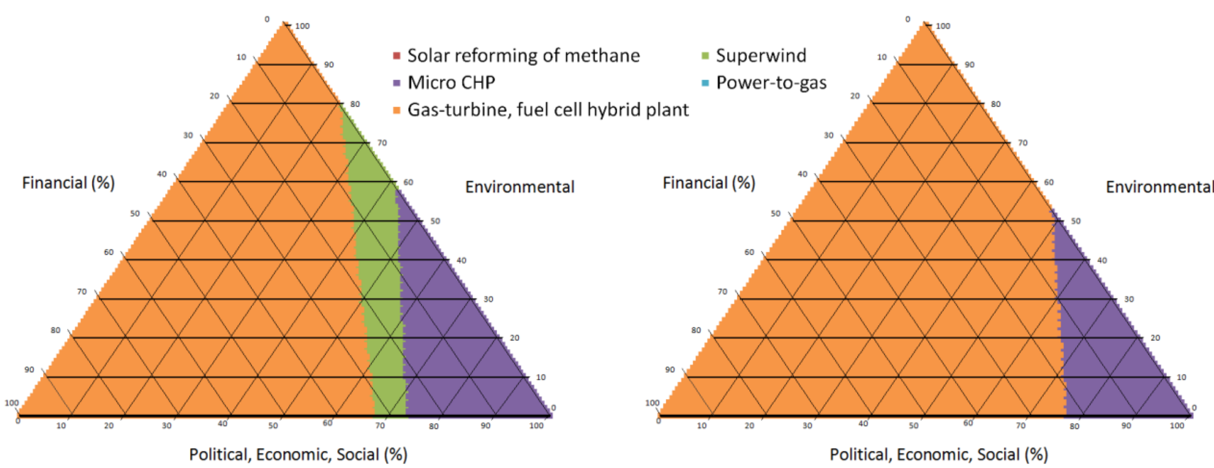


Figure 6.8: Increase of technical weight from 50% to 55%

This analysis suggests that the solar reforming of methane is the matter of choice for a sustainable regime, Micro CHPs are most preferable for an actor coalition that is concerned with the security of energy supply and hybrid gas turbine fuel cell systems are most preferred by a fossil fuel oriented actor coalition. The Superwind concept serves as an intermediate solution as it ranks first in the centre of the triangle, up to a technical weight of 45%. Given that all dimensions are rated equally, it is one of the most preferable options in all gray areas between the regimes of the major courses of development. Thus, it can be considered as a compromise for most weight distributions. It is most significant that the power-to-gas concept is not the most preferred option at any possible distribution of weights. This aspect needs to be explained by the fact that the analysis neglects the dimension *dynamics of technological development*, as explained in section 3.2.7. Thus, when neglecting all previous and existing interests the power-to-gas concept is not the matter of choice for further investigation.

6.4 Fostering Sustainable Development

The following section describes how to foster sustainable development. Thus, it is outlined what actions could be taken in order to avoid a future path that is fossil fuel based or solely concerned with the securing of energy supply but to arrive at the states 'RE', 'CC' and 'sustainable rethinking' of figure 6.1. As reflected in many concepts, such as the 'tragedy of the commons', sustainable development is a preferred way of future development but does not necessarily occur if all actors act in their own interest. For this reason, this section shifts to a normative perspective by describing how to reach a future state that is preferable from the author's point of view. More specifically, the section addresses how the most sustainable technology, that appears to be the solar reforming of methane, can be further developed. To do so, four dimensions of analysis are considered interrelated. They are typically used in the process of backcasting to develop future pathways after formulating a future scenario (Quist & Vergragt, 2006). Therefore, they are designed to be complementary and to cover a magnitude of parallel developments.

6.4.1 Required Changes

The following four subsections describe the content of all of these dimensions and analyze the changes necessary. Subsequent short-, mid- and long-term actions are suggested for the Dutch gas sector to develop sustainable, by utilizing the solar reforming of methane.

6.4.1.1 Technical Changes

The technical dimension describes what changes are required regarding the technological development and implementation of solar reforming plants and additional technologies. The large- scale implementation of the solar reforming of methane requires a range of technical changes to be made.

First, plants for the solar reforming of methane need to be built, preferably in countries with an abundance of sun. According to figure 6.9, which maps the insolation around the world, Spain and countries in North Africa appear to be most attractive for this undertaking. They have an insolation of up to 3000 kWh/m^2 and a fair geographic proximity to the Netherlands (Cinti & Hemmes, 2011; Mahmah et al., 2009). Especially, huge areas of the desert are inhabited and face an enormous solar radiation. The exploitation of these solar energy resources through the construction of large-scale power plants is a massive opportunity to *"ensure the necessary energy provision for many countries throughout the world"* (Mahmah et al., 2009).

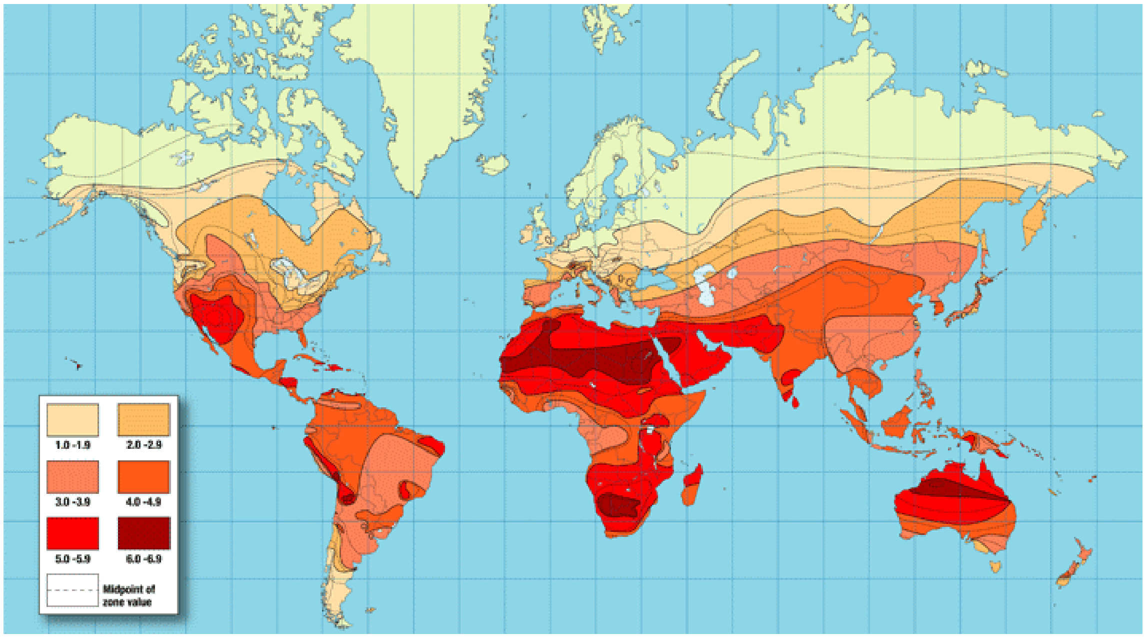


Figure 6.9: World insolation (RED, 2009)

Second, an infrastructure needs to be built up that can transport the produced hydrogen to the end-user. Generally, there are several ways to do so, transporting liquefied hydrogen per ship or compressed hydrogen per pipeline being the two methods most often mentioned.

Third, changes need to be made to the Dutch gas infrastructure to allow accommodating the new source of hydrogen. More specifically, distinct infrastructure for hydrogen needs to be built up and natural gas pipelines need to be able to cope with a mix of natural gas and hydrogen to a certain share.

Fourth, changes need to be made to the consumer side of the gas value chain, to enable consumer devices of several sectors to run on hydrogen.

6.4.1.2 Cultural-Behavioural Changes

As formulated by (Mahmah et al., 2009), referring to (Goltsov et al., 2006), “transition from hydrogen energy to hydrogen economy and then to hydrogen civilization will lead to the global transformations of all aspects of human existence, human mentality, human society, environment and industrial development …”. Having said that and given that energy is a substantial, integrated part of society, the large-scale introduction of solar reforming of methane to hydrogen requires changes in the culture and behaviour on an international scale.

First, cultural-behavioural changes are required from the inhabitants of ‘solar reforming countries’ who need to accept the implementation of solar reforming to supply hydrogen to Western European countries. This holds in particular for countries of Northern Africa which face high discrepancy in living standards compared to European countries and are politically unstable. In those countries, the reforming of methane and subsequent transport of hydrogen need to be deeply accepted by the population to avoid disruptions in hydrogen supply due to social unrest.

Second, cultural-behavioural changes are necessary in those countries that are planned to consume the produced hydrogen, for this analysis the Netherlands. One of the main concerns in this regard is the safety of hydrogen as it is very volatile and highly inflammable. Especially in the past, the idea of using hydrogen as a fuel for transportation has often been considered as a threat to the passengers' safety. Even though research shows that this is not necessarily the case anymore, it has also been concluded that users tend to demand more information on the implementation of hydrogen in society (Nagle, 2008).

Third, the most challenging cultural-behavioural change is of international scale as the production and transportation of hydrogen require the collaboration of a multitude of countries to ensure energy security. Thus, it is required for many nations to curtail their body of thought regarding national borders and the individualistic energy balance of countries. Given the fact that the solar radiation in the Sahara desert would suffice to supply more than 150 times more energy than is currently demanded on earth (Trieb & Müller-Steinhagen, 2007), the idea of energy system bounded to national borders seems less promising. Nevertheless, given the above mentioned aspects it appears as very challenging from a socio-cultural perspective.

6.4.1.3 Structural-Institutional Changes

The structural-institutional changes affect the 'rules of the game' that have guided the Dutch gas sector during the lasts decades. These rules have to change in order to accommodate the transition towards hydrogen production and transportation from North Africa. There are two main rules that currently dominate the mindset and therefore require adaptation.

First, apart from some interactions with surrounding countries, the current socio-technical system related to the gas sector is limited to the national boundaries of the Netherlands. In the past, the Dutch gas sector has focused mainly on the Northern part of the country as a centralized source of gas production. According to different scenarios of hydrogen use in future *"…and looking at the hydrogen vision of several stakeholders eight hydrogen production centres outside the EU25",* from 5 types of sources appear of particular potential for the European Union (Mahmah et al., 2009). The production centres as well as the corresponding types of sources are illustrated in figure 6.10.

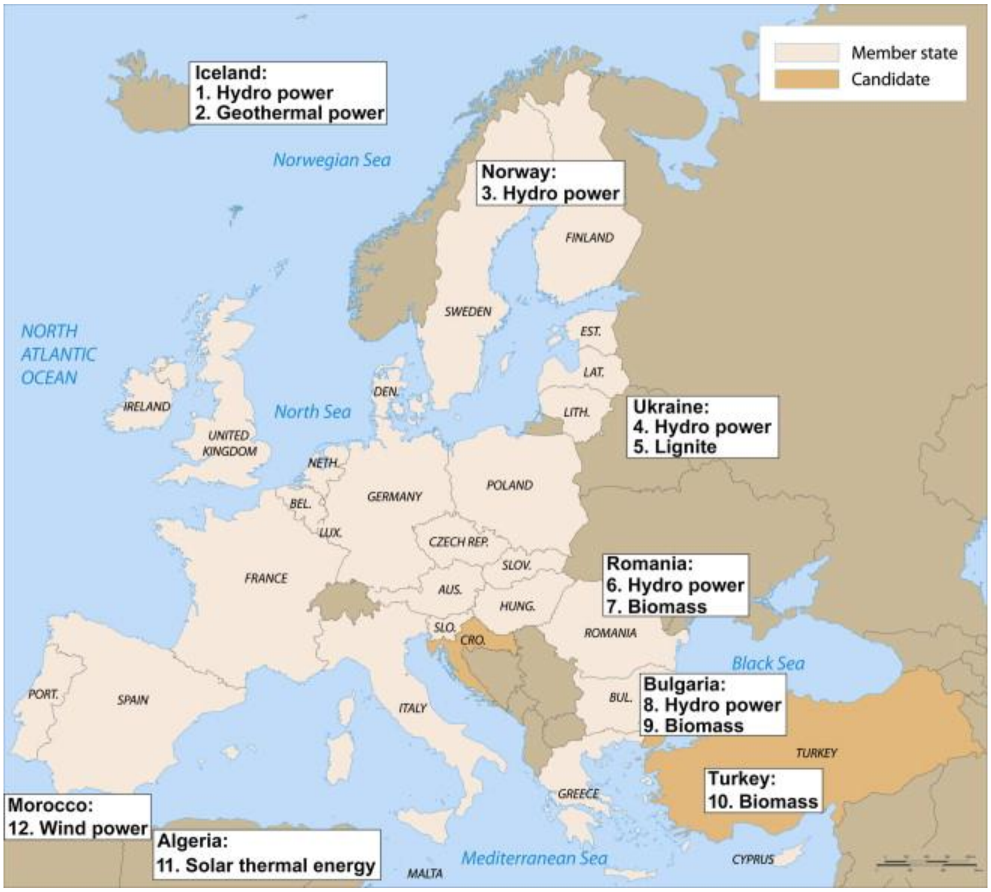


Figure 6.10: Selected hydrogen production centres (Mahmah et al., 2009)

In accordance with the above scenarios it is argued that the national focus of the Dutch gas sector needs to shift to an international level and readjust to the South of Europe and North Africa, because those countries will gain increasing importance in future (Mahmah et al., 2009). Thus, to maintain an important role in future the Dutch gas sector should abandon its current paradigm and expand its area of influence to an international scale by enabling the implementation of solar reforming of methane in sun-intensive countries.

Second, the Dutch gas sector has focused mainly, if not solely, on gas. However, the solar reforming of methane requires expertise on solar energy technology, and future developments are likely to require a broad expertise in renewable energy technologies. The Dutch gas sector has to incorporate this expertise in order to enhance its strategic positioning in future.

6.4.1.4 Organizational Changes

"Several recommendations of the experts indicate that the key to optimal utilization of this vast subterranean resource needs to be sought in the elaboration and implementation of development strategies that maximize foreseeable benefits and minimize deleterious effects" (Mahmah et al., 2009 referring to Janci, 2003). Consequently, the organizational changes required for the implementation of solar reforming plants in North Africa are of crucial importance. In general, organizational changes describe how the organization of the Dutch gas sector has to change in order to accommodate the remaining dimensions of change.

At large, the Dutch gas sector has to diversify its organization to cope with its new boundaries of gas production. On the one hand this diversification needs to be understood in geographic terms, requiring the integration of the Dutch gas sector in other countries by means of international co-operations, acquisitions or development projects. Regarding this aspect, the transition from natural gas to hydrogen is considered by the European community *"…as a durable link of future cooperation"* (Mahmah et al., 2009).

Therefore, the implementation of solar reforming plants in Africa also affects the subject-related boundaries of the Dutch gas sector, which needs to cooperate increasingly with actors from other sectors such as electric grid operators or companies related to renewable energy technologies.

6.4.2 Identified Measures

The following section addresses what actions should be taken in the short-, mid- and long-term in order to reach from the current situation of the Dutch gas sector towards a large scale implementation of solar reforming of methane.

6.4.2.1 Short-Term (< 10 years)

The short-term covers the timeframe from the current point in time to the next 10 years, thus until 2023.

Technical

In order to drive forward the implementation of plants for the solar reforming of methane, some technical aspects, which are also addressed in the EDGaR program, need to be further researched in the short-term. For example it should be researched how to increase the intermittency of hydrogen production, how to store and distribute hydrogen without leakage, how to control its injection to the grid and how to transport it together with natural gas. Moreover, research needs to address the economic aspects of solar reforming of methane. Thus it needs to be investigating how to make hydrogen, produced in North Africa, cost effective. The latter aspect is strongly related to the experience gained with this technology. It is therefore proposed that for the short-term a pilot plant should be built in Spain which should shift its focus over time from testing to commercial application. The hydrogen produced in this plant can be injected into the Spanish gas grid or shipped liquefied to the Port of Rotterdam.

For the short term it is suggested that no infrastructure should be built from Africa to Europe yet because the construction of an intercontinental hydrogen pipeline requires some more experience in the handling of hydrogen and, because of its high investment, should be built in a manner that accounts for the long-term development of hydrogen supply from Africa (Mahmah et al., 2009).

In contrast, the Dutch gas infrastructure should be prepared for the uptake of hydrogen. To begin with, the share of hydrogen as part of the pipeline mix should be gradually increased, which would raise the energy value of the gas mix that is supplied by pipeline. Recalling that the city gas which was produced locally also had a high share of hydrogen, the mix of hydrogen and natural gas in the pipeline can be considered as uncritical to a certain mixing ratio. However, before raising the share of hydrogen above this edge, consumer devices need to be gradually prepared for this change. A promising start to begin this transition with is the increased usage of hydrogen for the sector of transport or electricity. In terms of transport, the network of hydrogen filling stations should be further extended. In doing so it should also account for an immediate increase of public transport purely based on hydrogen. Regarding the electricity sector, the large-scale cogeneration of heat and power from hydrogen should be introduced, because it is a centralized manner of generation and therefore easy to control.

Socio-Cultural

The socio-cultural measures that are proposed for the short-term mainly address the acceptance of hydrogen usage. As mentioned above, user tend to require more information on hydrogen as a fuel within society (Nagle, 2008) and experience from the introduction of bio-based gasoline in Germany shows that weak information of car users can result in a hampered adoption of a new fuel (Schütte et al., 2011). Therefore, when introducing hydrogen as a fuel for transportation it is crucial to inform users about its merits. This is especially the case for hydrogen because it will not be compatible with current car engines but will require the adoption of new engine technology. Aspects such as the life expectancy, performance and reliability of these engines are expected to be main concerns for users who had to adopt this new technology. The introduction of public transportation based on hydrogen can serve this purpose greatly because key information can be provided to the users during the transport. It is argued that people are likely to be less concerned about buying a car themselves that is running on hydrogen, when they have experienced the successful application of hydrogen in buses for some time. Besides that, broad information campaigns including television programs, posters and information desks at strategic points should be used to further increase the acceptance of hydrogen within the Dutch society.

Part of these educational efforts should also prepare the Dutch population for the fact that the cooperation with North African countries can be highly beneficial in order to counter a potential energy crisis of Europe in future.

An important means to do so is to communicate the importance of sustainable development and to pinpoint its global range. Raising awareness of sustainability, and highlighting also the economic benefits it offers, can support greatly the corporation among countries. Especially in the beginning of a transitional phase from a fossil fuel based system to an energy system which operates fully on renewable sources, the mindset of people has to allow for a change to hydrogen because teething problems might require higher understanding and tolerance.

In order to enable these socio-cultural changes, it is suggested to integrate sustainable development stronger as a compulsory part in educational system of participating countries of Europe and North Africa. As being already the case in some Dutch universities, sustainable development should be illuminated from several perspectives and highlighted to be a resolvable problem. Thus, the trust in renewable energy sources should be strengthened, especially for regions where inhabitants face a high financial burden, so that they appear naturally to be part of the solution and promising from an economic perspective. This educational process has also to take into account several actor perspectives and account especially opponents of renewable energy systems. Furthermore, it needs to be taken care that the need for sustainable development is not presented as a problem of energy scarcity because this might have an adverse effect on international collaboration. Lastly, system integration should be emphasized stronger as a solution that allows for synergies and therefore considerably eases the process of sustainable development. Together, the socio-cultural changes expected from these measures should lay the foundation that allows for physical steps to be taken.

For the short-term it is not considered as a crucial measure to create acceptance among North African populations for the construction of methane reforming plants. However, efforts towards this direction should start at the end of the short-term, being more of preparative nature and aiming to obtain an impression of the people's mindset regarding the supply of Europe with hydrogen. Therefore, surveys or meetings of focus groups can be conducted.

Structural

The latter efforts that aim at the acceptance of methane reforming plants in North Africa should be accompanied by the establishment of a spin-off research centre on gas in North Africa. Doing so not only enables the creation of local knowledge, employment and adoption of hydrogen in North African countries but also grants the Netherlands to become a strategic partner for those countries which would be capable of producing a major share of Europe's fuel in future. Algeria is particularly promising as a first country to participate from the African continent because it has been *"…a major gas producer with important links to Europe"* (OPEC, 2012). Given the fact that several gas pipelines have already been established between Algeria and European countries, also Spain, Algeria appears in several future scenarios as one of the main gas suppliers of Europe (Wietschel & Hasenauer, 2007). The support of Belgium, France and Spain as the first participating countries is required in order to connect the Netherlands to North Africa, by means of a pipeline. Moreover, the solar radiation of Spain allows for the development of a first commercial application as described previously.

Furthermore, the extension of subject-related boundaries should be initiated in the short-term. This could be done by subsidy schemes aiming at end-consumer products that are propelled by hydrogen. Typical examples of these products are hydrogen driven cars as well as portable fuel cells.

Given that these products require an increased effort of technological development, which implies costs and risks for developing companies, the implementation of financial incentives, for example subsidies, allows companies to dedicate more resources to the development of these technologies. As a result, the time to market of technologies is likely to decrease. On top of that, it is expected that the provision of subsidies attracts entrepreneurs who are likely to innovate radically because they are not bound to the current paradigm of natural gas. The implementation of subsidies could provide them with necessary financial means which allow for the incubation of their products.

Organizational

To organize the above changes nationally, an umbrella organization should be formed in order to coordinate efforts of key players of the Dutch gas sector. This umbrella organization should represent the interest of the country in front of other countries such as, Belgium, France, Spain and Algeria. In addition, the implementation of hydrogen within the Netherlands can be supported by this umbrella organization to spread the initial risk among several actors.

Together with the representatives of other countries this umbrella organization should initiate a platform whose objective is to drive forward the production and supply of hydrogen from North African countries. It therefore supports Algeria in the short-term with the planning of a solar reforming plant and drives forward the international issues that revolve around the distribution of hydrogen from North Africa to Europe. However, for the short term, the international participation should be limited to the above mentioned countries in order to reduce the political and administrative burden which results from international collaboration.

6.4.2.1.1 Mid-Term (10 – 25 years)

The mid-term ranges from 2023 until 2038. The measures defined for this time period seamlessly built on the efforts of the short-term.

Technical

In the mid-term first plants that reform methane into hydrogen by solar radiation should be implemented in Algeria. Next to that, the construction of biogas plants should be initiated in order to facilitate a reforming of bio-methane in the long-term. Also the involvement of other hydrogen producing technologies that are based on solar radiation, for example the power-to-gas concept, should be investigated.

The total capacity of the solar reforming plants in Algeria is expected to be still limited in the mid-term. Thus, it is assumed that it is possible to feed the produced nitrogen into the natural gas pipelines which reach from Algeria to Europe or to ship the hydrogen liquefied. Distributing the hydrogen produced over several pipelines, which are illustrated in figure 6.11, allows increasing the security of supply from the beginning on (Mahmah et al., 2009). However, in the mid-term also the construction of distinct hydrogen pipelines from Africa to Europe should be initiated in order to be able to transfer pure hydrogen when the capacity of North African plants is too high to be fed into the gas grid.

Figure 6.11: Gas pipelines across Mediterranean and Sahara (Wikimedia, 2011)

After introducing hydrogen to the Netherlands through public transportation, the mid-term stipulates that further infrastructure for hydrogen should be built in the Netherlands. It is suggested that ‘hydrogen zones’ are implemented in new urban areas and at strategic parts of the country, such as city centres, which are equipped with hydrogen storages and filling stations. This allows accommodating the operation of an increasing number of hydrogen propelled cars and other consumer products. To facilitate this consumer-oriented development a transmission pipeline for hydrogen as well as some distribution pipelines should be constructed. Besides, a growing number of homes need to be connected to the hydrogen grid. Later development should subsequently focus on further refining the network of hydrogen distribution and storage. Also, it is necessary to explore the production of hydrogen from local sources, for example from power-to-gas, in order to diversify the hydrogen mix of the country and to increase the security of supply. Regarding the power sector the large-scale cogeneration from hydrogen should be further pursued. Therefore, the capacity of hydrogen propelled power-plants needs to be increased.

Socio-Cultural

Given that the capacity of solar methane reforming plants is expected to increase in the mid-term, these developments should be accompanied by efforts to increase the acceptance of these plants by stakeholders in North Africa. An important measure to do so is the creation of local knowledge regarding the construction, maintenance and operation of these plants. Consequently, the employment that results from the construction of solar reforming plants can mainly benefit African countries, whereas European countries are rather understood as knowledge providers.

To foster the acceptance of hydrogen by users, first hydrogen-based products in the market should be subsidized because the willingness to pay by private users might not be as high as for gasoline based products yet. However, shortly after their market entrance hydrogen propelled cars and other products related to hydrogen are likely to be more expensive than products based on current energy carriers, such as gasoline.

Also, the geopolitical development should be further improved during the mid-term, for example through an active exchange among the participating countries. One means to do so is the creation of events, such as conferences, around the production of hydrogen by the established international platform. In addition to the Netherlands, Belgium, France, Spain and Algeria as the first participants, more countries of North Africa and Europe should join this coalition. From the Tech Mining part of the thesis, Switzerland, the United Kingdom, Germany and Italy appear as particularly promising partners to increase the body of knowledge within Europe. Regarding the African member states, Morocco, Tunisia and Libya offer attractive geographic characteristics for the solar reforming of methane.

Structural

For the mid-term the geographic boundaries of the gas sector are expected to be further broadened. To do so, the Dutch gas sector should actively seek to expand its operations in foreign countries which were suggested for the short-term. Next to the establishment of spin-off research centres in other countries, the three technical universities (3TU) should thus found a spin-off in one country of choice and pursue an active partnership around the topic of gas and renewable energy, including common classes, exchange programs and events. This way, an academic relation to the North African energy sector can be initiated.

On the other hand, the Dutch gas sector should also aim to diversify its hydrogen sources by incorporating other countries such as Norway and Iceland that could produce hydrogen from hydropower or geothermal energy, respectively. This way, instead of remaining a round-about for natural gas, the Netherlands can take the lead in becoming a hydrogen distributor in Europe.

After subsidizing the development of hydrogen related products in the short-term, the mid-term should focus on the implementation of those technologies in the market, in order to broaden the subject-related boundaries of the Dutch gas sector. Thus, there should be a change in subsidies, which previously targeted companies, towards the demand side of the market. Considering the implementation of solar panels in Germany (Jacobsson & Lauber, 2006), it is argued that the subsidizing of hydrogen products could initiate a feed-back loop, which would allow customers to commit to hydrogen related products from the beginning and ease their market implementation. Having said that, demand for hydrogen would increase and the establishment of hydrogen in society would be accelerated, causing again an increase in demand for hydrogen.

Organizational

In the short-term the umbrella organization of the Dutch gas sector should be further diversified, including players related to other sectors such as transport, agriculture and electricity. As a consequence, the aspects covered by all companies of the umbrella organization diversify further which allows for the establishment of a robust energy mix within the Netherlands. Also, the organization should remain scouting for new technological developments which are likely to enable the transition to hydrogen as an important fuel. To do so, different divisions and subordinate departments should be created, each of them administrating a region or country, respectively.

6.4.2.1.2 Long-Term (> 25 years)

Technical

In the long term, solar reforming plants should be up and running in several countries of North Africa serving European countries with hydrogen. Next to natural gas, bio-methane plants should be established to serve an increasing share in feeding these plants. Also, the construction of other solar-based technologies should be increased to diversify the energy mix.

In the long-term, several pipelines are lead from North Africa to Europe and ensure the security of hydrogen supply through several routes. Moreover, pipelines should be constructed from Iceland and Norway to the Netherlands to deliver additional hydrogen.

On top of that, electricity and hydrogen in the Netherlands is produced via renewable sources whereas the remaining methane is reformed to hydrogen because this local process has less global warming potential than the decentralized combustion or leakage of natural gas. As a result, the Netherlands can serve its total electricity demand through large-scale cogeneration plants propelled by hydrogen together with other renewable energy technologies. Besides, the country can trade a hydrogen surplus with other European countries, supplying a large share of their gas demand. Also, customer devices propelled by hydrogen, such as cars or portable fuel cell products, are applied on a broad scale. However, the further widespread among the Netherlands and other European countries requires the continuous refinement of the national hydrogen distribution system as well as international transmission pipelines during the long-term.

Socio-Cultural

With the beginning of the long-term solar reforming plants are expected to be generally accepted in countries of North Africa, because they are recognized as one of the main pillars of the North African economy providing employment opportunities and prosperity to the area. On the one hand it is also expected that a growing capacity of solar reforming plants and other energy technologies requires continuous effort to maintain acceptance among the population. On the other hand it expected to require the involvement of a growing amount of trained labour and specialists. Therefore, it is suggested for the long-term to increase the number and depth of educational programs, of different levels, in North Africa, which are related to renewable energy technologies.

Within the Netherlands, the technology-push of hydrogen-based technologies is expected to develop into a market-pull before the long-term. As a consequence, hydrogen-based technologies are widely accepted and entrenched in society which drives down their costs and allows for the cut-down of subsidies. Nevertheless, for those areas in which fossil fuel-propelled products still prevail, taxes should be introduced which penalize their purchase.

As a result of the North African–European energy system, both regions are expected to move closer together. As a result, it should be prepared for further co-operation, benefiting other sectors through free-trade agreements or adjuvant immigration policies for academics. These measures are expected to create a virtuous circle for the development of North African countries and the collaborative mindset of Europe and North Africa.

Structural

During the long-term the Dutch gas sector should not broaden its subject related boundaries further but begin to shift away from its current field of expertise – natural gas. Assuming that the rise of hydrogen and the environmental concerns related to the exploitation of shale gas and coal-bed methane hamper the exploitation of the last remaining gas reservoirs, this change is inevitable to remain the strategic relevance of the Dutch gas sector in the long-term. In so far, the traditional gas sector is not expected to be existent anymore but rather to continue as a conglomeratic energy sector. At this stage, many hydrogen applications are not dependent on subsidies anymore, which allows for strategically subsidizing incremental innovations that have potential but have not reached mass market application yet. These innovations can focus on several forms of renewable energy technology.

New alignments of the geographic boundaries of the Dutch gas sector mainly aim to further develop additional regions in North Africa and Iceland as well as to develop the East European market. On top of that, the Dutch gas sector should start to export its knowledge to other regions of the world. Not in relation to its own energy supply but to sell the knowledge gained during its own transition. The latter suggestion coheres with the aim of the EDGaR project to a large extent.

Organizational

The organizational changes that are necessary for the Dutch gas sector in the long-term should aim to close the foregoing development and change from a growing energy sector to a rather static administration. Therefore, new economic opportunities, which are likely to occur from the collaboration with North African countries, Iceland and Norway but are not related to the energy sector as such, should be transferred to a new umbrella organization that allocates the required tasks. This way, new instabilities are not as prone to impact the established energy system.

6.4.3 Stakeholder Analysis

In order to enable the above measures, the strategic formation of actor coalitions is a crucial step. Especially the inclusion of actors that have a neutral attitude towards sustainable development but a high power position is very important. Also, those actors need to be managed that are against an increased share of renewable energy sources as part of the Dutch energy mix. Next to negotiating compromises with these opponents, they need to be accommodated when important achievements towards sustainable development are reached (De Bruijn & Heuvelhof, 2008). The following stakeholder analysis aims to explore these aspects and to define what stakeholders should initiate the above measures towards sustainable development. Therefore, it is built on the stakeholder analysis of section 6.3.2.3.

Figure 6.12 illustrates the seven main actor groups analyzed previously. They are classified in accordance to their attitude towards sustainable development as described in section 6.3.2.3.

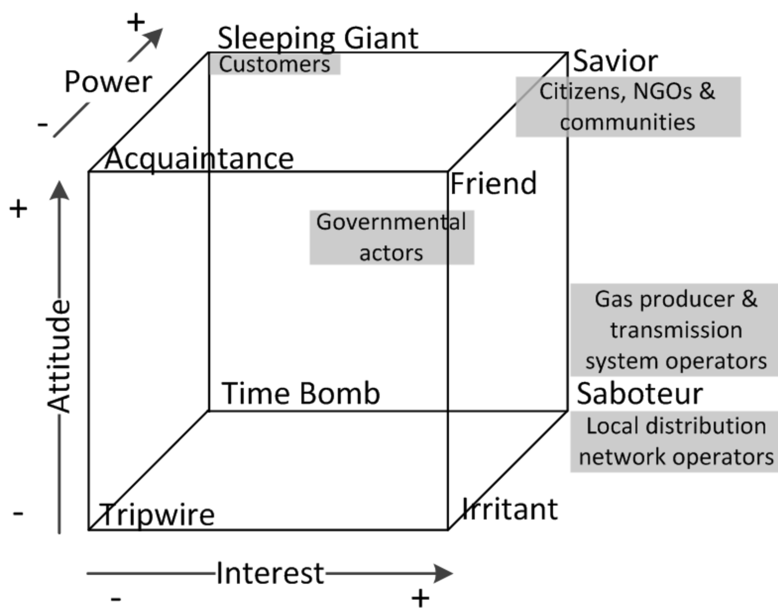


Figure 6.12: Actor positions regarding sustainable development

To simplify the illustration, the European commission, the Dutch national government and local Dutch governments are summarized as governmental actor and illustrated at the back wall of the cube. The reason is that all of them have an advance power position but due to their holistic political agenda, sustainable development does not experience their exclusive attention. Thus, their attitude and interest regarding sustainable development cannot be considered as persistent. In order to foster sustainable development the support of governmental actors can thus be of great advantage and the attention of these actors should be caught. Actors that have been frequently doing so are citizens, NGOs and communities. Their attitude and interest towards sustainable development is positive. However, on their own they have only a limited power position and thus should keep raising the attention of other, more influential actors. Customers, rated as sleeping giants, are another group of actors, citizens NGOs and communities should focus on. Assuming that customers would collaboratively support the production of hydrogen by integrating sustainability as an important criterion in their decision making process, other actors were forced to change practices which are motivated purely financially. Despite the curious attitude of many gas customers for hydrogen as a means towards sustainable development (Nagle, 2008), it is not of high interest to them at the current point in time. As a result, gas producer & transmission system operators as well as local distribution network operators have been able to defend their position as saboteurs in terms of sustainable development.

Research facilities which have been left out in the above stakeholder analysis can accelerate the efforts of other stakeholders greatly by providing specialized knowledge relevant for the implementation of solar reforming plants in North Africa and further renewable energy technologies in other regions. Thereby, private and public research institutes are also a valuable participant for the aforementioned umbrella organization of the Netherlands or the international platform of participating countries. It is suggested that the EDGaR program coordinates with other programs in order to create a common base of knowledge and spread the costs and risks of research. For example, institutions of the Roads2Hy project are potential partners of strategic importance because their research has focused purely on topics related to the transition towards a hydrogen economy (Roads2HyCom, 2009).

6.4.4 Embed Results & Stimulate Follow-Up

The above steps indicate how the results of the MCDA and the pathway analysis can be used jointly as an input for the process of a normative backcasting analysis. Next, it is important to specify the suggestions made in the backcasting above, to test for their feasibility and to implement the results. For example, it is important to determine the required quantity of hydrogen that needs to be supplied during different periods of the day, month and year. Also further partners of the Dutch umbrella organization and international platform should be approached and sources of funding should be defined. However, these steps are beyond the scope of this thesis and, next to a further desk study, suggest a participatory approach (cf. Wangel, 2011a). For example, a focus group with participants from the EDGaR program, the Roads2Hy project as well as representatives from Dutch industry and North African universities could be formed in order to get an impression on how the implementation of solar reforming plants is perceived and how it can be initiated within the short-term. Furthermore, it seems promising to apply the framework of this thesis to further technologies and to investigate a normative approach for other sustainable options, mentioned briefly in the above backcasting. As a result, a set of normative analyses can be conducted which complementarily points at a sustainable energy mix for the Dutch gas sector. The more diversified these efforts are conducted the more likely is their – partial- implementation in future (Quist, 2007).

6.5 Conclusion

This chapter reflects on the results of chapter five against the background of future uncertainties. Moreover, it elaborates on how to pursue sustainable development as one of different possible future pathways of the gas sector. To do so, the chapter is divided in four parts.

The first part defines sectors and factors of development based on which current and future states of the Dutch gas sector can be defined. As a major input for this part serve the future scenarios of (Weidenaar et al., 2012) that are explored as part of the research context of the thesis. Following a simplified approach of Field Anomaly Relaxation (FAR), the sector-factor combinations in this chapter describe the scenarios of (Weidenaar et al., 2012) in terms of their underlying attitude towards sustainability, energy collaboration and economic efficiency. Moreover, the source of energy for each future state is considered.

In the second part of the chapter the current situation and intermediate states, likely to emerge in the short-and mid-term are defined in the same manner (in terms of sector-factor combinations). A main outcome of this process is the identification of three major courses of development that can summarize all potential future pathways identified. These major courses are related to (1) fossil fuels, (2) energy scarcity and (3) sustainable development.

The third part of the chapter builds on this outcome by exploring actor coalitions that are likely to emerge with each major course of development. Moreover, the third part relates each major course of development to assessment dimensions of the previous chapter. Whereas the financial dimension is likely to experience a higher weight in a fossil fuel based future, the PES dimension is argued to be of higher weight in a future scenario dominated by the fear of an energy crisis. The environmental dimension is considered as being preferred if the future focuses on sustainable development. Besides, it is argued that the technical dimension is of equal importance for every actor coalition that might form along a future pathway. The dynamics of development dimension is left out in the analysis of this chapter since it is argued that the development state of a technology does not affect the preference of a stakeholder coalition for a certain technology. At the end of the third part of this chapter, all insights are brought together in six triangular diagrams that demonstrate the most preferable technology, at all possible weight distributions. From these diagrams it can be seen that the solar reforming of methane is mostly preferred in the context of sustainable development, Micro CHPs are most preferred by actor coalitions that are concerned with energy scarcity and hybrid gas turbine fuel cell systems are, next to the solar reforming of methane, a potential option for a fossil fuel focused regime if the technical weight accounts for at least 20 percent. With an increasing technical weight and thus a smaller impact of the other three dimensions, the hybrid gas turbine fuel cell system growth in dominance. It needs to be highlighted that the power-to-gas system looses ground in this analysis because the dimension *dynamics of development* is neglected. This aspect points to the fact that the power-to-gas system might not be the matter of choice if the sunk costs of all past developments would be set to zero. Furthermore, it is important to note that Superwind appears to be a no-regret solution that scores best in the gray zones between the three main regimes and in some areas of the distinct regimes. It gains increasing importance towards the centre of the triangle, which represents a moderate regime that has only a slight preference towards one of the three dimensions.

The fourth part of the chapter addresses how sustainable development can be fostered. As mentioned above, the solar reforming of methane appears to be most sustainable among the options assessed. Thus, this part of the thesis explores how sustainable development can be fostered based on the large-scale implementation of solar reforming plants.

The technical dimension describes what changes are required regarding the technological development and implementation of solar reforming plants and additional technologies. Next to the construction of solar reforming plants in Africa and other countries as well as the build-up of other renewable energy technologies, changes (like biogas plants) are suggested to be made to international as well as Dutch gas infrastructure, which would have to accommodate an increasing share of hydrogen. Moreover, the implementation of hydrogen-based customer products needs to be driven forward. The cultural-behavioural dimension includes all changes that need to be made to the mindsets and habits of people, related to the construction of solar reforming plants in North African countries. Identified necessary changes are an increased acceptance of hydrogen plants in North African countries, the acceptance of hydrogen as a fuel in societies as well as the clearing of geopolitical discrepancies between Europe and North Africa. The structural-institutional dimension is understood as 'the rules of the game' of the Dutch gas sector. Necessary changes identified for these rules are the broadening of the Dutch gas sector from a geographic perspective as well as from a subject-related perspective. The organizational dimension addresses changes that are required in the organization of the Dutch gas sector to accommodate the changes of the remaining dimension. Regarding this dimension, two measures are suggested in the chapter. First, the establishment of an umbrella organization, consisting of diverse players of the Dutch gas sector, which coordinates the national efforts of the Netherlands to drive forward the solar reforming of methane in North Africa as well as the implementation of further renewable energy technologies in other countries. Second, it is proposed to form an international platform to coordinate the efforts of several countries to implement the solar reforming of methane in North Africa. Thereby, the umbrella organization represents the interests of the Dutch gas sector within this international platform.

Based on all four dimensions the chapter defines measures for the short-, mid- and long-term to foster the implementation of solar reforming plants in North Africa, as a means towards sustainable development. Last, the chapter picks up the analysis of the actor coalitions of the third stage of the chapter and pinpoints what actors are likely to, and should, take which role regarding these different measures identified.

With respect to the perspective of the EDGaR program, the insights of the foregoing chapter point out what technology to research to foster sustainable development. Moreover, it demonstrates how backcasting can be applied to operationalize these insights. Based on the analysis provided in this chapter, further technologies can be connected to different, and favourable, future pathways and the backcasting efforts taken can be further specified to foster the implementation of the solar reforming of methane.

The chapter is also of great value for policy makers in general because it demonstrates, based on the concept of social reconfiguration, a novel way how several, diverse actor groups can be incorporated into a MCDA procedure, which is traditionally meant for one single decision maker. Moreover, it provides an insight how future uncertainties can be accounted for, by exploring several potential pathways. Together with the above insights which specify the integration of backcasting to pursue a favourable pathway, the MCDA framework, applied in the fifth chapter, is turned into a strategic tool which not only makes the decision problem more transparent to the decision maker. It also allows for defining actions which enable a future pathway that is desirable from the perspective of the decision maker, while taking into account the attitude and related actions of other actor groups.

7 Overall Conclusions, Reflections and Recommendations

The following chapter closes the thesis with conclusions, recommendations and reflections. The conclusions provided in this chapter are structured by means of the research questions, introduced in the first chapter. The subsequent reflections point out the limitations of the thesis, highlight how the results should be interpreted and give an insight into the experiences of the author gained during the research. Based on both, the conclusions and the reflections, recommendations are provided at the end of the chapter which suggest a focus of continuative research.

7.1 Conclusions

On the basis of the insights from the different stages of the thesis, its research questions are answered in the following.

7.1.1 'How can the Foresight of Technological Options for the Dutch Gas Sector be Integrated within a Holistic Approach?'

The first research question can be answered by recalling the research approach, introduced in the third chapter. Bringing the objective of the thesis in context with its structure, it serves to identify and assess a set of technological options that appears relevant to the gas sector. Figure 7.1 recalls, the research approach of the thesis. The bracketed numbers indicate the different stages of the research.

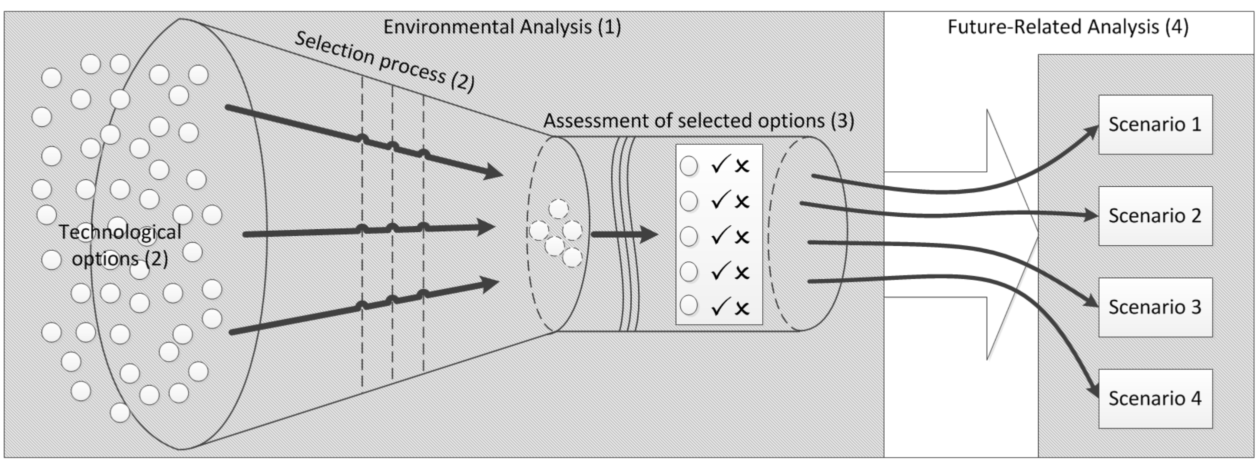


Figure 7.1: Recalling the research approach

The first stage of the thesis is addressed in the fourth chapter. It conducts an environmental analysis of the Dutch gas sector by means of a socio-technical map and a PESTE analysis. The major insight from this stage is a broad overview of the environment, emerging technologies, related to the gas sector, are likely to face. In the second stage, the thesis identifies an inventory of technological options and applies a technology screening that selects the most promising technological options. In the third stage, the selected technological options are assessed in further detail by means of an MCDA framework. The fourth stage reflects the gained insights on potential future pathways and actor coalitions related to these pathways. Moreover, measures are defined to foster a favourable pathway – sustainable development.

Whereas, other Technology Assessment studies frequently conduct only one or two of these steps, the thesis aims to provide a more holistic picture. To do so, it can be concluded that none of the steps can be left out without compromising on the insights of the thesis. Also, it is argued that the order of the above mentioned stages cannot be changed because it would be too time consuming. However, it is argued that the connection between the environmental analysis and the remaining stages of the thesis could be made more explicit and is in the current status somewhat tacit. A general drawback that results from the broadness of this refined methodology is that it requires limiting the depth of analysis. In accordance to the objective of the thesis the methodology thus can provide recommendations for continuative research but cannot be regarded as a stand-alone research.

7.1.2 What are Static and Dynamic Aspects of the Dutch Gas Sector?

The second research question is further divided into two sub-questions. Both of them can be answered by the insights of the third chapter. The first is related to the socio-technical map whereas the second sub-question is answered by the results of the PESTE analysis.

7.1.2.1 What is the current Socio-Technical System associated with the Dutch Gas Sector?

As explained by section 4.1 and 4.2 the description of the socio-technical system associated with the Dutch gas sector can be divided into a technical map that addresses the physical assets related to the Dutch gas infrastructure as well as a social map that portrays the main actor groups that are associated with the Dutch gas sector.

The technical map identifies technologies in the UP-, Mid- and Down-stream of the Dutch gas infrastructure. More specifically, the exploration and production of gas as well as its cleaning are the major elements in the Up-stream of the gas value chain. The transmission and storage of gas are the two major components in the Mid-stream. The Down-stream of the gas value chain comprises the distribution and consumption of gas.

The social map identified a total of 13 actor groups that are associated with the Dutch gas sector and classified them as related to the market, to research, to society or to the authorities. By number of actor groups the market is the largest stakeholder class, comprising gas producers, gas traders, transmission system operators (TSOs), local distribution network operators and industrial consumers. Whereas research actor groups are further classified as public research institutes and commercial research institutes, the European commission, the Dutch national government as well as local Dutch governments form the class of authority actors. NGOs, private customers as well as citizens are considered as being related to the society. Subsequently, these thirteen actor groups are further condensed, in accordance to their preferences for future developments.

These insights provided by the socio-technical map are of static nature because they do not account for trends that affect the number of, or relations among, physical assets of the Dutch gas sector or its stakeholder groups.

7.1.2.2 What are Recent Trends affecting the Development of the Dutch Gas Sector?

The PESTE analysis conducted in the second part of the fourth chapter takes a satellite perspective and adds dynamic aspects to the static picture provided by the socio-technical map. In doing so trends are classified in accordance to their impact on the Dutch gas sector as political, economic, social, technical and environmental (PESTE). In the frame of a desk study 16 trends are identified:

The change of international power positions due to location of gas resources and an increasing power position of societal actors are regarded as political trends. The development of the gas price, the liberalization of the European gas market and the decreasing ratio of gas exports to gas imports are considered as economic trends. An increasing number of households that needs to be served by gas, increasing attention of environmental aspects as well as demographic changes are classified as social trends. Due to the technological focus of the thesis, technical trends are further classified as related to the Up-stream, Mid-stream or Down-stream of the gas value chain. The diversification of gas types is related to the Up-stream of the gas value chain. The increasing importance of gas storage technologies and the rising age of the gas grid with its related consequence are associated with the Mid-stream. The down-stream of the gas value chain is considered as being related to the increasing difficulty to match demand and supply of gas as well as the restructuring of gas demand. Last, climate change, the increasing interference of activities related to the Dutch gas sector with sensitive natural areas and the depletion of gas resources are considered as environmental trends in the context of the PESTE analysis.

Furthermore, the insights from expert interviews are used as a means to reflect on the above insights. Within this process, the change of international power positions, an increasing power position of society, an increasing number of households to be served by gas were confirmed by both experts and therefore appear to be of especial relevance. Moreover, the diversification of gas types seems to be currently the most important trend that affects the Dutch gas sector as it was highlighted independently by both experts. Despite the fact that other trends, identified during the desk study were challenged by one of the two experts or not commented, all trends were confirmed by the expert to be part of the discussion on the dynamics of the Dutch gas sector.

7.1.3 What Criteria are relevant for assessing Technological Options of the Gas Sector regarding their Relevance for Continuative Research?

The third research question is also divided in two sub-questions because the thesis needs to apply two different sets of criteria. In accordance to the research objective the first set aims to identify technologies that appear particularly relevant to the objective of the thesis. The second set is meant to further assess the technologies that are selected by the first set of criteria.

7.1.3.1 What Criteria are relevant to narrow down the Selection of Options?

The first sub question is answered at the beginning of the fifth chapter, which conducts a screening of all technological options that are suggested in the research context of the thesis. To do so, four screening criteria are formulated, based on the overall goal of EDGaR and the technological focus of the thesis. All four criteria are summarized in the following.

First, it is argued that the technology should be an *integration option* because it assures its disruptiveness in the context of the Dutch gas sector and associated higher expected returns. Second, the technological option should have the potential to be operated sustainably to come up to the overall goal of the EDGaR program. Third, the technological option should use gas as a main energy carrier in order to assure the relevance of expertise of the Dutch gas sector. Fourth, the options to be assessed should be at the level of an energy technology and not at the level of a component, side or sector.

7.1.3.2 What Criteria are relevant to assess a limited Set of Technological Options?

From the pool of all technological options that have been suggested within the research context, the application of the above explained, four screening criteria resulted in the selection of the *(1) solar reforming of methane, (2) the Superwind concept, (3) Mini/Micro CHPs, (4) the power-to-gas concept and (5) hybrid gas turbine fuel cell systems*. These five technologies fulfil all four screening criteria and are therefore selected for a further assessment by means of the second set of criteria. The latter contains five dimensions of assessment: Technical, Financial, Environmental, PES (Political, Economic and Social) as well as Dynamics of development. Each dimension is assessed by a set of subordinate indicators.

The technical dimension aims to analyse the technical specification of the technologies. To do so, the average efficiency coefficient [%], the average capacity factor [%], the flexibility of dispatch [ordinal: 1-5] and the technology's availability and readiness [ordinal; 1-5] are specified for each technology. The financial dimension of the technology assesses the costs that are associated with each option by means of total overnight costs [€/kW], operation and maintenance cost [€/kWh], cost of fuel [€/kWh] and the impact of fuel price changes [%]. The environmental characteristics of the technologies are assessed by analyzing their average external cost [c€/kWh], their associated loss of life expectancy [days] and their green house gases emitted during operation [g/kWh]. The PES dimension aims to portray the affect of a technology on the competitiveness of a country's gas sector and is assessed by specifying the autonomy of electricity generation [ordinal: 1-10], the job creation [job-years/GWh], the potential of conflicts induced [ordinal: 1-5] and the necessity of a participative decision making process [ordinal: 1-5] for every technology. The last dimension, that is dynamics of development, aims to portray the efforts that have been spent on developing the five technologies. In contrast to the other dimensions, the data collected for this analysis was not gathered from literature but by Tech Mining as described by (Porter & Cunningham, 2004). During this process, two scientific databases were searched for their publications on the five technologies. The results were compared and translated into two indicators: The number of total publications [#] that has been published on a technology and the likely future trend of annual publications [ordinal: 1-5].

7.1.4 What is the Value of the different Technological Options studied in View of the second set of Assessment Criteria?

The fourth research question can be answered by the insights provided in chapter five. The first sub-question requires an overview of the five technologies with respect to every dimension of the assessment. The second sub-question requires the accumulation of these results into an overall score. This is done within the Multi-Criteria-Decision-Analysis (MCDA) section of the fifth chapter.

7.1.4.1 What Advantages and Disadvantages do the different Technologies face regarding different Dimensions of Assessment?

Table 7.1 summarizes the ranking of the different technologies for all five dimensions.

Table 7.1: Ranking of technologies regarding different dimensions

Rank	Technical	Financial	Environmental	PES	Development	Total
1	Hybrid gas-turbine fuel cell system	Solar reforming of methane	Solar reforming of methane	Micro CHP	Power-to-gas	Power-to-gas
2	Power-to-gas	Hybrid gas turbine fuel cell system	Superwind	Superwind	Micro CHP	Micro CHP
3	Micro CHPs	Superwind	Micro CHP	Power-to-gas	Solar reforming of methane	Superwind
4	Superwind	Power-to-gas	Hybrid gas-turbine fuel cell system	Hybrid gas-turbine fuel cell system	Superwind	Solar reforming of methane
5	Solar reforming of methane	Micro CHP	Power-to-gas	Solar reforming of methane	Hybrid gas-turbine fuel cell system	Hybrid gas-turbine fuel cell system

As shown in the table, the ranking of the technologies varies broadly across the different dimensions. Also, no technology dominates another, by being ranked better in every dimension. Thus, in order to come to a conclusion what technology to prefer over another, a closer look needs to be paid to the scoring of the technologies for every dimension because the ordinal ranking provided in table 7.1 does not account for the difference between the different places of ranking.

7.1.4.2 What is the Overall Value of the Options Assessed?

The MCDA that is conducted in the fourth part of the fifth chapter scores the indicator specifications of the technologies with a linear target function, weights the scores and accumulates them. As a result of this process, Micro CHP units and the power-to-gas concept appear to be the most promising options to focus future research on. To account for inaccuracies in the scoring of the technologies this section also conducts a Monte-Carlo-Simulation that tests for the stability of the results as well as for critical indicators that have a high impact on the overall outcome. Out of a total of 10,000 random trials, the power-to-gas concept scored best in around 7500 occasions. In the remaining cases, Micro-CHP units rank highest. Therefore, it can be concluded that, given the assessment framework established, the power-to-gas concept can be regarded as the most promising of the five options, followed by Micro CHP

Units. However, it needs to be noted that the dimension *dynamics of development* plays a crucial role in this result because of the highly differing number of publications of Micro CHP units and the power-to-gas concept on the one hand, and all other technologies on the other hand. It is further elaborated on this aspect in the answer to the following research question.

Furthermore, the Monte Carlo Simulation shows that the job creation by Micro CHP units, the external costs of the power-to-gas concept and the judgment on the autonomy of electricity generation by the power-to-gas concept are critical indicators to discriminate between the power-to-gas concept and Micro CHP units as the most relevant option for further research. When rated above 3.95 [job-years/GWh] the specification of the indicator *job creation* for micro CHP units determines on its own that this technology is ranked first, even though all other indicators are rated at a minimum.

However, all these results have the underlying assumption that the decision maker has no preference for one of the five dimensions of assessment and thus neglect future uncertainties regarding the formation of actor coalitions. This aspect is also further discussed in the answer of the following research question.

7.1.5 What can be learnt by comparing the Results from the Analyses of the different Technological Options in order to make Recommendations on what Technologies to address in Continuative Research?

The fifth research question is addressed in the sixth chapter of the thesis that identifies sustainable development, the adoption to an energy scarcity, and a fossil fuel based future as three major courses of future developments. In the sixth chapter it is argued that a regime concerned about energy scarcity would give particular weight to the PES dimension, a regime that favours sustainable development would emphasize the environmental dimension and a regime that pursues further exploitation of fossil fuels would consider financial criteria as most important. The boundaries between these three regimes need to be considered as gradual, transitional areas. Moreover, it is assumed that the actor coalitions of different courses of future developments have an equal preference for the technical dimension. Besides, they are assumed not to be bound to sunk costs and therefore neglect the dimension *dynamics of development.*

7.1.5.1 Given different Future Developments, what Technologies appear to be a robust Choice to research further?

Given the fact that the Monte Carlo Simulation at the end of the fifth chapter concludes that differences in scoring impact hardly what technology ranks first, the sixth chapter answers this research question by analyzing what technology scores best if the weights of the different dimensions are alternated systematically.

From this analysis it can drawn that a regime pursuing a fossil fuel based future would either prefer Superwind or the solar reforming of methane if low preference is given to the technical dimension (i.e. < 15%). Starting from a technical weight of 20% a fossil fuel based regime would choose at an increasing number of weight distributions for the hybrid gas-turbine fuel cell system, given that the preference for the technical dimension further increases. A regime that is concerned about energy scarcity would almost always prefer Micro CHP units, except the weight for the technical dimension approaches 70%.

Similarly, a sustainability regime ranks first the solar reforming of methane at almost all weight distributions until the weight of the technical dimension exceeds 40 %.

Most significantly, the Superwind concept appears to be a robust solution for all transitional weight distributions between different regimes as well as for decision makers that have no or hardly any preference for one of the five dimensions of assessment.

It is also important to highlight that the power-to-gas concept is not ranked first at any weight distribution if the dimension *dynamics of development* is neglected. Thus, given that the rationality of the decision maker is not bounded (e.g. due to sunk cost), the power-to-gas concept does not appear as a preferable technology future research should be focused on.

7.1.5.2 How can Sustainable Technological Options be further developed?

The last section of chapter six elaborates on measures to foster sustainable development. To do so, it explores the large-scale application of the technological option which appeared in the context of the thesis to be most suitable for sustainable development – the solar reforming of methane. Based on a large-scale application of his technological option, a further wide-spread of renewable energy technologies is explored, to increase the sustainability of the Dutch gas sector. Therefore, technical, cultural-behavioural, structural-institutional and organizational changes are identified.

The necessary technical change that have been identified to enable sustainable development in this way are the construction of solar reforming plants and other renewable energy technologies in North Africa and seven further locations around Europe. Next to that it is considered as crucial to build up a national and international network of hydrogen pipelines and to develop and implement hydrogen-based consumer products, especially in the transport sector.

Cultural-behavioural changes that are necessary for the large-scale implementation of solar reforming plants in North Africa are classified as being related to one of three topics. The first topic is the acceptance of solar reforming plants in North Africa. The second topic is the acceptance of hydrogen as a fuel by European societies. The third topic is the clearing of geopolitical discrepancies between Europe and North Africa.

From a structural-institutional perspective, the Dutch gas sector has to extent its boundaries in geographic terms as well as in subject-related terms. Thus, next to its expansion to North African countries and other regions, it should also build up a broad expertise of renewable energy technologies.

The organizational dimension specifies that the Dutch gas sector should form an umbrella organization to synchronize its national efforts and to represent its interests collaboratively in front of other countries. On an international scale, a research platform should be founded which coordinates the efforts of several participating countries of Europe and North Africa.

For each of these identified changes measures are defined for the short-, mid- and long-term to operationalize the implementation of solar reforming plants in North Africa as a means towards sustainable development. Also, it is explored how the different condensed actor groups should be involved in this process, what is their attitude likely to be and what actor groups are of strategic importance to drive forward the sustainability of the Dutch gas sector. The latter insight is not specific to the solar reforming of methane but also applicable to other emerging technological options that are related to the Dutch gas sector.

7.2 Reflections

The following section reflects on the process of the research study as well as its results. In doing so it follows the sequence of the thesis.

First it needs to be noted that this thesis is of explorative nature. Thus, no ready-made methodology could be chosen. Despite the fact that the methodology as applied in this thesis is selected to the best of the author's knowledge another author could have used a differing set of research methods which had resulted in deviating research results. Besides, the thesis is mostly based on a desk study that is exposed to the risk to be affected by the researchers subjectivity or being incomplete. Nevertheless, it needs to be noted that the rationale behind explorative studies is the widely gathering of information that provides a broad overview on a diversified context and hints towards certain aspects. This purpose has guided the process of the desk study.

Second, the static and dynamic picture of the gas sector that is provided in the third chapter of the thesis suggests very simple relationships between different elements of the technical and social system. It needs to be noted that much more factors come into play in reality that are too complex to take into consideration. Additionally, the trends and their direction as presented in the third chapter are meant to reflect the discussion on the dynamics of the gas sector. Despite the fact that trends such as the development of the gas price are often presented as straightforward within literature, the experts interviews conducted in the frame of the thesis reminded the author of the fact that future trends which might affect the gas sector are in many cases uncertain and difficult to estimate. Similarly the classification of trends within the PESTE framework is ambiguous because trends can have multidimensional impacts on the gas sector. However, it needs to be emphasized that, in the context of chapter three, the classification of trends served primarily the purpose of providing a complete picture of the dynamics of the gas sector, in a systematic way.

Third, the technology screening conducted in the fourth chapter of the thesis applies a list of screening criteria that is neither exclusive nor exhaustive. Thus given another research context, different focus of the thesis or deviating preferences of another author, another list of criteria could have been chosen which had resulted in a different set of technologies to assess. Despite the drawbacks inherent to the distinct screening criteria, as outlined in section 3.2.3, the list of criteria and the resulting set of technologies that are identified in the beginning of the fifth chapter appear to be a reasonable choice for the technology assessment.

Moreover, the pool of all technologies the five options are selected from is subject to the imperfect information of the author. Strictly speaking, other technologies that are not listed in the pool might have fulfilled the screening criteria as well and scored much better in the fifth and sixth chapter of the thesis. Despite this limitation, the thesis had to be conducted within a given time frame that allowed only adding those technologies to the pooling that have been mentioned within the research context. Besides, even an unlimited time frame does not assure perfect information and the consideration of only those technological options that have been suggested previously as relevant appears to be a reasonable boundary for the exploration of technological options.

Fourth, the body of technology assessment does not account for a standard set of MCDA indicators. Thus, after exploring related literature, choices had to be made by the author how many and what indicators to include. As with the list of screening criteria, a different choice of assessment dimensions and subordinate indicators could have led to different results of the thesis. For this reason the selection process of all indicators is made transparent in the methodology chapter and can be adopted in accordance to the preferences of other authors. Also, the scoring of the technologies that is done as part of the MCDA analysis is based on a choice by the author and therefore requires reflection. Given the fact that the specification of indicators for each technology varies across different sources of literature and is even not available in some cases, low base and high values are identified for the specification of indicators regarding the different technologies. It was assumed that all specifications for the different indicators are of equal probability within boundaries of the low and high case.

Fifth, the Tech Mining process of the thesis is limited due to several reasons. First, none of the technologies assessed has reached mass market application yet. For that reason the number of publications is still limited and might not be representative. However, the thesis assumes that publications of scientific databases reflect only a minimal portion of actual research activities which are linearly related to the real circumstances. Second, the process of Tech Mining experienced technical difficulties due to the fact that the use of the scientific database Science Direct resulted in a sufficient number of publications but does not provide data on related countries or affiliations. In contrast, the database Web of Science provides only a very limited number of publications on the technologies researched but allows for the export of information on related affiliations and countries. For this reason the insights of both databases needed to be combined under the assumption that the insights provided by both databases are compatible. The same assumption holds for the triangulation of these results with Scopus and the Derwent patent index. Third, the queries that are developed in the context of the thesis are far from perfect but are regarded as sufficient for the purpose of the Tech Mining section. That is, as described in Appendix B, their precision and recall appear reasonable. However, they allow only for a very basic application of Tech Mining, as conducted in this thesis and should be further developed for continuative studies that aim to reap deeper insights from a Tech Mining analysis. Fourth, it needs to be mentioned that the Tech Mining results are somewhat limited regarding systemic technological options, such as the Superwind concept. Namely, because they could also be operated with other sources of renewable energy and are still in the conceptual phase of development. Thus, similar technological options might have attracted the attention of several researchers but are named differently and therefore not captured by the Tech Mining efforts of this thesis.

Sixth, the actor coalition approach to MCDA as applied in the sixth chapter requires reflection because it allows incorporating the perception of several actors into MCDA as applied in the fifth chapter. Based on the exploration of actor coalitions and related attitudes towards different future pathways, the MCDA framework can be used to make decisions that are not only favourable for oneself but several decision makers. On top of that, the integration of these insights with a backcasting analysis allows defining strategic actions towards preferable future outcomes, while accounting for other actor groups. This insight of the thesis is of broad applicability to decision makers, not only for pathways but also for other decision making problems.

Seventh, it needs to be pointed out that the backcasting conducted at the end of the chapter is only preliminary. A further elaboration of the backcasting section could benefit the findings of the thesis in order to validate the feasibility of solar reforming plants in North Africa. However, the purposefulness of backcasting studies has been proven repeatedly during the last decades and methodologies exist to carry further the insights provided in the backcasting section of this thesis. Therefore, the backcasting analysis conducted in the sixth chapter is considered to fulfil its main objective, by demonstrating how to combine the previous insights with the definition of strategic measures that foster the pursuit of a normative future state.

7.3 Recommendations

The recommendations suggested in the following paragraphs are based on the conclusion and reflection of the thesis.

Regarding the focus of continuative research each of the technologies would be a reasonable object of further investigation, whereas future research could further discriminate between their potentials. A first approach to do so is to involve experts in the scoring process of the technologies in order to limit the bandwidth of their ranking. This is of particular importance for critical indicators such as the *job creation* by Micro CHP units, the *external costs* of the power-to-gas concept or the *autonomy of electricity generation* by the power-to-gas concept. Given the consecutive application of Tech Mining in these studies, it is recommended to further sophisticate the queries developed in the context of this thesis. An interesting insight that is beyond the scope of this thesis is to determine which aspects have been researched to which extent regarding each of the five technological options. Also, the queries should be further developed to account for systemic innovations, such as the Superwind concept, that can occur in several configurations.

Yet, recommendations on what technological option to address in continuative research can be made, based on the insight of this thesis. Depending on the innovation strategy of the EDGaR program and the researchers' preferences, different technological options can be recommended for continuative research. Given that continuative research decides to converge with the efforts of other authors and affiliations, the power-to-gas concept or Micro CHP units are recommended to address. Neglecting the previous efforts of other affiliations and authors and aiming towards sustainable development, the solar reforming of methane appears to be most reasonable. Given the objective of the EDGaR program the latter option appears to be most relevant.

At the background of the sub-project *Technology Assessment,* this thesis is part of, the social implications and difficulties the five technologies are associated with are of particular interest. Especially the implementation of the power-to-gas concept and the solar reforming of methane call for further research in this area because they require hydrogen infrastructure of a large-scale, which in turn requires the change of societal habits. The conducting of a constructive technology assessment seems particularly promising in this context because it requires stakeholders, who are involved in the decision making process, to communicate about their expectations and related preferences. Based on that, it is also possible to further specify the actor coalitions related to the three major regimes of sustainable development, energy scarcity and fossil fuel that are identified in the sixth chapter of the thesis. A potential way of realizing these efforts could be the organization of workshops that can serve as a protected environment in which a diverse group of stakeholders can communicate their concerns and reach middle grounds (cf. Mulder et al., 2012).

Apart from that, other energy technologies of interest should be investigated by the methodology of this thesis to obtain a broad overview before studying some of them in-depth. In doing so, indicators and dimensions can be added to the assessment framework in order to highlight certain fields of interest or to improve the framework iteratively.

Another insight that raised the attention of the author during the research, and appears as an interesting topic for continuative research, is the exploration of the innovation system related to the Dutch gas sector. So far, no study has systematically mapped the structure or functions of the innovation system related to the Dutch gas sector.

Finally, it is recommended that the actor coalition approach to MCDA, which is applied in the sixth chapter, should be further investigated and turned into a novel, independent and holistic methodology that is applicable to several problem settings of decision making.

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8 Appendix A – Expert Interviews

8.1 Protocol

Topic			Sub-Topic	Question
Intro: Driving towards sustainability, thus assuming a high share of renewable energy resources, I would like to discuss the trends, functions and system options that could accommodate this change: Pre-questions Who are you? What is your role in the EDGaR project? How do you see yourself in the gas-sector?				
1	Trend Analysis	TECHNICAL	Political (Changing international power positions, increasing power of society)	(Creating an inventory of trends/ developments) ***1.1 Would you agree on the non-technical trends identified?*** ***1.2 Can you add other non-technical trends that affect the transition towards a sustainable gas system?*** ***1.3 What are the main non-technical trends?*** ***1.4 How do you expect the non-technical trends to***
			Economic (Exports/Imports, Energy prices, liberalization)	
			Social (Increase in households, environmental awareness, Demography)	

			Environmental (Climate Change, Sensitive Areas, Depletion of resources)	***develop?*** ***1.4.1 Magnitude*** ***1.4.2 Direction*** ***1.5 What difficulties or enhancements for the gas sector do you expect to arise from these developments?*** ***1.6 How should the gas sector respond to these trends apart from technical measures?***
			Legal (Incentive to shift towards smaller gas fields)	
		PESEL	Up-Stream ***1. Decentralization of production*** ***2. Diversification of gas types***	***1.7 Would you agree on the technical trends identified?*** ***1.8 Can you add other trends in the up-, mid-, and down-stream that affect the transition towards a sustainable gas system?*** ***1.9 How do you expect the main technical trends to develop?*** ***1.9.1 Magnitude?*** ***1.9.2 Direction?*** ***1.10 What difficulties or enhancements for the gas sector do you expect to arise from these developments?*** ***1.11 How should the gas sector respond to these trends apart from technical measures?***
			Mid-Stream ***1. Increasing importance of storage*** ***2. Increasing importance of system-integration (with electricity grid)*** ***3. Aging gas grid***	
			Down-Stream ***1. Difficulty to match demand and supply*** ***2. Increase/ Decrease in gas demand***	

Interview Guide:

- The previous questions aimed to detect technical trends affecting the gas sector and to identify non-technical reactions to these trends.

- In the following the interview turns to the technical aspect and aims to identify and analyze technical measures that could reap arising opportunities from these trends.

- Introduction of selection criteria for technologies & argue for their importance

- Disruptiveness: In order to change the current system, mostly dependent on fossil fuels, the current entrenchment needs to be loosened up

- Sustainability potential: In order to enhance the feasibility of the technologies and make them desirable for powerful actors, technologies should be 'compatible' with the current system. However, the technologies should also be potentially fully sustainable in their operation.

- System integration: As identified by literature, system integration is crucial in future to enhance efficiency of technologies and to create synergies

2	Technology exploration	Design Choices 1. ***Operational with renewable gases*** 2. ***System-integration-technology***	***2.1 What is your opinion on the design choices made?*** ***2.2 Are there other choices to be made for the selection of technologies that are crucial for the exploration of relevant technological options (…to drive the gas sector towards sustainability)?*** ***2.3 Can you think of a scheme to classify system-integration options?*** ***2.4 Which of these options do you regard as most disruptive? Why?*** ***2.5 Which of these options do you regard as most beneficial? Why?***

Preliminary mapping of technologies

1. ***Superwind***
2. ***Micro CHP***
3. ***Fuel cell topping***
4. ***Fuel cells (esp. polymer)***
5. ***Gasification***

10. ***Kalina cycle***
11. ***Micro Heat pump***
12. ***Efficiency technologies (axial fan)***
13. ***Liquefaction***
14. ***Compression***

6. Pyrolysis ***7. Unconventional gas*** ***8. CCS*** ***9. Syngas***			
	Technology exploration	Identified Technologies	***2.6 Would you like to add a technology or remove one? Why?*** ***2.7 How would you classify the technologies in accordance to the scheme for system-integration discussed previously?***
3	Technology Analysis	Rough Analysis	***3.1 Do you generally expect most important technology advancements to be in the up-, mid- or down-stream or do you regard the position within the gas value chain as not important? In other words: Do you think there is a reverse salient within the gas system that could be solved with more sustainable technologies?*** ***3.2 What technologies have a high, middle, low potential to be disruptive (i.e. change the system towards sustainability)?***
		Detailed Analysis (given 5 technologies of high potential)	***3.3 How do these technologies interrelate with the trends identified?*** ***3.4 To what extent can these technologies modify the identified trends (i.e. interaction)?*** ***3.5 How do you expect these technologies to develop in future?*** ***3.5.1 In terms of economic aspects*** ***3.5.2 Technical effectiveness*** ***3.5.3 Environmental impact*** ***3.5.4 Social acceptance***

			3.6 Are there other aspects these technologies should be assessed on that are crucial? Which?

8.2 Interview with Dr. Kas Hemmes

Q 0. How do you see yourself in the Gas Sector and in the EDGaR project?

I am a researcher mostly looking at long-term energy options. Moreover, I have a background in fuel cells. Combining both aspects, I also have some knowledge on how to integrate fuel cells in the gas sector, including technical but also social and economic aspects.

For the EDGaR project we have to look towards the future. In this sense, everything that is relevant for the gas sector we should include in our study, also to prepare the people in the gas sector better for the future.

Q1.1/ Q1.2 Do you agree on the following non-technical trends identified and can you add others?

Political: Changing international power positions:

I agree. Generally there is a changing world. However, it is important to note that power has two meanings. First, International power refers to the fact that, for example, the BRIC countries are becoming more important. Second there is energy power, which is probably more important for the thesis because it relates to the Dutch gas sector and its future. Energy power is currently owned by OPEC countries and is also likely to change in future. Particularly the energy power position of 'solar countries' around the equator is likely to rise significantly as solar power has a lot of future potential regarding electricity and heat production. These countries can be referred to as the 'new OPEC' countries. Also, biomass is likely to become increasingly important. Therefore, countries with a lot of biomass are likely to gain increasing energy importance in future. A countries' suitability for wind energy needs to be considered in a renewable energy scenario.

Political: Increasing power of society:

The protests against CCS in Barendrecht [from 2007 to 2010] *are a strong case for involvement and resistance of society. However, the public has been protesting in the 70s against nuclear energy. Thus, increasing power of society is not necessarily a new trend.*

Are there other political trends?

Yes. First, the Netherland has a strong focus on the gas sector and it is known that the Dutch gas will end one day. Thus, a current political trend is an increasing attention on the gas sector by politics, which is addressed in suggestions such as the gas-roundabout.

Second, I got to know that the United States is/was not allowed to export fossil fuels. You have to research further information. However, this could be a political statement of countries and practiced more often by countries in future to safeguard their own supplies and stocks of gas.

Economic: Decreasing ratio of exports/ imports:

We call the project 'the next 50 years' because it is now about 50 years ago that Slochteren was discovered and we expect the field to last for 30 to 50 more years. However, it is also about the price. It is not that we do not have any more gas after Slochteren but Russian gas is cheaper. Logically, you get more money from selling gas than trading it.

Economic: Energy prices

My guess is as good as everybody else's. Everybody thinks it is going up and if you go to the gas-station it is indeed going up. However, with respect to the shale gas development, gas prices are likely to decrease. In predicting, it is hard to account for a combination of both developments.

Social: Increase in households

This trend holds for the Netherlands and worldwide. The changing energy power position of countries we discussed previously is based on this trend as with an increase in households, the demand for power also goes up. Famous examples are China and India. Strongly connected to this relationship is also an increased welfare of people.

Social: Environmental awareness

I don't expect environmental awareness to change a lot in future. In contrast, it could decrease in future. Especially if economic aspects take over in future, for example through economic crises, the environment probably comes second.

Social: Demography

Apart from Europe and the United States, the number of people is obviously increasing.

And does the increasing age of experts have an influence on the gas sector?

You hear that a lot and, indeed, a company should always have resources in form of knowledge. It could become a problem for nuclear power plants. If no nuclear power plant has been built for 10 to 20 years, construction companies might struggle to incorporate new technologies in their design of the past. But generally, I don't see this aspect as a big problem because knowledge will never be totally gone. If there is demand, there will always be means to expertise.

Environmental: Climate Change

Climate change is now a big issue. Therefore expectations are that discussions will go down in future. In any way, it is amazing that scientific discussions about climate change have ruled the political agenda for such a long time.

But do you expect awareness about climate change to go further up?

For our project it is less relevant to identify one scenario as the most likely future. Rather, it is important to explore several possible futures. In the past, people often reached consensus that one scenario is the most likely one. However, almost always expectations were turned upside down by an unexpected event. You could see this happening particularly in the field of fuel cells. Thus, we should certainly not try to predict the future in the EDGaR project but explore it. This also holds for the future relevance of climate change.

Environmental: Sensitive natural areas?

It is maybe just a complaint/lobbying by the companies that do not want to stick to all the environmental policies. The Waddenzee has been a long discussion and resulted in a drilling from the land. Yes, because of that it is more expensive and in Russia they would just drill directly and not mind about the landscape

The small field policy is not new anymore. Are there other legal trends?

We don't know how it will develop but as most interesting I see future policies regarding shale gas, CCS and LNG. There could be a ban on Shale gas [due to strong opposition] but the question would be in that case a policy enhancing LNG might be required.

Which of the non-technical trends we discussed do you regard as most important?

The high increase in demand of gas from new countries

[The following information stems from a further point of the interview but is listed at this point due to its relevance for the question.]

Another general trend is that villages start initiatives to really become autarkic. On the one hand, this happens because of their awareness for energy and the energy use. People think more and more about the possibility to create their own energy. Why do you need a gas pipe to your home? On the other hand, some villages want to become energy independent for social reasons.

An example for the former is the province Friesland which was a bit ahead of everybody else. Following the fact that it is possible to build houses with a very good heat conservation, the provincial government was about to implement a regulation which allows only the construction of very efficient or even energy-neutral houses. Without regard to the fact that this initiative was overruled by the Dutch government because it lacked a transition period, it was very close to its implementation.

An example of the latter is the village of Dongen in Brabant. It has been very involved in the energy discussion, resulting from the fact that their population decreased because young people moved away. Local politicians wanted to increase attractiveness of the village by becoming energy independent and install renewable energy systems. In this case Energy has been the wagon to roll but not the initiative itself. Thus, it is more about the sustainability of energy supply [People, Planet Profit] instead about renewable energy sources. In other words, in the case of Dongen it was about building a community and energy was one way to do so. Local politicians could also have built a swimming pool or a cultural centre, but they chose energy.

Both cases might indicate a trend which could involve a snowball effect. After one or two success stories all other people might not want to connect to the gas grid any more. This change could go very rapidly.

What are your recommendations for the Gas sector to treat the non-technical trends discussed?

This question is difficult to answer because it needs to be distinguished between a governmental and a business perspective. Furthermore, it is important to discriminate between types of businesses as they might need to take different actions.

However, in any case it is crucial for actors to know about trends and to develop business models based on these trends. In doing so, one should also take broader perspectives and, for example, questions whether we should rely on gas as a main energy carrier at all or ask, if gas supplies would diminish, whether it was possible to go back to underground coal gasification.

Technical

I decided to divided technical trends as related to up-, mid-, and down-stream.

It is limited to define technical as up,-mid and down-stream. You should be aware that, given this division, you set a boundary condition, restrict yourself to the gas system and only to those technical trends that emerge within the gas sector. However, solar cells, for example, could have a big impact on the gas sector even though they cannot be classified as up-, mid-, or downstream.

Up-stream: Decentralized production:

Yes, this holds for natural gas as well as biogas.

Up-stream: Diversification of gas types:

Yes. For this trend it needs to be distinguished between diversification regarding the gas source and diversification regarding the composition of gas.

Mid Stream: Aging gas grid

Even though I heard that the gas grid is replaced bit by bit on a regular basis, I am not sure how it is developing.

Do you think decentralized production of gas requires a two-directional transport of gas?

I don’t think that the two-directional transport of gas is required. But this depends on the scale of localized gas production.

Mid Stream: Storage technologies

It is important to distinguish between electricity storage and gas storage. Gas storage is becoming more important to have enough supply in the peak periods. Even if the gas field in Slochteren still has a large capacity that does not mean we have enough transport capacity to supply sufficient gas in peak hours. As a result, you have to transport gas to local storages in summer to close gaps in supply. Storage of electricity relates to the intermittency of renewable energy sources. In this aspect, people are working to produce hydrogen from electricity.

Moreover, storage needs to be classified in terms of storage capacity and the possibly stored amount. The storage amount relates to the fact how much can be stored. The storage capacity determines how much can be stored or released in a given period of time. [In combination, both aspects determine the appropriate purpose of a storage facility]

Down-Stream: Difficulty to match Demand and supply

As mentioned before, it is important for this purpose to have local gas storages.

Which of the technical trends we discussed do you regard as most important?

By far shale gas, that even suppressed the rapid development of LNG. Next are LNG and coal gasification. Moreover, biogas production is going on in Friesland and in the East (Leeuwarden). [Thus, the diversification of gas types by source]

It is also important that houses are better isolated. Together, with the increasing power of society this raises more frequently the question whether houses should be connected to the gas grid or not.

For my thesis, I want to focus particularly on renewable gas technologies, integration options and disruptive technologies. What are your thoughts on this focus?

I like the focus because integration is important. Moreover, you get to study new options, nobody else is thinking about. Thus, it is complementary to what has been done. Otherwise the risk is to repeat what everybody else is saying.

However, this focus bears the risk that your result might not be relevant in the long-term. However, it is relevant for our project and its focus on different scenarios: Again, you should not predict but explore what are potential developments.

Can you think of a way to classify system integration options?

Yes, for example with reference to their maturity level and scale. The maturity level relates to the development state of the option. Some integration options are of large scale, some aren't yet, and some are of small scale and always will be on a small scale.

Would you like to add a technology or remove one? Why?

I supervised two other master theses cf. (Aftzoglou, 2011; Elango, 2012). If the focus of your thesis is not to explore new options you can build your work on their reports.

Are there any criteria you would like to suggest for the assessment of integration options?

First, you should identify criteria to select some of these options. Second, you should look at standard technology assessment criteria

Do you expect system integration options to be likely to change the current trends or their system?

Yes, all of them would, if they don't fail. In this sense it would be interesting to look at the characteristics of system integration options and to see if [or how] they interact with the current trends.

What characteristics would you suggest to look at?

Generally, the depth of your research on the different characteristics depends on the focus you want set for your thesis.

Cost: Costs are always difficult to take into account. Often, [very] new options are too expensive. Otherwise they would already be in place [, the market]. On the other hand, if integration options are near commercial stage, their specifications are often confidential. Moreover, [as discussed previously] the cost of fuel relates to a lot of uncertainty. Normally, I stay away from costs for these reasons.

However, there are some lists from chemical engineers from which you could roughly estimate how much a combination of certain equipment costs.

Technical: You could include some technical flow sheet calculations that specify the figures on flows as well as mass and energy balances of these systems.

Environmental aspect: You could conduct a quick scan that points out where the issues are and, for example, research how much CO_2 is saved by a certain option.

Social acceptance: The inclusion of social acceptance depends on how far you want to take it. Usually, this dimension is subject for a whole study on its own. You could point out and reason for potential obstacles to social acceptance regarding a certain option.

8.3 Interview with Floris van Foreest

Q 0. What is your role in the Gas sector and in the EDGaR project?

I am working for Kema, which supports the electricity/power industry with fundamental research, testing of equipment, power generation, transmission, distribution, cable testing and other forms of studies. When the energy market liberalized KEMA also had to convert itself to a real consultancy firm. That process started in the beginning of the 2000s and four years ago Kema acquired the engineering & technology department of Gasunie. As a result, the company also got gas expertise regarding gas infrastructure and gas quality types. Within the past few years the company gained expertise in the field of market studies and improved its economic skills.

Last year KEMA was acquired by the Norwegian group D.N.V. which is mainly focused on oil and gas industry in maritime sector. Regarding the EDGaR program KEMA is involved as a representative of Gasunie.

Q1.1/ Q1.2 Do you agree on the following non-technical trends identified?

They are all quite right but on a high level of analysis. I could think of many developments on the subordinate levels of these trends.

Changing power positions

We face depletion of natural gas that means if we continue to use as much gas as we use today, the Netherlands will become a net importer in the 2020s or 2030s, and more dependent on Russian and Norwegian supply. Norwegian supply is quite stable and Russia has proven to be a reliable supplier for Western Europe, even though there were some disruptions in other countries in the past. There is also the Iran that has massive Gas resources. Moreover, the developments in the U.S. are becoming more and more important. First, the United States can rely increasingly on its own energy sources, which influences the political system. Second, the U.S. might export gas from 2015 or 2016 onwards. Furthermore, there is also LNG, which is a global market and its supply is not related to one country.

Next, there is China which is still a large user of coal but has been involved in discussions with Russia about the supply of Russian gas. So far, there have been disputes about the pricing formula for many years and also infrastructure wise it is a huge challenge to bring gas from Russian fields to China. This partnership would mean that Russia served two main markets, which could also have an effect on different European gas users. In contrast, China might also become a large user of LNG affecting its prices. Moreover, experts have estimated that China has massive shale gas reserves. If the country would exploit those, it would also have a massive effect [on international relations].

Increasing power position of society

Of course you hear that communities start their own energy initiatives in small villages but I think it won't have an effect in the medium term. What I do see is that the impact of local stakeholders on energy projects such as large generation plants or exploration and exploitation of shale gas increases.

In general, there has been some opposition which resulted in delay of these projects. For instance the shale gas project is in a very early stage but local stakeholders opposed and now it has been send back to local authorities.

So, you think there is more power of local stakeholders than in the past?

Not necessarily but I think they are using their means more effective. For example, in Germany there is also the opposition for the usage of maize for biogas. In general the opposition of local stakeholders has become a hurdle for people who want to develop those projects.

Economic: Exports/ imports

Of course, the income from Dutch gas exports decreases. On the other hand you could argue that the Netherlands will reduce its gas use due to higher efficiencies and therefore, at least partly, offsets its decrease in gas production.

Economic: Energy prices

[There were no additional comments by the interviewee on this trend as described in section 4.4.2]

Economic: Liberalization of the market

A few years back, the third package of the EU was implemented, which signifies better organized access to the gas transport system, for anyone more transparency as well as more advanced verification/clarification of the use of transport capacity, and so forth.

Additional economic trend: Economic viability of new technologies or renewable technologies

Just focused on gas it is biogas, hydrogen in the future or bio SNG but it applies to almost all renewable sources. They depend on subsidies but especially in the economic downturn we have now it is questionable whether subsidy schemes will be continued. It will have an effect on the future of gas. So, renewable sources will be more developed which would impact gas demand in power generation, in households but it can also affect the future of gas in a positive way where you have low carbon gas, it can be developed.

Social: Increase in households

Even though there is still a slight increase in households, our population growth is flattening. Therefore, the Dutch population is estimated to peak around 17 million in the 2020s. You could argue that the Dutch population is aging and people who are older require a higher comfort, thus more heating, which raises gas demand. However, this reasoning might be too farfetched.

Social trends: Demography

One the one hand you hear that there is a lack of experts, and that this is a wider problem than just for the gas sector. On the other hand, it can be argued that this is not a real issue because you need less and less people to maintain the gas system which is becoming more and more automated. Besides, the current economic downturn might have a positive effect on this specific problem as it could lead to a *re-education of unemployed in the field of gas. Another option is to employ experts from abroad taking into account that Europe's labour market is getting more and more open. Thus, this trend might not necessarily impose an issue. However, people who actually operate the infrastructure can comment probably much better on this trend.*

Environmental: Climate Change

[There were no additional comments by the interviewee on this trend as described in section 4.4.5]

Environmental: Sensitive Natural Areas

Recently, there have been discussions about the Earthquakes in the North of the country. As a consequence, research on this issue started this year that could already have an effect in the short-term.

Especially in the winter, when gas production is high, there are many earthquakes close to the big field in Groningen. Despite the fact that there have always been small earthquakes for many years, the intensity of the Quakes appears to increase. As a consequence, there are more damages in buildings than before and if constructions collapse it can have a very detrimental effect. Thus, especially regarding onshore exploration this might become an issue.

On the other hand it was recently announced that production from the sea between the islands and the mainland [Waddenzee] will be increased and also production from other sides was started.

Environment: Depletion of resources

[There were no additional comments by the interviewee on this trend as described in section 4.4.5]

Legal: The small field policy is not new anymore. Are there other legal trends?

The small gas policy has a certain time frame, which will end within the next years. It might be interesting to see what happens when the small gas policy is outdated.

Can you add other non-technical trends we did not discuss yet?

From political, environmental side there are targets regarding the share of renewable energy sources and CO_2 emissions. Both are a driver for developing renewable energy sources and developing national energy policies including subsidies that foster their development. This will also affect gas because it plays such a big role in the Dutch energy system. Therefore the introduction of any new energy source will have a converse effect on the share of gas in the Netherlands.

Technical

Up: Decentralization – *This is not necessarily a trend because it can be argued that there has been a development towards smaller fields for many years.*

Up: Diversification of gas types

[There were no additional comments by the interviewee on this trend as described in section 4.4.5]

Mid-stream: Increasing importance of storage

Currently, the storage market in Western Europe is depressed but it might become more important in a few years time again.

In addition, there are already quite some storage facilities and in the next few years a new storage facility in Bergen will come online. Thus, the Netherlands is basically oversupplied with storage arguing that gas-fired generation will become increasingly intermitted in order to accommodate the growth of renewable energy sources. As a consequence, more short-term gas storage capacity is required to manage fluctuations in gas demand of these gas-fired power plants. Short-term, high cycle storages can facilitate that. For example, storage capacity in salt caverns allow for the withdrawal of gas on very short-term.

Energy storage in general will become more important if all plans are being executed regarding large wind-parks and a high share of solar power.

Moreover, it needs to be distinguishes between central storage and decentralized storage. In that sense, it is possible to store energy in a local area with batteries or hydrogen, for example, or to have a central storage utilizing compressed air, for instance.

Thus it is rather local storage which is becoming more important?

It is both, assuming that the introduction of large scale renewable will take place.

Mid-stream: Aging gas grid

The gas transport sector is regulated. Thus companies receive a return from the government for operating their assets. If gas demand or domestic production decreased and the infrastructure would be less utilized, it was still questionable whether it would be dismantled or not because companies would still receive money from the government. Therefore, this is also a political question. Thus, I don't see this trend as a real hurdle for the Dutch gas sector.

Mid: Two-directional gas grid?

This is already taking place on a small scale to bring gas from low to high pressure.

Furthermore, if the biogas is injected to the gas grid, it must have the specifications of natural gas. Besides, there is the distinction between low and high calorific gas. L-gas comes from the Groningen field and is used for heating buildings and also smaller industries. To use biogas for these applications it is indeed necessary to bring it to the specifications of L-gas.

Down-stream: Difficulties to meet supply and demand

The line of reasoning [as pointed out in section 4.4.4.3] is clear but questionable. With better insulated houses, especially in new houses with floor heating systems, the demand for space heating goes down as do the peaks in energy demand for heating. Thus, if the infrastructure can accommodate current peaks in energy demand it will also be able to accommodate the smaller peaks in energy demand of the future.

Next, the improvement in energy efficiency of buildings is a very gradual development that is mainly caused by new buildings that are added to the building stock, being almost energy neutral. Therefore, given a gas infrastructure that can facilitate present peaks it is unlikely that from one year to another energy demand characteristics cannot be fulfilled anymore. To summarize, the current system is designed for the energy peaks of today, which are much bigger than those of the future, and is unlikely to be ever adjusted to a base load situation. Maybe the gas infrastructure will be adjusted but it is not a tremendous problem.

For the electricity grid it is different. There is an increasing penetration of solar that is likely to be the determining factor of required capacity of the electricity infrastructure for the build environment because in the summer and in the spring there is large power generation from solar radiation and people are not home. In other words, almost no demand occurs in the buildings and almost all solar electricity be delivered to the grid. This is the key issue for the electricity infrastructure going forward.

Down-stream: Changing gas demand

It has been argued for a decrease in gas demand for a few years. Especially regarding the gas demand for housing (residential and commercial) a slow decline in gas demand has been noticed. However, this is probably temperature related. Consequently, for this winter, which was very cold, there will probably be an increase of gas consumption. Nevertheless, it is a fact that buildings get more efficient and that gas demand will go down.

Another trend is that for power generation gas demand is going down because there are three new coal power plants. Today, coal is cheaper than gas and therefore coal-fired plants push gas out of the market.

What is the opinion on the design choices made and are there other aspects to add?

A relevant aspect would be the linkage of technologies to their end-users. That way, it is possible to obtain a view on the potential and the reach of a technology and where it competes with existing technology. For example, CHP can be designed for residential heating and power generation or it can also be scaled up for larger buildings. Combined cold power, in contrast, you could imagine mainly for commercial buildings but not for residential buildings in the Netherlands. Another example with reference to the Superwind concept is that hydrogen can be used for different purposes: such as transportation, partial injection to the grid, or combined heat power from a local unit.

Another relevant aspect might be to give an overview of the gas and electricity system intersecting. And, to illustrate where the gas and electricity system meet, given a low carbon future scenario. One example for this is the usage of electrolysers for the production of hydrogen to level out surpluses of electricity from wind and solar power. This hydrogen can be used for different purposes and can also be converted into electricity again. To summarize, there are different interactions along the whole value chain. Another example is the production of biogas or bio SNG from biomass, which can be used for the generation of heat and power or upgraded to bio-methane and subsequently injected to the grid.

9 Appendix B – Developing of Tech Mining Query

This appendix throws light at the query development for the Tech Mining conducted as part of the MCDA procedure. For every technological option a query is developed that aims to reveal as much relevant publications for the technological option and to create as few noise, in the form of irrelevant publications, as possible. Given that different scientific databases as well as the Derwent Patent Index diverge regarding their required syntax, the query is expressed in the form for SciVerse, which hosts Science Direct and Scopus. For each technological option the query is described. The appendix closes with a general evaluation of the query development as pursued for this thesis.

9.1 Queries

Table 9.1 lists the queries that are used for the Tech Mining analysis of the thesis. The development of these queries started with general words including '*energy system', 'integrated energy system'* or *'integrated'* together with key words specific to the technological options. However, these attempts yield only very few results in the scientific databases searched. Also, in the beginning one query was developed for all five options connecting different sections for single options with the Boolean expression 'OR'. The results obtained in this way were, however, needed to be separated subsequently. The final queries presented in table 9.1 were thus developed separately. Moreover, they address more the technologies' specifications, naming components, processes, inputs or outputs. The goal of the development is to modify the query for each technological option in order to yield as much relevant results as possible but not more than 5000. However, given the technological availability and readiness of the options assessed, none of the queries yielded such a high amount of results. Finally, the search of all databases is limited from 2000 to now in order to assure the timeliness of the results retrieved.

Table 9.1: Queries applied for the Tech Mining

Technological option	Query used	
Solar reforming of methane	({Concentrated solar power}OR CSP) AND methane AND Hydrogen OR {Solar-Thermal Steam Reforming} OR {thermal decomposition of methane} AND ({concentrated solar power} OR CSP)	
Superwind concept	Science Direct Scopus	(Superwind AND "wind turbine" AND "Fuel cell") OR (Superwind AND {energy system}) OR (Superwind AND "fuel cell") OR (Superwind AND (DCFC OR SOFC OR MCFC)) OR {Multi-Source Multi-Product}
	Web of Science Derwent	TS = Multi-Source-Multi-Product
Micro CHP	{Micro Combined Heat power} OR {micro CHP} OR {Micro cogeneration} OR {Micro-cogeneration} OR {Micro Co-generation}	
Power-to-gas	"Power to gas" OR ((Methanation AND hydrogen) OR (Electrolysis AND Renewable) AND {energy system})	
Gas turbine fuel cell hybrid system	{fuel cell topping cycle} OR ({fuel cell} AND {gas turbine} AND topping)	

9.2 Evaluation

Given the explorative nature of the thesis the queries developed aimed to provide a basic overview on the research and development activities related to the different technological options assessed. In contrast to more sophisticated Tech Mining problems that strive to reveal specific aspects in a technology's development and therefore develop queries particularly targeting sciences or components related to a technology, the queries developed for this thesis was of very broad nature. Therefore, the efforts are concentrated to gain a broad collection of papers or patents (depending on the database searched) that are related to the technological option at hand. To assure the precision and recall of the query, the results of the last year of publication are therefore scanned and the query for all years modified if irrelevant results are retrieved.

It needs to be understood that the above queries developed are good enough to support the Tech Mining efforts of this thesis but are far from perfect. In contrast, the development of queries needs to be considered as an evolutionary process (cf. Mogoutov & Kahane, 2007) and the above efforts would require further refinement if Tech Mining efforts are picked up in continuative research. For example, attention could be paid in continuative research what scientific fields or aspects are most researched with respect to the different technologies and which require further attention. Also more sophisticated queries should account for the fact that for systemic technologies, like the Superwind concept, which can be operated from different sources, Tech Mining tends to yield fewer results.