

Scenarios for the natural gas market

An outlook to 2050

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by

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Preface

Most people that I have spoken with in the duration of this project noted that it is not the things you deliver but the lessons learned both from oneself and of from management that is the true merit of graduating. Which at those moments I found appalling to hear. At the start of this thesis I set out goals for myself, mostly focused on hard skills. One of those goals was to learn to code. I picked a universal programming language which I wanted to learn, Python. And I chose the dedicated type-setting language \LaTeX . However, while trying to master these concepts and deliver a thesis provided enough material to work on my soft skills like time-management, dealing with blow-backs and managing expectations. I did not set out specific goals for these soft skills, so I had to find out the hard way. Although the first line of this section started with a very cheesy platitude, it has proven itself to be true. If I were able to start over again, both this thesis and the process to write it would be completely different. The thing I take away from this thesis are the skills, both hard and soft, that the journey of this project have taught me.

The following document is the final chapter of the final piece of the master of science program program Complex Systems Engineering and Management. The focus of this program is on designing and making decisions in a technical environment. The intended reader of this work is my graduation committee, fellow students who are preparing their thesis and last but not least the Fundamental Analysis team of Eneco.

For the later I owe a great gratitude for their support in making this thesis possible, a special thanks to Robert Praet for his guidance and patience throughout the process. Further more I would like to thank my commission for their continuing feedback and support.

B. Huisman
Delft, March 31, 2018

Summary

Natural gas is an essential part of our energy system. It is used to heat our homes in a central heating system, to cook our food, as a feed-stock fuel for electricity generation, as feed-stock in the heavy industry and in transportation. It is an essential part of the world we live in today. Yet it is a fossil fuel with the inherent characteristic that it has a finite reserve (on the human scale of things). As reserves get depleted the distribution of natural gas becomes even more unevenly distributed than it has already is today. There are environmental concerns both on a global scale in the light of the global warming, and on a local level with the concern about the safety for the surroundings in natural gas winning areas. The previous technical concerns are supplemented by the political concerns about the regions that are endowed with natural gas. Our dependence on unstable regions increases. These dynamics make us more and more interested in what lies ahead. We want to see the future in order to be able to plan accordingly, but maybe even more so because we want to know what we can do to bring a better future about.

This is where future studies and scenario planning help us. Since only those with a crystal ball are able to predict the future, we should address any analysis about the future with caution and be aware of the uncertainties and the underlying assumptions. For this reason we do not make a prediction about the future, but merely tell a story with a coherent set of assumptions about expected and possibly unexpected developments (hence a scenario). These scenarios should stretch the boundaries of what is thought to be possible. Within this thesis we will use three scenarios provided by Eneco, these scenarios are tailored to the electricity market, however they address dynamics far beyond the energy market. The first scenario is "Circles" where we live in a world of cooperation and growth, there is a clear focus on sustainability. "Tides" is a world of a boom-bust economy, where overheated economies fall into recessions, which hampers a long term strategy to deal with the challenges on the energy market. The third scenario is called "Paces" and describes a world of two speeds. The EU is divided and on the brink of collapse, which hampers economic growth in this region. At the same time the rest of the world undergoes a long period of high economic growth. Within this scenario any focus of the EU on renewables is lacking and the bet is on shale gas to provide for the energy hunger. These scenarios are made to be debated and should not be seen as any prediction of which one will prevail. For the time being they should all be assessed equally likely to fold out and could and should be exchanged for any other scenario as the future unfolds or the research question changes. This research is not aimed at assessing or proving the validity of the scenarios but merely at colouring the picture they tell.

In this thesis we want to help communicate these scenarios and the implications they hold for the future of the gas market by making a qualitative assessment by modeling the world gas market. The main point of focus is the Northwestern European gas market in the coming decades until the year 2050. In order to take long term trends and depletion of world reserves into account the modeling scope is not limited to the Northwestern European market. The world is formalized in terms of demand and supply regions modeled as actors that are bidding into one or multiple markets. These markets clear the bids and declare the result to the respected market participants. The model is written in Python and constructed in an object-oriented way based on the Agent-Based Modeling paradigm. The analytic work has been in an open environment and available to all to expand or review. The Agent-Based Approach (ABM) is chosen in order to address the complexities of the gas market, which is far from a perfect market. This approach provides the freedom to deviate from assumptions of a natural optimal outcome steered by the invisible hand of the market or of the assumptions of a rational actor. The ABM approach allows all actors to hold their own rationale about the market and their respected behavior. Within the formalization of this research three demand groups with their own characteristics are distinguished, consumption in the built environment (primarily consumption for home and office heating), consumption in the electricity sector and consumption in heavy industry.

We conclude that demand for natural gas is expected to grow for the European region in all scenarios. The amount of growth in demand differs among the scenarios as do the consumer groups this growth is attributed to. It matters who consumes the natural gas, since different consumer groups have different seasonal consumption patterns. Demand in the heating environment is strongly concentrated in the winter while demand in heavy industry is more evenly distributed over the whole year. In the Paces scenario demand in the built environment is expected to be more significant in respect to the other scenarios, leading to more seasonal variation in demand. The demand growth in Circles is driven by industrial consumption and has therefore a

lower seasonal variation. Lower variation leads to more efficient usage of (transport) infrastructure and can therefore attract different investments over time.

Supply of natural gas is expected to be sourced to a greater extent from outside the European Union. The driving force behind these increased imports is the depletion of European based reserves. How we make up for this decline in domestic production differs among the scenarios. In Paces the bet is made on shale gas which is expected to be found in big reserves in Eastern Europe, where Ukraine is to become the main supplier to Europe. In the Circles scenario Central Asia and to a smaller extent Northern Africa are expected to become major suppliers to the European region. In the Tides scenario Russia remains a major supplier together with Central-Asian countries in supplying the European mainland. Since Europe is relatively closely situated to possible supply regions they will be outbid on the LNG market by countries who are less fortunately situated and rely more heavily on LNG imports.

In all scenarios there is consolidation of supply, meaning that fewer sellers supply a bigger share of the natural gas consumed. This raises the question how the European Union is to deal with this increased market power. Although this research does not quantify how different policy measures impact the future gas market, it does underscore this concern. The European Union, through the implementation of an Energy Union, tries to mitigate the market power of the suppliers. The philosophy is that in a liberalized market, where short term supply contracts are openly traded, the information monopoly of the sellers will be weakened and this will make competition more attractive. This a break with the long-term bilateral contracts which are common place in the current market. The formalization of the model used in this research does not take long-term contracts into consideration and therefore resembles the vision of the European Union. In order to cap the amount of price setting power of the sellers, the region could make sure it stays connected to the LNG market. The global price on the LNG market would effectively put a ceiling on the natural gas price asked by the sellers.

For further research we define two categories of improvements or extension of the work done in this thesis. One is aimed at improving the given scenarios and the other is to improve or extend the modeling effort done in this thesis. The scenarios were not originally made to tell a story of the natural gas market. This leaves a lot of interpretation to the reader of what is expected specifically in relation to factors influencing the natural gas market. One example is the feedback loop of price in long-term demand. How do high market prices influence the shift to redundant energy carriers (coal, renewable energy carriers)? And what happens in the future in relation to the coupling of economic growth and the use of natural gas? On the basis of the formalization in this research the scenario description should be assessed. This model takes other energy markets as static, however energy markets can hardly be studied as a singular entity. Running this model synchronously with other models or even subsequently in an iterative process might help to lay bare the interconnected dynamics and how they influence each other.

All models are a simplification of reality. In the parametrization choices have been made about the scope, which could be reconsidered when more resources would be available. Demand is aggregated to demand region and in the absence of detailed consumption information assigned to end-user groups with a broad brush. A more detailed analysis of country based consumption and the expected dynamics within a country might help to improve the accuracy of and trust in the model. On the supply side the same logic holds, especially production cost data is hard to acquire but will lay bare a long-run bottom of the market price. The effect of long-term contracts and the cost of large scale investments are not taken into account. Since they are (possible) policy instruments it might be of interest to be able to address these dynamics and their impact on the gas market. This would require to make more detailed assumptions about the behavior of actors on the gas market and their goals.

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acronym

EUR	Estimated Ultimate Recovery, The amount of oil or gas that can be ultimately be recovered from a certain wellhead
Rig	A (drilling) rig is a machine that creates holes in the earth sub-surface
Wellhead	A Wellhead is the component at the surface of an oil or gas well that provides the structural and pressure-containing interface for the drilling and production equipment
Wobbe-index	An index which indicates the calorific value of a gas at zero degrees Celsius
G-gas	Gas of the Groningen field or of the same composition, this gas falls within the bandwidth of L-gas
L-gas	Low calorific gas, gas with a low Wobbe index number
H-gas	High calorific gas, gas with a high Wobbe index number
EIA	Energy Information Administration, official Energy Statistics bureau from the U.S.
LNG	Liquefied Natural Gas, cooled natural gas to below its boiling point
GTL	Gas to Liquids, a synthetic gasoline produced from natural gas
LPG	Liquefied Petroleum Gas, a mixture of butane and propane one of its purposes is a vehicle combustion engine
CNG	Compressed Natural Gas, in contrast to LPG the main ingredient in CNG is methane and the gas is still in gaseous state
Boil-off	Boil-off is the vaporization of LNG during transport or storage that is unavoidable, this gas can be partly be re-liquefied but not completely. This gas is therefore used for the facilities or fed into the main grid
OTC	Over The Counter sales are sales where both parties bilaterally make a deal. Opposed to a (open) market where buyers and sellers offer goods and a market mechanism clears these bids and asks



Introduction

“Begin at the beginning,” the King said gravely,
“and go on till you come to the end: then stop.”

Alice in Wonderland
Lewis Carroll

Within this introduction I would like to tell the reader what to expect when reading this report. The introduction chapter touches lightly on the substance of the main topic, the natural gas market, and sets out the research goals for the thesis. After reading the introduction the reader should be able to have a general understanding of the topic of the thesis and the research design. In short it should know what to expect in every chapter.

1.1. Problem orientation

Natural gas has been of a great importance to the Netherlands. For decades it has been the main supplier to Northwest Europe. Historically the Dutch model of natural gas pricing has tied the natural gas prices to the crude oil prices, a decision that still impacts the gas market today. The gas revenues have had a big impact on the Dutch economy and have contributed to the welfare state it is today. However, policy surrounding the natural gas exploration and infrastructure has been two-faced. The Dutch disease and earthquakes above the Groningen gas field are a product of the Dutch natural gas story as well. The gas market has been very volatile in the past years. Imports increased due to depleting reserves in Europe and safety concerns in Groningen. The move to liberalization on the European gas market has made the market less controllable. This made the European gas market more vulnerable to world market developments. The global gas market as a complex system will be of increasing importance to the Northwestern European region.

The main developments shaping the European gas market today can be sketched as follows below.

- Historically the gas price has been tied to the crude oil price (for specifics see Brigida[11]). This link has been made to maximize (state) profits when natural gas was discovered on the European continent. Since a market for natural gas was lacking, national governments decided to link its price to substitute energy sources, which at the time was crude oil. This link has survived for decades even when the first talks about liberalization began in the 90s[38]. At present the prices seem to diverge significantly and although general market trends of crude oil still seem dominant, this movement could indicate a trend[47]. Due to increased liberalization[41] and a very volatile oil market a separate gas market emerged[6].
- The European Union has expressed its wish for a liberalized energy market in the (multiple) gas directive. Integrated energy companies, that both own the grid and are either producing or selling to the consumer, explicitly or implicitly obstruct a liberal market in the EU viewpoint [71]. This has been the driving force behind the unbundling of energy companies in the past decade[88]. The preferred scenario that is accompanied by ownership unbundling is antitrust enforcement, the abolition of destination clauses in long-term contracts, access tariffs and network codes. This is expected to favor short-term dealings[79].

- Declining reserves and already noticeable cut backs in production of European natural gas producers make one trend undeniable, increased imports. In general all literature agrees that the coming decades imports will increase on the mainland. At this moment the major producers in Europe are The Netherlands, UK, Norway and to a smaller extent Germany and Denmark. This resulted in a general Northwest to Southeast flow of natural gas. Increased imports will revert this stream[22, 58]. To facilitate this trend large transmission investments are needed.
- Liquefied Natural Gas (hereafter LNG) is the technology to compress and/or cool natural gas to its liquid phase. This allows the natural gas to be transported in flexible manner. LNG assets have the advantage of not being site specific. Where the pipeline infrastructure can only be used to transport gas over a certain route, LNG infrastructure provides more freedom for transport routes. This advantage can lead to more short term contracts and a lower barrier for new entrants, both objectives for the liberalized energy market. LNG imports could increase significantly if it were to take the place of the declining domestic European production[24].
- Political uncertainty of importing regions is expected to become more relevant on the European market as imports increase. The Ukraine Russian gas disputes are impacting the European region since the early 90's. Eastern Europe in particular experienced disruptions in supply for decades. This disruption, with the most famous and recent complete cut-off of the Ukraine transit route in the winter of 2009, has had major impacts on political relations with Russia. The security of supply of Gazprom has been seriously doubted and the reputation of Ukraine as a reliable transit country took a serious hit. The construction of diversified transit routes for the Russian-NWE transit route has emerged, resulting in the North-Stream 2 and South-Stream projects. There is no economical rationale for any of these projects, the benefits of these projects rely solely on the Ukraine dispute[15, 58, 73].

Gas plays an important role in the climate change debate since it is a major primary energy source. The future development of the role of natural gas in this respect is highly uncertain. Although natural gas is a fossil fuel, the carbon emissions are a fraction of the emissions of coal or oil. In power generation, gas fired power plants are highly flexible. A high share of renewables, e.g. wind and solar, which inherently to their technology are intermittent and unpredictable in their output, ask for redundant highly flexible electricity production capacity. It is therefore expected that natural gas will fulfill this role. However, the output of gas fired power plants has been declining while the output of coal have been increasing in Europe [12, 84]. In the light of the intensifying climate debate this development contravenes climate policy and is mainly driven by market developments. From a policy perspective more insights in future development of world trends on the European market are relevant to achieve climate goals.

1.2. Research problem description

Within the research problem description the system behavior and current market drivers will shed a light on the knowledge gap. From the knowledge gap a problem statement will be formulated which will lead to a research objective. This research objective has a scientific and a social relevance. Within every research the problem should be the focus of attention and the methodology the means to address this problem[82].

"Never model a system, model a problem"

1.2.1. System behaviour

The global gas market can be seen as a system of nodes and edges, where the nodes represent either supply or demand regions and the edges represent transit technologies. Supply regions are located near gas reservoirs. At the moment the major supply regions are Russia, the Middle East and North America. Shale reserves, Biofuels (or synthetic gas) could change this picture but is not significant in the near future.

Demand regions are located in the major OECD countries. There is a demand hub in Europe, Northern-America and Japan - Korea region[18]. Demand can be divided in industrial and residential demand, of which industrial demand takes up the major part. Within the industrial demand there is elasticity of demand since there is a certain redundancy in energy sources, within the residential sector the demand is considered inelastic. Around these three demand regions, three markets emerged with their own characteristics, connected by the global LNG market.

Transit regions are in majority countries where pipelines are located which connect supply and demand regions (e.g. Ukraine). As of this moment LNG is a key driver on the global market as a price setter for the East

Asian gas hub. The LNG market could open up new potential transit routes (LNG vessel routes) and transit regions (LNG regasification points).

1.2.2. Knowledge gap

From the previous description several knowledge gaps can be identified. The region of interest, Northwest Europe, is expected to become less self-sufficient in supplying its natural gas demand and therefore experience more influence of world dynamics. Which world gas market drivers are of interest to the European market and how are they expected to develop on the short and long term? What exogenous factors are of influence to the European gas system? The second knowledge gap is the development of the European gas market itself. The market structure of the European market itself will influence investment decisions. What endogenous factors shape the European gas market? In this section we will examine how other studies addressed these issues.

It is part of human nature to want to know what lies ahead, to be able to predict the future. Aside from horoscopes and crystal balls there is no reliable way to predict the future and to decisively answer the questions above. This does not make any future study valueless. Future studies help us to see the boundaries of what is possible and help us to plan for whatever the future may hold, it may even help us to shape the future and bring a better one about [19]. The art of dealing with long term uncertainty is called scenario planning and usually involves a qualitative story of possible futures, called scenarios. Models help to translate these scenarios into quantitative figures and provide a picture of possible market conditions under these assumptions.

When approaching the modeling of markets the most obvious that comes to mind is, do we not have economic theory for that? There has indeed been a standing body of theorems going back as far as Marshall in the late 1890 [65] that study markets and the position of firms and countries in competition. In this topic we examine a selection of economic models focused on crude markets with a focus on natural gas markets. These models typically simplify the world into a series of supply and demand equations and compare the found optimum with real world values. Another typical economic approach would be time series analysis of historic data possibly combined with trend exploration.

We will however not limit ourselves to economic models. Natural gas experts tend to see the world as a network, consisting of nodes and edges. Edges represent transport routes and nodes represent demand and supply regions. These models are typically Linear optimization programs. LP programs will balance supply and demand given a series of equations and study congestion. The price on any node in the Network should be equal to one of its neighbours plus the transportation costs. When there is a price deviation this means there is congestion on the network [7].

The third and last category of models discussed are complementarity models, a relatively new type of non-linear modeling technique. It defines the problem in a series of separate optimization problems bound by the combined complementarity problem, expressed in KKT conditions [33]. The computational complexity of this approach in general limits its applicability allowing to consider only a limited group of actors to be completely strategic [34]. The strength of this technique lies in the fact that it takes a holistic approach by also defining the problem in terms for less prominent actors like traders and shippers, which in virtually all other approaches are considered to be static.

In the summary below I will try to group the different models according to the above-given characterization. This is arguably also the way this field of study advanced, giving the story line a historic context.

Golombek falls in the classical economic equilibrium theory. He studies the impact of liberalization of the EU energy market on the natural gas market in Northwest Europe in a series of maximizing social welfare functions under scenarios of successful liberalization of the energy market and without liberalization. His findings suggest that liberalization increases social welfare and, combined with a breaking up of selling consortia, decreases profits for non-European producers [36].

Krichene takes a world-scope in modeling natural gas market prices over the time period over the whole 20th century. The study focuses on the price elasticity and market shocks during this period and finds that shocks on the oil market have a great impact on the price of natural gas. Furthermore he studies how shocks on these markets impacted the price elasticity of consumption and production. He modeled short- and long-run price elasticity with a statistical time series model and concludes that long-term price elasticity of demand of crude oil shrunk in response to market shocks. The mechanism at play was the response from importing regions, which led to a shrinking of the elastic demand portion through taxation, energy saving and substitution, leaving only a non-elastic base. In response the price elasticity of producers decreased as well signaling the movement from a competitive market to a market-maker structure during the 1970's.

However the price elasticity of natural gas increased in this period signaling natural gas to be one of these substitutes[55].

The earliest model discussed in this paper is the model Manne made in 1986. This model researches how the security of supply relates to import tariffs. The main output of this model is the probability of disruption of supply to Northwest Europe. The model tests which import policy best serves general social welfare. In the status quo policy the EU will be dependent for more than 40% - 60 % percent on insecure imports by the year 2000. This undesirable situation can be dealt with by market instruments, which can roughly be categorized in quotas, setting the quantity requirements and leaving the price to the market, or tariffs, influencing the price and leaving the exact quantities to the market. Which of these policies is optimal depends on the disruption probability[63].

Abada assessed the gas market in a primary linear optimization model and adds the non-linearities as KKT conditions. It builds upon assumptions made in Mannes model. The model assumes perfect competition and is tested to two case studies where this is obviously not the case. Due to the oligopolistic nature of the supply side of the market and the highly regulated transport market discrepancies are expected. However Manne predicted that a security margin would apply next to the expected oligopolistic margin. Within the case studies performed by Abada a security model consistent with the likelihood of disruption is found[1].

Perner uses the simulation tool EUGAS to forecast for a period up to 2030, although the model has run until 2060 to make this forecast agree with the long life-cycle of the assets. Investment decisions in new production and transportation are made autonomously. The model aims at identifying possible security of supply issues and investment decisions. The model shows no gas scarcity for the coming decades up to end of its horizon in 2030. Diversification of supplies and political considerations are the main determinants for the EU market, the model foresees significant transportation investments within this time frame[72].

Chyons model describes the European gas market until 2030 and assesses the economics of the South-stream project. The gas market is modeled on a global scale using aggregate gas consumption and production regions. The focus of the model is an economic valuation of the planned South Stream project, the findings suggest that there is no economic rationale for this project. The main benefits of this project lie in the non-economic, in this particular case political, gains[15].

Holtz uses the GASMODO model[45] with a time horizon until 2025 the model uses the Mixed complementarity format with a PATH solver. The model focuses on the European market and the sources of import. The model predicts a growing LNG hub in the UK serving the mainland and predicts that a diversification of import regions will serve the growing import[46].

Lochner focuses on the differences in prices at the different nodes. When the price difference at the nodes exceeds the transport costs to this node there is congestion. In the literature on market integration the price difference between markets is referred to as the parity bound [7].

The (improved) TIGER model of Lochner studies the price difference between these nodes, hence the aggregate interconnector capacity between two countries. The main bottlenecks are found in Eastern Europe and between Denmark and Germany. Congestion however is from a society point of view efficient since the cost of lifting the elevation can exceed the benefits. This is probably the case between the UK and Belgium[60].

Dieckhöner extends the above model and assesses a longer time horizon. Lochner predicts the state of the gas market in 2015 where Dieckhöner looks at projections until 2019. The model is tested in five scenarios where different future projects are integrated into the model. The model suggests that a lot of the congestion is located in Eastern Europe, this is roughly the same as the conclusions from the above Lochner model. The projects undertaken to alleviate these risks are mainly undertaken in the NW-E gas market where market integration is already high and therefore does not alleviate the expected congestion[23].

The MAGELAN model is used to capture the dynamics between the gas markets in the USA, the EU and Japan [60]. Not surprisingly this focuses on the role of LNG, since this connects the markets. The role of LNG will grow although in a different way in each region. LNG will decrease in the EU because its geographical location transport by pipeline is expected to be the major supply method. The US and Japan are expected to be more exposed to the LNG market.

Gabriel's study is more a show case of his conceptualization than a means to analyze the future of the gas market, as he conclude himself in his conclusion. He models the natural gas market as a complementarity problem and solves the resulting model with a PATH MCP solver. The model studies market power of suppliers and the security of future supply to the European market. In order to limit the complexity of the problem he only awards full strategical behavior to the suppliers and defines all other actors on the gas market as price takers, what he judges to be a realistic assumption of the distribution of market power in the European gas

market[34].

Modeling gap

When assessing this wide variety of models one comes to think about what else there is to wish for. What is still missing from these approaches and is there a blind spot among these techniques? The modeling techniques are all using optimization techniques to determine the path to the future. Optimization either from a god like stand standpoint pinning to a global optimum of the solution state, hence where should we alleviate constraints in order to improve our optimum. Although this might sound reasonable to an economist, it is hard to argue that actors on crude markets always behave in an economically sound way. From the modeling done in the above example we are unable to conceptualize irrational behavior. Note that this irrational behavior does not mean we expect the actor to purposefully hurt his own interest. The basis for this behavior could either lie outside the optimization scope, e.g. state-run actors who have to take domestic issues into account. Another example would be the fact that certain information might not be disclosed to the actor or he might even be deliberately mislead.

Another drawback of the discussed models is the limited applicability to social and technical challenges. The mathematical formulation makes it hard to adjust to the socially desired outcome or build-in technical paradigm shifts. In short the models above are all based on some sort of optimization algorithm which by definition is not extensible. This limits the usefulness of the model for scenario analysis since we are unable to detach ourselves from the 'normalcy bias'. Meaning that when we ask anybody to predict the immediate future, there is a bias in thinking it will not differ to much from the world we see today.

From the above literature assessment we conclude that there is a variety of modeling techniques being used in the natural gas market and we observe a development of modeling to a more holistic and lower scale approach. However the methods leave open a gap of knowledge in implementing more complex behavior. A new approach to modeling the gas market which addresses this behavior offers a promising academic opportunity. From a societal and company viewpoint it could be a useful tool in the art of scenario analysis. Within this thesis we will introduce a new approach to gas market modeling and discuss its formalization and implementation.

Author	Year	Output	Meth.
Manne	1986	Probabilities of disruption under different import policies	Eq ¹
Golombek	1995	Effect of liberalization on social welfare	Eq
Krichene	2002	Effect of market shocks on the elasticity of consumers and producers	TS ²
Chyong	2014	Predicts gas flows in the European region, with the main finding that there is no economic rationale for South Stream project Global	NPV ³
Perner	2004	EUGAS model predicts no supply side scarcity, big transportation investments are needed	LP ⁴
Lochner & Bothe	2009	The TIGER model assesses the role of LNG will be relevant even if volumes are modest, since it is the marginal producer	LP
Abada	2011	The model describes the European market as if it were in perfect competition and studies the imperfection	NLP ⁵
Diekhöner	2013	Adresses how planned projects alleviate the expected congestion in the EU	LP
Holtz	2009	Predicts gas flows in the European region and imports sources, with the main finding that a major LNG hub will provide EU mainland	MCP ⁶

¹Equilibrium Modeling

²Time Series

³Net Present Value

⁴Linear Programming

⁵Non-Linear Programming

⁶Mixed Complementarity Modeling

Gabriel	2012	Mathematically formulates the problem for a broad variety of actors, compares the market power and optimal solution of market prices in a handful scenarios	MCP
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Table 1.1: Overview of literature modeling methodology

1.2.3. Problem statement

Following the knowledge gaps the project can be delineated further. The exact definition is also a methodological choice since the approach used to answer the problem provides a certain paradigm that inherently influences the results. It depends whether we see the gas market system as a complex system of actors interacting with each other where emergent or even evolutionary behavior is expected (Agent Based Modeling). Or do we see the market as a set of equilibrium equations based on economic theories and consider the places where they do not hold as market imperfections (Equilibrium modeling). Or are we studying the market as a set of players which are pursuing a certain strategy (Game theory)[81].

The problem we would like to address is the impacts of world dynamics on the European market prices. Models found in literature are high in granularity and geographically restricted. A high level systematic approach on world trends would suit our research problem best. As we discussed there are multiple interconnected markets with dynamics reaching farther than the economic rational.

Chapter 4 on modeling methodology will conclude that in order to address the complexities discussed there is no ready to use model and formalization available and we will have to come up with a new formalization. The “glasses used” to address the problem description are based on the Agent Based Modeling (ABM) methods.

1.2.4. Research objective

The objective is to formalize how key world drivers influence the natural gas market in Northwest Europe and build a quantitative tool-set to translate scenarios into market conditions. These market conditions are highly relevant for infrastructural investment decisions as well as for energy companies and their customers in hedging their contracts. For more information on the latter please see social relevance. Major investment decisions are needed because of the physical changes of the gas flows that are expected. Gas price predictions are needed in order to make these investments and the proposed model can help to determine these prices.

1.2.5. Scope

The scope of the problem confines the research objective. Within this section we would like to draw the outer boundaries of problem scope. During the research in this thesis the focus will be narrowed further. The scope provided below should be read as the largest diameter of this funnel.

The **time horizon** is limited to 2050. The natural gas market is characterized by long lead times of investments and projects to materialize. This supports a study over multiple decades.

Geographical the Northwestern European region is of particular interest since historically gas has been of major importance to the region. The region is subject to systematic changes. However to fully understand the dynamics the study should look at all possible connections which are of interest to this region. When addressing a scenario study of carbon based energy carriers one can not ignore the finite reserves and the transition dilemma. Therefore a special focus on Northwest Europe does not mean that world dynamics fall outside the scope.

The **result** of the study is a scenario analysis for the Northwest European gas market, where market prices, consumption and production quantities, as well as the origin of the imported gas become apparent.

1.2.6. Scientific relevance

Scientific value can be found on multiple levels, as discussed above the field of natural gas market modeling has a blind-spot in modeling complex behavior. Addressing this behavior from an ABM perspective provides a new paradigm in gas market modeling.

Capturing the world prices and quantities in a high level systematic way we will be able to incorporate the finite supply of natural gas. By studying the literature a high level (low graininess) has not been found. The scope of this approach to the problem would therefore have scientific merit by itself.

More scientific relevance can be found in the insight the study produces. The increased exposure of world trends on the European gas market has not been modelled so far on a systematic level. Models tend to focus on internal factors as congestion and market power within the European market. Providing quantitative results about how the world will develop colours the picture of the gas market and could shed another light on the previous studies.

1.2.7. Social relevance

There are two ways to address the social relevance of the proposed research problem. The first perspective is the strictly economic component and the second is the sustainability of our energy supply, which has an ethical component as well.

Economics studies the allocation of scarce resources. Resources are limited in the natural gas system and should be allocated optimally to ensure maximum social welfare. Resources studied within this research problem are investments in congestion and technology within the European gas market.

Climate change is shaping the policy agenda and defines new societal goals as “leaving a better world for our (grand-)children” or “reducing our ecological footprint”. The energy system today is highly dependent on the availability of natural gas. It is hard to imagine a world without natural gas and it could play an important role as a ‘transition fuel’ to a sustainable future. However natural gas as being a fossil energy carrier, has an ecological impact of itself. Another part of the sustainability question is the availability of energy in the future, since the natural gas is scarce on the human scale we should prepare for a world where this energy source is not abundantly available. Providing data for this debate and providing policy makers with tools to test and study policy choices is in societies interest.

1.2.8. Research question

From the above analysis the following research questions can be distilled. The sub-questions will help structure the answer to the main research question.

"How are the North-Western European gas prices influenced on the long term by the drivers of the global gas market?"

To break down the above question sub-questions have been formulated.

- How is the demand for natural gas going to develop?
- How is supply of natural gas expected to change?
- How do market imperfections impact the natural gas market?
- What is the effect of the discussed market changes on Eneco and what strategies can it pursue to adapt?

1.3. Thesis structure

The above described problem statement will be answered by providing a general description of the gas market in chapter 2 to bring the reader up to speed about the context of the problem formulation. This chapter will introduce terminology which is expected to be general knowledge in the following chapters. Besides informing the reader about the context of the gas market it also serves the purpose of defining concepts. Terminology in the natural gas market can be ambiguous and has a lot of grey areas. To provide one example, what are considered to be conventional or unconventional reserves of natural gas can depend on the geographical or historical perspective we take. A conventional field can, for example when the pressure drops, be mined with unconventional mining methods. One of the points of this chapter is to provide a ‘lexicon’ of terminology.

In order to narrow the story down back to the problem definition we will conceptualize the gas market in a qualitative model description in chapter 3. We will visualize the complex system of the gas market and fit this to the problem description. This first demarcation of the gas market determines what we take with us to a quantitative phase of the thesis. Another purpose of this chapter is the introduction of a special stakeholder, the Dutch Energy company "Eneco". The role of Eneco in the gas market will be discussed and how Eneco will fit in the conceptualization provided in this chapter.

The model methodology chapter 4 will discuss the methodological choices of the research. We will discuss the positive aspects and drawbacks of and Agent-Based Modeling approach in contrast to what is common practice in literature. We will discuss the formalization with the help of a proof-of-concept of the model.

After picking a modeling paradigm we should assess the problem description through this new pair of glasses. The implementation chapter describes how the real world has been caught in this model. At the end of this chapter 5 the reader should have a feeling of what is modelled and what the results might tell us. An assessment of how successful the model implementation was will be the concluding piece of this chapter.

In chapter 6 is discussed how the model runs are set up. How the scenarios are translated to external factors and what assumptions are made in the parametrization of the model. Within this chapter the verification process is described as well, meaning how did we test if the behaviour of the model is as we intended.

The results yielded from the experiments are discussed in chapter 7. Within this chapter we discuss how the numerical results translate to the real world and how they help to answer the research question. A validation of the results is conducted in order to assess if the results are credible and if they line up with existing literature. Readers only interested in quantitative outcomes can start reading from this point on.

The conclusions found in chapter 8 will discuss how the research questions are answered and summarize model findings. The dynamics behind the results will be discussed as well as what this means for the energy market and Eneco in particular. Within this chapter we will also reflect on the external factors derived from the scenarios that were used during the quantification of the natural gas market and make recommendations for further research. A reflection on how the methodology helped to address the research problem is provided as well.

1.3.1. Units in the natural gas world

In order to improve readability we want to shed some light on the units the reader will encounter when reading this thesis or other sources regarding the gas market. The world of natural gas trade knows a lot of confusing parameters. The diverse conversion rates used in this report are summarized below. All units convert metric units are natural gas at typical pressure and temperature, unless stated otherwise. As is common in the gas terminology when referring to the left-hand side of the table M = 1.000 and MM = 1.000.000. MWh is an abbreviation of Mega Watt Hour and refers to 1.000.000 Watt hours[29].

Conversion table

1 MMBtu	=	0.293	MWh
1 Mcf	=	0.299	MWh
1 Mcm	=	10.6	MWh
1 ton LNG	=	14.44	MWh

Table 1.2: Unit conversion

One final word about the content, which is more of a warning. Gas markets worldwide use different metrics, currencies and in some rare cases different definitions for the products they are selling. In this report in an attempt to improve readability and to be as consistent as possible the units have been converted to Euro per MWh and the products being assessed are spot prices, which in general means the prices on the Day Ahead market. These two definitions are problematic in at least two instances. The Euro only exists since its introduction in 1999. When prices are assessed before this period the conversion rate of the introduction is being extrapolated, a solution that does not win the beauty contest. And when addressing LNG markets, around 20 to 30 percent of the gas sold world wide, a spot market is sometimes lacking or is stretched to LNG being sold as far as 6 months into the future. This discrepancy between what is considered spot is not reflected in the graphs that are plotted but should be kept in mind.

2

Gas market basics

"The fundamental business of the country, that is, production and distribution of commodities, is on a sound and prosperous basis."

Herbert Hoover, 1929
president of the USA

In this chapter the natural gas market will be described. In the first part we will discuss the physical part of natural gas exploration, transportation and consumption. The system will be described in the order of the supply chain, visualized along the figure 2.1. Within this figure we will highlight the part of the value chain we are discussing. The second part of this chapter will focus on the gas market structure, the natural gas market is a virtual market place. Both in the fact that there is no single physical place these trades are made, and in the fact that the traded good can be a contract not representing a physical delivery of natural gas. Although not everything discussed in this chapter will end up in the model formalization it is important to have a general understanding of the market. Since this market is characterized by a sometimes conflicting terminology (e.g. the different ways concept "shale" or "spot-market" is defined) the goal of this chapter is also to define these concepts on how they are used in this thesis. In other words to bring everyone on the same page.

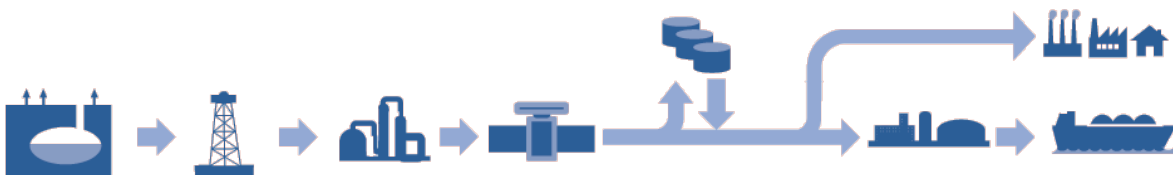


Figure 2.1: Natural gas chain

2.1. Supply characteristics

The supply side of the gas market is defined as everything that is considered to be of relevance in the exploration stage. This section will discuss the geographical endowment and the exploration of natural gas.

2.1.1. Endowment

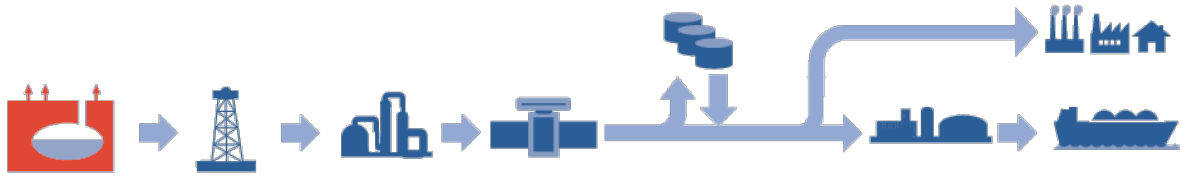


Figure 2.2: Natural gas chain "endowment"

Natural gas is found in a few major regions which in most cases are far removed from a demand region. The only exception was Europe, but reserves are depleting. The US became self-sufficient due to shale discoveries. But still roughly sixty percent of proven reserves worldwide are found in the top four of this list (Iran, Russia, Qatar and Turkmenistan), shipping their gas through pipelines or by LNG vessels to Asia and Europe.

However this is not the end of the story. The composition of natural gas found in a field is unique, but when delivered to the market it is expected to be a single comparable product. Therefore refinery steps are necessary to bring the gas to the same quality standards. This quality is known as the calorific value and can be expressed in the Wobbe-index. In short this is the behaviour of the gas when it is burned. Most of the gas found in the world and being sold on the markets is H-gas, high calorific value gas. However the composition of the Gas of the Groningen field or of the same composition, this gas falls within the bandwidth of L-gas (G-gas) has a lower calorific value. Since the Groningen field was the main supplier of the western European gas market for decades, a lot of appliances have been adapted to this standard. This led to a separate market for lower calorific (L-gas) in this region.

The use of shale gas in the US has vastly increased its reserves, the reserves of worldwide shale gas reserves are in great extend estimations with great uncertainties and little test drills. Studies suggest that unproven shale gas reserves will roughly double the worlds known reserve[3]. A wide exploration of known shale gas reserves will shake up existing conventions of what are exporting and importing regions in the world. These new shale gas reserves are expected to be situated closer to demand regions, for example the east coast of China or in the Ukraine. However these figures are estimates and whether these are truly technically and economically feasible reserves has yet to be seen.

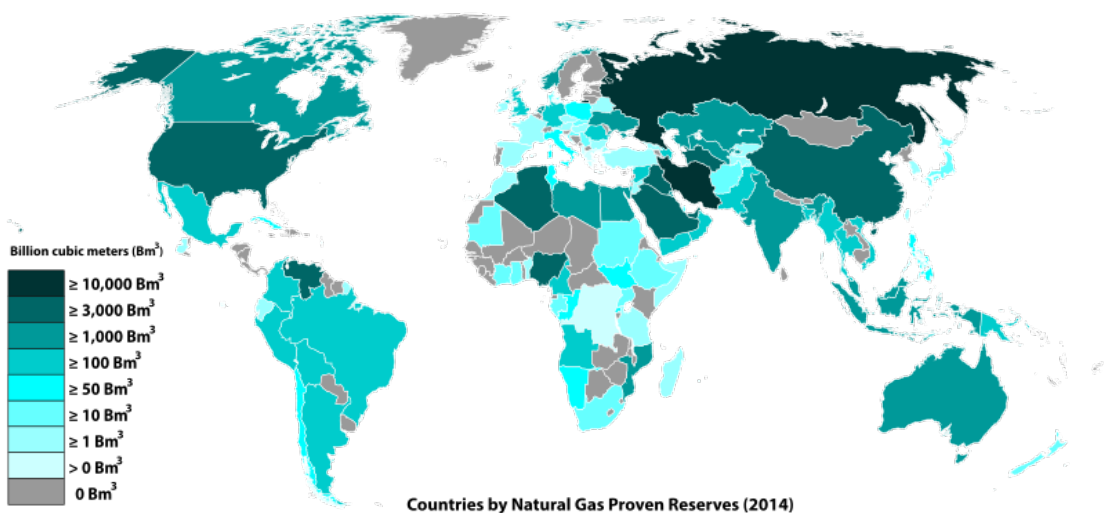


Figure 2.3: Natural gas endowment

2.1.2. Exploration

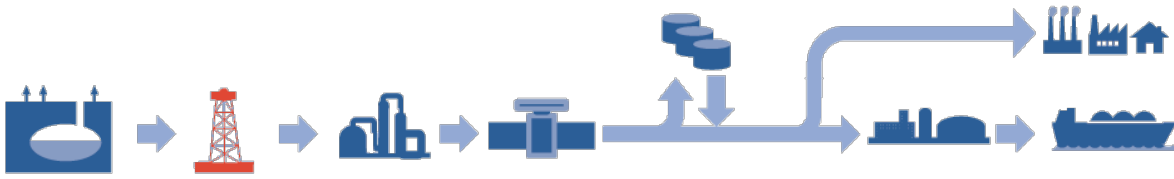
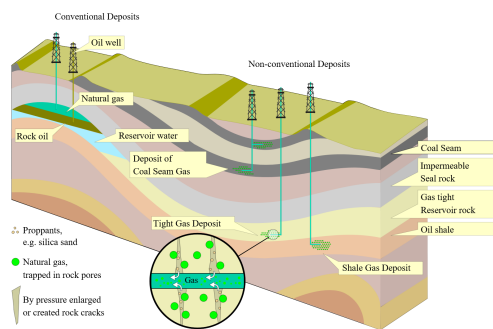


Figure 2.4: Natural gas chain "exploration"

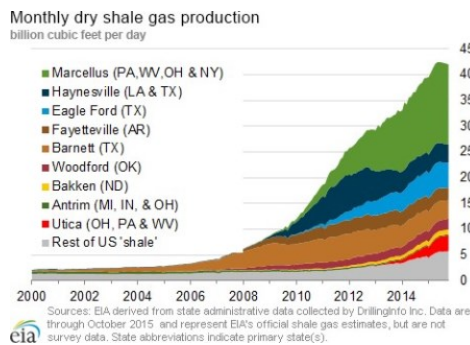
When we speak about natural gas exploration, we distinguish between conventional and unconventional sources of natural gas. Conventional sources are major gas fields formed by layers of biological material that has degraded. The gas that formed in this process became trapped under a non-permeable earth layer. These gas fields are mostly located above oil fields or coal layers. The Groningen field is one example of a conventional producing gas field.

The past years non-conventional gas sources have been on the rise. Technological advances and a high gas price have made it possible to access natural gas sources that are more difficult to exploit. Shale gas is such an unconventional natural gas source. Shale gas is gas trapped in shale layers. This geological strata has a low permeable and thereby requires fracking (breaking the formation) to bring the gas to the surface. The same is necessary to acquire tight gas deposits. Tight gas is not found in the shale strata but in rock formations. In the production of shale wells both natural gas and oil are produced, as well as a condensate of higher hydro-carbons (like butane). These products all have a different market. The revolution of shale gas in the US is partly due the fact that the wells being constructed were primarily there to produce oil. The natural gas was a by-product that was sold at any price not necessarily reflecting the cost of exploration. The figure 2.5a below sketches the different types of exploration of natural gas ¹. Note that whether gas is conventional or non-conventional and what is shale gas or tight gas is a matter of definition and might be hard to define due to the fact that all fields are unique. Another difficulty arises that how fields are extracted can change over time, when a new field is found the pressure is high and conventional exploration techniques are used. When the field gets near a state of depletion the pressure drops and unconventional methods are used to keep extracting natural gas. So was this a conventional or unconventional field? The word conventional also has a subjective meaning, as technology progresses when will an unconventional technique become conventional?

In this thesis will make a distinction between proven technical recoverable reserves and unproven reserves. We will use the definitions and data provided in the BP Energy Outlook[10] and the CIA Factbook[3].



(a) Overview of different type of natural gas exploration



(b) Shale gas production in the US (EIA)

Figure 2.5: Difference between shale, tight and conventional gas

¹Figure credits: https://en.wikipedia.org/wiki/Shale_gas in August 2017

2.2. Processing, transport and storage characteristics

In this section everything of relevance to the gas sector that is not considered to be either upstream or downstream is called midstream and is defined as "business category involving the processing and transportation sectors of petroleum industry. Example: transportation pipelines, terminals, gas processing and treatment, LNG, LPG, and GTL" [32]. In this section processing, storing and transporting gas will be discussed.

2.2.1. Processing

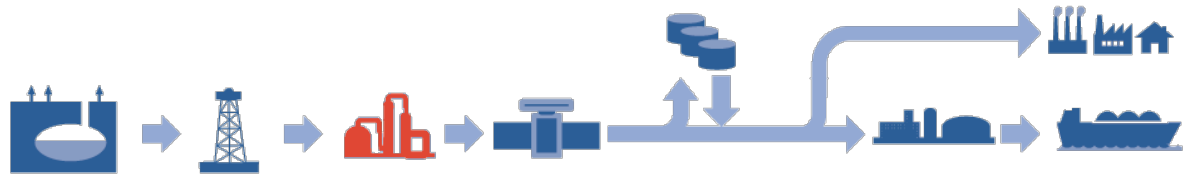


Figure 2.6: Natural gas chain "processing"

Since all reserves have a unique composition of chemicals, the natural gas needs to be transformed to a uniform product in a processing facility. In general the crude product is dried (removing of water) and the different chemical components are separated. However one particular processing step requires some attention. This is conversion of high to low calorific gas. Since decades the Groningen field provided the Northwestern European region with G-gas. Appliances in this region have been adjusted and converted to the calorific value of this gas. At the time this seemed like the logical decision. Nowadays diversity of supply sources is seemed desirable and most supply regions are providing high-calorific gas (H-gas). So H-gas has to be converted back to L-gas by diluting the H-gas with nitrogen to give it the same calorific value of G-gas. This pushing around of nitrogen is relatively costly. The costs of converting H-gas to L-gas are being borne by the transmission operator in the Netherlands and are therefore not part of the buy or sell decision on the demand and supply side of the gas market. L-gas is mainly consumed in Northwest Europe by households and small businesses and is being delivered by the utility companies. H-gas is being supplied by the transmission operator to energy intensive industry and the electricity sector.

2.2.2. Transportation

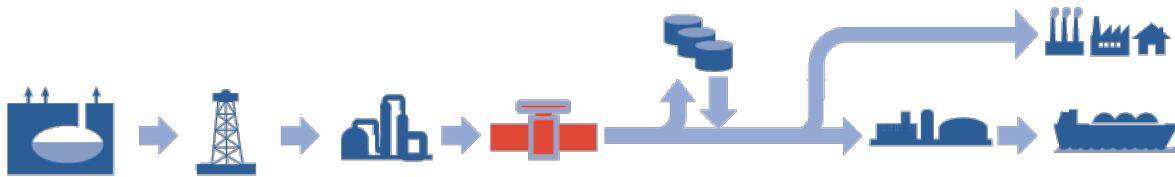


Figure 2.7: Natural gas chain "transport"

The transportation of natural gas depends highly on the distance covered from the supply region to the demand region. When the supply region is relatively close to the demand region the gas is transported by pipeline. The gas is compressed and transported by high pressure pipelines. Examples of these connections are the pipelines connecting Russia's fields to the European market. To keep the gas pressurized over a long distance compressors have to re-pressure the gas along its way. To fuel the compressors a little bit of gas is consumed, the amount is dependent on the relative roughness of the pipe among other variables.

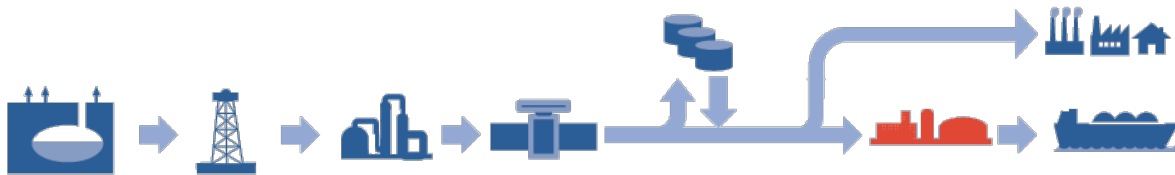


Figure 2.8: Natural gas chain "liquefaction"

Another way of transporting gas is to liquefy the product and transport it by means of LNG tankers or trucks. This step requires liquefaction and storage facilities at the production side. Natural gas is being cooled to at least -163 degrees Celsius, a temperature below its boiling point. The liquid state of natural gas has a 600 times smaller volume in comparison to its gaseous phase. The energy density therefore increases by the same amount making transport viable and making it able to compete with other energy carriers, like diesel. The liquefaction process of natural gas consists of a liquefaction plant where the gas is converted to its liquid phase. LNG terminals store the gas, the terminals need to be present in both the supply region and the demand region. When the gas is fed back into the grid it needs to be boiled to become gaseous again, this process is called regasification. Keeping the gas liquid is a continuous process, since small portions of the liquid become gaseous over time. This gas (which is called boil-off) is partly re-liquefied and partly fed into the main grid. Processing capacity of LNG regasification and liquefaction capacity are capital intensive investments. These investments are in general made in combination with long-term contracts to guarantee a return.

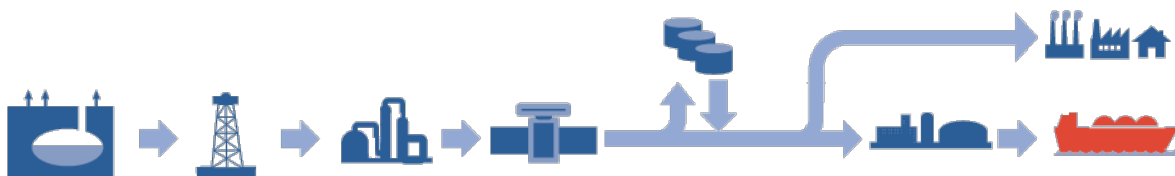


Figure 2.9: Natural gas chain "LNG shipments"

In the demand region there need to be regasification and storage facilities to boil the gas back to its gaseous state. Liquefaction, regasification and storage facilities can be both on land or floating. LNG facilities are capital expensive and their construction is in general being hedged with long-term contracts. Liquefaction and regasification are energy intensive and transport by tankers requires fuel and boil-off². LNG

²Boil-off is the vaporization of LNG during transport or storage that is unavoidable, this gas can be partly be re-liquefied but not completely. This gas is therefore used for the facilities or fed into the main grid.

experiences exponential growth which is best captured in the growth of processing capacity as described in figures 2.10a and 2.10b[80].

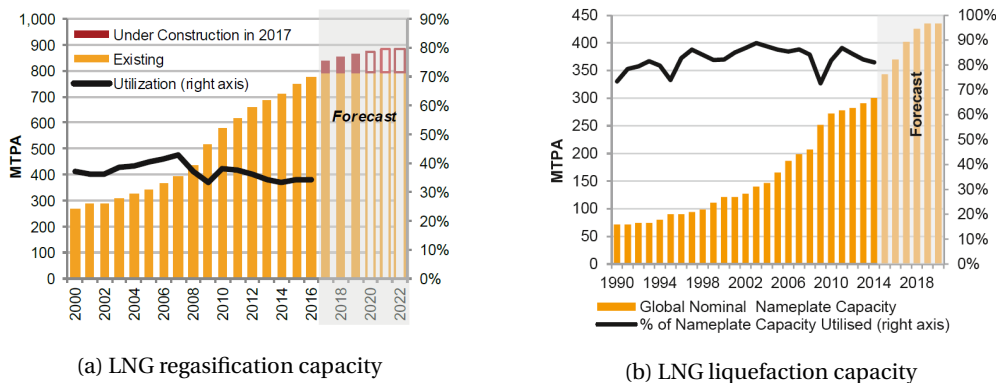


Figure 2.10: Growth in LNG regasification and liquefaction capacity

Liquefaction and regasification use a substantial part of energy, however transport by tanker is relatively energy efficient in contrast to pressurizing the gas over long distances in pipelines. So over short distances pipelines are the preferred method of transport, but over longer distances LNG has the advantage. The break-even point between these two technologies from a cost perspective lies at three thousand kilometers[51]. However as is characteristic for the gas market, cost considerations are part of the equation but not the whole story. Diversification of supply sources is desirable from a negotiating perspective but as well from a geopolitical perspective since supply regions tend to be quite unstable. A pipeline does not foster a diversity of supply sources since in general it connects a single supply region to a single demand region. Investments made in the pipeline project are sunk-cost and can only be recovered by maximizing revenues in general by maximizing throughput. LNG however is a world market and offers the flexibility to buy from different sources, it makes the buyer and seller less dependable. Furthermore it connects regions which are relatively far removed from supply sources. For example eastern Asia is for the majority supplied by LNG for their need of natural gas.

Besides clear supply and demand regions one can also distinguish transport regions. These are regions between demand and supply who play an important role in transporting the gas. Eastern Europe, and in particular Ukraine, can be categorized as a transport region. The stability of those regions is of vital importance in connecting supply and demand. This lesson was learned the hard way at the start of the Russia-Ukraine conflict which caused major supply issues all across Europe in 2006[54][8]. In a search to reroute this major gas supply region projects in the Black Sea have been proposed landing in Turkey and thereby making Turkey a transit region for western Europe. With renewed tensions in Turkey new pipeline projects in this country equally entail supply disruption risks. The Nordstream project directly connects the north of Germany with the Russian gas fields and with Nordstream 2 on the way expanding capacity on this route. When accessing the European expected demand and supply patterns Western-Europe is destined to become a transport region for middle and eastern Europe. However major interconnector capacity is needed to facilitate the streams[58]. Interestingly old transport regions become importing regions for geopolitical reasons. The capacity along Nordstream is expected to be sufficient to supply Northwest Europe in the foreseeable future[16].

2.2.3. Storage

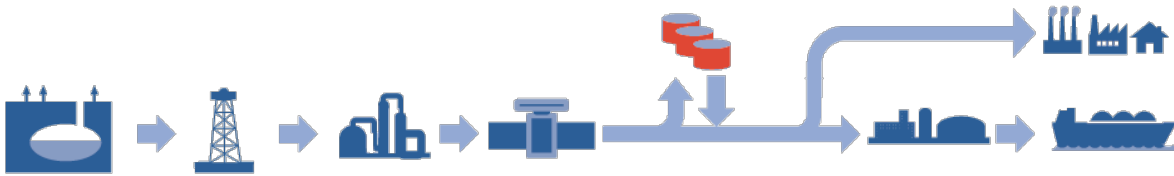


Figure 2.11: Natural gas chain "storage"

Since consumption of natural gas is for a major part seasonal, the way to smooth production and transportation is to employ storage capacity. Major storage facilities are in general depleted gas fields, salt caves and aquifers. These are filled up during the off-peak season and are in general located in the demand region. In Northwest Europe seasonal demand fluctuations were historically supplied by flexible regional production, however with declining reserves in Europe this flexibility is expected to be compensated by an increase in working gas storage capacity[44].

Another form of storage can be found in LNG storage facilities. A large part of the technical details have already been discussed in the section above. In existing operational LNG facilities in Europe there is storage capacity for 10 million cubic meters of LNG and another 5 million is under construction and 14 million cubic meters planned³.

In general storage smooths natural gas production and transportation. It thereby addresses price arbitrage conditions between seasons and hedges for supply disruptions. In economic theory the price difference between winter periods and summer periods should reflect the storage costs of natural gas. In a longer time frame it allows trading between low price periods and high price periods. When prices are considered low storage facilities fill up and when prices are considered high storage levels drop as with all commodities.

³1 cubic meter LNG is equivalent to 0.405 tonnes LNG

2.3. Demand characteristics

Within this section the general characteristics for the demand of natural gas will be discussed. Demand for natural gas can be divided in three main groups. Firstly, the use of natural gas for the purpose of heating in the urban environment. This entails the use of natural gas in domestic residences as well as office heating. Secondly, demand in the heavy industry where natural gas is seen as a feedstock in industrial processes. Lastly demand in the electricity sector, where gas is used to generate electricity. The stranger in our midst is the demand for LNG as a product, which will be discussed first.

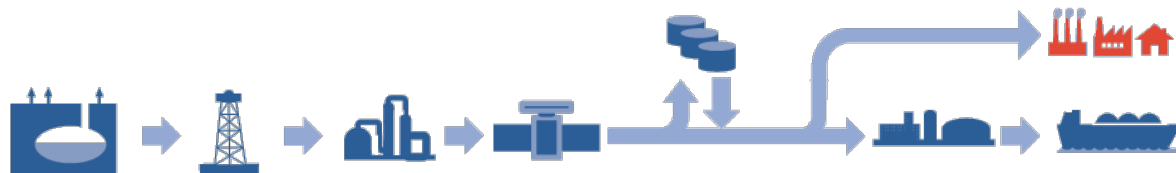


Figure 2.12: Natural gas chain demand

2.3.1. Demand for LNG as a product

As far as discussed until now LNG has been addressed as a mode of transportation and possibly storage, not as a product in itself. Within this section we would like to address the demand for LNG as a product. As discussed earlier, LNG is natural gas cooled down to the point where it resides in a liquid phase. In a liquid phase the same amount of gas holds a 600 smaller volume than its gaseous brother. With this volume reduction comes a higher energy density, which makes the product viable as a fuel for transport.

LNG as fuel for the transportation sector is widely debated as an alternative for diesel in road trucks or bunker fuel in vessels. This would come with benefits in terms of reduced small particle emissions and greenhouse gas emissions[56]. Trucks running on natural gas have other non-climate related benefits, like noise reduction and legislation advantages which make them attractive for inner-city transportation.

The share of natural gas in the European transportation sector is 0.4%, which is not of great influence on the market. This incorporates all natural gas usage in the industry in Europe without making a distinction between LNG and CNG. Apart from the transportation sector there is limited use for LNG as a product just as a means of transportation to sites that are either not accessible by pipelines or where flexibility is required.

2.3.2. Heating in the built environment

Gas demand is generally associated with its use in the building environment as heating fuel. Both for central heating as for cooking gas is burned to transfer heat. The demand for central heating is as expected seasonal and dependent on the weather. Roughly 70 percent of gas consumed by households is consumed for house heating purposes during the colder months of the year. During the warmer months of the year a baseline consumption of natural gas is consumed in households, which is limited to cooking and water heating for residual purposes like showering. This year round consumption is cyclical within the day and consumed at peak hours in the morning and evening.

However, gas usage per capita is declining due to energy savings and efficiency gains. Over the past decades the efficiency of boilers has improved reducing demand per household. At the same time the recent focus on isolation and efficient use of heat flows has further decreased consumption of natural gas for heating purposes.

Society's use of electricity is increasing. Electricity is used in more fields and replacing the energy need for other fuels. This phenomenon is called electrification of society and also impacts the consumption of natural gas. Examples are electrical cooking, heat pumps regenerating heat from ventilation systems and heat pumps which use geothermal energy. These new technologies reduce the need for natural gas in the built environment. The investments for connecting homes to the existing natural gas infrastructure are significant and require certainty of future consumption patterns. These trends have moved distribution companies in the Netherlands to stop connecting newly built homes to gas infrastructure as standard procedure. The resulting situation is that not all new building projects are connected to the gas grid, thus further reducing the demand for natural gas.

The amount natural gas that is consumed for central heating is measured by statistical agencies in two

formats. One is 'heating days', which entails the days when outside temperatures drop below a point where people are likely to turn on their central heating systems. However, this does not take into account actual temperatures below these threshold lines. "Heating degrees" is the difference between the average daily temperature and the point where people are likely to turn on their heating. Two factors are of influence here that we want to discuss. The first one is that because of increased efficiency of appliances that consume natural gas and because of increased isolation of buildings, natural gas per heating degree day is expected to decline. The other factor that should be taken into account is that because of changing global temperatures, these heating days and heating degrees are expected to decrease, thereby reducing the demand for natural gas for heating.

All the above-mentioned trends are leading to a decline in natural gas per capita. A decline of consumption per connection of around 1% is already measurable. Since new additions to the grid are not certain anymore, this decline is likely to be present in total consumption figures soon.

2.3.3. Heavy industry demand

Another big consumer of natural gas is the heavy industry. Within the heavy industry, natural gas can be divided into two subgroups. The consumption used to provide heat and consumption where gas is used as a feedstock. Examples of gas usage for heating purposes are the production of glass and the incineration of household waste. For some industrial processes, natural gas is a chemical feedstock. An example of such a process is the production of fertilizer and methanol. Methanol is used in the production in a variety of processes.

Gas usage in the heavy industry combined with the electricity sector accounts worldwide for 73% of the total gas consumption and is expected to grow to 74% in 2040[30].

2.3.4. Demand in the electricity sector

Natural gas is used in gas-fired power plants to generate electricity. Accompanied with the use of energy in the heavy industry, this accounts for three quarters of the total gas consumption worldwide. Coal and natural gas make up roughly 63%[74] of the world electricity production. The European Union, however, has a different mix of sources for their electricity production, 45% is carbon-based. Respectively, 16% is natural gas and 28% coal.

In this section, I mention natural gas together with coal for the following reasons. Both are major carbon-based sources. Therefore, they are mentioned together in the debate about greenhouse gases. Natural gas is twice as clean as coal. Coal emits between 205 and 220 pounds of CO₂ per Btu, depending on which type of coal is used, while natural gas emits 117 pounds of CO₂ per Btu[28]. The relative contribution of the two for the energy mix is dependent on their relative price and the price of carbon emissions. From 2008 onwards, the United States has been producing shale and tight gas to unprecedented levels. This made the US energy independent. Until then, the US has been a net importer. The production of cheap gas pushed out coal imports, which resulted in a price fall. Cheap coal started pushing out natural gas at the European mainland as a source for energy production. This has led to a cancellation and, to some extent, even closing of new gas-fired power plants and the opening of new coal ones. This trend was in stark contrast to projections made before the shale gas revolution. One of the main villains in this story is the CO₂ price. The European Union has adopted in the early 2000s a trading scheme for CO₂ emission rights, called the European Trading Scheme (in short ETS). The ETS is a policy instrument to regulate CO₂ emissions of certain sectors to achieve the targets set by the Kyoto agreement. However, the objectives got extended to the point where the CO₂ price was supposed to reflect the external cost of greenhouse gas emissions and to make cleaner technologies more competitive. The CO₂ price, however, never reached projected levels (in part to external reasons and in part to design flaws). A low CO₂ price combined with a completely crashed coal market made this unexpected comeback possible. And to the horror of environmentalists, new coal-fired power plants started to be planned and constructed in Western Europe.

Apart from being cleaner, natural gas has another advantage over coal, its flexibility. Gas-fired power plants are more flexible than coal-fired power plants in ramp-up and ramp-down capacity and the time required to bring an installation on-line in case of a cold start. In an era where production has to follow demand and fossil-fuel based generation capacity is expected to fill the void of the intermittent production inherent to sustainable energy sources like wind and solar, flexibility has an undeniable value.

Another advantage of gas-fired power plants are their scalability. The construction time is significantly shorter than its coal-fired counterpart. Moreover, they can be constructed in smaller sizes, turbines can be added to existing installations or taken off-line. This scalability has an advantage in the vast changing landscape of electricity production.

The most efficient way to produce energy in a gas fired power plant is using the waste heat for other purposes. This is called combined heat and power (CHP). The electrical efficiency decreases, while total energy efficiency increases. The heat extracted from this process can be used for industrial processes or district heating. The drawback of this technique is that it makes the installation less flexible, since it should also take the heat demand into the equation. In the current system this is addressed by having backup boilers to deliver the heat demand in case the CHP is offline.

2.4. Market behavior

In the sections above the natural gas value chain is addressed from a physical perspective. In this section the focus lies on the gas market, which can be a virtual business. Two things should be noted about the natural gas market. The first one is the fuzziness that surrounds the sector. In contrast to the electricity market, Over The Counter (OTC) sales are responsible for the majority of the sales in the European markets and Asian markets. OTC deals are not made public and therefore an analysis is difficult to make. Market analyst agencies like Bloomberg and Heren sell estimations of this data which they gather by expert judgment and by interviewing traders over the phone. This makes this data hard to verify and to come by or expensive.

The second point to make is that state run companies might have a non economical agenda. Regulated monopolies and oligopoly situations make economic assessments difficult. Within this section when applicable these concerns will be raised.

2.4.1. Divergence or convergence of world market prices

In maturing world markets we expect the convergence of prices, with the only denominating factor being the transport cost. Since technology is expected to be progressing, the Gravity law⁴ of economics predicts prices to converge. Figure 2.13 is a typical picture of world markets showing price divergence instead of convergence. Market prices are based on the BP Energy Outlook [10].

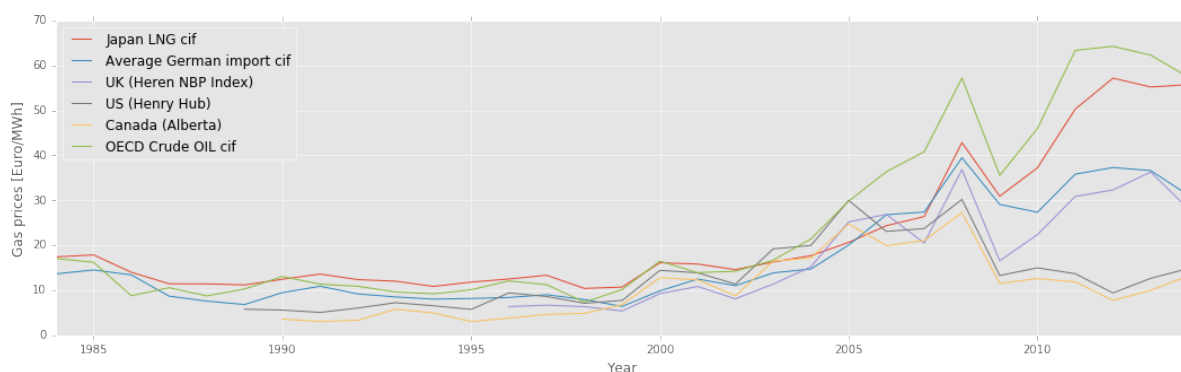


Figure 2.13: Historical world natural gas prices

Multiple factors are driving this behavior, the most notable one is the Fukushima disaster. In the aftermath all nuclear power plants of Japan were taken off-line. For (historical) political reasons Japan had relied greatly on nuclear power plants for its electricity production. As discussed earlier natural gas is more flexible than coal. In the absence of significant coal production capacity natural gas is the only viable alternative for electricity production. A demand driven price spike was the result, since Japan is not well connected by pipeline capacity, the main form of natural gas supply is through LNG terminals[39]. The other big demand regions, the US and Europe, do not rely heavily on LNG imports for the security of supply and could shift away from LNG when prices rose. This resulted in a spike in prices on the JKM while NBP and HH did not[13]. Furthermore we see prices in Europe (German & UK) couple. The same is applicable for Canada and the US. This supports the premise that when the JKM sucks up all LNG capacity, the coupling between different demand regions loosens and regional pricing prevails.

As discussed above, in maturing world markets, where globalization has been the driving force of the world economy, we would expect prices to converge to a world price with the only denominator being the shipping costs to different regions. Ever advancing technology would eventually lower shipping costs and

⁴The Gravity law is called after the famous formula for gravity, due to its similar form.

would make prices converge even more. Price difference between regions should be a driver for investment in shipping capacity until the 'arbitrage' conditions are lifted. The use of carbon based energy carriers like natural gas (and coal and gasoline) is coupled with economic growth. For this reason security of supply is of key importance for a country. Therefore transport capacity is in general bigger than current consumption. Bigger transport capacity could lower regional pricing since restrictions on transport capacity as a diverging force are being removed. Another reason for this is the usage of natural gas for heating homes. This makes natural gas a necessity driving over-provisioning of transport capacity. Security of supply is also reached by the diversification of the origin of supply. For these reasons we would expect regions to be coupled and world prices to converge.

In general we were expecting convergence of prices but due to an unforeseen event on one of the world markets this did not happen. Due to coupling on within the regions and a lack of connectivity between the regions we observed regional pricing. A growth in connection capacity between markets could take this away.

2.4.2. (Extremely) low market prices

In the last two years market prices have dropped significantly on both the TTF (and other EU hubs) and the HH. According most analyses the price dropped below the break even point of most wells on for example the HH. How is this possible and is this sustainable? The answer to this is twofold. In the first place, well extraction projects require large investments beforehand and have very low variable costs. When there is oversupply, according to classical economic models prices are equal to variable costs. Since the variable costs are a fraction of the break-even price we observe prices below the break-even price. During this period of low prices investments in new extraction capacity are low and therefore capacity tends to scale back and scarcity arises, accompanied by high prices (either due to the depletion of existing wells or due to increasing demand). This phenomenon is referred to as the Pork Cycle. In the figure below we observe this steep decline in production capacity (wells) after the HH spot market took a dive.

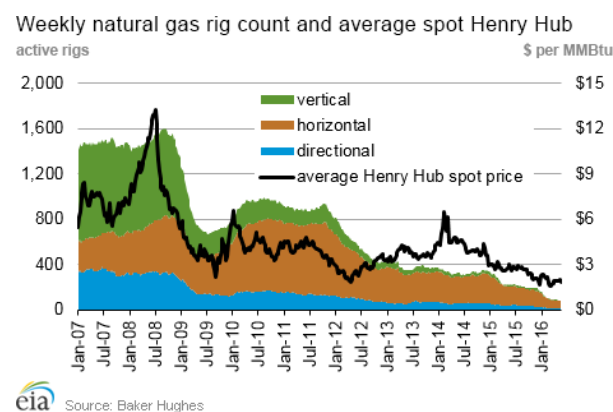


Figure 2.14: Rig count vs natural gas price at the Henry Hub (EIA)

The other side of the story is the fact that in certain areas gas and oil (or other hydrocarbons) are produced from the same well. This means that one or the other can be regarded as a byproduct. Therefore they are sold at whatever price the market is willing to pay for them. In certain cases even separation or distribution costs are not a factor due to legislation against flaring (burning by-products). Flaring is prohibited in certain parts of the world due to its environmental impact.

2.4.3. Irrational behavior of state run actors

In parts of the world suppliers are state-run and their motives are not always easy to explain by economic rationale. Examples of classical state run parties are Russia, Qatar and Iran. In a classical (upward sloping) supply curve we would expect that when the price is low the quantity sellers are willing to produce less. In the gas industry every well has its own characteristics and costs. When the prices are low only less expensive wells operate and less is produced. However in certain situations we observe the contrary, when prices are low more quantity is brought to market by certain sellers. State run actors can have a high dependency on revenue from oil and gas and therefore might be willing to sell more gas when the prices are low in contrast to economic belief.

Another example we should address are the actions of Russia following the dispute with Ukraine. After a political feud Russia tied off gas to Ukraine which is both a transit and import country. This hurt the whole of Europe which did not anticipate this move. It backed the call for diversification of energy sources possibly hurting the Russian interest in the long run. In the same light and during the same period several eastern European countries decided that they did not want to buy their gas from Russia anymore due to Russia's role in the destabilization of Ukraine. Instead they decided to buy natural gas through the German markets, arguably the same gas (since Germany bought the gas from Russia) for a higher price.

In short a lot of irrational behaviour from an economic theory can be observed on the gas market. Some of this is based on black swan events and close to impossible to account for. Others are explainable, however very difficult to predict.

2.5. Conclusion

In this chapter we discussed the gas market in general terms. After reading this chapter the reader should have a basic understanding of both the value chain and the market. The reader should also have an understanding about how key concepts are defined in this thesis. When talking about the gas market we should bear in mind that the market is difficult to summarize in general terms. One example of such an ambiguity is when do we consider an well or natural gas source to be conventional and when do we consider a source to be unconventional. In this thesis we will make a distinction between what is considered proven, technically recoverable reserves by the CIA factbook and the BP energy Outlook and what is considered unproven reserves by the same two sources. When scenarios talk about reserves we will categories them according to this distinction.

The main form of transportation of natural gas is by pipeline, when a demand region is far removed from a supply region and has access to sea shipping routes LNG shipments become a viable option. In a quantitative formalization the distinction between how supply and demand regions are geographically located matters.

On the demand side the key take away of this chapter is that demand can be categorized in three major demand groups. Namely demand in the electricity sector, heavy industry and in the building environment. These demand groups all have different characteristic of how seasonal the demand is and how elastic the demand is.

When making a quantitative assessment of the natural gas market one should think about to what extend we model complex behavior specific to the natural gas market. The behavior on the natural gas market can be complex and defy economic laws. In a quantitative assessment we want to be able to deal with this complex behavior. In the coming chapter we want to conceptualize the gas market(s) in order to find a first demarcation of a quantitative assessment.

3

Intermediaries

Any event, once it has occurred, can be made to appear inevitable by a competent historian

Lee Simonson

In this chapter we would like to make a bridge between the description of the more descriptive phase of the thesis to the modeling phase. We will start with focusing on the question what is feasible for the problem we like to answer. As this chapter is meant as a bridge between the real world description in the previous chapter and a model formalization in the chapter hereafter. We will also discuss the role of intermediaries in both the real world and how they will play a role in energy market modeling. The market does not only consist of buyers and seller but there are other entities not falling in one of these two categories, here called intermediaries. One example is the role of big energy companies (in the Netherlands for example Eneco). They buy for the main purpose of selling the product to end consumers. Their role will be discussed as well in this chapter. We will introduce the scenarios provided by Eneco that will help us to sketch the story line for the future studies.

3.1. Choosing the granularity of the scope

When addressing the natural gas supply and market system different scopes can be taken. In this section we want to discuss the examples of scope and determine the right geographical scope and granularity for the thesis.

As discussed we want to address the developments of the Northwest European gas market for the coming decades. The time horizon is chosen to best represent the developments on the market. In chapter 2 we discussed the fact that major projects in the gas market have long lead times. In most cases these projects are undertaken with the perspective of profitability over decades of operation. Examples of these investments are major transport pipelines and regasification & liquefaction terminals. The farther we look forward the less likely our predictions are expected to reflect reality. However, making an analysis of the natural gas sector which is limited to a shorter period will disregard these major investments. Another reason to take a long horizon is the fact that in scenario planning we want to think the unthinkable. Scenario planning is not about coming as close to the truth as possible, but more about exploring possibilities and being prepared. When taking a shorter time frame we are bound by assumptions about today's reality and are less likely to truly stretch our imagination. The best prediction for the world of tomorrow is today, taking a longer time helps to determine truly diverse scenario's which justifies the effort of scenario analysis. The last but not least reason for taking a longer time frame is the inherent fact that natural gas is a fossil fuel with a limited lifespan. The current reserves are formed over millions of years and the reserve to consumption ratio right now for most European gas fields is several decades (example is the Groningen field). How and if these reserves are replaced poses interesting questions which justify the time frame (till 2050).

The main focus of the thesis is the Northwestern European gas market. This gas market faces an interesting dynamic. Due to the tight integration of the energy markets pursued by the governing bodies (EU) we see price converging. Declining reserves in the region will shift import and export profiles of natural gas. The past

decade one of the major producers (the UK) has become an importer and this is expected to happen for the Netherlands as well. What are the options for replacing these flows? This is one of the interesting dynamics in this region.

In a complex system as the gas market looking at one component in isolation does not answer all the questions. If we want to quantify the Dutch gas market from a bottom-up approach we see the market is linked with surrounding markets as the NBP (UK), Gaspool (DE) and Zeebrugge (BE). Assessing only the TTF and not regarding dynamics on the neighbouring markets does not give the full picture. The quantification of the convergence of these markets is demonstrated in Appendix B.1. So by studying the EU as a single market we should address the overarching demand region as a whole. Since a small number of countries houses the vast majority of the world-wide proven conventional reserves[3], the entering or exit of one major player by an event can significantly impact the market. One example of such an event is the high spike of LNG on the Asian market leading to assets being underutilized on the Northwestern market. If we look at dynamics in a certain demand region we should at least make assumptions about how other demand regions are going to develop in order to assess in what direction supply is going to develop. Demand in other world regions is also important for the question about how reserves are going to develop. The different scopes have been summarized in the table 3.1 below. For scenario analysis on the Northwestern European market we should use a multi-decade time frame while looking at the world dynamics of supply and demand.

Table 3.1: Models of different granularity

Scale	Dimensions	Goals	Assumptions
4	World	Reserves	- Demand and supply developments of different world regions
3	Regional (continent)	Security of supply of single region	- Demand developments in region - Reserves of supply regions
2	Single market (national)	Market behaviour	- Demand & supply within a single market - Integration with neighbouring markets - Reserves of supply regions
1	City level distribution	Delivery optimization	- Demand characteristics

The key take away from table 3.1 is that when we are interested in a particular region, in this thesis NW Europe, we need to make assumptions about dynamics of the on the dimension above this particular focus area. In future studies with a large time window this becomes a more significant factor. In the scenario study proposed in this thesis the choice to model a global market is (partly) based on this argument.

3.2. Role of intermediaries

Intermediaries are here defined as not being buyers or sellers. Within the gas market we can define multiple agents or institutions who fall under this description. One could see transporters, storage operators, traders, markets a whole, big energy/utility companies as intermediaries. Within this section we will discuss the role of the last two.

3.2.1. Role of energy companies as intermediaries

We tend to speak about sellers and buyers as if they are the only classes of agents participating. However in the real world another group of agents is also present, re-sellers. These are companies buying with the sole purpose of reselling (or at least buying on behalf of clients). A particular type of agents are (big) energy companies that are delivering gas to the built environment. These companies buy on the gas market with the sole purpose of delivering to end consumers.

These companies unite consumers. On the Dutch balancing gas market, the TTF, only the 'Big Boys' operate. The intermediaries unite big groups of consumers and represent small consumers on this market. Without these intermediaries every household should be active on the wholesale market. United consumers would have more bargaining power and be able to buy cheaper. However these intermediaries complicate some market behaviour discussed below.

There is a clear advantage for small households not to participate on the very complicated energy market, not in the least because predicting your energy need is close to impossible. The natural gas market in par-

ticular is weather dependent, which is by definition impossible to forecast accurately. The other fact of this natural representative consumer is that we do not see the real time price of natural gas. In Northwest Europe energy companies will typically set the price for a certain period of time. In the Netherlands these periods range from a year to multiple years. Next to setting the price these companies in general will also smooth out the payment over the contract length although the consumption is seasonal. During the whole year a fixed monthly fee is billed to flat out the spending on energy. These two institutions make the average consumer completely price oblivious. In economics we assume there to be a marginal price. A price for which the consumer and producer are roughly indifferent to 'produce and consume' or trade one more good. Since on the gas market a large part of the consumers is not aware of the price they are paying for their gas this price is hard to determine. Energy companies fulfill this task on behalf of the consumer.

Since energy companies flat out spending on energy by storing payments throughout the year, one logical step for them would be to also play a balancing role on the gas market by smoothing the natural gas bought on the market by buying when demand is low and deliver this gas when demand is high. When we look at the map of storage operators we can observe some familiar names like Nuon and Eneco both intermediaries at the Dutch energy market [31]. We also observe some producers with storage capacity (NAM and Gazprom) and some seemingly dedicated storage operators.

3.2.2. Role of markets as intermediaries

Another way of looking at intermediaries is as a facilitator who brings supply and demand together, similar to a trader agent. Taking this conceptualization one step further the market itself can be seen as an intermediary. In a bidding market, the market agent aggregates the bids and asks of suppliers and consumers and performs a clearing action. Blume formalizes this conceptualization in an market model [9]. Modeling the market as an intermediary is consistent with a spot market approach to the energy market due to the clearing actions of the market agent.

3.3. What do we assume about the world?

When talking about scenarios as discussed at the start of this chapter we are merely doing an exercise and not a forecast. We want to develop a story line that is plausible but doesn't necessarily reflect our expectations. In scenario analysis we want to think the unthinkable and break the 'normalcy bias'. For this thesis we will be exploring the scenarios of Eneco. Eneco developed three scenarios envisioning three different futures. These scenarios are 'Paces', 'Tides' and 'Circles'. I want to describe these worlds briefly. However this description will by no means address the full complexity of these scenarios and for a complete description I would like to refer to the Review of Energy [21].

Paces

"The European recession returns, whereas the economy in other parts of the world grows. With EU agreements buckling under large refugee streams from the Middle East and Africa, European governments turn to protectionism in order to secure their borders. Similarly, repeated financial crisis in EU member states cause the collapse of the euro. Together, these effects break up the EU into parts. European integration ends and sustainable energy is no longer high on political agendas. In Europe, people want secure and cheap energy, outside of Europe energy demand continues to grow significantly due to economic growth and steadily increasing socio-economic growth and steadily increasing socio-economic welfare."

Tides

"After the current crisis in many countries, the global economy picks up again and enters an absolute boom based on the promise of abundantly available cheap fuels such as shale gas. As the global economy grows rapidly, the Chinese economy at some point overheats and companies start to default on their debts. The flaws of the Chinese banking system soon become apparent and the global economy comes to a grinding halt. At a later stage, promises of cheap fuels remain unfulfilled and hamper economic growth that just started picking up again, resulting in yet another crisis. In this highly capitalist world, income is distributed increasingly unequally and the switch to a cleaner energy system is delayed."

Circles

"Technological breakthroughs propel the world in a clean and stable direction. Especially the combination of cheap and efficient solar pv and storage results in very low energy costs. The economy thrives and climate objectives are met. In this stable world, European integration resumes and the energy transition takes place much more rapidly than even the most enthusiastic climate campaigner could have dreamt of. Electricity becomes abundant and almost for free."

3.4. Role of Eneco

The European Union called for integration of the energy market. The first step to integrate the market was to privatize actors on this market, which up till then had mostly consisted of local energy companies that handled the selling, delivery and billing of electricity and natural gas. In the Netherlands Eneco was formed by merging the Energy companies located in the province South-Holland. The movement of consolidating local energy companies took place all over Europe and led to big energy conglomerates. In the Netherlands competing firms of Eneco, Nuon and Essent, were bought up by foreign companies. In the wake of these sell-offs energy companies were split up by law in distribution system operator (DSO), who had to stay in public hands and energy selling companies. Eneco was one of the few that stayed integrated (delivery and energy company) for a long time and remained public property.

The integration of the energy market succeeded in the sense that energy companies consolidated over borders, hence cross-border operations of energy companies. Eneco remained in public hands and became a dwarf among giants in the Netherlands. Since it remained in public hands it was able to keep part of the distribution network and thereby had an advantage over other players on the Dutch energy market. By the way, it should be noted that other European countries chose a different implementation of EU directives and did not require energy companies to divest from their infrastructure assets. In 2017 Eneco was forced to divest from their delivery assets and lost its unique position of integrated energy company. Subsequently a majority of government bodies that are owners of Eneco decided to sell off their shares of Eneco.

The role of Eneco on the energy market and the natural gas market is not expected to be one of great market power, due to their relative size. However they still are operating storage fields and have a stake in LNG regasification facilities at "GATE". Furthermore they have a 50 % stake in a Dutch gas fired power plant. This wide variety of investments throughout the whole gas chain bolster the idea that they believed more in the downfall of coal than they truly had a consistent belief in the gas market itself. LNG needs a high natural gas mainland price to be competitive for regasification and feeding into the main grid, since liquefaction, transporting and regasification are energy intensive and thereby expensive. Natural gas power plants are considered to be quite expensive and have been seen as "the Lamborghini of electricity production". To make natural gas competitive for electricity production a low natural gas price is needed. Eneco has a stake in nearly every step of the supply chain. Upstream it has a stake in the regasification facility GATE. It is a middle man for household consumers, small and big industries and the commercial sector in the nature of it being a energy selling utility company. Furthermore it is a big consumer itself with its gas fired power plants and boilers for the district heating network. Last but not least it operates storage facilities for natural gas throughout Northwest Europe. This makes Eneco a flexible player in the sense that it can steer consumption and delivery. Although Eneco is not expected to be a major market force on a European scale, it is perfectly positioned to balance consumption and supply and take advantage of windfall profits by short-term price movements. For this reason Eneco would be particularly interested in scenarios with sharp increases or decreases of the natural gas price as well as seasonal fluctuations.

Energy selling utilities play the role of aggregate consumer on the natural gas market. They unite demand users and thereby provide them with some market power, avoiding the impracticality of all individual consumers having to enter complex markets. These companies also deal with an interesting fact of the natural gas consumption, the unpredictability. In the Western world end consumers are in most cases totally unaware of both the current price on the gas wholesale markets and of its current consumption. Once a year the meter reading is reported to the billing agency. On the spot pricing of consumption is in most cases not possible. Energy companies sell in fact the guarantee that they will provide the commodity. For this reason we make the assumptions that the household group will consume no matter the price and only long term trends will shape consumption patterns. In the current system the price of natural gas is +- 20 euro cents in Western Europe while the price consumers pay on their energy bill is around 70 cents. This confirms the assumption that they are very price inelastic. A big price change on the commodity market will not directly lead to decreased demand for the reason this will be perceived as a relatively small increase by end consumers. It

is up to the energy company to make sure that this price inelasticity does not lead to exorbitant pricing during high demand episodes. The energy company should also make sure it is able to fulfill the unpredictable demand at any time. In the Netherlands energy companies are required to buy according to a certain 'shape'. At the end of everyday major nodes in the network will report what has been extracted and fed in to grid. Energy companies have to make sure they have positions according to their share of customers. After roughly two years if all meter reading data is added to this equation and the yearly consumption of individual users is known, a correction is made. In this way utility companies are incentivized to estimate as precisely as possible the consumption of their customers and negotiate the lowest average price with producers. If they can undercut the competition they receive more customers and force down prices. Since there is a risk of rising prices a premium is paid somewhere on the chain. As we proceed we see how energy companies play the role of aggregating the small consumers.

3.5. Causal Relation Diagram

To visualize the complexity of the world-wide natural gas system a causal relation diagram is made to make the interactions clear. These diagrams are not exhaustive but are meant to sketch the trends that have dominated the different markets. Because the markets are fundamentally different and a variety of local factors determines market behavior we will start with drawing causal diagrams separately for each market. The goal of making these diagrams is to conceptualize the complex system and help the demarcation of what is feasible to quantify in the remainder of this research.

Demand Supply effect

In every diagram there is a causal loop between demand, supply and price. The price determines supply through a supply curve known from economics. The mechanism at work here is that for a higher price more supply is provided by the market. A fundamental reason would be that on the short run more wells will be able to operate above their break-even price and on the long run investments in exploration activities will increase resulting in more gas fields being brought on-line. The demand curve denotes that when the price increases less quantity of the product is demanded, vice versa when the price decreases more quantity is being asked by the market. As a more fundamental mechanism for the gas market we note that gas is competing with other energy carriers like coal and liquid carbon fuels in the electricity market in the short run. The "spark spread" of a gas fired electricity generator is the minimum market price at which it is profitable to operate. In practice this determines when the generator is called for in the merit order. The "dark spread" is a comparable formula for coal fired generators. When the dark spread falls below the spark spread the coal will be used for energy generation. A higher spark spread will therefore mean a higher spark spread for gas fired generators and a decrease in demand for natural gas.

3.5.1. Asian market

The Asian market is characterized by its exposure to the LNG market. The East Asian coast is badly connected with pipeline capacity to major production regions, therefore the region is supplied mainly by LNG vessels. These vessels have been supplying the region from the nearest fields, for Asia this was Australia and Qatar. The distance traveled is one of the main price determinants for LNG. The price at the LNG market has been dominated by a surge in demand from the Japanese market. In the aftermath of the Fukushima disaster, all nuclear electric capacity had been shutdown and this capacity had to be replaced. A big rise in demand for gas was the result. The high demand for natural gas dominated the LNG market in the past years as can be clearly observed from figure 2.13. On the JKM, the main Asian market for gas, roughly 80% is traded in long term contracts¹. Long-term contracts are in most cases indexed to the JCC, a marker published by the Japanese government once a month. The formula represents the average import price paid for crude oils. The volumes traded as spot, not indexed short-term contracts, are only indexed by Bloomberg for the recent years. However since there is a move towards more spot trading, this kind of trading becomes more important. Long contract lengths means a bigger impact of the JCC price (which is closely linked to the crude oil price) and shorter contracts allow more room for different dynamics. In general a premium is being paid for certainty of delivery by the consumer in long term contracts, a decline in contract length therefore denotes a decrease in prices.

¹Reported by Platts (link: <http://www.platts.com/price-assessments/natural-gas/jkm-japan-korea-marker>)

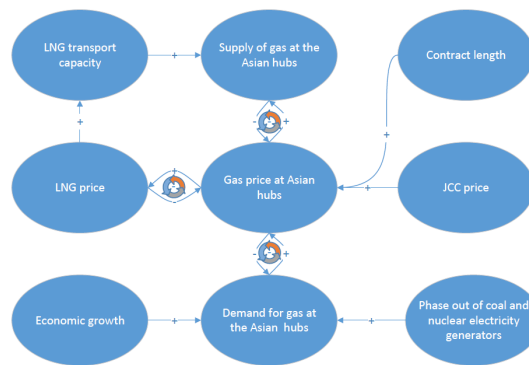


Figure 3.1: Causal relationship diagram of the Asian gas market

3.5.2. EU market

Supply side

The main supplier for the EU is Russia, that is responsible for 23% of the gas consumption of Europe[16]. However this is not evenly spread throughout Europe. As was to be expected, eastern European countries depend on Russian imports for their total consumption. This dependence from Russia has been interpreted as problematic since the 2009 gas crisis, when Russia squeezed the gas transported through the Ukraine transit pipelines due to a dispute on payments for intercepted gas. As a result major regions in Europe experienced a supply disruption. In combination with a severe winter and low storage levels this led to price spikes. The recent geopolitical disputes over Crimea and Eastern Ukraine emphasized this troubling situation. In the past years indigenous production has been responsible for roughly half of the EU consumption. Major supply regions are Norway, the Netherlands and formerly Great-Britain. The latter has become a net importer of natural gas due to depleted reserves. The Netherlands is expected to become a net importer within the next decade. Only Norway is expected to remain a net exporter for the foreseeable years to come. The overall decline of indigenous production will increase the need for imports. This is expected to be filled partially by present import regions and partially by LNG imports. The south of Europe imported 50 Bcm of LNG in 2014. In the Netherlands the GATE terminal has been constructed which has a put-through capacity of 30 Bcm. However a fraction of this capacity has been used in the past years. The price of LNG has been higher due to the developments on the Asian market, which surged all the available capacity. Increased capacity is expected to become available in the coming years, thereby increasing the share of LNG in world-wide gas trade. At the moment Northwest Europe could be seen as the LNG sink, all LNG that could not be sold to higher buyers is sent to the European markets. This due to the fact that the European markets have a variety of sources and are not willing to pay the increased prices. The European Union strive to implement an Energy Union where natural gas is traded freely between countries on a common market principle. The idea behind the energy union is to decrease market power on the supply side. The logic is that a transparent market will and trade between demand nodes within Europe will efface the ability of sellers to charge different prices to different regions and or consumer segments. Therefor decreasing the overall price paid and making gas flows more efficient between countries. Another aim is to depoliticize the gas market. The full implementation of the Energy market is delayed multiple times and should have been in effect from the year 2014 according to the planning.

Demand

Demand in Europe has been closely linked to the price of competing crude oil, if not in volumes then in willingness to pay. After the US basically stopped importing energy crude due to their shale revolution, the European market has been flooded with cheap coal. Gas fired power plants became unprofitable (shifting in the merit order). And three new coal fired power plants being built in the Netherlands alone in 2015 and 2016. In respect to emission reduction agreements and the Paris treaty there has been political pressure to phase out coal plants, which led to the closing of a series of old coal plants. Increased renewable electricity production will increase the need for short run balancing electricity capacity. This can either be done by energy storage or by relatively flexible gas fired power plants. The increase in intermittent (renewable) electricity production was expected to increase the role of gas fired power plants within the energy system. In the past years gas has not lived up this expectation but it might do so in the future. On the other hand do renewable energy sources

compete with natural gas since they are bid in at marginal costs (being zero) on the electricity markets and thereby pushing out expensive gas bids. Although gas is seen as relatively clean, this image can shift, thereby hampering the gas demand in a push to more renewable world.

Transit routes

In 2009 80% of Russian gas delivered to EU markets was delivered through Ukraine. This has decreased to less than 50% in 2014. The alternative pipelines Nordstream and the Yakal route are being used far below their maximum capacity. The dependence on the Ukrainian pipeline and therefore the exposure to the ongoing political dispute is at the moment 12% which is expected to be compensated by either spare capacity of other routes or alternative sources[8]. Therefore this not seen as a real security of supply threat.

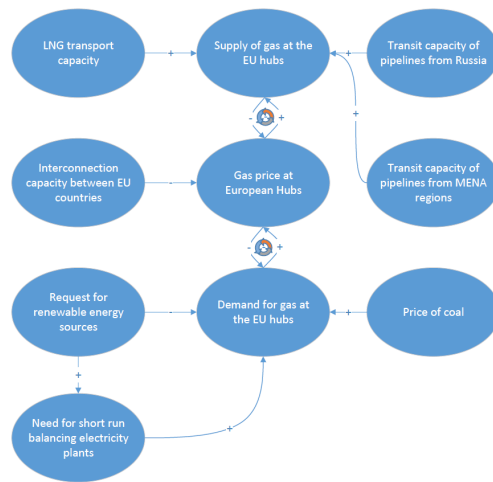


Figure 3.2: Causal relationship diagram of the EU gas market

3.5.3. US market

supply

The supply side of the US market has been dominated by the shale revolution. The discovery of shale gas and the technological feasibility have turned the North-American region from a net importer to a self-reliant market. The huge supply that came on-line in the past decade has reverted gas transports around the globe. The technology of fracking, which is inherent to shale gas, is very local in its nature. The result is that well heads in general do not produce large quantities and new well heads have to be taken into production to keep up production levels. When prices drop below the break even price, a drop in newly constructed well heads is to be expected. The financing is done to a great extent with borrowed money. This led to the behavior that the revenue of shale gas projects at least had to produce revenues for interest payments. Prices below break-even prices are the result of this construction. On the short run this takes the floor out of the natural gas prices on the US market where the price is determined by the financing costs. On the long run shale is to balance the market on the long run. A shale gas project is constructed relatively fast when the markets become above the break-even price and the wells are depleted fast.

Demand

Gas demand and economic growth are correlated. Economic growth increases output and thereby the need for energy. It goes without saying that this applies to all natural gas markets. What is particularly interesting in the US, is the absence of exports. The low prices on the HH would possibly make a viable business case for liquefaction and the export of natural gas. However the US has had a ban on the exports of crude oil. Now this ban is lifted this could increase prices on the US markets but decrease prices on the world markets, since exports in essence increase the price paid on the domestic markets. Because the ban has been in place for 40 years infrastructure to support major export still has to materialize[20].

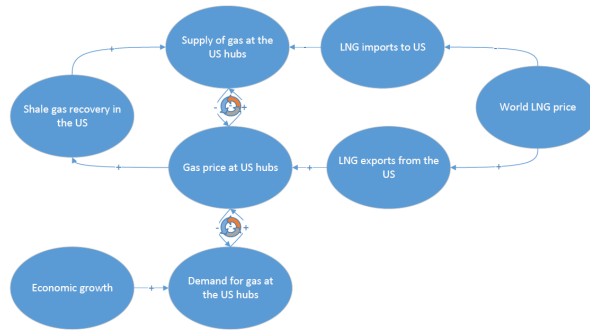


Figure 3.3: Causal relationship diagram of the US gas market

3.5.4. Aggregation of local causal relation diagrams diagrams

In the world gas market there are three main markets, centered around the demand regions. These markets behaved differently the past years but the fundamentals are comparable. Therefore we reduce the above three diagrams to one general diagram in figure 3.4. On the different markets these factors will roughly trigger the same behavior. However due to the fact that they differ in impact this can lead to different results. For example the Asian market has seen an increase of the natural gas price in the same period other markets experienced a decreasing price. For a more complete description of how the scenarios fit in to the causal relation diagrams please see appendix A.



Figure 3.4: Generalized causal diagram for a gas hub

3.5.5. Conclusions of causal relation diagrams

The causal relation diagrams tell a story of the inter-dependencies between natural gas markets world wide and across different energy markets. The demand for natural gas is for example dependent on the demand for coal since they compete on the electricity market. In the quantification effort we will be building up complexity. This means we will start simple with a buyer and a seller exchanging goods on a market. By

building up complexity we should not lose our focus on the problem definition and should choose what to include based on how it helps us answer the problem description. The Eneco scenarios paint a picture of the lower part of the causal relation diagram. It provides us with economic figures and tells a story about the development of demand. The upper part focuses on production and reserve, the bare essentials when addressing a market of buyers and sellers. These figures can be found in statistical studies. However the right part of the diagram with a focus on transaction costs and institutions in the gas market will be very hard to quantify. We will 'park' this part of the conceptualization and readdress it after quantifying what is actually addressed by the Eneco scenarios or quantifiable by other means. However this should not be interpreted as a disregard for institutions on the gas market or as a valuation of it being of lesser importance.

3.6. Schematic representation of the gas market

In the previous chapters we described the problem formulation, the basic gas market and the demarcation of the research area. In the schematic representation below we want to communicate what we expect a quantitative analysis will entail and/or answer.

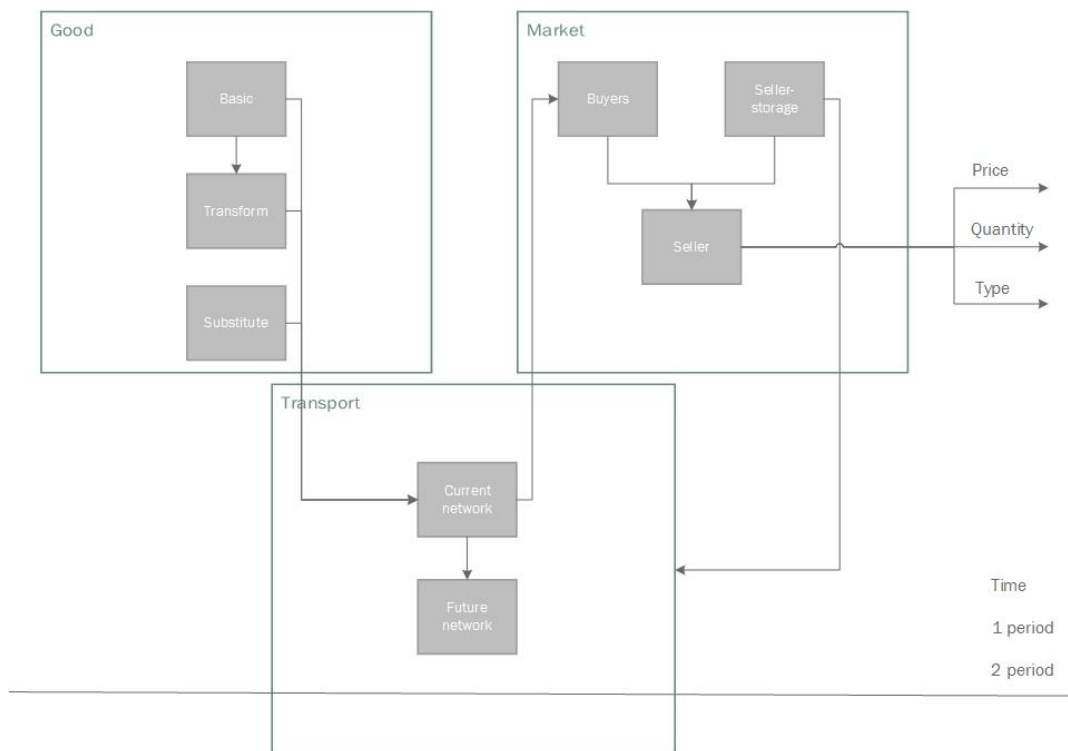


Figure 3.5: Input-output diagram of modeling challenge

When assessing the gas market, we can distinguish three major components to be of particular interest. The good, the market and the transport of the good. The market is in a certain way a virtual market. The good is not handed over at every transaction. Most of the trades are merely 'positions', meaning it does not translate one to one to market values. In fact one 'unit' of good is traded multiple times and the amount of times it is traded is called the 'churn rate'. A high churn rate means a volatile market and is considered to be an indicator of how well the spot market is performing. In general the major European spot markets (TTF & NBP) have matured [78]. It depends on what part of the world you are whether the gas market is for the major part spot or otc (over the counter). Within this quantification we will approach the market as a spot market, firstly because the spot part is growing over the world and it is the path policy makers envision in the EU. Another reason to perceive the market as a spot market is that it resembles a basic market, hence it is more suitable to be used in algorithms.

We would like the quantitative analysis to deal with all forms of the goods in the category of natural gas, including LNG, CNG and related gaseous forms. Furthermore we would like to address the transport problem of natural gas. How do quantitative optimization or simulation results reflect the current limitations posed by current infrastructure?

3.7. Conclusion

In this chapter we argued that the best way for a long term outlook on the Northwestern European gas market is a quantitative analysis that takes into account world flows of natural gas in order to assess how transport flows will be impacted. We addressed the role of intermediaries in the gas market and how they

Secondly we introduced the scenarios which we will use as inputs for external variables into a quantitative exploration. These three scenarios (Circles, Tides and Paces) have three widely varying world views with respect to but not limited to energy consumption. These should demarcate the problem sufficiently to come to a quantitative analysis.

We draw causal relations diagrams to show how different the three demand markets are and what dynamics are dominant on these three markets. We combined this to an aggregate causal relation diagram to generalize this to a gas market. While assessing this causal relation diagram we came to the conclusion that in the quantitative formalization the inclusion of institutions is going to be a challenge and might not be possible in the scope of this research.

4

Model methodology

The reader should realize himself that it could not have happened otherwise, and that to give him any other name was quite out of the question.

— *Nikolai Gogol, "The Overcoat"*

In this chapter a formalization of the problem will be given. First will be addressed why we model the problem and how this will answer the research questions. A short introduction to the different forms of optimization and simulation should fresh up the readers knowledge. Lastly we end with the mathematical formalization of the model, which entails the demarcation of the problem.

4.1. Methodology

In order to answer the main research question, how will prices on the Northwest European market develop on the long term, we need a quantification. Scenarios help to sketch a qualitative world but are less suitable to produce quantitative outcomes. In this chapter the conceptualization of a computer model will be described to arrive at quantified results.

4.1.1. Systems engineering approach

In order to design the model we follow a systems engineering approach. Systems engineering helps to structure the process of formulation, analysis and interpretation. Sage and Armstrong defined several frameworks of systems engineering design [76]. At this point multiple modeling techniques can be used to answer (parts of) the posed questions. All of these techniques have their own strengths and shortfalls. Within this chapter we would like to walk past these different models, get our feet wet by applying the technique to the problem situation and develop a final product that can best answer the problem description. This approach resembles the evolutionary approach seen in figure 4.1. The different iteration all produce a (partly) functional design but do not necessarily end up in the final model. This is in contrast to an incremental design in which first a kernel and one increment is added, and after every iteration one more element is added. However as soon as we know what modeling technique suits the problem situation best, a shift to an incremental systems engineering approach can be beneficial.

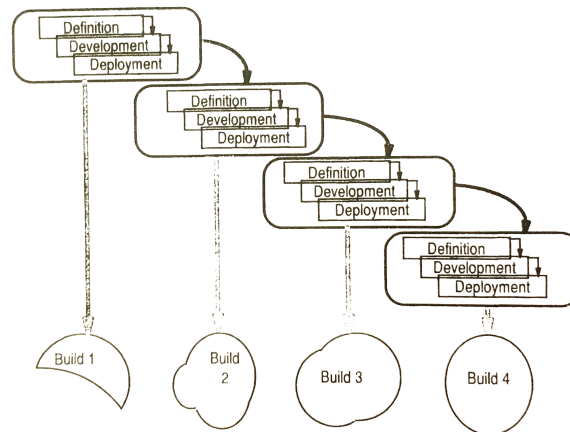


Figure 4.1: Sage and Armstrong Evolutionary approach

4.1.2. Modeling approach

Choosing a model to describe a certain system is determinative for the outcome on two fronts. First of all, the model itself has a certain set of input and outputs, thereby drawing boundaries on the applicability. The second deterministic element of the model choice lies in the assumptions of the model about the real world, the paradigm of the model. For example, agent-based simulations are studying the system wide behavior which emerge (therefore called emergent behavior) when individuals interact. An example of a macro-economic model would be the impact of certain policies.

Modeling can be either done top-down or bottom-up. Since not the final economic state but the interaction is important in this study, a bottom up approach is more suitable. What I mean is that we are interested in where the gas is being imported from and the different prices. Therefore we need to study the complexity of the system itself. The methodology that seems to suit the research question best is a bottom-up agent based modeling approach.

Other possible ways to model the natural gas market are provided in the literature assessment in chapter 1, which I will try to summarize here as short as possible. For more information one could read appendix C. When assuming the demand to be completely inelastic the problem is effectively a system cost minimization model. An example of such a model is a economic dispatch model, where producers optimize how to use their production assets as efficiently as possible. Another more complex example is a netflow model, that studies a system of a series of nodes and arches. A netflow model would answer the question what the optimal flow within a network would be. If demand is not assumed to be completely inelastic, hence adding elastic demand to the problem, it becomes a welfare maximization model. Elastic demand allows the demand to be dependent on the market price. If the natural gas price increases (assuming all other variables to remain static) we expect a decrease in consumption since some consumer groups will consume less natural gas. For example within the electricity production there is a competition between coal and natural gas. When one of the two becomes relatively more expensive a portion of the installations become uneconomical and consumption will shift towards the competitor.

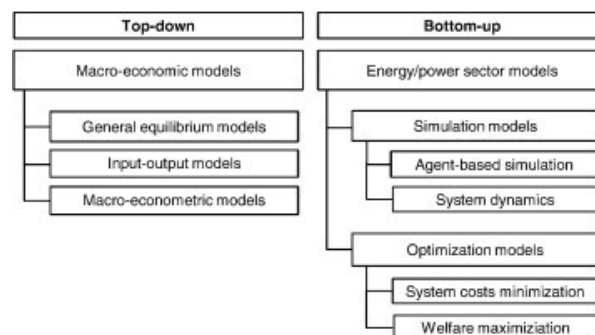


Figure 4.2: Jagemann classification of modelling in the energy sector

The global gas market consists of three main markets, centered around the major demand regions. The North-American market has as main indicator the Henry Hub market for natural gas. The European region is represented by the National Balancing Point (NBP) and in the Asian market the Japan Customs-cleared Crude (JCC) is the main market. These demand regions are supplied by a limited number of production regions. These regions all have different production costs and production characteristics. The geographical endowment of natural gas determines the transit technology and routes that connect production to demand. The JCC is connected by Liquefied Natural Gas (LNG) shipping routes with the Middle East, the European market is supplied by pipelines from Russia, Northern-Africa and indigenous production, while the American market became almost completely independent since the shale gas revolution[18]. These different markets clear independently from one another. In a (maturing) perfect market, price convergence between the markets is expected the marginal transport costs are the only discriminator. The lack of convergence indicates market power and a non-perfect market[7]. Running the model under different scenarios will provide more insight on how the prices on the European gas market will develop.

4.1.3. Modeling specifically to problem description

Our problem description focuses on market behavior on the Northwest European gas market. This market is mainly supplied by indigenous production of major gas producing countries like the Netherlands and Norway¹. Demand that cannot be addressed by indigenous production is supplied by imports from mainly Russian gas fields.

As in any market there are buyers and sellers. In a simplification we can see producers as sellers. On exchanges like the NBP and the TTF transactions are not necessarily made by the producers or the end users. Also a lot of transactions do not reflect any physical delivery of the product but are merely positions being traded. However for the sake of simplicity these actors are not taken into account within this description. The underlying product of these transactions remains natural gas and the prices of these transactions reflect the monetary value of this product. Therefore all transactions that are made are regarded as producers selling their product to end consumers. One thing is most notably missing from the above model behavior description, namely institutions. Institutions on the gas market can be easily found. In this section we will discuss one most notable institution, the long-term contract. In the gas market it is common place to trade natural gas in the form of long-term bilateral contracts. The rationale behind these long-term contracts is that assets in the world of natural gas are capital intensive and require a long time span, in some cases decades, before a return on investment is expected. Long-term contracts limit the risks from the investor's point of view. For this reason financial institutions who are involved in big infrastructural projects will demand long term contracts.

Long-term contracts however will defer price signals, thereby hampering effective allocation of investments. Furthermore it distorts the effective functioning of a market since it withholds information from other actors on the market and limits their ability to develop strategies accordingly. Forced unbundling as it has been implemented in recent years requires the bilateral contract to be disclosed to at least the transporter, which in return would be able to disclose market relevant information about the contract to the relevant parties, thereby limiting the market distortion effect of these contracts. This is in a short summary the TTF implementation of dealing with bilateral contracts. This institutional fix provides an argument to model the gas market of the future to be a (more) perfect market.

4.1.4. Finding the right modeling tool-set

After we have discussed what behavior we expect to address in a first quantification of the market, we are ready to pick a modeling technique. As discussed in chapter 1 implemented techniques of past literature vary and do not provide us with the clarity allowing us pick just of the shelf the 'best' way to model the gas market. In this section we will compare three modeling paradigms (economic dispatch with elastic demand, NetFlow model and ABM) where we will conclude that our problem description is best answered through an Agent Based Model. This process of forcing a proof of concept as a minimum viable product resembles the Evolutionary approach of Sage and Armstrong as discussed at the beginning of this chapter.

In order to understand why we are looking at the following three modeling paradigms it is worth noting what has been done in existing literature. In table 1.1 an overview is given of modeling related to natural gas markets. In the recent natural gas modeling we observe both linear programming and to a lesser extent NLP

¹Although Norway is not part of the European Union, it is part of the European Market and due its geographical location can therefore be considered as part of EU within this problem statement

modeling to be the main practice in natural gas market and flow modeling. Within this demand and supply is modeled as linear or non-linear functions and the optimization algorithm allocate the natural gas the most optimal way.

The most recent development being MCP modeling which is a concept of complementarity modeling where multiple (non) linear programs are combined into a new problem formulation. Since this formulation also requires the formulation of the sub-problems into a LP or NLP formalization we will discuss the two most common ways (N)LP models are used in natural gas market modeling and will briefly touch upon how this is reflected in the MCP formalization.

The models described in literature fail to model complex behavior, or have to make serious compromises in doing so. Expanding the existing scientific research with a new approach that is able to model complex behavior would increase the usefulness of using modeling in future/scenario studies. Such a model will be presented in the last part of this chapter.

4.1.5. Experimental economics

When we turn our back to optimization theory and equilibrium models when assessing markets we enter the field of experimental economics. This this is a modern field of study and applies experimental methods to study economic questions[52]. This can be done for example by holding real life experiments with test subjects to study economic behaviour. A recent development in this field is to use computer simulation models based and on the agent based modeling approach to simulate experiments and test economic theories. The clear advantage is that the economy does not allow experimentation. When studying our economic system we can not replicate the past events with other parameter settings. Simulation models allow such experiments and make it possible to test policy options that would otherwise could not be tested.

4.2. Agent Based Model methods

In the real world the outcome is not always 'optimal' and behavior is not always driven by a holistic view of the whole system. Actors follow their own interest or can have conflicting interests. Not seeing the problem (solely) as an optimization problem but as actors acting autonomously in their interactions with each other is closer to the real world.

The above description resembles the philosophy of Agent-Based Modeling. In this philosophy all agents get a set of instructions and for a finite amount of time the model will interact. Within ABM we look for emergent behavior, behavior not specifically instructed to the system but still observed. The flexibility of Agent-Based Modeling makes it suitable to study complex systems where the whole is not fully understood or it can help to study game theory since it can resemble more behavior.

Note that ABM is not optimization but simulation. It lets the actors behave on their own regardless of the system outcome and the result is not necessarily an optimum, neither globally nor even locally. ABM can have a self-selecting mechanism to steer by 'natural selection' to a equilibrium but this does not reflect real optimization. However optimization can be introduced as behavior of an agent if desired.

Given the fact that ABM is simulation rather than optimization the question arises, whether that is a problem for our problem description. All models discussed in this chapter and in the presented literature are in fact optimization models. From an academic viewpoint (macro-economic and micro-economic theory) this makes sense since the invisible hand of the market will steer a less ideal situation to an optimum, with or without some help of policy making/intervention depending on the school of thought. However this requires some sort of belief in an ideal market. The gas market is arguably not an ideal market. There are high entry barriers, little access to information and even political motives for certain actors. Stepping aside from an optimization approach and accepting the fact the story is more complicated than the mere market problem of matching supply and demand is defensible. The invisible hand of the market can make it seem as if optimization can answer the questions of market equilibrium and show the most sound investment opportunities, although these ideal conditions are not met in any market. They are as argued in particular not applicable to the world gas market.

Agent Based Modelling assumes a certain randomness in the model which allows emerging behavior to exist. It also contributes to the philosophy of ABM that complex systems can not be completely determined. For a correct implementation of ABM some form of randomness needs to be added to the model.

4.2.1. Actors

As stated before within the agent based approach we define agents (actors) who interact with each other. In an early proof of concept we expect a buyer and a seller to interact on a market. The bidders will place their bids, which are assumed to increase as demand rises. In the short run the quantity sold on the market is sold a lower price point than the subsequent one. The bids are ordered by ascending order (an example is provide in figure 4.3a) while the asks are ordered in descending order (figure 4.3b). To adhere to the dogma of ABM these bids are drawn from a (pseudo) random uniform distribution between a lower and upper bound.

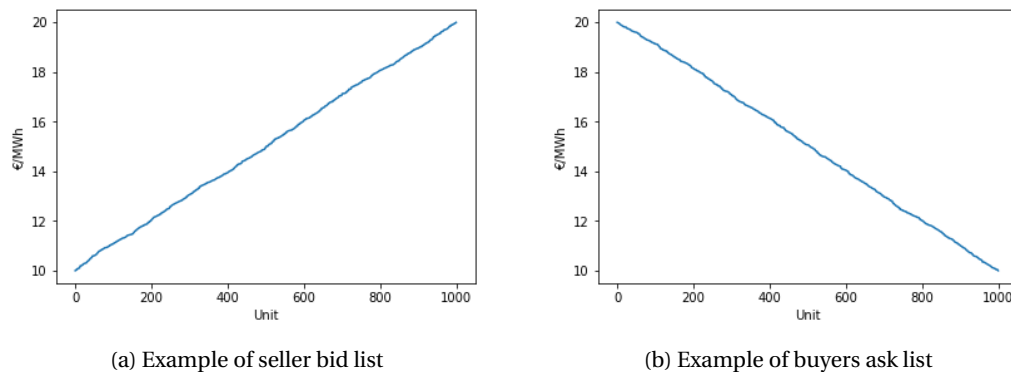


Figure 4.3: Example bid and asks curve

Within this formulation three design choices become apparent. How do we set the upper and lower limits of the bidding bid curve and of the ask curve and how do we determine the shape of these curves? First and foremost since we are observing long-term scenarios we are searching for figures 'in the right ballpark' instead of accurate prediction. Although a 10% increase might mean a world of difference for producers, today this is a common error margin for models trying to predict prices a year from now. Over the last year we observed in generally a movement between 10 € and 20 € on the TTF. We will assume this as starting point and allow buyers and sellers to adjust this price throughout the run time.

Some actors want gas more than other actors. As discussed in the beginning of the chapter some actors on the wholesale gas market function as middleman for a very inelastic end consumer. Others, for example the electricity producers, are not willing to pay any price on the given energy market. Within the behavior of the agents we would like to see this different type of behavior to be accounted for.

4.2.2. Clearing mechanism

The clearing mechanism we use to clear the bids and asks of the seller and the buyer is based on the aggregation of all bids and makes a merit order of all bids and asks, hence sorting the bids and asks on the price. All bids reflect one unit of the good, therefore the lists are matched in size so that bids or asks which are not going to be met are removed from the process. The two lists are matched and the marginal bid/ask is determined, the marginal bid being the last bid/ask combination that is cleared. This bid/ask combination is presumed to be the market price. All bids below the market price and all asks higher than the market price are marked as cleared in the ledger. Cleared bids and asks are communicated back to its representing buyers and sellers. This clearing mechanism does not reflect the real clearing mechanism at the local markets. Not all markets operate the same way. However since we are likely to aggregate nearby markets to a single market and the time granularity will be monthly while trading is done in real time on some markets, it is safe to assume that there is a homogeneous price being paid.

4.2.3. Single market in ABM

In the first prove of concept we will recreate the following market which is being shown in figure 4.4. We create a market which operates a book (aka ledger) that is being filled with bids and ask by buyers and sellers. Although the notation of figures 4.4 and 4.5 is clearly inspired by the UML notation this is not meant to be a complete or full model or code description, but merely a way to communicate the line of thinking. In chapter 5 we will dive deeper into the formalization.

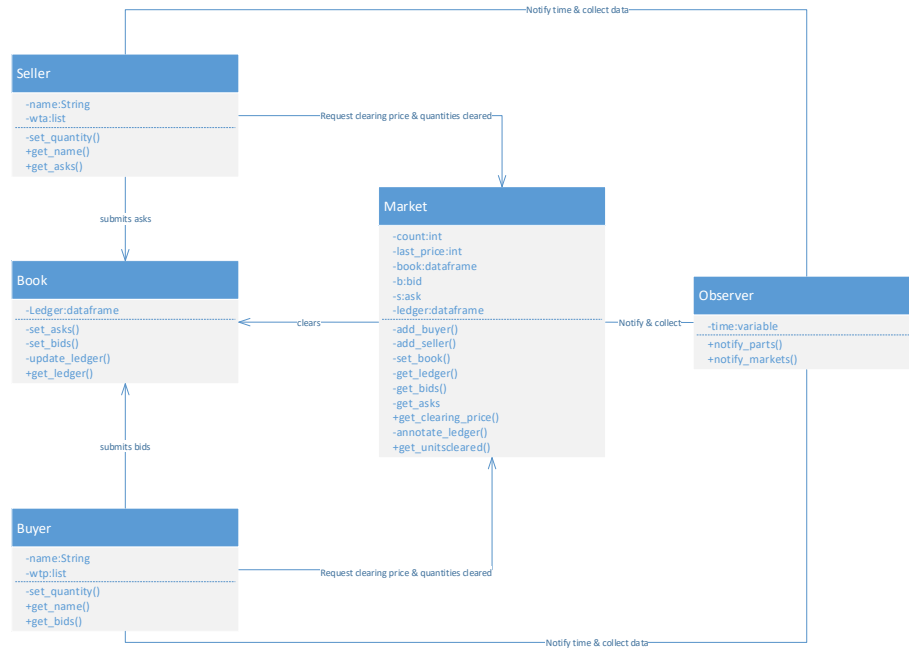


Figure 4.4: Single markets in ABM

4.2.4. Multiple markets in ABM

To operate on one market with sellers and buyers does not reflect the complexity as described in the problem formulation at the beginning of the thesis. As described above there are three main demand hubs and a few major exporting countries which provide all these hubs or are bound to a certain market due to their geographical position. Therefore our ambition is to choose a technique that is scalable and is able to model a representation as given below in figure 4.5. In this representation multiple markets interact within the same model. This interaction is lacking in all models observed in literature being discussed in previous chapters.

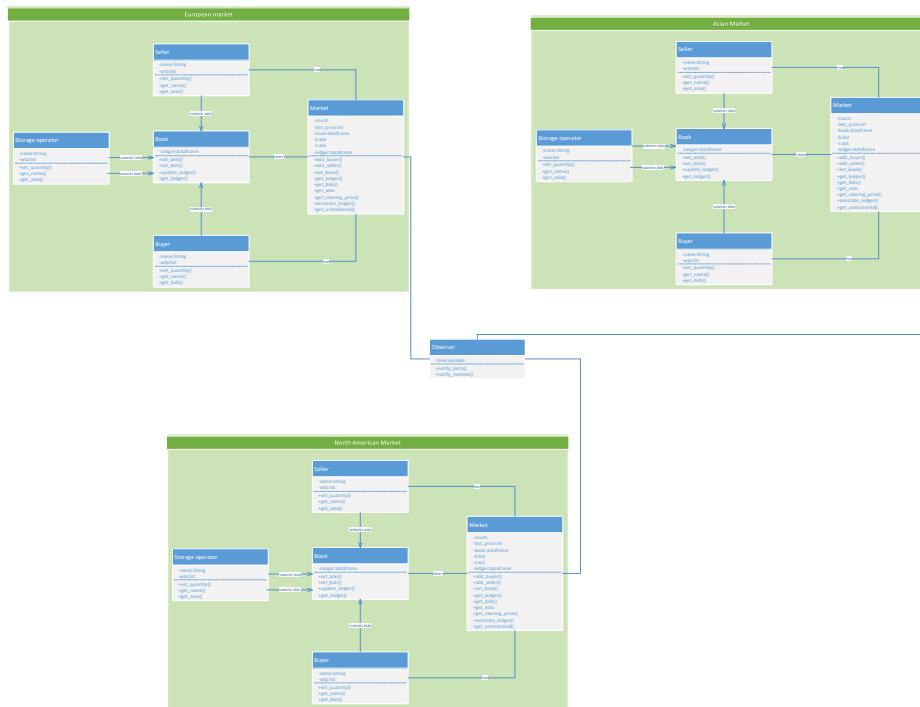


Figure 4.5: Multiple markets in ABM

4.2.5. Preliminary results

An ABM approach addresses the concerns about the simplicity concerns in the optimization approach of the problem and allows more freedom in the behavior of the actors on the gas market. In the implementation choices we should be able to seize the opportunities of this implementation.

4.3. Conclusion

After examine various modeling paradigms in this chapter the conclusion is reached that an Agent Based approach is the best suitable way to address the problem formulation described. Optimization based techniques have difficulties in addressing some key concerns. All modeling techniques have shortcomings and strengths. The strength of ABM in allowing more complex behavior of actors, is perceived to be the most important in addressing long-term scenario analyses. In the following section we will try to formalize the implementation of the chosen approach.

5

Implementation

Essentially,
all models are wrong,
but some are useful.

George E. P. Box,
Empirical Model Building
and Response Surfaces

In this chapter the implementation of the model methodology in a gas market model will be discussed. The programming language will be presented. The software, packages/libraries and solvers that were used during the modeling will be discussed as well. After reading this chapter the reader should have a basic understanding about the tools used to build the model. The goal is to invite people to contribute to the model and facilitate a transparent process.

5.1. Software

In order to model the problem situation we need to pick a modeling paradigm and the integrated development environment (IDE). Choosing a modeling language comes at a cost, possibly monetary in the form of proprietary software or in trade-offs due to strength and weaknesses. A complete comparison of all available languages, software tools and solvers goes beyond the scope of this research, so I will focus on the reasoning behind the choices made and will disregard as much as possible the reasoning not to choose a certain implementation.

In choosing the the modeling paradigm there was a strong wish to make the model as open and transparent as possible. Studying previous models made about the gas market we found one striking resemblance across the board. All models were proprietary. In some cases part of the formalization was given in scientific papers or white papers, none of them published the source code of the underlying models. In almost all cases the model was used for consultancy purposes by the authors. For the purpose of this thesis we reached out to multiple authors and they all denied the request to share the model or its source code.

From a scientific viewpoint this does not encourage duplicability. Any study should be replicable in order to be verifiable. Hiding the source code of the research work makes replicability harder and the work less scientific. In searching for a method to build a model of the gas market we are searching for tools that encourage this effort instead of discouraging it. Therefore the languages, packages and solvers should not only be transparently communicated but also be as freely available as possible. This means that no proprietary software should be used and the tools should be freely and widely available.

Another point about the secrecy that surrounds the models used in other studies is that it does not foster progress. Doing scientific work is building upon the shoulders of those who came before you. Scientific research is about pioneering in the unknown. Finding knowledge gaps and filling them up the best way known. By withholding your research methods you are forcing others behind you to reinvent the wheel. This is to a certain extend wasted effort and goes against the morality of science. In the search of a modeling paradigm we should search for packages and tools that encourage others to build upon the research and not

waste effort trying to figure out trivial questions about methods. In the search for artifacts future development of the tools used should be one of the criteria.

5.1.1. Python

As discussed above we want the language to be freely accessible, easy to understand and encouraging to build upon. The language Python scores high on these requirements. Within this section I would like to explain why. Python is a programming language that is built for flexibility. The language is used for a broad set of applications and is actively maintained by its community. It is a popular language on multiple platforms and is used in widely different fields of applications. The syntax is constructed with a strong focus on readability. The philosophy behind the language is coded into its 'ground rules', which state that readability counts¹. This makes it easily verifiable and easy to contribute to. Due to its simplicity the language is popular for proof of concept purposes as well as in the academic world. A drawback of python is the speed. Since python is an interpreter language (although it can be compiled), the language is therefore slower and is not ideal for performance tasks. Python seems the perfect match for thesis related models where the above factors are of particular interest and encourages others to participate or build upon the result.

5.1.2. Anaconda, Spyder & Jupyter Notebook

Anaconda is a cross-platform open-source free-ware software suite and package repository. Anaconda is available for Linux based systems, mac-OS and Windows based machines. It is an open-source platform meaning the source code is freely available to review or improve. Furthermore it is free of charge for non-commercial use. The software suite contains various programming languages like Python and R and it is a package repository meaning it is a distribution system for libraries for these languages. The open nature of this suite makes it especially suitable for academic purposes, the standard installation provides a variety of data analytic and math packages ready to run everything you need for a good research project.

Anaconda comes with some software tools like Spyder, an interactive IDE, a software suite that helps you to write your code which you can live test during this process. Jupyter Notebook is both an interactive IDE and a presentation tool. It runs in your web browser and allows you to write, distribute and present your code primarily focused on math, data analytics and the presentation of your code. For this reason we chose Jupyter Notebook to represent both the model code and the results.

An alternative to installing a complete suite like Anaconda is WinPython. WinPython is set of compatible dependencies which can function with limited rights and will not impact a current environment on the system. The drawback is, as the name suggests, that it is only compatible with the Windows ecosystem. Furthermore it is not part of a repository, so upgrading or adding packages might become a limitation for active developers. However the modeling efforts in this thesis have been tested to work on this package and WinPython is a great tool to 'experience' the code at zero costs.

5.1.3. GitHub

In order to be as transparent as possible and to encourage reviewing and improving/building upon the work done in this thesis, the model will be published and made available at GitHub. GitHub is a code sharing platform for various software. It is often used to publish open-source codes and supports a wide variety of coding languages.

The code used for this thesis is available via the following URL below. GitHub makes it easy to collaborate on a project via a pull-request and makes it easy to start a new project based on an existing project by making your own branch. This makes it easy for anybody to start from where you had left.

<https://github.com/bahuisman/NatGasModel>

Within the main directory the model is tailored to run a 5 year simulation while in the Long run section the model runs for the maximum time frame. The short run in the main directory is meant to keep the model runs modest to make development easier.

.ipynb files

The Notebook files contain the model and the visualization. The notebook files run Python code. Both in markdown blocks and within the code notes have been made to make reading the code easier and explain the thoughts behind the coding. GitHub might have some problems at certain times to display .ipynb files.

¹see PEP8 code for further explanation

When you the error "Sorry, something went wrong" emerges copy the link (ending with .ipynb) and paste in <https://nbviewer.jupyter.org>

.json files

In order to communicate information of the model between the different files and to help the visualization of the model run results. The Json format (although based on JavaScript) is human readable in any text editor.

.pickle files

A multilevel dataframe is too complicated to be communicated by a Json file. Therefore we use a Python dedicated file type. However using dataframes is computationally intensive, so for simpler operation we keep using .json files and arrays.

.xlsx files

The excel files are mainly used to import data and configure a model run. It contains parametrization and should follow a precise predefined format in order to be readable by the .ipynb files.

.py files

The python files are proof of concepts or not yet implemented functionality, made to function outside of the Jupyter Notebook environment.

5.2. Model structure

In this section the implementation of the formalization will be discussed. During the building of this model the evolutionary approach described in Sage and Armstrong[76] has been used. Every iteration is a functional model by itself. For a list of iterations/stages please see appendix D. In this appendix we also describe the requirements of the model. The following section will discuss a selection of model functionality and parametrization choices of the final product.

We model the actors as objects in Python, all objects must have a class. A class can be seen as a template of how the objects are created. Object oriented programming (oop) creates objects which have methods. Methods are functions specific to the object created. Attributes of the object are stored in the "init" method and are used to store object specific parameters. We model five classes, so there will be five types of objects, largely based on the proof of concept discusses in chapter 4. The UML-classes diagram below is made with the Pyreverse package and displays all the methods and attributes of the objects created.

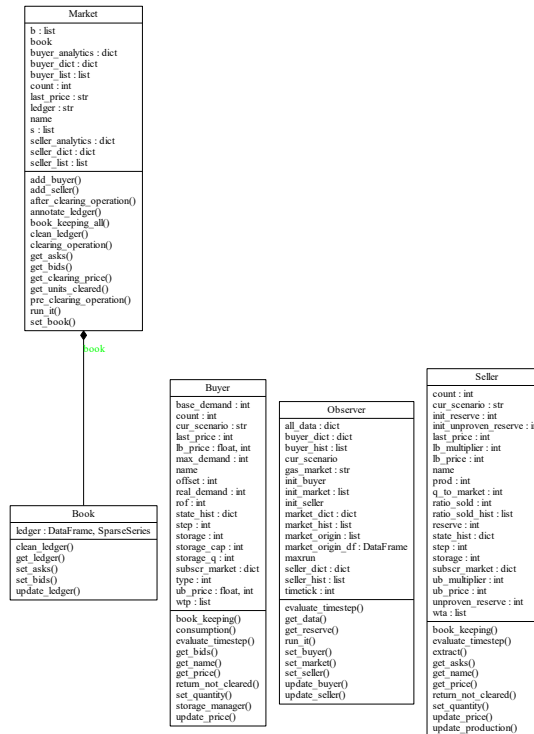


Figure 5.1: UML Classes diagram of model

The classes buyer, seller and market should not be a big surprise and have been elaborated on in the previous chapter. Two classes have not been discussed so far, the observer object and the book. The book is an object that is owned by the market. The market records all the bids in the book and uses the "book" object to keep track of its ledger. The book itself is not an agent in the ABM paradigm but merely a way for the market to manage its ledger. One observer is created per model run and keeps track of all the agents. It performs two critical functions. The first function is that of a clock. All agents are being notified that a time step (tick) has passed and it nudges the agents to perform all actions they wish to do within the time step. The second function is that of information aggregate, it collects and stores the information of every model and passes it on to the 'functional' part of the script, so that it can be stored and analyzed.

In the model we manipulated the observer to notify the LNG market the latest of all markets. This way local markets are cleared first and either production not being sold or demand not being met is transferred to the world LNG market, if the agents have access to this market. This reflects the reality that the LNG market is usually the more expensive option for both technical reasons and the fact that the price is determined by the world's highest bidder. Gas traded on local markets can vary in price due to local dynamics, the LNG price however is set globally. This behavior is now reflected in the model design.

5.3. Parametrization assumptions

In order to run the model we should provide it with assumptions about the real world. Within this section some key assumptions and philosophies are given. The parametrization effort will provide us with the starting state of the model and show how the reality has been codified. A more detailed parametrization of variables will be provided in chapter 6, this section will focus on the philosophy behind and sources of parameters.

5.3.1. Parametrization of demand

As discussed before we assume three big demand groups, which are presented below.

1. Household and consumption in the built environment are supplied by regional gas grids and these actors in the real world have a fixed contract with a utility company and are therefore on the short term inelastic. Within the model house hold consumers are forced to consume their total demand. Within this implementation this is done by forcing this consumer group to retain a form of storage from where they will consume their total demand. On the long term the assumptions about energy/climate awareness and isolation as well as the electrification of society play a role. Therefore the demand parameters will be adjusted during the model run with a parameter specific to the current scenario.
2. Electricity producers are quite price elastic in the real world. Whenever the price of gas rises (in respect to other energy carriers) their demand drops. Furthermore there are lot of technical considerations about the stability of the grid, if waste heat is being used in district heating and ramp-up and ramp-down constraints/costs. The Eneco scenarios provide growth expectancy figures for the European demand in the electricity sector. Those figures have been used in determining the demand.
3. The heavy industry demand is being determined by economic growth figures as discussed in chapter 3. The Eneco scenarios provide these figures and the demand is expected to grow according to the economic growth of the particular region.

Price forming demand

A buyer in the model makes a bidding list per time step as described in the previous chapter. It draws the prices from a uniform distribution, thereby making an ascending linear slope when ordered. After the market is cleared the buyer gets informed which bids were accepted at what market price. The buyer will then reset his bidding parameters to reflect the market conditions. The TTF has been moving between the 10 and 20 €/MWh and these will be the initial parameters for the buyers. In preliminary model results we observed a hockey-stick curve for the clearing price curves going into billions of dollars per MWh. This impossible behavior has been limited by capping the market price at 100 €/MWh. Although this is still a very unrealistic price and regulatory bodies will most certainly step in for a commodity like natural gas, this will allow the model to freely move the price and find an equilibrium.

5.3.2. Parametrization of supply

The seller at the market reflects countries with a significant amount of natural gas. When the amount of natural gas is not significant they will be grouped together to form a significant producer for their region in order not to miss significant world supply in the model. Sellers have two types of reserves, proven and unproven. The proven reserve of a seller is the technical reserve known today. The unproven reserves are the amounts of shale gas these countries are estimated to possess. The numbers are based on the BP Energy Outlook[10] and the CIA factbook[3]. Both studies are meta studies where existing research is analyzed and aggregated in order to provide world statistics about the gas market. In order to bring reserves to market, production assets are needed. Producers therefore have a production parameter which reflects the maximum production capacity. This will be the number of bids all producers bring to market. Producers will reflect on the last 12 months and adjust production if their sales to production ratio is 80% percent or higher. In the Paces scenario technological and policy breakthrough allow the shale gas potential to be exploited. Since this is not expected to be an overnight discovery, every year a portion of the 'unproven' reserves is added to the proven reserves.

Price forming supply

Prices of producers are assumed to be cost-driven. Production costs will increase as fields get depleted. Producers do not adjust their prices in respect to market conditions, however the price will possibly increase

above of the price level being asked by producers since consumers do take historical market prices into account.

5.3.3. Parametrization of markets

All buyers and sellers have markets they are 'subscribed' to. This forms in essence a network of nodes and arches. Big producers of natural gas tend to have big inland consumption which is modelled as a separate (domestic) market. After every clearing procedure the markets notify the buyers and sellers which bids have been cleared. Sellers and buyers that are active on multiple markets can update their bidding lists before another market will notify them to hand in their bidding list. As described before, the LNG market is forced to be run the latest providing a market of last resort, where the prices are expected to be higher.

How markets are geographically demarcated can be found in appendix E. Within this section the buyers and sellers can be found as well.

5.3.4. Focus on EU

As discussed in the problem statement the focus is on the EU market with a particular interest in the dynamics of the Northwestern market. The consumer groups for this market are being parametrized to a greater extent in order to help answer the problem description. Another reason is the availability of the data. For Europe and North America consumption data is available from multiple sources and in similar granularity. Although the model focuses on NW Europe, there is useful data available for different demand groups in North America, which will be used as well. For all other parts of the world the model sees a representative group of the type 'heavy industry'. These countries are developing countries (non-OECD) and their consumption of natural gas is expected to grow as their economy grows. The heavy industrial consumer demand is dependent on economic growth and therefore resembles this consumer the best.

5.4. Market clearing mechanism implementation

We implemented a clearing mechanism based on the matching market approach. In broad terms this means we match bids and asks, however we kept a uniform clearing price for all buyers and sellers. This is done by implementing an intermediary agent who matches bids and asks and handles the market clearing task. This intermediary is modeled as a 'market-agent', consistent with the Blume implementation of matching markets [9]. In appendix D we showcased the market clearing mechanism code snippet.

Within this code snippets the formalization of the matching process is shown as well as the process to capture the clearing price. The simplicity of the formalization is one of the strengths of this approach. As can be observed in the code snippets provided the clearing mechanism is straight forward and can be understood without a mathematical background. If one wants to add more complexity to the model the way the buyers and sellers come up with their bid list can be amended or expanded.

5.5. Conclusion

Within this chapter we elaborated on the modeling tools we used to formalize and present the problem. The leading philosophy was to make the process as transparent and accessible as possible. The second part of this chapter was dedicated to the parametrization process of finding real world parameters for the simulation runs. Within this part the external information from the scenario runs, the starting position of real world values and design choices of the model were combined, forming the final model. In this chapter the reader must now have acquired a sense of how the methodology discussed in the previous chapter has been implemented. We hope the reader feels encouraged to get their feet wet and start to expand or improve the model to his or her needs.

6

Experimentation

Everything not saved will be lost

Nintendo "Quit Screen" message

In the experimentation chapter the formalization of chapter 5 is implemented. First we will discuss the set-up of the experimentation. We will shed some light on the circumstances of the model runs and describe how we combined previously discussed and newly presented external parameters. In the second part the verification and validation efforts are discussed. In this part we test if the model behaved as we expect, in order to see whether formalized the problem correctly. And we will the validation of the model outcomes, by comparing the model outcomes with known data.

6.1. Set-up of experiments

For the experimentation set-up we will run three model runs according to the Eneco scenarios. These scenarios sketch three different worlds. "Circles" is a world of cooperation and sustainability, "Paces" is world of segregation where economic growth in Europe trails behind that of the rest of the world and where a clear focus on a sustainable future is absent. In "Tides" a short-term focus leads to a boom-bust economy[21]. A more comprehensive description of these scenarios can be found in chapter 3 and in appendix A.

6.1.1. Parametrization

The model needs a starting set of assumptions, a snapshot of the world today. This starting set of assumptions is the same for all model runs and consists of data from a variety of sources. For countries reserves and consumption data the World Statistical Review of Energy[10] is the leading source. Unproven reserves and the assumptions about shale-gas are based on the CIA factbook [3].

In chapter 3 and chapter 5 we discussed some key assumptions about how the scenarios are translated into external parameters. Examples are economic growth figures under the different scenarios and growth in natural gas demand in the electricity sector. However the scenarios were not constructed for the purpose of gas market modeling. Therefore some assumptions had to be made.

6.1.2. Economic growth

Economic growth and energy consumption are historically tied together [61]. There are multiple reasons for this causality. One is the fact that high economic growth leads to more buying power of consumers who will in return buy energy-intensive goods. Another dynamic is that economic growth causes an increase in economic activity, which for a part is expected to be energy-intensive. Although energy consumption is not the same as natural gas consumption, we find a positive correlation specifically for natural gas [4]. Within the Eneco models 1 % increase in economic growth translates to 1% more consumption of natural gas in the industry sector. Apergis finds a correlation of .7 % as an average. For a relatively heavy industrialized country 1 % seems like a figure in the right 'ball park'.

In the Paces scenario the world develops in different paces, economic growth in Europe is trailing behind the world. In this scenario the economic growth of the world approaches 5 percent in the coming decades

while Europe enters another recession to catch up with the rest of the world around 2040. The formula below is used to approach a constant growth path for the rest of the world.

$$\% \text{ economic growth} = \arctan\left(\frac{\text{year}-2013}{.5 * \pi}\right) * .05 + 0.03 \quad (6.1)$$

In the Tides scenario the boom-bust economic cycles dominate economic growth figures. High unsustainable growth causes overheating economies and leads to recessions.

In the Circles scenario the focus lies on sustainable economic growth caused by focus on long-term growth and investments in future-proof industries. A graphical representation of these scenarios can be found in figure 6.1.

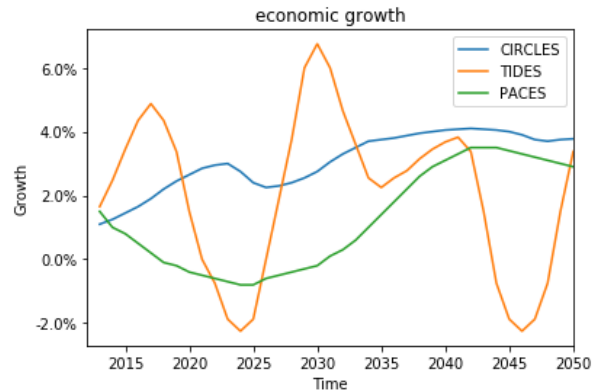


Figure 6.1: Economic growth forecast in the Eneco scenarios

6.1.3. Gas demand characteristics

Ideally an assessment of the natural gas demand takes into account the total expected energy need and calculates the expected share of natural gas based on variables such as the price of competing energy carriers and availability of supply. However this requires estimates of characteristics of competing energy carriers and other information not available at this point. The Eneco scenarios describe annual consumption figures for the electricity sector in the Netherlands. Since these figures are based on world markets and characteristics not limited to the Dutch energy market, the assumption has been made that these figures can be extrapolated to the European Union.

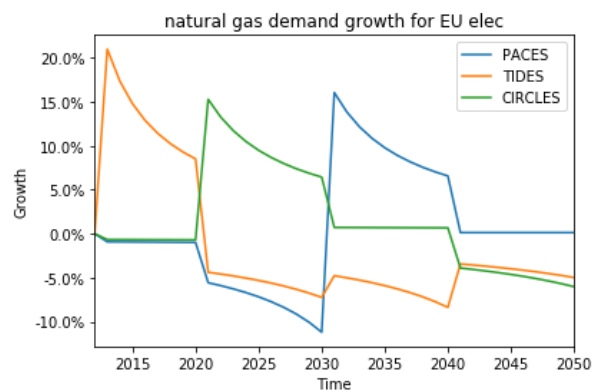


Figure 6.2: Growth in gas demand by EU electricity sector forecast in the Eneco scenarios

Household consumption of natural gas for heating purposes is expected to decline due to energy efficiency measures and to the fact that newly built houses are not necessarily connected to the natural gas grid. For Eneco a 1 % decrease in demand is already noticeable among household consumers due to efficiency measures in appliances and isolation efforts. There is no exact figure given in the scenarios description. We

change this to a 1 % increase within the paces scenario. Due to a growth in households, even when the average consumption declines an increase is still feasible. In the Paces scenario we foresee an average decline of 1 % for household use of natural gas. In the Circles scenario we foresee a 3% decline on annual basis. This is in line with the philosophy that in Circles the focus lies on green and sustainable energy consumption.

When we take a look at total consumption in the European Union we see that all three demand groups form a U-shape figure. Stacked together this will of course yield an even clearer U-shape figure. For this reason we see all different demand groups consuming on a yearly curve reflecting the seasonal change in consumption. This curve is represented in the following co-sinus 6.2, where self.offset stands for the shift in the year the consumption takes place. It can be either summer or winter in January depending where you are on the globe. Electricity consumption can be particularly high during summers in certain parts of the world while it can peak during winter periods in other parts of the world. b represents base demand, m represents peak demand and x the timeticks in months.

$$y = b + m * (.5 * (1 + \cos\left(\frac{x + \text{self.offset}}{6} * \pi\right))) \tag{6.2}$$

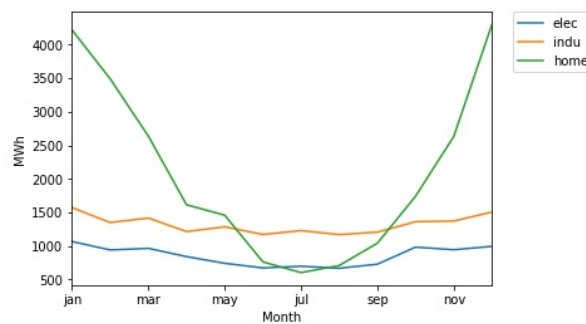


Figure 6.3: Demand groups NL

Seasonal differences in demand form in the long term almost perfect sinuses. Even industrial consumers and electricity producers consume with seasonal variation. If we examine the Dutch energy consumption we see that these different consumer groups consume in phase. However as we can see below in figure 6.4, these demand groups can also consume out of phase. This will result in a W-shape consumption pattern as opposed to the U-shape pattern. The high spike in electricity consumption during the summer period can be attributed to the use of air-conditioning. In parts of the world where we would expect air-conditioning to be a major energy consumer we would expect to see W-shape consumption patterns.

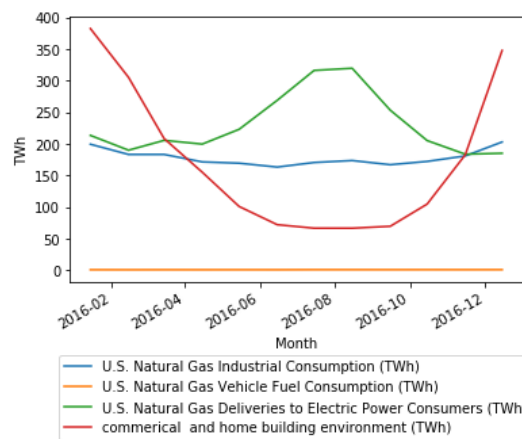


Figure 6.4: Demand groups US

One consumer group not previously mentioned is the transportation sector. Natural gas can be relatively easily used for transportation. Natural gas driven consumer cars are already on the road and the majority of

public transportation buses are driven by natural gas in the Netherlands. However these figures are insignificant in comparison to demand of other major consumer groups, as can be seen in 6.4.

6.1.4. Gas supply characteristics

Characteristics of the supplier are difficult to come by. Extraction costs are considered to be competition sensitive information and therefore not publicly available. There is assumed to be a wide variation in extraction costs of different fields and also dependent on the extraction technique used. Shale drilling and horizontal drilling are for example more expensive than conventional drilling methods.

In order to work with a "ball-park" figure we can resort to two types of existing data. Market analysts and literature study. Market analysts tend to sell their data and analysis while literature studies have a habit of hiding their assumption with the argument that it is not part of the 'scientific' story. A full comparison between a wide variety of sources is for this reason difficult. Nonetheless we will present two publicly available assumptions on production cost estimates. Market analysts of Deloitte assess that the market price in the US has to reach at least \$ 3.75 - 4.35 per mcf (roughly between € 10 - 15 per Mwh) to justify operational and capital costs[20].

In literature study of Gabriel [33] the costs to the producer form the mathematical fairly complicated line below. The shape aims to 'force' producers to supply at the optimal designed quantities, since the marginal costs become negative if the production falls back to much and rises exponentially if it increases beyond the design limits. The seasonal flexibility on the supply side is virtually non-existent. If we take known fluctuations of supply into account we can assess this 'punishment' of producers not supplying optimal quantities is to strict.

We assume natural gas producers to make a bidding curve of between the 10 and 20 € per MWh, this is consistent with the assumption of Deloitte. Assuming production costs rise when wells get depleted, the producer will raise these prices when their fields get depleted.

To illustrate this point the bidding curve of the producer is presented next to Gabriels assumptions in figure 6.5.

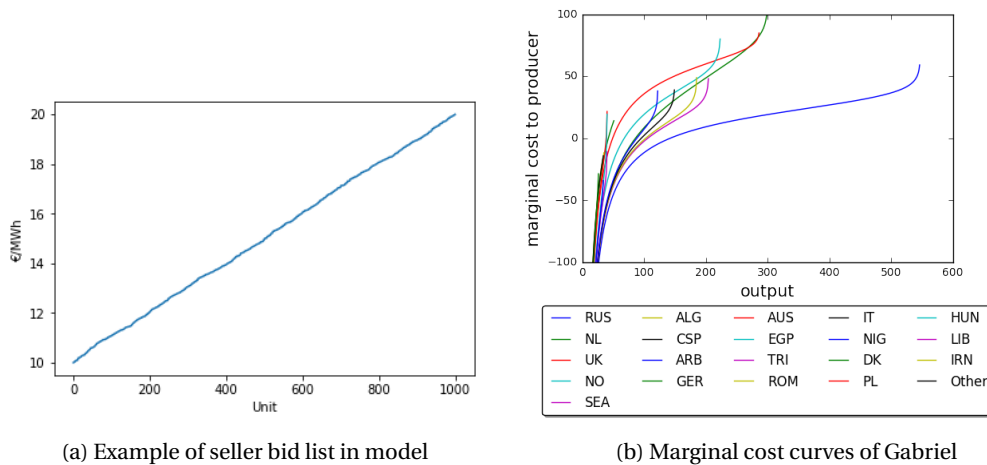


Figure 6.5: Comparison of Gabriels production curves and model production curve

6.2. Verification efforts

When verifying the model we are assessing if the behaviour of the model is as we expect it to be. In other words, is the conceptualization correctly implemented in this formalization. Firstly we will do a series of model runs with the same parameter settings to asses the variation of different model runs. Secondly we will vary parameters in order to see if the outcome moves in the expected direction.

In order to test the robustness of the model we ran all scenarios multiple times, in order to find out how the results vary in different model runs. Within this section a selection of the results will be presented. The selection will focus on the problem description and the research questions of the thesis. Hence we will focus on markets relevant for the Northwestern gas market. All graphs can be found on the GitHub of this project introduced at the beginning of this chapter.

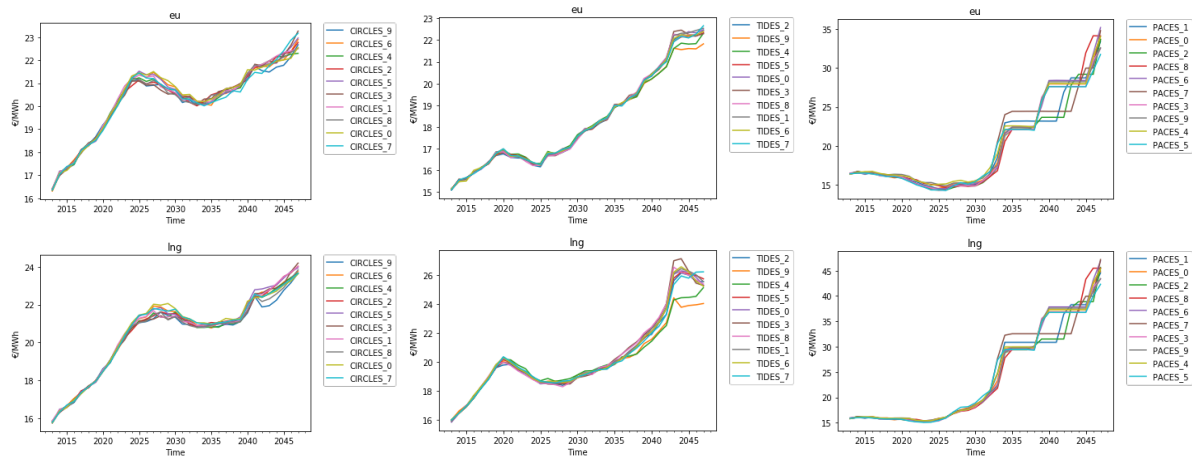


Figure 6.6: Validation multiple model runs

In order to test whether the model behaved as expected we tested the precision of the results by running the model under the same assumptions multiple times. The premise is that a model with low precision is not very useful as a tool for planning against future uncertainties. If the model shows variation but not of a significant kind, the model seems to be pretty precise. Note that this does not mean the model is accurate. When a model is precise, it allows us to analyze individual model runs in greater detail.

6.2.1. Parameter sweep

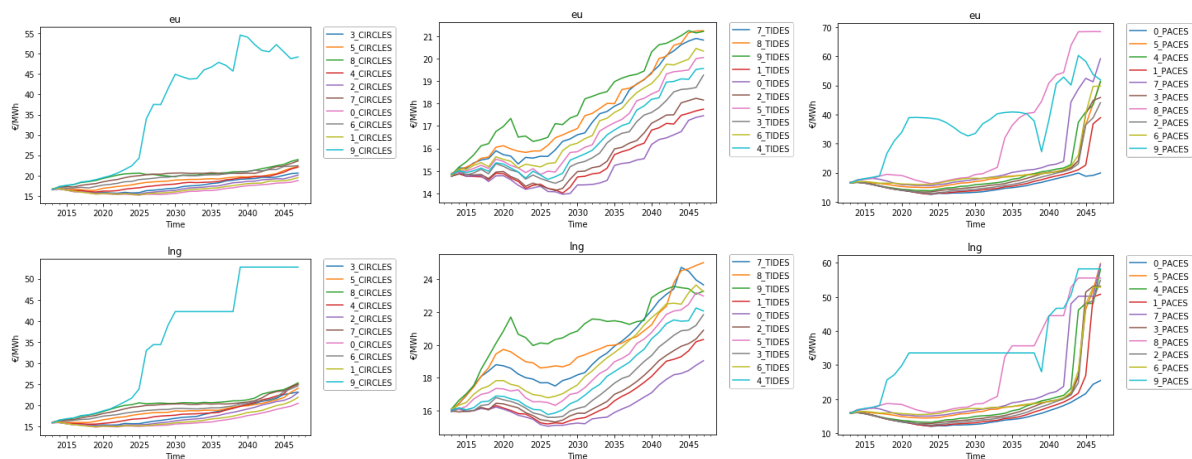


Figure 6.7: Validation parameter sweep of investment appetite of producers

In order to test whether the model is robust, parameters are varied and we are looking for values where the model still behaves as expected. The parameter chosen is the "yearly average threshold" parameter which tells the producers to react to market conditions by increasing their production. All producers keep track of

the average utility of their assets over the past 12 months. If this figure passes a certain threshold the producer starts to increase his production. The parameter is varied from 50% (run 0) to 95% (run 9). As we expected we observe that when producers expand production early market prices will remain low. However when producers are conservative with investments, prices rise. We see that the range of values where the model keeps making sense ranges from 50% to 90% which is a surprisingly broad range.

Seeing that run 0 results in all cases in a lower market price and a more stable market than run 9, we note that this is the expected behavior of the model. This indicates that behavior is correctly implemented in the model. Hence a passed verification step.

6.2.2. Extreme value testing

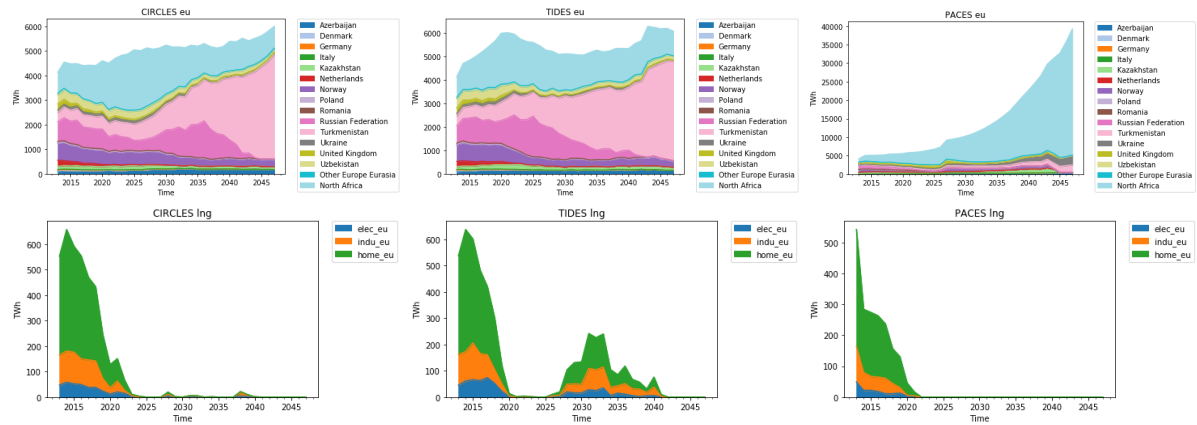


Figure 6.8: Verification testing of Groningen field reduction

One other test we conducted is setting the production of the Groningen gas field to zero. However we kept this scenario as realistic as possible and chose not to suddenly set it to zero but gradually phase out production. Production will decrease by 10 % every year. Since the role of the Netherlands is insignificant compared to Russia or Central Asia, a scale-back of the Dutch production would not change our import/export ratio drastically. It also does not lead to a significant increase in LNG consumption to compensate. However in this particular model run Northern Africa manages to win a surprisingly big market share. Repetitive model runs are necessary to observe whether this is an out-lier or if this is somehow connected to the extreme value testing.

It should be noted that not all production from the Netherlands comes from the Groningen field, so decreasing by 10% could mean the production at the Groningen field is scaled back significantly more every year.

6.3. Conclusion

Within the experimentation chapter we discussed the set-up of the experiments done with the model. The verification and validation efforts were discussed in the first part of this chapter. The overall conclusion on these issues is that when changing variables and initial conditions, the outcome did not change drastically, hence the model is robust. A verification process was conducted and the model was concluded to be verified for the function it was designed for. In the next section we will dive deeper into the numerical analysis.

7

Numerical results

Never again will a single story be told as though it's the only one.

John Berger

In the previous chapters we discussed the problem formulation, described the gas market, determined the correct model methodology and discussed how this was implemented. Furthermore we discussed how the experiments were set up and described the verification process. Within this part we will discuss the interpretation of the model run result.

7.1. Regional results

The LNG market is the global link between natural gas markets. LNG is in the real world more expensive due to mechanisms discussed in chapter 2. In the model runs the observer agent is manipulated to run the LNG market the latest of all markets to reflect the real world place of the LNG market. This means that the LNG market is both for sellers and buyers a market of 'last resort'. The collapse of the LNG market in the Paces scenario has the basis in a growing demand of the originating countries limiting the availability of supply to the LNG market and to the major suppliers to the LNG market (e.g. Australia) run out of known supplies.

7.2. Findings

When assessing markets we tend to look at two things, quantities and prices. The modeling done in this thesis this is no different. The markets report a clearing price and cleared quantity. Examples of such results are provided below in figure 7.1. On the left we see the monthly prices. Since the consumption of natural gas is seasonal we expect this to be reflected in the quantities passed on to the market. Quantities reflect TWh consumed, prices are expressed in €/MWh on the wholesale market. When demand exceeds supply these seasonal fluctuations are less prominent or non-existing since all supply is bought, in short there is a shortage when the line is flat (and not zero). We would expect prices to rise in these instances and new supply being brought on-line to fulfill this demand. This represents quantities consumed and does not reflect real world spot natural gas markets where in a virtual market the same quantity can be traded countless times.

However in this case our interest is broader than mere quantities and prices. We are also interested in the origin of natural gas. First of all because it requires infrastructure which has to be built. LNG requires regasification terminals, liquefaction terminals and transport vessels, while transport in its gaseous phase requires pipeline infrastructure. Apart from the infrastructure problem there is also a political reason why we are interested in these answers. Natural gas tends to come from regions of unrest. Instability of energy supply is very undesirable.

We will focus mainly on the EU and the LNG market, because they relate most to the problem description. Results for all agents can be found in appendix E, more visualizations are available on the corresponding GitHub in the Jupyter Notebooks. Within this chapter I would like to focus on how to interpret the results and how they help us to understand the gas market. Technical modeling questions, as far as they are not

addressed in chapter 5, might be answered in the requirements appendix D, where we focus on the modeling journey.

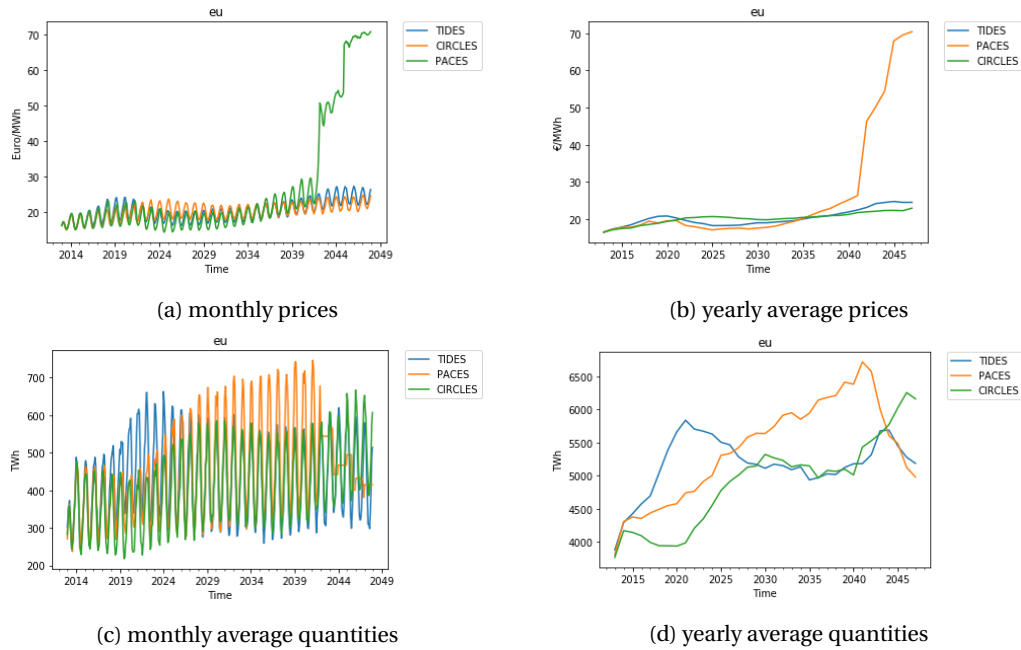


Figure 7.1: Results EU market quantities

7.2.1. How do the model results answer the research questions?

We will answer the research question by answering the sub-questions with the analysis of this thesis. Both the conceptualization done in the chapters before and the model results will be used. The analysis made in the previous chapters distilled trends and fed external parameters and are thereby a key puzzle piece in answering the sub-questions. However the results of the model run itself will provide other key components of the answers.

How is the demand for natural gas going to develop?

The demand for natural gas varies within the three scenarios and should be seen in combination with the production of natural gas. A phenomenon we observe throughout the world in regions with a lot of natural gas available, is that when a lot of gas is produced a lot natural gas is consumed within that region. When the good is scarcely available in that region less is consumed. We see this in the model results of the Paces scenario, where the discovery of shale gas leads to an abundant availability on the European mainland and consumption subsequently rises as well. The consumption figures of the three representative consumer groups on the European market are presented in figure 7.2.

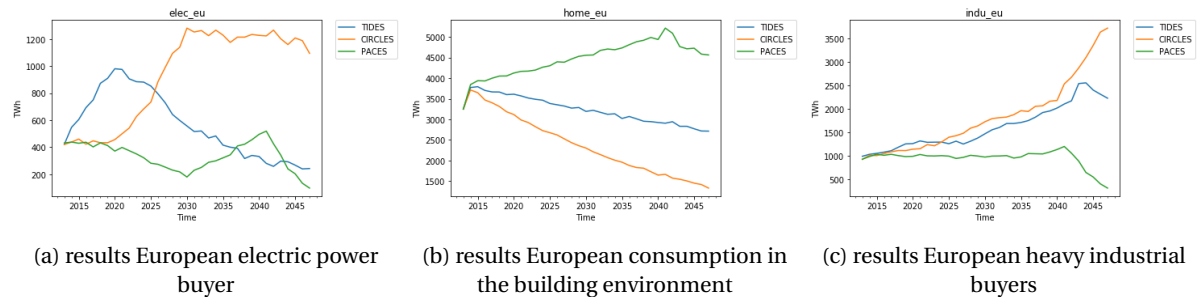


Figure 7.2: European consumer groups

From figure 7.1 we learn that on the European market demand is going to rise for natural gas. However extreme the scenarios differ on their assumptions about underlying trends like economic growth and energy

savings, quantities traded in the Circles and Tides scenario are surprisingly similar. When we examine the sources of demand in figure 7.3a we see that a steeper decline of usage of natural gas in the built environment in Circles is largely offset by increased consumption in the industrial sector due to economic growth in the region.

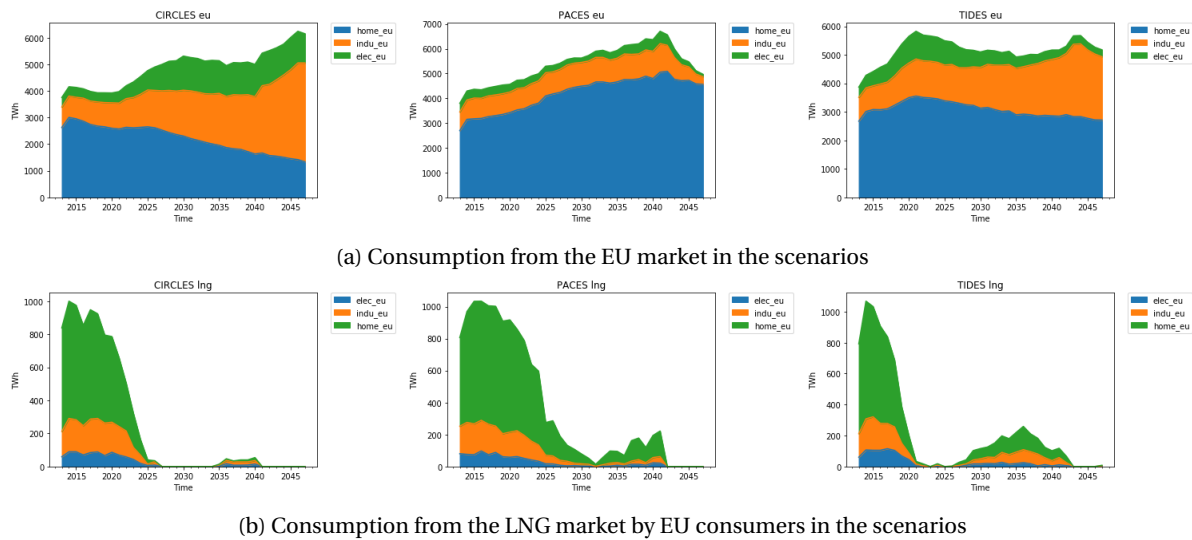


Figure 7.3: Consumption from the EU market in the scenarios

So what happens to LNG consumption in the different scenarios? For the total LNG market we observe a stark increase. The underlying trend is the depletion of local resources and the rising demand due to economic growth in non-OECD countries. Combined with the limited production capacity on the LNG market we see high demand is pulling LNG away from the European market. In all scenarios LNG quantities reaching Europe are declining. The trend has its foot in recent history, when European the usage of LNG infrastructure did not live up to expectations because of a sudden increase in demand from Japan. Europe is quite well connected to pipeline infrastructure with some local reserves, a well connected infrastructure to Russian fields and Northern Africa and potential in Eurasia. Both in the real world and in the model results other world regions will be willing to pay more for LNG than European consumers will (figure 7.4).

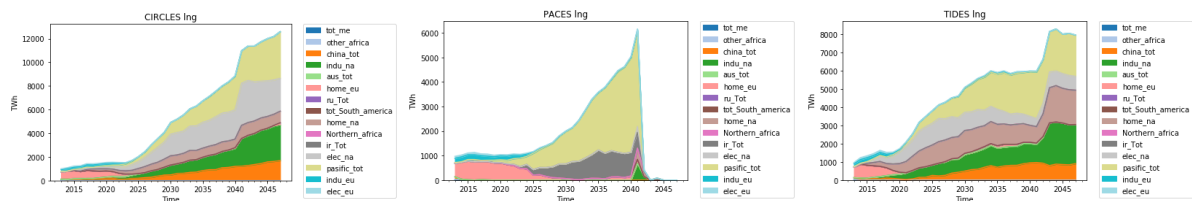


Figure 7.4: Consumption of all LNG consumers in the scenarios

How is supply of natural gas expected to change?

When speaking about markets, in general we speak in terms of consumers and producers or buyers and sellers. When looking at production, we speak about natural gas endowed countries, countries that are likely going to export natural gas to demand regions, thereby fulfilling the role of producers. In order to find a meaningful answer to the seller side of the market analysis we want to reveal which sellers are supplying the market.

The endowment of natural gas determines the location of the production of natural gas. The ability natural gas endowed countries to produce and to bring the product to market is determined by their production capacity and reserves. The relatively small reserves on mainland Europe are expected to dry up in the coming decade. Since exploration costs are expected to be higher for nearly depleted reserves the depletion is expected to fade out instead of stopping abruptly. Nonetheless these reserves need to be replaced. What is going to replace them differs in the scenarios.

In the Circles scenario the main premise is that the world is moving faster towards a more sustainable future. Households in Europe will save more gas on average than in the other scenarios. This impacts the amount being consumed in the built environment and flattens out the demand profile. This is probably one of the reasons why Turkmenistan is able to acquire its market share. Bringing production on-line and building infrastructure can be done more easily when there are low seasonable demand fluctuations. Russia remains one of the main suppliers, however it is noteworthy that supply is expected to dry up within the given time-frame.

In the Paces scenario shale-gas recovery on the European mainland is replacing conventional resources. In figure 7.5 we see that there is a lot of shale gas and unconventional resources in eastern Europe will likely be brought to the European market. Russia will remain a major supplier for the coming decades, however within the modeled time-frame it will be replaced. The Paces scenario foresees an inevitably big role for Ukraine and Turkmenistan. The reason for the former is the big shale reserves the country is expected to have and the reason for the latter is the big amount of conventional resources that are not yet being brought on line. In this scenario we also see the Netherlands playing a major role until roughly the end of the model horizon. The Netherlands is expected to have a significant amount of shale reserves [3] and is bringing that to the surface within this scenario.

The Tides scenario appears to be an in-between version of Circles and Paces. This makes sense since the philosophy of Tides is the fact that we do not learn from the past and keep doing what we have been doing. It also is the only scenario where Russia appears to remain a stable supplier throughout the whole model run. Europe's mainland production is on the decline, however it is able to remain a supplier throughout the whole model run. The repeating story line is that central Asia, Turkmenistan in particular, is becoming a major supplier, keeping Russia in second place. The coming decade however Russia is expected to be more dominant.

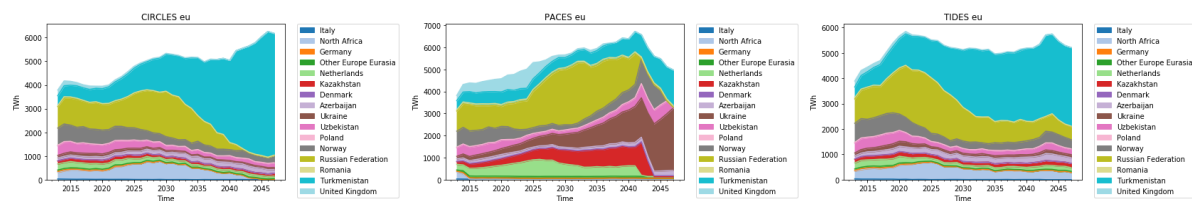


Figure 7.5: Supply to the EU market in the scenarios

To start where we left off in the previous section about consumption, European consumption of LNG is expected to rise in the coming decade but in all scenario runs will fall afterwards, due to the fact that we will be pushed off the market by other newly entering consumers. LNG is an expensive way of transporting natural gas compared to pipelines. However these costs are not modelled since another real world phenomenon is far more determinative for the price. Namely the fact that the world price is determined by the world marginal consumer because the LNG market is a world market. This is presumably the reason why in different scenarios different producers are pulled towards the market.

Another reason the LNG market varies widely is the inland consumption on these markets. Consumption is tied to economic growth. In the Paces scenario the world around Europe develops at a steady pace. In this scenario the LNG market dries up within the given time frame. This is preceded by a boom of unconventional resources of non-traditional producers in the Middle East. In the Tides scenario we observe a boom in the LNG market, although led by traditional producers that are currently supplying the market as well. The reason why these producers are not present in the Paces scenario is the fact that the region is flourishing economically and natural gas is used domestically. Since LNG liquefaction facilities require tremendous upfront costs, it is reserved for places where there is almost no other means of transportation. If there is a choice between consuming it domestically or transporting it by pipeline to a nearby market, usually the first option is chosen. In that respect the model mimics real world behaviour.

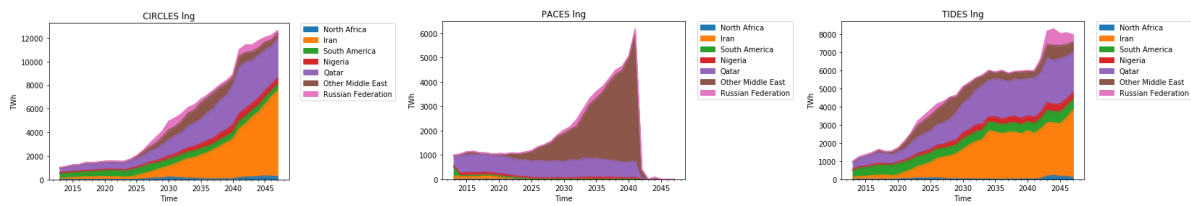


Figure 7.6: Supply to the lng market in the scenarios

How do market imperfections impact the natural gas market?

When we speak about perfect markets we generally speak about the economic definitions of a perfect market allowing buyers and sellers to arrive at a fair price. A fair price means that buyers and sellers are exchanging their goods in an optimal way. The buyer should buy the cheapest unit of gas that is available to him, while the seller should sell for the highest price he can get. Within this definition anyone can feel the main requirements of this perfect market. Everybody should be able to have full information and access to the market. There should be enough buyers and sellers to allow some kind of competition, thereby not granting one side of the market the power to determine the market conditions. In classical economic theory this should lead to a race to the bottom leading to zero profits. You do not need to be an expert to see that the latter does not hold for natural gas market.

There is limited freedom to information on the natural gas market, the majority of gas is traded in bilateral (long term) contracts. This one of the reasons why it is a non perfect market. There is a spot market which is in a sense open and provides more information to market players. The model addresses the natural gas market as a spot market where all players have equal information. This is a simplification and does not reflect the gas market today. Long term contract were outside of the scope of this thesis and would require a significantly more complex structure of the model. This limitation results in surprising drops in prices or quantities sold seemingly from one day to the other. In reality contracts will result in a smoother transition, since even if buyers or sellers have other incentives they will be bound for the duration of the contract. One example of this is the Groningen gas field where the argument of binding contracts is being used in the political debate to cut down on production in specific wells. However although a hundred percent spot market is not close to reality it is the gas market vision of the European Union[71]. The spot markets world-wide are becoming more common practice and the markets at the European mainland are maturing. Addressing the natural gas market from this light has its foundations in reality.

One market imperfection that is not going away any time soon is the fact that natural gas is not distributed evenly across all countries. It is inevitable that within the horizon of the problem definition a few sellers will remain dominating the market. In the Paces scenario shale gas is reshuffling the decks. However in this scenario demand is also expected to explode, leaving the question open in all scenarios how this oligopoly is going to change market conditions. Although currently the gas production and reserves are not distributed evenly, the fact that a few from the global perspective minor players are supplying local markets can make them the marginal supplier forcing a bigger player not to abuse market power since that would most likely cost him market share on the short term. And how counter-intuitive this might sound, short term is the longest term a significant part of the sellers are willing to look into the future. The mechanism at play here is that since these natural gas selling entities are partly or completely state-owned and revenues are being used in current budgets, losing market share will mean austerity measures[48] or even a completely imploding political system (for example Venezuela). In the current system small marginal players can manage seasonal imbalance, but this situation is not sustainable as reserves are drying up in these small production countries (for example The Netherlands).

The efforts of the European Union and the world upswing of spot market trading can be seen as an institutional answer to increasing market power. The philosophy is that when there is a completely transparent spot bidding market for the whole European Union, buyers will not have the disadvantage of having to negotiate as an insignificant player against a de facto monopolist. Another perceived advantage of moving from a bilateral market to a spot based market is the fact that it opens up the market. It allows for a transparent entering process of newcomers both for buyers and for sellers.

7.3. Validation

Validation is the process assessing the results to be realistic. A possible validation step is to compare the model results produced in the quantitative phase to either known real world data or to findings of comparable studies.

The validation efforts consist of comparing insights of the model runs to existing literature on modeling gas markets. One thing to look for is whether the natural gas market models agree that some trends are imminent, and if so, whether we see the same trends in our numerical analysis. The philosophy being that 'if it seems like everyone else is wrong, you are likely wrong'.

How do these models differ in their methodology and conclusions about the gas market? Manne foresees the imports from unstable regions to be problematic and suggests either a quota or a tariff imposed by the importing nation[63]. Manne's model (as well as Lochner's model) has the unique characteristic of being caught up by reality. Imports have increased but this has not caused problems of disruption in Northwest Europe. Tariffs and quotas on the importing nation side have not emerged. Security of supply is still on the agenda and the discussion proposed in the paper is still relevant today as the share of imports from unstable regions is expected to grow significantly in the future. Holtz's model contradicts Manne's viewpoint, diversification leads to security of supply in his model and imports from Russia (which are the main concern of Manne) stabilize at roughly one third of imports. Holtz states that there is enough supply side reserve and capacity for security of supply not to be threatened.

On the supply side reserves and production capacities the reviewed literature that incorporates this in their analysis or assumptions, roughly agrees. Holtz, Perner, Lochner and Dieckhöner all see enough reserves. Diversification of suppliers for the European market is expected due to declining reserves and production capacity. Global production is more than able to supply this fallback.[22, 45, 60, 72]

The role of LNG in the European gas market differs among the models studied, even with the same researchers. Volumes will increase in the coming decades but the share and importance is not agreed upon. Lochner (2009) and Bothe see a modest role, but an increased importance on the world gas market where shares are expected to quadruple and prices converge. Locher (2005) and Perner predicts a significant role in NW-E with the UK as a major LNG regasification supplier. Dieckhöner foresees a more modest role for LNG.

All of these models expect increased liberalization on the European mainland. Liberalization will lead to an integrated market with converging prices. All models expect increased interconnector capacity and international pipelines to facilitate the liberalization process. Dieckhöner notes that most infrastructural investments at this moment are planned in NW-E, a market that is already interconnected, and that congestion is expected in Eastern Europe. Liberalization is a means to an end, namely a fully integrated and free gas market in the EU. Congestion that hampers integration is therefore a threat to the free market. Golombek quantifies the benefit of liberalization in increased social welfare and decreased market power for non-European producers subsequently limiting the profits for these non-European producers[36].

Gabriel foresees that the majority of trade flows to the EU will be by pipeline, in the range of 85% while 15% are expected to reach Europe via LNG facilities. Flexibility is key in providing security of supply. This can either be done by expanding the pipeline connections to regional suppliers of natural or by LNG. Observing the high investments in LNG infrastructure Gabriel assesses LNG to be the provider of future flexibility to Europe. His numerical results show that there is no serious security of supply issue, even in the case of curtailment on transport routes from either Algeria or Ukraine.

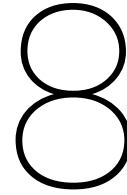
When assessing numerical results of existing literature we observe they vary widely in the assumptions they make about the markets of supply. One of the most notable conclusions of our numerical results is the complete downfall of LNG imports to the Europe mainland. Currently these imports make up a substantial part of EU consumption. We observe that for example Gabriel makes the same assessment about the future of LNG for Europe. All models see some significant changes of sources. Increased imports from the Eurasia region and Northern-Africa, are common place[33].

One observation nearly all models agree upon is the fact that production of the Netherlands will increase significantly in the coming decades. This differs significantly from the model results of our model where production is about to decline. The political decisions and recent dynamics support the model results of the model presented in this thesis, a sharp increase in production from the Groningen field is considered to be very unlikely. The numerical results presented in this chapter do not seem to be an out-lier and therefore pass the validation tests.

7.4. Conclusions

In this chapter we discussed the numerical results of the model runs. These runs were conducted with the scenarios of Eneco and provided a picture of market conditions in the light of these scenarios. The numerical results have been used to reflect on the research questions.

In the validation efforts the outcome of the model was compared to known results from long-term predictions and models. And the conclusion was drawn that the model outcomes are not alarmingly deviating from existing literature and market insights.



Conclusions & recommendations

I have seen the future and it doesn't work.

Robert Fulford

In the conclusions and recommendations chapter we will take a moment to take reflect upon the work done. Firstly the answer to the research question is discussed. In the following section we will discuss the process from a methodological viewpoint. In the last part of this chapter the focus will be on further research and recommendations.

8.1. Answering the research question

At the start of the thesis we stated the research questions which we would like to answer by addressing the sub-questions. The first two sub-questions focus on market conditions and are therefore (partly) answered by the numerical model results. This section is therefore a shorter recap of chapter 7 where these findings are discussed at greater length. The last two sub-questions focus on a more qualitative assessment where we will combine model results with the analysis spread out over previous chapters.

How is the demand for natural gas going to develop?

Global demand for natural gas is expected to grow in all scenarios. However there are still differences in the amount of growth in demand and in the source of demand. The source of demand shapes the seasonal pattern and is therefore of importance to infrastructural planning. In this section we will briefly discuss the differences among the scenarios from the demand perspective.

In the low growth in the European region scenario of Eneco there is less focus on renewable energy. This leads to a low availability of substitutes for natural gas in the European region. In this scenario the rest of the world undergoes high economic growth figures compared to the European market. These two are the main drivers for growth in the Paces scenario. The link between economic growth and energy demand leads to a relatively low demand in the industry sector. A missing focus on sustainability leads to a low energy saving percentage in natural gas use in the built environment, leading to high seasonal fluctuations.

In the Circles scenario the world is at harmony and there is high economic growth among all world regions. World-wide agreements are possible and economic growth leads to growing focus on sustainability. There is a high demand in the industry and electricity sector and a lower demand in the built environment. This leads to less seasonal fluctuating demand in the European region and a modest growth of demand on the long term.

The Tides scenario is driven by a boom-bust economy of overheating growth periods followed by recessions. The scenario can be seen as a 'base' scenario since it resembles the recent economic past. It therefore positions itself between the Paces and the Circles scenario, with a slowly declining demand in the built environment in Europe, moderate growth in industrial demand and declining demand in the electricity sector.

How is supply of natural gas expected to change?

Conventional reserves in Europe are depleting. Former natural gas net exporting countries, e.g. the Netherlands and Great Britain, are becoming net importing countries. Since demand is not expected to decline as

we concluded from the previous sub-question, current production has to be replaced.

In the Paces scenario this replacement comes in the form of shale-gas exploration. Shale reserves fall under the category of unconventional resources of natural gas. This means that there is uncertainty about the total reserves and technical and economical viability. The CIA estimates shale reserves to be located in Eastern Europe, in particular Ukraine. In the Paces scenario this will become the major export region to Western Europe.

In the Circles scenario these reserves are not available and the reserves of Central Asia are located advantageously to replace the declining production capacity of indigenous European producers and eventually Russia.

In the Tides scenario Russia and Central Asia share the European market, where halfway the model run around 2030, Turkmenistan will overtake Russia as the major supplier to Europe.

Models that solely focus on the European Union tend to foresee a major role for LNG as replacement of declining production capacity on the European mainland. However from a world view, Europe is situated relatively close to major reserve regions like the ones discussed above. Development of demand in other regions will most likely be more reliant on LNG shipment due to their geographical locations. In our model runs LNG plays a significant role in the in the coming years but will move away from Europe as soon as other regions are expected to develop demand for energy.

One of the major issues for the Northwest Europe production landscape is the future of the Groningen Gas field. At the moment Groningen, a gas field located in the Netherlands, supplies the North Western demand region with natural gas. Due to the technical properties of the field it has been operated as a swing producer for this region. It was able to ramp up supply in the winter. In the past months the discussion about the safety of the population living close to this field has forced to scale down production. As of this moment it seems imminent that Groningen is not able to fulfill the role of swing producer any longer. The production of this particular field was expected to decline in the coming decade because of depleted reserves. Recent discussion moved this time-line up. Within the time-frame and the scope of this model these developments are not significant. The reserves of the Netherlands were one of the indigenous European supply regions that will be replaced by imports from the regions discussed above.

However national dynamics not taken into account will be highly impacted by these developments. As discussed in chapter 2 there is high and low calorific gas. The Netherlands now stands before the a decision how to replace the low calorific gas from the Groningen field with high calorific gas from elsewhere. Appliances and demand can be adjusted to high calorific gas or nitrogen mixing facilities could be constructed to dilute the high calorific gas to low calorific gas. The decision between these two techniques lies outside the scope of this thesis.

And how to address the seasonality of demand now one import swing field is being taken offline in a more rapid fashion than planned. A possible replacement of this swing capacity is LNG shipments who are more flexible in nature or storage of natural gas in depleted fields or salt caverns, however an in-depth analysis of replacement technologies falls outside the scope of this thesis.

How do market imperfections impact the natural gas market?

Throughout the document we discussed market imperfections and their impact on the natural gas market. The choice of modeling technique was (partly) inspired by the inadequacy of existing research to deal with this imperfection. A perfect market could be modeled by optimization techniques under the assumption that market mechanisms allocate the available demand and supply optimally. However the conditions for a perfect market are violated in the gas market on multiple counts. There is an information asymmetry and availability of prices to name one.

Game theoretic models would require the market players to have a strategy and/or rational behavior. Since the gas market has a significant amount of state-run actors that do not behave strategically or rationally in economic terms. Game theoretic models fall short in quantifying the gas market. Example of this type of behaviour is the Ukraine conflict, which led to a supply crisis in Europe and price spikes in the winter.

Although we chose a technique to address market imperfections and decisively broke from conventional theory, the implementation of designed market imperfections are limited. Complex behavior is not modeled in great detail, so a numerical quantitative answer is not provided by the model results.

However what we are able to see is that market power on the supplier side is increasing in all scenarios. At the moment a significant part of the production is being delivered by countries whose reserves are depleting. With increasing demand this leads to situation where supply is concentrated with a hand-full of sellers. How to deal with the increase of market power on the supplier side is part of the current political debate. The

plans of the European Union to intensify its Energy Union is inspired by this outlook. The assumption is that spot market trading is preferred over long-term bilateral contracts. These spot markets would make it easier to provide an equal market price for all buyers and sellers and would limit information asymmetry. If these measures help or are adequate in dealing with this outlook would be a subject for further research. Staying connected to the LNG world market would at least provide a ceiling to the prices mainland buyers and sellers are able to ask for natural gas. Hence the numerical results of our model runs in respect to LNG supply to Europe could be seen as unfavorable in the light of market power and market imperfections. This provides a political argument for investments in LNG assets.

What is the effect of the discussed market changes on Eneco and what strategies can it execute to adapt?

The last research questions focus on actors within the energy market of Northwest Europe, with a special focus on the role of energy companies like Eneco. As discussed in chapter 3 Eneco is a relatively small company on the energy market and its strengths should not be sought in acquiring or executing market power. However the rapidly changing world of energy markets requires its actors to adjust. Scenario planning is a tool to explore different futures without being held back by the tunnel-vision of today's assumptions. The quantification of scenarios in model runs is just one tool to make implications apparent. To answer this question one should look further, especially since this model does not address Eneco as a specific actor. Although relatively small Eneco is present in all parts of the value chain of natural gas. In this section we will speak about the value chain from the viewpoint of Eneco.

In the upstream part of the chain Eneco has a stake in the LNG terminal GATE, located in the harbor of Rotterdam. In this terminal LNG tankers are able to dock and off-load, re-load or load up their cargo. The facility is connected to the main grid of the Netherlands via a regasification facility[35]. As discussed LNG is a relatively expensive technology and although it interconnects gas markets on a global scale, the price of natural gas should not only be high but should be relatively high compared to other markets to be competitive. From the scenario runs we learn that LNG is not the future. If other parts of the world develop their energy hunger they will out-compete Europe. When compared to the other parts of the world Europe is relatively well connected with an existing infrastructure to conventional fields in Russia, Eastern Europe and Northern Africa. Other parts of the world are not as well connected and rely more heavily on the LNG infrastructure. A taste of this phenomenon was at display when a sudden increase in demand from Japan shook the LNG market and drained all supply. Based on the model simulation LNG should not be the focus in any scenario.

Eneco has an interest in storage facilities in the Netherlands and in neighbouring countries. Storage smooths out seasonal consumption and allow for some arbitrage opportunities. It is an essential part of the natural gas system because it allows infrastructure and production capacity to operate efficiently. Without storage natural gas infrastructure has to be built for peak demand leaving the majority of assets idle most of the year. The depletion of fields in Europe will require more import. With increasing imports new transport capacity is required which will need local storage to be operated efficiently. Therefore a focus on storage is advisable in all scenario conditions. Looking ahead at the discussion to scale back on production from the Groningen gas fields, storage will only grow in importance. Storage has not been part in the modeling efforts in this study. However the implementation of forced consumption for natural gas in the built environment resembles storage to some extent.

Eneco is a re-seller of natural gas to the built environment, where natural gas is used primarily for heating and in a smaller scale for other purposes like cooking. With more efficient appliances and alternative ways of providing central heating (e.g. heat-pumps) in combination with a growing focus on better isolation demand is bound to decline. For the Netherlands, this requires institutional change in written law for example. It was required for local utility companies to connect every household on the gas grid when requested. Legislation to change this is part of the current debate. In the scenarios Circles and Tides a decline is part of the external parameters of the scenarios, in Paces demand keeps growing. A growing demand is not unthinkable since alternatives for heating are not obvious and require high upfront investments. Better isolation can be offset by a growing population and decreasing the average number of persons per household. The results and conclusions are ambiguous for the prospects for natural gas in the built environment, although in all scenarios Eneco should be prepared for an alternative way of heating the built environment.

In the south of the Netherlands Eneco owns an electricity production facility which uses natural gas as its feed-stock. So what do the scenarios tell us about the prospects for natural gas in the electricity sector? The biggest swing consumer of natural gas is arguably the electricity sector. It is in constant competition with coal and more recently renewable electricity production entered the electricity market. Natural gas has been

regarded as a transition fuel which was able to provide the base-load and flexibility in electricity production at a smaller cost both to the environment and technically. However the decline in the price of coal due to low demand and unexpected developments on the carbon market withheld this 'inevitability' from becoming reality. In the Circles scenario natural gas becomes grows in significance, in both Paces and Tides gas is shrinking, although in the latter it grows in the coming years. For natural gas all chips have to fall right for it to have a more significant future. There should be an institutional fix for for the carbon market to function as intended and push natural gas up on the merit order. It should not price itself out of the market and even if the latter two requirements are met, technological advancement in renewable energy production is most likely to decrease production. Holding on to natural gas fired electricity production assets is not consistent with the scenarios.

So how do the answers on the above sub-question relate to the main question at the start of the thesis?

"How are the North-Western European gas prices influenced on the long term by the drivers of the global gas market?"

All things combined scarcity is imminent and gas flows are bound to change. The underlying dynamics can differ, either a growing demand of natural gas in developing regions or the depletion of known resources can be leading the push. The region of focus, the natural gas hooked region of Northwest Europe, has to adapt. The way of adaptation will depend on the scenario followed. However, with a probability bordering on certainty the current price is about to rise as long as the underlying structural demand for natural gas remains and a paradigm shift of energy needs is out of sight.

8.2. Methodological reflection

Scenario analysis of long-term gas market modeling is new for two reasons. The first is the wide geographical scope of the model. Gas market literature in general has a very regional scope, limiting the problem formulation to focus on one of the three world markets and addressing either the market problem or transportation problem of that region. In scenario planning of the gas market such a limited scope does not answer key questions about the finite of known reserves. Since scenario planning is not the art of predicting the future, but aims to sketch the now perceived possible boundaries of the future, a limited geographical scope that is unable to answer the key questions concerning carbon energy sources, is not fit for its purpose. When broadening the scope, uncertainty increases. These uncertainties will be discussed in greater detail in the last section of this chapter. The key lesson is that uncertainties are not bad in themselves, one could argue that they even help scenario planning. It helps to broaden the boundaries of our imagination. The founding father of scenario planning writes in his handbook that it is essential to take a long time frame for exactly this reason[53]. When interpreting the results of model runs we should take into account this uncertainty and be cautious to interpret the results as a 'glass ball' into the future.

The other novelty of this thesis is the use of a matching market as a market clearing mechanism. Future studies of the gas market use optimization as a market clearing mechanism. The choice of formalization matters because it defines the paradigm of the problem. In other words, the glasses we use when examining the world determine what we see and more importantly what we do not see. The use of optimization assumes there is some form of rationale in the market. Either the players in the market behave optimally or the market itself allocates the demand and supply the optimal way. It should not come as a surprise to the reader that the carbon crude market is not necessarily rational or at least their players are not. Gas selling entities are in general state-run actors with behavior not always explainable with conventional economic wisdom, for example the disruption of the supply through the transit region Ukraine. Another drawback of optimization is that it becomes increasingly complicated when it addresses real world problems. This leads to either complicated mathematical formalization or arbitrary cut-off points of the rationalization. Gabriel for example gives the supply side of the market strategic powers while the demand side of the market is a price taker.

The Agent Based Modeling approach taken in this thesis aims to avoid the 'optimization paradigm'. ABM emphasizes on actor behavior and not on an overarching optimal state. It is therefor more suitable to deal with problems where the optimal outcome is not the only perceived outcome. The interaction of agents reveals a system behavior, how the agents interact is defined in a set to the agent. This leads to emergent behaviour of the system, meaning behaviour not explicitly stated to the system. Evolutionary behaviour is when the system adapts to this emergent behavior. To what extent emergent behavior or even evolutionary behavior is witnessed in a model is inherently hard to predict. We can state that it is dependent on the degrees of freedom in the model.

The feedback loops within the model were quite modest. Agents anticipated on historical market prices communicated back to them. However long-term demand feedback loops were left out of the modeling, for example substitute long-term demand for other energy carriers is not modeled. Neither was gaming behavior of market agents. There is no capacity with-holding for strategic reasons for example. Adding rules to the agents to mimic this behavior would make a more 'pure' implementation of the ABM philosophy.

We had to choose between modeling close to the ABM paradigm allowing or staying close to the problem definition. The provided scenarios constrained the degrees of freedom. Making assumptions on alleged strategic behavior and on how feedback mechanisms worked, would require interpretation beyond what was provided. The scenarios obviously were not designed to be used as input for an Agent Based Model. In the later part of this chapter we will address how the scenarios can be amended to address these considerations. Agent Based Models tend to focus on highly theoretical situations making far-fetched assumptions with a higher than realistic degree of randomness and a highly Darwinistic selection mechanism to force interesting dynamics, whereas optimization models tend to have a normalcy bias towards what we perceive credible, with for example continuous growth figures and perfect allocation of resources. This thesis can be read as a trade-off between the weaknesses and strengths of the two approaches or as being neither fish nor fowl. In the latter case the open nature of the design and conceptualization makes it easy for anyone to adjust the balance to their needs and liking.

In this thesis we propose a new way of modeling the natural gas market. We used matching as a market clearing mechanism and showcased an experimental economic model to test this approach. The results are promising and open up new possibilities of natural gas and energy market modeling from an ABM paradigm. It provides a new set of opportunities for modeling complex behavior. Our goal was not to find an optimum but to make quantitative modeling a useful tool-set for scenario analysts. The application of this technique should therefore not be seen as a replacement for future exploration techniques as Delphi and FAR. The techniques presented in this thesis should provide a way to complement a story line or future scenario developed in such a setting. The presentation and communication of such scenarios could be supported by showing a numerical analysis. It would also open the door for experimental economics to test possible strategies to deal with the uncertainties of the scenarios developed.

In our implementation we regarded the market as an intermediary, consistent with how Blume implemented an auction model[9]. He proves that any equilibrium outcome leads to the efficient allocation of goods. So we can assume our model does so well. Under this assumption the applicability of ABM market matching has a potential beyond future simulation. In the next paragraph a suggestion of such a new field will be provided.

Now that we successfully implemented an exchange model in an Agent Based Model the question arises if this technique can be used outside the scope of modeling markets for goods. Coleman [50] approached decision making in social systems (a web of actors) as the exchange of interests and control over the process. He called this the Linear System of Action (LSA) and formalized this exchange of interests in linear functions. Hermans and Cunningham proved in a laboratory setting that this theorem is applicable to public policy making [42]. The notion that the brokering of interests between stakeholders can be assessed as an exchange opens the door to agent based simulation as a tool to support decision making processes.

8.3. Recommendations

Scientific work is never finished or completed. A model is always a simplification of reality and the amount of reduction of complexity is both determined by the scope of the research question and by the limited resources (both in time and otherwise). The recommendations below are divided into two categories, one reflects to the quantitative effort of this thesis. These are points I would have liked to include provided more time and by my assumption would improve the model. The second section is dedicated to the scenarios of Eneco, these scenarios provide the external factors and philosophy behind the different scenario runs.

8.3.1. Model improvements

In the modeling efforts for this thesis trade-offs have been made in resources both in time and in computational complexity. For further research I will present possible directions which can serve as a guide to improve either the models validity or broaden its applicability.

Granularity and data precision

At the moment the models time granularity is set to monthly values, this allows the model to address seasonal flexibility in a semi-smooth way. However when looking at real TTF values we can see daily prices deviating

greatly from monthly averages. The model tells us a story about seasonal fluctuations. It does not tell a full story about the range at which market prices are expected to vary. These values are important for energy companies that are hedging risks or are planning investments based on the arbitrage opportunities in daily variations. A daily granularity might improve the applicability of the model to this kind of questions. It would also allow more randomness in the model, for example introducing daily heating degrees. Randomness in external factors will improve the robustness of the model and the philosophy of Agent Based Modelling.

Another granular improvement can be to decrease minimal trading volumes. At the moment the model trades TWh while on the TTF MWh are traded. Decreasing the minimal trading volumes might reveal some interesting patterns about either small producers and consumers as it would allow a more gradual change, thereby improving the precision of the model. However all granular improvements come at a cost, most notably in computing power. Given the fact that computing power is finite, there is a natural trade-off between decreasing the minimal good traded on the market (increasing granularity by allowing the actors to trade MWh instead of TWh) and repeating the experiments. In repeating the experiments there is the advantage of being able to test parameter values and test for natural variation (hence uncertainty) of the results.

The data precision is very limited in the current implementation, in particular for Non-OECD countries, Data for a more precise estimation and segmentation of consumption is not publicly available. Consumption patterns can vary between consumer groups and this can impact seasonal variation on the markets. It would improve the validity of the model if these quantities are addressed in more precision. There is also room for improvement on the producer side of the equation. Production costs are hard to come by. A literature review revealed that the variation between studies of these costs is large. The current model uses ballpark figures of the little data that is available. A more precise estimation of these figures and how they are expected to change would increase confidence in the models results.

More complex decision making of actors

In the current model the actors have a very limited ability to adjust their strategies based on market conditions. The gas market in particular has complex actors and sometimes irrational actors. Introducing some more complex behavior letting actors choose between a different set of strategies might reveal interesting behaviour on the gas market from a game theoretic viewpoint. This was not part of the current research scope, however it is a promising extension to the current research.

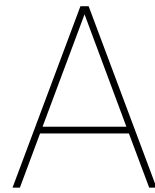
Another improvement on the decision making by actors would be the adding of feedback loops. The scenarios provide for example carbon emission trading prices and the price of coal. The electricity and heavy industry consumers could make a more deliberate choice for natural gas or other energy sources based on historical market prices in combination with the above. Such feedback loops would make the model more accurate. It would also open the door for some complex, unrelated dynamics which could influence decisions to run a power plant even when the natural gas market conditions are unfavorable. For example the fact that Combined Heat and Power generators might have more variables than those discussed in this paragraph.

8.3.2. Scenario improvements

The scenarios of Eneco are primarily focused on electricity production. The quantitative figures provided related to electricity production are based on a highly granular quantitative model. The merit order of electricity production is partly determined by natural gas prices and availability. The relationship between these two is not addressed sufficiently within the scenarios. A quantitative model of the natural gas market as provided in this thesis should not be seen in isolation but as an integrated part of the scenarios since they provide each other's external parameters. This could either be done as a one integrated system or by running them subsequently in loop while measuring how much the result changes each iteration, repeated till no significant gain in accuracy is made.

Another improvement to the model would be the adding of qualitative explanations of future energy sources. Unforeseen technological breakthroughs are part of a story line, which can feel like magic to the average reader. A fallback on magic in explaining these phenomena would not be necessary if correct feedback loops of price and quantity are used. This could help to build trust in the scenarios. The fact that carbon based energy needs are not addressed in great detail and that a holistic world view of depleting reserves is missing in the scenario might be the basis for these unconventional claims. The work done in this thesis may help to address this hiatus and complement the scenarios.

Appendices



Scenarios for the gas market

"We are in the midst of an energy revolution ...
against this backdrop it is impossible to forecast
a single energy future over the long term"

Marcus Stewart, 2016
Head of Energy Insights

Withing this appendix I would like to discuss the different scenario setups. The scenarios have been made by Eneco with the idea to envision three widely different worlds. These scenarios and what they mean for the gas market. The scenarios are called Paces, Tides and Circles. The aim of the scenarios is not to predict the future but to sketch possibilities. The aim while making these scenarios was to sketch three worlds that are vastly different. None of these scenarios is considered to be more likely than the other.

A.1. General introduction to the scenarios

The father of scenarios is Kahn who pioneered in the seventies with the technique he called "future-now"[53]. This technique was used in military planning and consisted of envisioning a future post nuclear warfare. Kahn wrote reports about events like they were written by people from the future. He borrowed the term scenarios from the Hollywood film industry. The idea behind scenarios is to tell stories to make people/organizations think the unthinkable. The philosophy of scenario planning is not to predict the future but to open the eyes to a landscape of possibilities about the future[14] and to anticipate.

At first the technique was in general used for governments bodies. Shell was one of the first to adopt scenario planning into there business processes. Spanning their planning period from 6 tot 33 years (up to the year 2000) provided enough lead time to anticipate on trends. When the Yom Kippur war broke out and the oil price crashed Shell was prepared. Their ability to act fast made them market leader and guided them through the turbulent 70s and 80s [83].

A.1.1. Gas market scenarios

As in every market their is a supply side and a demand side. Any trend in the market can be characterized can have effects on the supply side or the demand side of the market (e.g. the discovery of shale gas increases supply or a recession limits economic growth hampering demand). The markets itself can in the future have three states. The first being a suppliers market, a market in scarcity where demand exceeds supply. Suppliers control the market and therefor the prices. The second being a buyers market, a market where supply exceeds demand. Buyers control the market and determine the price paid for a product. The third state will be a practical none existent market, where there is either no demand or no supply. The three stories being told in this chapter will each focus on a market state.

In the following sections the different scenarios will be introduced and their story of the gas market will be told including the factors that are relevant to tell this story. This story will be told with the causal relation diagram (CRD) drawn in chapter 2 as point of departure. The factors that will have major impact on the market will be colored according to their direction of movement. E.g. increased economic growth will be colored green and decreasing prices of coal will be colored red.

A.2. Paces

Within Paces the different economies in this world move at different speeds. In short the EU falls behind in the recovery from the recent financial crisis.

A.2.1. EU

Phase 1

The scenario for Paces is a world that is moving at different speeds. While the world around us recovers from the crises the EU is diversified and does not tackle the challenges that lie ahead. There is no unified energy policy and the EU falls apart. The lack of the EU to unify itself and to establish a climate pact. Because of the cheap gas around the world coal is being out competed and dumped on the European market. This leads to a low demand for gas. A diversified Europe is unable to make a strong stand against supply regions of gas and low liquidity leaves a small role for gas hubs. This leads to high prices for gas and drives away remaining heavy industries to energy cheap regions of the world. This is phase one of figure A.1.



Figure A.1: Causal relation diagram EU under Paces scenario phase 1

Phase 2

However after decades, starting in Eastern Europe, shale gas is being discovered and explored. This triggers economic growth and allows the countries to take a stand against Russian gas suppliers. Eastern Europe leads the way and attract heavy industries back to Europe. Europe catches up to the rest of the world and gas starts to play a bigger role in the energy demand. Technologies from the more advanced Asia and the US leap frog to Europe. Industries are located close to cheap feedstock, meaning Eastern Europe (or US and Asia).



Figure A.2: Causal relation diagram EU under Paces scenario phase 2

A.2.2. Rest of the world

The rest of the world, in this case Asia and the US pick up quickly after the recession. Within this scenario shale gas plays a big role, Eastern Asia discover and develop the shale gas that is expected to be found in this region. This leads to an abundance in gas within this region, similar to the shale gas revolution taking place in the US right now. This leads to low energy prices and attracts businesses. The main energy carrier is gas being flooded to the market due to new discovered easily accessible shale gas reservoirs. Some sense for this cheap while still relatively clean feed-stock.



Figure A.3: Causal relation diagram US/Asia under Paces scenario

A.3. Tides

Within Tides the world quickly recovers for the recent crises due to rising expectations from shale gas. However production fails to meet expectations and turns out to be a bubble across the world. Within this scenario the world moves in tandem. No continent proves to be a clear winner and the economy move in boom and bust cycles.

Production of shale gas fails to meet expectations and does not provide the world with cheap energy. Depleting reserves around the world make gas a scarce good. Producing regions exploit market power or suffer from political tensions and turmoil in the middle east. Market liquidity is low and the main energy carrier is coal.



Figure A.4: Causal relation diagram EU under Tides scenario

A.4. Circles

Within Circles similar to Tides moves in tandem but in the opposite direction. Efforts in energy efficiency pay off and decrease gas demand for heating. Supply meets demand for production and the rise of renewable energy replace fossil fuels steadily. Supply regions are forced to dump gas at low prices to compete with green energy sources. The main fossil fuel being used is natural gas but the main sustainable energy sources are dominant. This world is abundant of resources and has a steady economic growth percentage.



Figure A.5: Causal relation diagram EU under Circles scenario

A.5. Bridge of scenarios to computer based modeling

Scenario planning is the art of telling a story. The emphasize of scenario building should lay in reasoned judgement and intuition making it a very qualitative approach according to its founder Kahn. However when the methodology was being picked up by management scientist it was combined with mathematical modeling and labeled Operational Research / management science.

[scenario building] methodology incorporate some form of information as inputs, the information is manipulated into varying states through processes, and eventually a scenario is built that tells a story. Most of these methodologies then feed the information back to refining the stories. Because they require inputs, processes, outputs and feedback, scenario planning can be framed as a system.

[14]

A possible step in building these scenarios is quantifying certain key elements. This quantification can be done by using techniques from operational research, like computational models to solve the mathematical formalization. Construct these computational models and feeding this information back to the scenario building can be seen as combining classic scenario planning with modern operational research techniques. This could vastly improve the usability of the scenarios and help to identify signals to identify the future to walk a certain path.

The following factors vary among the scenarios. The first three factors influence the demand side of the of the market and the latter two are of importance to the supply side of the market. These factors require a closer look within the next chapter.

Inputs for the model

The model input are the factors that vary between the scenarios as defined in the last chapter. Within this section they will be operationalized.

varying inputs across scenarios

Economic growth	[%]
Competition with coal	[% of coal in electricity mix]
Growth of RES	[% of RES in electricity mix]
Shale gas recovery	[Bcm (of shale)]
Instability of supply regions	[Bcm/year]
Demand for natural gas	[Bcm/year]

Table A.1: Varying inputs and their operationalization



Price convergence and market integration

'The future is already here – it's just not evenly distributed.

William Gibson

B.1. Visualize prices for the North Western European hubs

In the following piece of code I would like to visualize the data from “Heren”, a company who sells data from and to traders in the energy business. The data set used consist of all the price information from the hubs in North Western Europe. In the next section I will describe the different hubs and their characteristics. The plot below visualizes the Day A Head prices, hence the spot prices. In Natural Gas trade this is the price what is agreed between the contracting parties for delivery scheduled the next day. (Note that delivery is virtual and can differ from hub to hub, in general this means one party is obliged to feed the agreed amount into the grid and the counter party is required to withdrew the amount from the grid so the total sum nets to zero)

B.1.1. Introduction

Within this document we walk step to step through the market data to research price convergence at the different markets

Zeebrugge

Zeebrugge is the Belgium (virtual) hub, the name is relates to the village Zeebrugge where the inter connector connects Engeland, European mainland and the Scandinavian region. The prices from this hub date back to 2006 and is therefor the third oldest hub within this data frame.

TTF

The Title Transfer Facility is the Dutch gas balancing market and was established in 2003 this makes it the second oldest hub within this set. The TTF trades large volumes since

PEG NORD

France is being divided in three balancing hubs. PEGNORD is the most northern hub, PEG SUD the middle hub and TGIF covers the southern regions on the border with Spain. PEG NORD is the sixth most liquid hub in Europe. The Day A Head prices date back to the late 2012's.

NCG

Net Connect Gas is one of the two German gas hubs. NCG covers the south of Germany and has both an H-gas as an L-gas network. The price data of NCG dates back to early 2012.

NBP

The National Balancing Point is the British national gas hub. The hub is the oldest and the data acquired from this hub dates back to 1996. However since there was no euro back then and no other hub we will only study this hub from the year 1999 when the euro was (formally) introduced. Real (convergence) analyses is done from the year 2003 when the TTF was established hence there were two measurements points.

Gaspool

Gaspool is established March 2009 when four major regional gas distribution companies (Gascade (formally Wingas Transport), Gasunie Deutschland, Ontras (formerly VNG Gastransport) and Dong Energy Pipelines) bundled market area in a new cooperation named Gaspool Balancing Services. It merged with Aequamus in 2011 and covers the North of Germany with on the west the L-Gas network and on the East the H-gas network. The south of Germany is being balanced by NetConnect Gas.

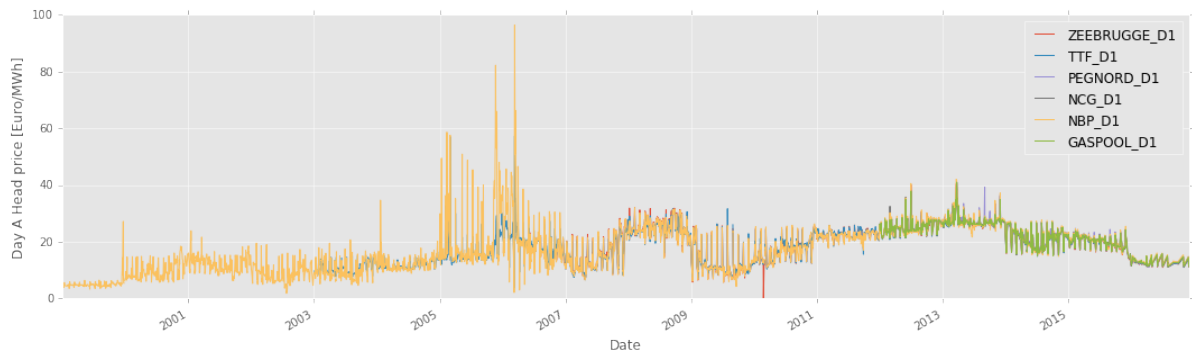


Figure B.1: NWE prices historically (Heren)

B.1.2. How about the noise?

After a first exploration of the data we dive a little deeper. One of the things we want to find out is if there is price convergence between the nodes. So lets study the way the markets move in respect to each other.

Variance

The variance is the difference between measured data points and the expected value. Using this algorithmic the difference between the mean and the data points itself can be quantified. The variance has been plotted on a logarithmic y-axis.

Using this algorithmic the difference between the mean and the data points itself can be quantified. The Pandas package uses the following (naive) algorithm to calculate the variance:

$$s^2 = \frac{\sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2 / n}{n - 1}$$

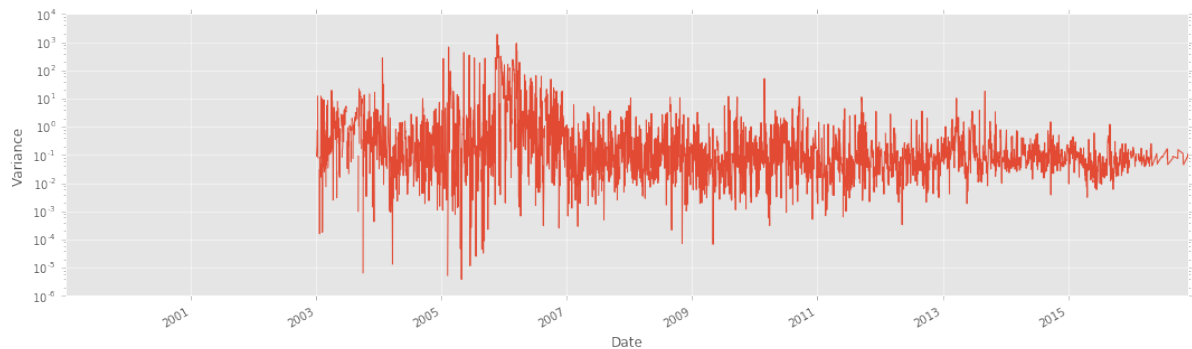


Figure B.2: NWE variance historically (Heren)

Coefficient of variance

The variance measures the distance to to the mean as an absolute value. when the prices drop on the natural gas market this is reflected in the variance. To adjust for this effect the coefficient of the variance can be studied, which is unit-less and therefor not subject to absolute changes in the prices.

The coefficient of variation C_v is defined as the ratio of the standard deviation σ to the mean μ

$$C_v = \frac{\sigma}{\mu}$$

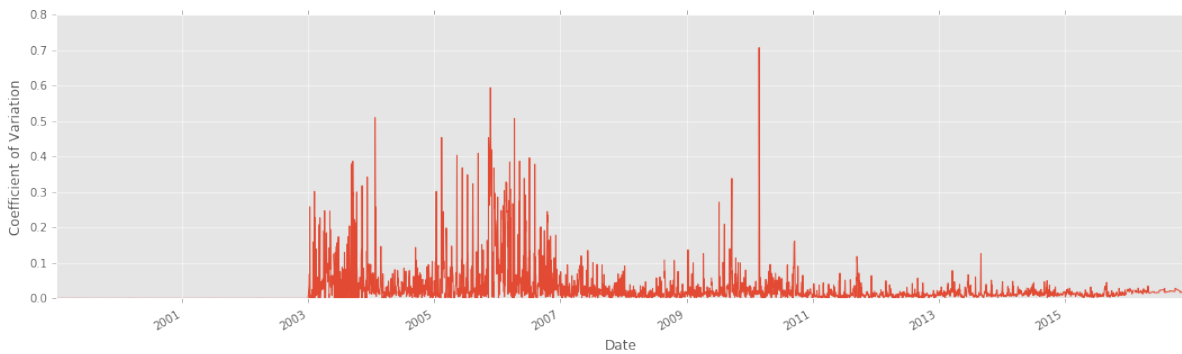


Figure B.3: NWE coefficient of the variance historically (Heren)

B.1.3. Covariance

The covariance measures the correlation between two variables, within this analysis it measures whether the markets move in the same direction. Within market coupling it is expected that the general direction of one market is being followed by direction of the other.

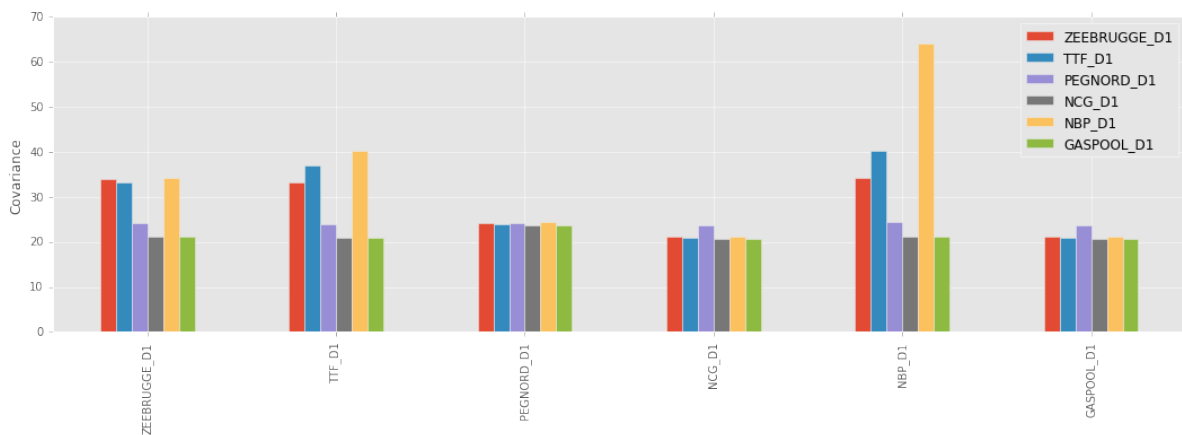


Figure B.4: NWE covariance historically (Heren)

B.1.4. Conclusion

When assessing the data, we clearly see price convergence. The variance decreases notably over time. The covariance is positive for all markets, meaning they move in the same direction. This was expected and consistent with economic theory.

B.2. Visualize prices for the world hubs

Within this document we walk step to step through the market data to research price convergence at the different markets

B.2.1. Introduction

In the following piece of code I would like to visualize the data from “Bloomberg”, a company who sells data from and to traders in the energy business. The data set used consist of the price information from four hubs world hubs. In the next section I will describe the different hubs and their characteristics. The plot below visualizes the Day A Head prices, hence the spot prices. In Natural Gas trade this is the price what is agreed between the contracting parties for delivery scheduled the next day. The comparison is difficult since, the hubs differ in characteristics. The markets are traded in different energy units (MWh, BTU) and different currencies (USD, British pence and EUR). The numerical values therefor are to be interpreted with caution. However they sketch major movements on the world markets.

NBP

The National Balancing Point is the British national gas hub. It was the main gas hub in Europe, but is now being matched in traded volume by the TTF. Factors like the introduction of the Euro limit the usability of this data. When searching for a representative hub for the European demand region, a choice between the NBP and the TTF has to be made. The NBP is the oldest and always had bigger trade volumes than the other European Hubs. However due to the geographical characteristics, namely UK being an island with limited inter connector capacity and the currency differences with the rest of the European hubs are a reason to doubt whether the NBP is (still) the best marker for the European prices. A special characteristic of the NBP is that the trading parties do not need to be in balance, if at the end of the day the party is still out of balance this is automatically corrected with a “forced” transaction. This is not perceived as a penalty, in contrast to the TTF for example, and is being traded to prices equal or close to the end of day price.

TTF

The Title Transfer Facility is the Dutch gas balancing market and was established in 2003. The TTF is a virtual hub, meaning the trading partners do not sit a specific location. Furthermore do trading parties not need to worry about what kind of gas they are buying the the route the gas has to travel between point of entry and point of exit. Gasunie handles the congestion and balancing within the grid. The trading parties at the TTF just have to net their transactions. This is remarkable since a significant amount of the gas traded is Lgas of Groningen which is of different quality than imported gas, from example Russia. Gasunie therefor balances and mixes the gas with nitrogen to make it applicable for the perceived use. In volumes the TTF is matching, and perhaps surpassing, the NBP. Making it a candidate for being the main marker for European gas prices. The prices are traded in Euros and are therefor easier comparable to other European hubs. For a detailed assesement see above.

HH

The Henry Hub is the main American gas hub. It is not the only hub in Norther America, but it is being perceived as the most representative one. The Henry Hub has been established in 1988 and is the intersection point for gas pipelines of different states. The prices at the HH are widely used as index for gas prices over the continent and the HH is therefor a suitable marker for the demand region Northern America.

JKM

Japanese Korean Marker is the main Asian gas hub. It is relatively and for less liquid than the other hubs. The rise of a spot market for gas hubs is a relatively new phenomena and part of a liberalizing trend within the gas market. America liberalized its energy market some time ago, Europe is making great effort in doing the same for a variety of reasons. The JKM is relatively new and the product that is traded is LNG for geographical reasons. LNG shipments are non-continues (in respect to piped natural gas) so price information less adequate as well. Typically 80% of LNG is being traded in OTC contracts and are therefor not being made public. The resulting 20% that is being traded as spot, is not as spot as it might sound. With a delivery time as far as 6 months into the future, they can be regarded as futures as well.

B.2.2. Prices

The JKM limits the usability of the dataset to every period after 2014. For an estimate about prices before this period please see the main text with the analysis of the BP data set. We clearly observe decreasing prices from 2014 till 2016.

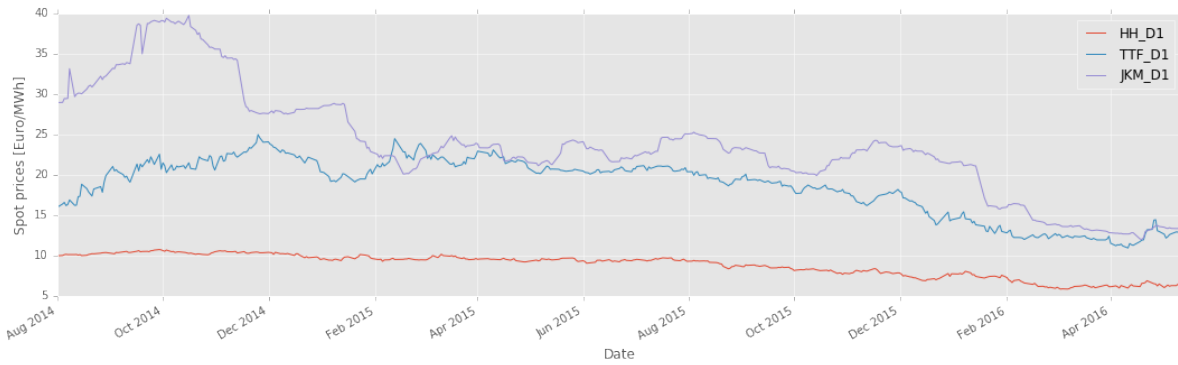


Figure B.5: Natural gas prices world markets (Bloomberg)

B.2.3. How about the noise?

After a first exploration of the data we dive a little deeper. One of the things we want to find out is if there is price convergence between the nodes. So let's study the way the markets move in respect to each other.

B.2.4. Variance

The variance is the difference between measured data points and the expected value.

<https://en.wikipedia.org/wiki/Variance>

https://en.wikipedia.org/wiki/Algorithms_for_calculating_variance

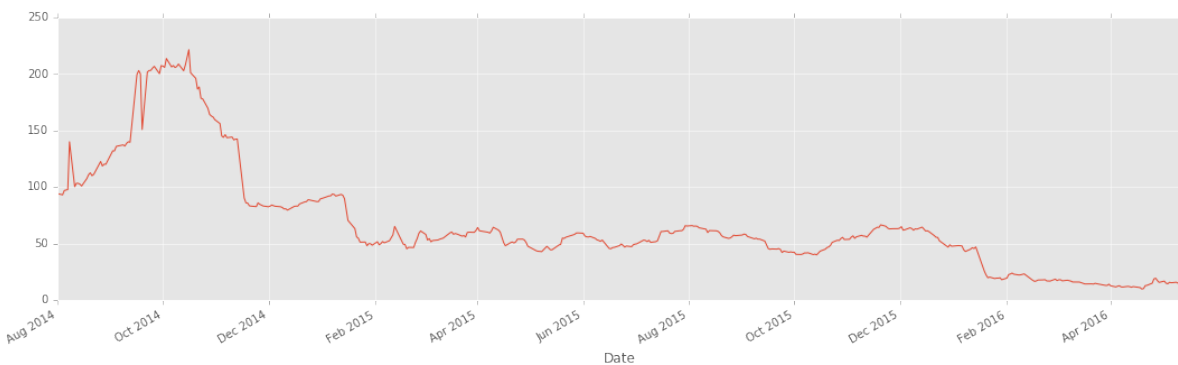


Figure B.6: Variance of world markets

Coefficient of variance

The variance measures the distance to the mean as an absolute value. When the prices drop on the natural gas market this is reflected in the variance. To adjust for this effect the coefficient of the variance can be studied, which is unit-less and therefore not subject to absolute changes in the prices.

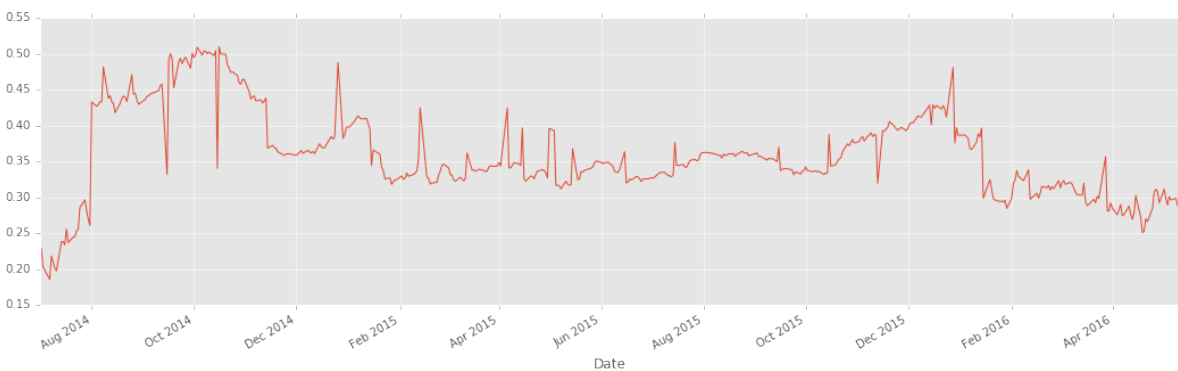


Figure B.7: Coefficient of the variance on the world markets

B.2.5. Covariance

The covariance measures the variation in relation to the other variables, this measure is dimension free. It measures the correlation and therefor whether the markets move in the same direction. First the markets are analyzed over the whole time series and later the set is divided by the period 2014 and 2015.

		HH_D1	TTF_D1	JKM_D1
2014	HH_D1	0.053006	0.133103	0.570238
	TTF_D1	0.133103	4.542173	-0.318779
	JKM_D1	0.570238	-0.318779	18.319915
2015	HH_D1	0.625612	1.392132	0.405827
	TTF_D1	1.392132	4.062905	0.228930
	JKM_D1	0.405827	0.228930	3.012481

Table B.1: Covariance of world markets

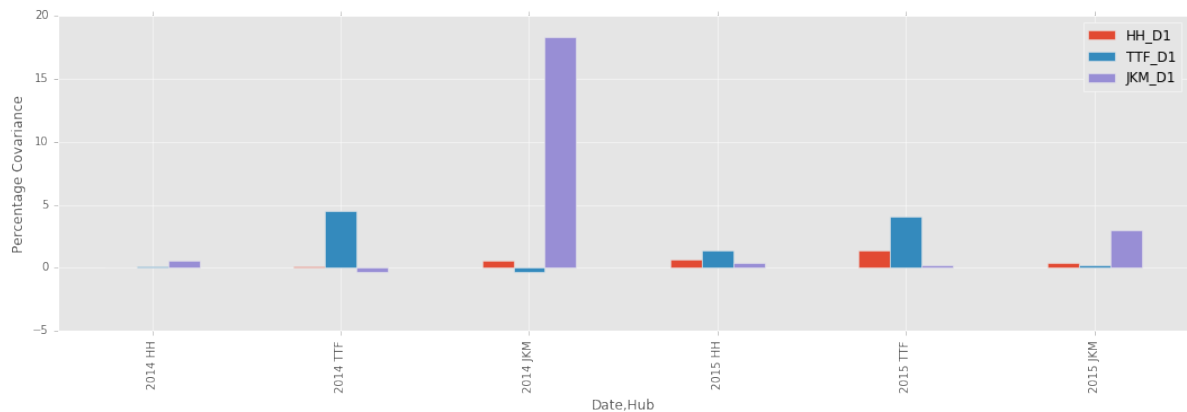


Figure B.8: Covariance on the world markets

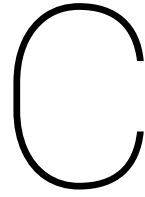
Interestingly we see a negative correlation between the JKM and the TTF over the year 2014. A possible, and widely accepted, explanation is the rising surge for gas in Japan following the Fukushima outage and the low demand for gas in Europe due to the fallback in production. The values are hard to compare, for now the only conclusion that can be drawn is that a positive number stands for a positive correlation and a negative number means the prices move in opposite direction.

B.2.6. Conclusion

The period from 1990 till 2014 was for the world market one of clear price divergence, as can be seen in figure 2.13. The question remains that with the emergence of spot markets and liberalization the prices converge back as would be expected in economic theory. After a record divergence in the years 2014 re-convergence can be seen in the past two years. Even when adjusted for lower prices we see observe the markets moving back together.

B.3. Conclusions of price convergence analysis

The data shows for Europe a clear price convergence that has been a trend for a decade now. This can be clearly observed from the data. For the world market the data set is a lot smaller and therefor less comparable. However after a period of clear divergence of all the markets convergence in the years 2014 till early 2016 can be observed.



Mathematical formulation

While physics and mathematics may tell us how the universe began, they are not much use in predicting human behavior because there are far too many equations to solve. I'm no better than anyone else at understanding what makes people tick, particularly women.

Stephen Hawking

In this appendix we will discuss examples of gas market modeling. These represent side tracks the research has taken until it hit a dead-end. Whatever is discussed in this appendix is not considered to be part of the main story line.

The models will assume for simplicity only producers and consumers unless stated otherwise. These producers are grouped into categories and each category has a representative consumer or producer at the market place. In the following sections these consumers will be discussed.

In our first modeling effort we are particularly interested in how it succeeds in modeling the following problem description. We examine the global characteristics and focus particularly on the Northwestern gas market.

Producers

As discussed above the Northwestern European gas market is supplied by indigenous production and imports. The total production capacity and reserves per country are considered to be one producer. This will leave us with the following list of producers to the NWE gas market.

1. The Netherlands
2. Norway
3. Russia
4. various LNG importing countries

Consumers

Buyers of natural gas can be divided into three main categories. First are the consumers who are connected to the distribution grid. This is consumption for the built environment, meaning households and offices. These consumers generally use gas for heating purposes, warm water and cooking. The next big consumer group is industry, which uses gas for thermal processes or as feed-stock in chemical processing. The last group are the electricity producers that use gas to fire up gas turbines.

1. Consumers on the distribution grid
2. Industrial demand
3. Electricity producers

Producers are expected to sell when the price is equal or higher on the market than their production costs. Production costs are fixed per quantity. This will result in linear cost functions. Although this might not reflect real world cost and expenses made these parameters can easily be converted to a non-linear cost function using Cobb-Dougllass functions. Sunk costs should in classical economic theory not play a role on the price forming in the market place and is therefore not addressed in a first modeling effort.

Consumers are expected to value natural gas in respect to substitute products for their respective use. But since most consumers are unable to change to these substitute products (for example oil and coal) in a short time horizon, we should keep in mind that there are rigidities.

C.1. Economic dispatch with elastic demand

The philosophies behind economic dispatch modeling with elastic demand, maximizing social welfare, is to maximize profits for the society as a whole. Profits of consumers can be relatively straight forward these are revenues minus production cost. Determining the 'profits' for the consumer can be a lot harder, we call these profits 'consumer surplus'. Within the social welfare theory the assumption of diminishing returns is imposed to help quantify these. The idea is that you would value your first consumption of a good more than your second and your second more than your third etc. If plotted these values we would get a descending slope. If we intercept the slope by the market price we could define the area under the demand function but above the market price the consumer surplus, hence profit for the consumer. Within this section we are going to discuss this approach, for a more elaborate explanation of this method and the math I would recommend reading appendix C.

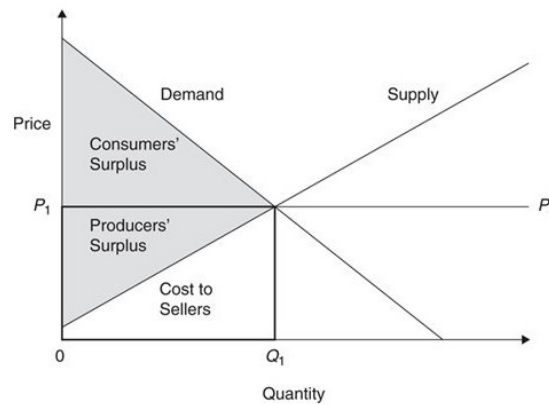


Figure C.1: Maximization of social welfare

C.1.1. Preliminary results

In a first attempt we modelled a simplified gas market with guesstimated data. For this reason the Y-axis is purposefully left unit-less. However the main characteristics sound familiar, heavy consumers and small consumers consume on a ration of 1:2 and Russia produces a little cheaper than the Dutch consumers. For more graphs please see appendix C figure C.2.10

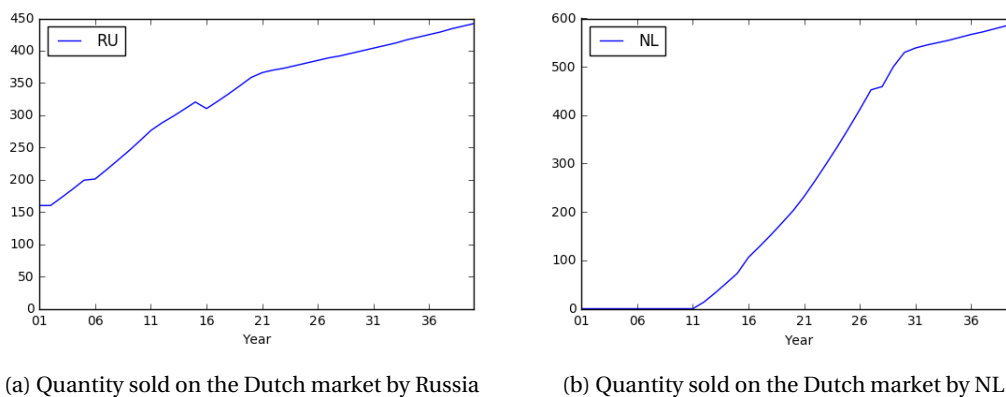


Figure C.2: Quantity bought on the Dutch market

As soon as we start to optimize on a multi-year horizon we see the limitations of this approach. The algorithm determines the optimal solution will be to import all our inland consumption till the end of the horizon. Although this argument can be made, if we expect the gas price to increase from a fiscal perspective the Dutch government should minimize extraction as long as possible. However this is for multiple reasons not a viable option, not in the last part since the Netherlands fiscally depends on the rents of gas of the yearly budget.

Another important limitation in this approach which arguable also contributed to this extraordinary result is what we call "last mover advantage" since the optimization algorithm knows what the final step of the game is it can anticipate by making irrational decisions in the end game. Hence maximize production regardless of market conditions since there is no money to be made after the last time step any way.

C.1.2. Complementarity and Game theoretic models

Some of these concerns can be addressed by changing the scope of the objective function or by using different mathematical techniques, like complementarity modelling and Cournot/Bertrand competition modeling (touched upon in appendix C). However these approaches would still not provide the freedom to model the more complex nature of the gas market. Furthermore will a model that is founded in optimization is rigid and hard to adopt to include game theoretic constructs.

C.2. Mathematical formulation

The general set up of an optimization problem is presented below. The first component is an objective function, which in general should either be maximized (in case of profits for example) or minimized (when it addresses costs for example). The objective function can be constraint by three classifications of constraints. The equality constraint should hold exactly, when we address energy systems the equality constraint is in most cases the demand-supply constraint. Demand must be equal to supply. In economics this is the basic requirement for a market equilibrium. For the technical part of the energy system, this implies the balance in the system. The energy network has very limited storage capacity therefor the production must equal demand almost perfectly.¹ The inequality constraint refers to physical limitations on the system, the maximum production capacity for example. A more contemporary inequality constraint can be the maximum emissions of greenhouse gases allowed.

¹Large storage capacity can be seen as producing units, with the usual characteristics like ramp-up/down rates, production capacity and efficiency coefficient. Examples are large scale batteries in the electricity sector or storage in depleted gas fields. Market implications for energy storage will be discussed in chapter 4.

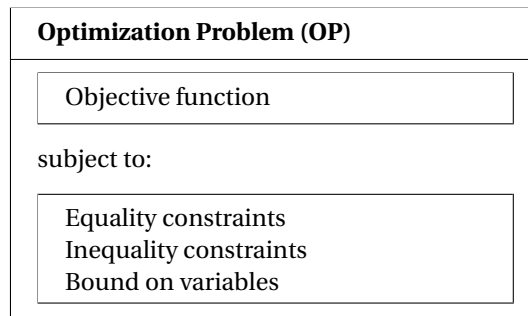


Figure C.3: The structure and components of an optimization problem

Mathematical this generally formulated as in equation C.1.

$$\text{Minimize}_x f(x) \tag{C.1a}$$

subject to

$$h(x) = 0 \tag{C.1b}$$

$$g(x) \leq 0 \tag{C.1c}$$

A boxed optimization problem, hence a problem formulated as above in figure C.3, provides a framework for structuring the problem.

C.2.1. Optimization problems in matrices

Let us take a step back and study optimization problems in general by the means of a simplified example. Let us imagine two producing units x_1 and x_2 , with cost of production of 35 and 55 per unit. The producer wants to minimize production costs but he has some constraints on its installations. Installation x_1 can not run over its maximum capacity of 600 and not below 0 while production installation x_2 has a lower limit of 100 and an upper limit of 300. The production location should at least produce the demand of 650.

$$\text{minimize } 35x_1 + 55x_2 \tag{C.2a}$$

subject to

$$x_1 \leq 600 \tag{C.2b}$$

$$x_1 \geq 0 \tag{C.2c}$$

$$x_2 \leq 300 \tag{C.2d}$$

$$x_2 \geq 100 \tag{C.2e}$$

$$x_1 + x_2 \geq 650 \tag{C.2f}$$

If we want to pass this problem to a solver we have to write the problem in its standard matrix form. To transform every 'greater than' to a 'less than' we multiply with -1 , note that we can also use this technique to transform any maximization problem into a minimization problem.

$$\begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \\ -1 \end{bmatrix} x_1 + \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \\ -1 \end{bmatrix} x_2 \leq \begin{bmatrix} 600 \\ 0 \\ 300 \\ -100 \\ -650 \end{bmatrix}$$

If we pass the above example to the solver we yield, not unexpectedly that installation x_2 produces its minimal required output and installation x_1 produces the required amount to fill the demand. Meaning $x_2 = 100$ and $x_1 = 550$. This is a linear optimization problem.

C.2.2. Linear complementarity modeling

The above problem statement is a cost minimization problem. However a real market there are consumers as well. When multiple objectives are being pursued we start to enter the domain of the linear complementarity problem. The main components of a market equilibrium problem in linear complementarity of the supply and demand side are provided below.

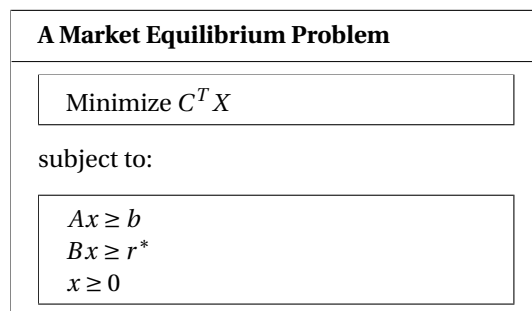


Figure C.4: A LCP market equilibrium problem

The demand side equation is given by

$$r^* = Q(p^*) = Dp^* + d \tag{C.3}$$

and the equilibration

$$p^* = \pi^* \tag{C.4}$$

$$y^* = c - A^T v^* - B^T \pi^* \geq 0, \quad x^T \geq 0, \quad (x^*)^T y^* = 0 \quad (\text{C.5a})$$

$$u^* = -b + Ax^* \geq 0, \quad v^* \geq 0, \quad (v^*)^T u^* = 0 \quad (\text{C.5b})$$

$$\delta^* = -r^* + Bx^* \geq 0, \quad \pi^* \geq 0, \quad (\pi^*)^T \delta^* = 0 \quad (\text{C.5c})$$

Substitute $Dp^* + d$ for r^* and π^* for p^* we get the LCP (q, M) matrix with

$$q = \begin{bmatrix} c \\ -b \\ -d \end{bmatrix} \quad M = \begin{bmatrix} 0 & -A^T & -B^T \\ A & 0 & 0 \\ B & 0 & -D \end{bmatrix} \quad Z = \begin{bmatrix} x^* \\ v^* \\ \pi^* \end{bmatrix} \quad (\text{C.6})$$

C.2.3. Model requirements

Based on chapter 3 and chapter 2 we now have a understanding of the gas market as a whole. This makes us able to sketch the model requirements.

Behavior for the model

The model should be able to handle dynamics of the gas market. This market is characterized with different behavior on different markets. The European market is dominated by Russian supply who strive for a maximization of the value of their gas, in contrast to a market share protection strategy. In the Asian market there was an oligopoly of Qatar and Australia supplying mainly LNG shipments to this market. While in the US there was a near perfect market.

The focus of the model should be at the supply side. The gas market is a market where demand for a major part is inelastic (Household demand) and where the demand is elastic there are some major rigidities (stiffness of market signals and responses). The supply side of the market however displays game-like behavior. Worldwide the market is dominated by a few major companies.

We want to model the supply side of the market. It is expected that the supply side of the market determines prices. A few big players determine are operating on the market with a lot of room for gaming behavior. Historically this was how the market was set up, the exploration of the natural gas was a state business in North Western Europe and Russian federation and (to some extend) it still is.

The region where we are most interested in is the North West European Gas market. Taking the other gas markets as given. The NWE-region is one of a lot of dynamics which are tied to the world market, e.g. the big share of LNG supply in the southern part of the EU, monopoly position of Russia in the eastern part. These characteristics require a broad view on the world, however taking world dynamics into account does not necessarily means modeling the whole world.

Scenario planning encourages people to think the unthinkable. When we address a scenario far in the future this will open our eyes to more possibilities. The time horizon of the model will be the present till 2050.

Decision variable can be read in two ways. First one is what decision variables do the actors have. When assuming some kind of elastic demand, the consumption levels decision variables. The supply quantities are decision variables as well, both in an optimization model as in a game behavior. In a market a player could compete on quantity or on price. When competed over price the price set could be a decision variable as well. (Bertrand Competition) In short: Price and quantity (Bertrand vs Cournot)

Individual companies have the objective of maximizing profits. However, since state run companies operate in the market. Objectives can be politically motivated or based on state budgets. Another theory is that a company can strive for profit maximization but alternatively can strive for market share.

Elastic demand means demand is dependent on the price asked for the good. A lower price means more demand and a higher price means less demand. However, on the long run lower price means less supply and less investments in exploration activities, ultimately ending up in a shortage in supply which drives the price. This wave like behavior of oversupply and undersupply are classical economic constructs which are especially applicable for the hydrocarbons business since market signals are delayed and invest have long lead times.

Outputs for the model

The model should answer the question what influence the different scenarios have on the prices on the gas markets. In particular the north western gas market since Eneco operates within this market. The liquidity of this markets and volumes traded is of interest to the value predictions of these markets. These outputs

can then be used to revise the scenarios, identify signals for a certain future scenario and develop response strategies.

C.2.4. Table functions / formalization

To formalize the above story we will define functions. In a first generalization we define the list of producers as $prod = [1 \dots n]$

Price

We determine the price as being dependent on how much gas is being offered at the market. The price is determined by a linear relationship for simplicity sake for now.

$$p(x_1 \dots x_n) = b - \sum_1^n x_i; \quad x_i \in [prod] \quad (C.7)$$

where $p \geq 0$

Cost

The cost for every producer are the marginal cost, related to increased output and in addition a fixed costs f .

$$c(x) = cx_i + f \quad (C.8a)$$

$$c(0) = 0 \quad (C.8b)$$

$$f \geq 0 \quad (C.8c)$$

Profits

Profits are revenue, which is defined as output multiplied with price, minus the cost of this producer.

$$\pi = p_i(x_1, \dots, x_n)x_i - c(x_i, c_i) \quad (C.9)$$

Objective

The objective of every player is to maximize profits

$$\max \pi(x_i) \quad (C.10)$$

$$x_i \in [prod]$$

Time frame

The model will run till the year 2050. Because we are not interested to look at the

$$t = [2015 \dots 2050]^T \quad (C.11)$$

Maximum output

Production has its limits, they can either be technical or non-technical. The dutch gas fields for example are limited to an output of 24 Bcm for the coming years while their technical extractability limit is closer to 68 Bcm, but for political reasons this has been limited. Wingas is a major party selling gas to the Dutch market and is a fully owned subsidiary of Gazprom. The limits of Wingas are mainly determined by interconnector capacity. Both of the pipelines of Russia to Germany and the inter connector capacity between Germany and Netherlands.

$$x_i \leq x_i^{max} \quad (C.12)$$

Maximum Demand

Demand is maximized to what household, industry and electricity sector is likely to consume. Household consume is to a certain part inelastic.

$$d_i \leq d_i^{max} \quad (C.13)$$

Reserves

One inherent characteristic of fossil fuels is the fact that their reserves on earth are limited. It took millions of years for biological compound to turn into the fossil fuels we use today. Within the time span of this thesis the reserves of fossil fuels on earth is limited by technical extractable fuels.

$$\sum_{t=0}^T x_t \leq x_t^{\text{reserves}} \quad (\text{C.14})$$

Bound on variables

Some variables have to be limited because in real life some behaviour is not possible or desired. One example is negative output or negative prices and negative production.

$$x_{it} \geq 0 \quad (\text{C.15})$$

$$p_{it} \geq 0 \quad (\text{C.16})$$

C.2.5. Game theory

Cournot Nash

To let multiple producers compete we define the gas market as a Cournot competition game. In a Cournot competition the producers compete on output level. They take the price that is given by a demand function and they take the output level of the competition as given. They maximize profits by determining their own output level.

Cournot Nash condition

Since every producer is dependent on the output of the other producers we define x_i^* as the optimal output level of firm i when he takes $\sum x_n$ as given and strives for profit maximization. arg returns the value of x_i . We calculate the Nash equilibrium by:

$$x_i^* = arg \max_{x_i} \pi(x_i, x_n^*) \quad (\text{C.17})$$

for each $i \neq j \in [prod]$

Every producer wants to maximize its profits. Assuming an parabolic profit function this is given by the first order derivative being equal to zero.

$$\left. \frac{\delta \pi(x_i, x_j)}{\delta x_i} \right|_{x_i=x_i^*, x_j=x_j^*} = 0 \quad (\text{C.18})$$

The reaction functions of to the other firms are in an equilibrium if $x = f(x)$. Where $r_i(x_j)$ is the reaction function.

$$\begin{pmatrix} x_1^* \\ x_2^* \end{pmatrix} = \begin{pmatrix} r_1(x_2^*) \\ r_2(x_1^*) \end{pmatrix} \quad (\text{C.19})$$

$$f(x) = \begin{pmatrix} r_1(x_2^*) \\ r_2(x_1^*) \end{pmatrix} \quad (\text{C.20})$$

C.2.6. Economic Dispatch with Elastic Demand

When we do not see the market as a game where players try to maximize profits but as a market where a perfect planner determines producers output and consumers demand we see a totally different formalization. This formalization is based upon the the notion of increasing cost and diminishing returns. As is described in micro economics. The assumed marginal cost of production is to increase by increased output, due to i.e. loss of efficiency or over-stressed equipment [62]. This yields the following marginal cost function where the the marginal cost MC is a function dependent on the output P_{Gi} . a_i is a constant cost that is unrelated to the quantity produced while b_i is a constant that is related to the total amount produced and reflects the loss in efficiency or the increased cost of production.

$$MC_i(P_{Gi}) = a_i + b_i P_{Gi} \quad (C.21)$$

To arrive at the total cost function C_i we integrate the marginal cost function over dependant P_{Gi} . The new constant C_i is the cost regardless of production and categorizes the fixed cost of the production facility whether the facility produces or does not produce any output. The production cost curve becomes:

$$C_i(P_{Gi}) = c_i + a_i P_{Gi} + \frac{1}{2} b_i P_{Gi}^2 \quad (C.22)$$

where i is a set of different producers to the market. We assume the characteristics for the demand side of the problem to follow the same logic.

$$MC_i(P_{Di}) = a_i + b_i P_{Di} \quad (C.23)$$

$$C_i(P_{Di}) = c_i + a_i P_{Di} + \frac{1}{2} b_i P_{Di}^2 \quad (C.24)$$

There are several ways to define the objective function of a optimization problem. The two most obvious ones are the maximization of profits to the producers or the maximization of social welfare. In the papers examined both were used. It all depends on the assumptions one makes about the (effectiveness of the) market. In a first proof of concept we will work with maximization of social welfare. The objective function of the optimization problem is defined as the maximization of social welfare.

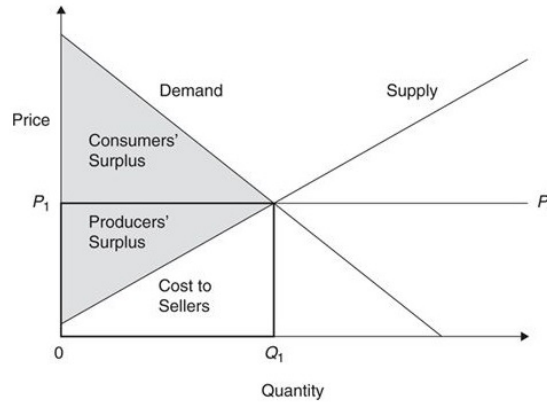


Figure C.5: Maximization of social welfare

$$\text{Maximize } SW = \sum_{i=0}^t \left(\sum_{i=0}^n c_D + a x_D + b x_D^2 - \sum_{i=0}^n c_P + a x_P + b x_P^2 \right) \quad (C.25)$$

$$\text{Maximize } SW(P_G, P_D) = \sum_{j=1}^m U_j(P_{Dj}) - \sum_{i=1}^n C_i(P_{Gi}) \quad (C.26)$$

To put the above in a boxed problem we have to define, next to the objective function, the constraints of the problem. First of all for a market to clear the production must equal demand, to put it graphically the

aggregated demand and supply curves should intersect (see figure C.7). The maximum production values of our production units, P_{Gi} , should be equal or smaller than our production limits, P_{Gi}^{max} . This production limits can be physical or imposed by regulatory restrictions. Not only producing units have limit, demand groups are limited as well (P_D^{max}). Even if the price drops to zero or even negative values there is a limit to what extend demand units (e.g. electricity generators) can consume. The combined production units can not produce more than the total reserves of a certain field. The total reserves of are given by $P_G^{reserve}$. The last set of constraints is the bound on variables. The values of the variables, the production and consumption levels in a given time period, are limited to a range that is realistic to the problem description. The bound has two objectives, it makes the solution the problem comes up with meaning full. In the example below negative consumption or production is not a realistic outcome. And it limits the solution space which helps computational time of the problem when implemented.

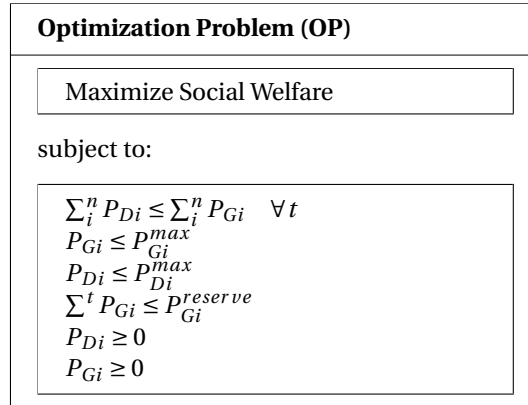


Figure C.6: The structure and components of the SW optimization problem

C.2.7. Capturing the market price

The price at the market is determined by the marginal cost of the marginal supplier or consumer. Since, in theory, all producing units have to produce at identical incremental cost and incremental cost have to be equal incremental utility. In a single period model this would be equal to the Lagrange multiplier λ . Using this method of determining the market price interprets the price forming process as the last producer in the merit order, hence the marginal producer to set the price on the market. This is consistent with classical economic theory about energy markets. But does not take price differentiation between producers into account. It assumes natural gas to be a homogeneous product sold for the same price.

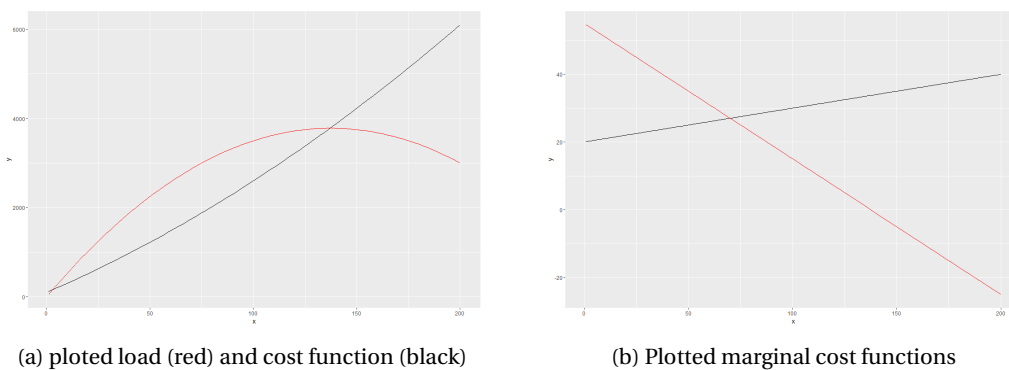


Figure C.7: Plots of the cost curve and the differentiated curves

C.2.8. Parametrization

The values of the different loads should reflect demand groups (e.g. industry, electricity generation, transportation, retail consumption etc.). The cost functions represent the different sources natural gas could be supplied from (e.g. LNG shipments from Qatar, gas through pipelines from Russia, gas from national fields

etc.) One way of parametrization is to perform data analysis on the limited data that is available. In this case the "Day Ahead Market" of the TTF. In appendix market convergence we observe strong market convergence in recent year. Therefor we presume that the data of the TTF is representative for Europe.

Data about the TTF Day Ahaed market is plotted in figure C.8. The dots represent quantity traded per day on the x-axis and the daily closing price on the Y-axis.

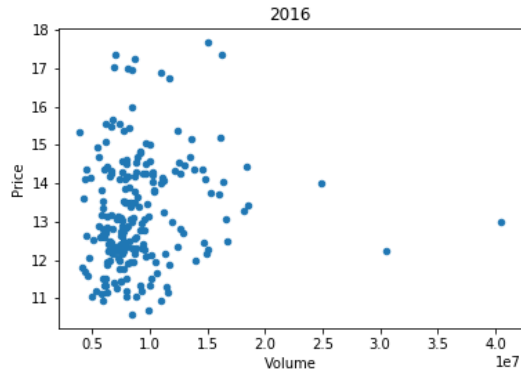


Figure C.8: Quantity price plot over the year 2016

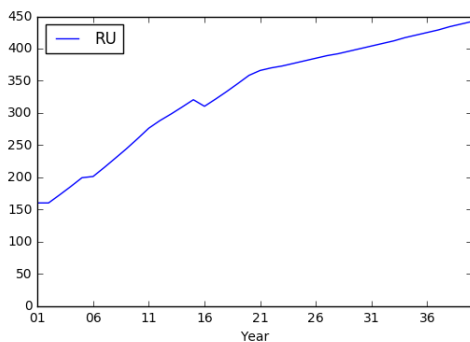
C.2.9. Converting to a multi period model

In a multi-period model commitment problem λ gives us the total system increment and is thereby a meaningless figure. We are looking for the sub problem of every time step. The shadow values of the time constraint however provide us with the *IC* and the *IU* of the problem. The shadow values of the constraint is the how much the objective functions changes if the constraint is relaxed by 1. Capturing these values would allow us to see the prices for which the market clears, assuming that (similar to the electricity market) the last producer sets the price on the market.

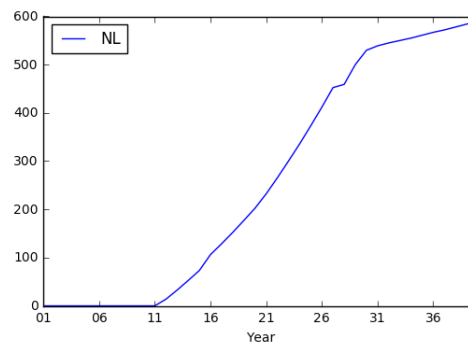
C.2.10. Preliminary results

In a first attempt we modelled a simplified gas market with guesstimated data. For this reason the Y-axis is purposefully left unit-less. However the main characteristics sound familiar, heavy consumers and small consumers consume on a ration of 1:2 and Russia produces a little cheaper then the Dutch consumers. As soon as we start to optimize on a multi-year horizon we see the limitations of this approach. The algorithm determines the optimal solution will be to import all our inland consumption till the end of the horizon.

Quantity

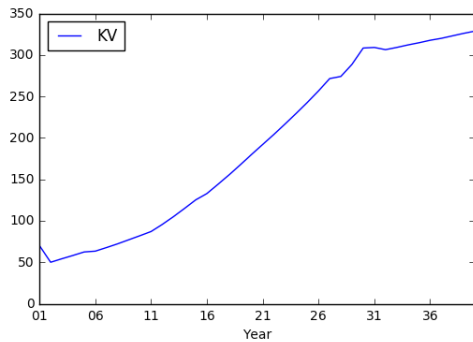


(a) Quantity sold on the Dutch market by Russia

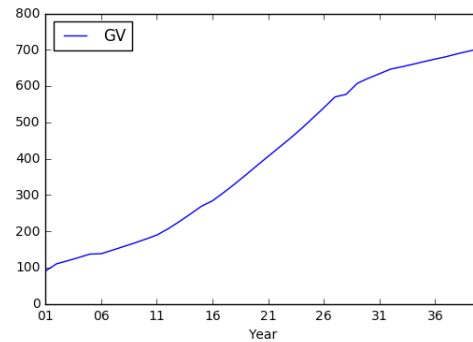


(b) Quantity sold on the Dutch market by NL

Figure C.9: Quantity bought on the Dutch market



(a) Quantity bought on the Dutch market withdrawn by small consumers



(b) Quantity bought on the Dutch market withdrawn by heavy consumers

Figure C.10: Quantity bought on the Dutch gas market

Price

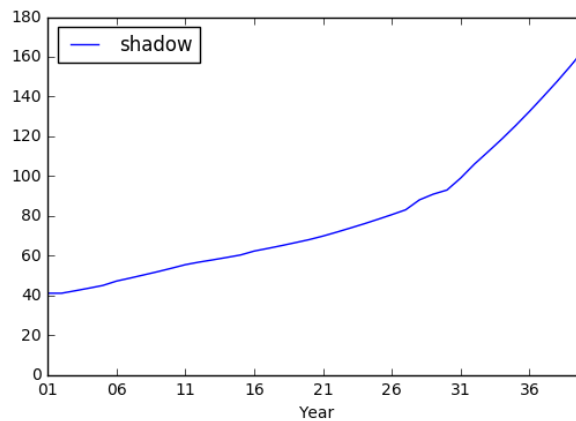


Figure C.11: Shadow prices of the year constraints

Policy below the break even line

At this moment according to financial and technical reports from the years 2012 till 2014 the market is below its break even point in at least 2 of the 3 major demand regions. EBN provides an 16 Euro per MWh cost price for its small fields which contribute to roughly 30% of the total Dutch Production. In the US the price is roughly a third below break even line of shale gas.

C.2.11. Cost curves to producers

Cost curves of producers are hard to come by, as an example we recreated the cost curves Gabriel used for his modeling effort. As can be observed from these figures is that Gabriel assumes a complex graph curve to force the producers to only produce at their optimal output levels. The underlying assumption is that producers are inelastic and are therefore not allowed to scale back or up on their production. However if we observe this graph we can see that the Groningen field in the Netherlands for example had to scale back their output rigorously and would under the underlying cost curve be ran at a loss. This would make these estimates and functions not usefull for long term scenario planning.

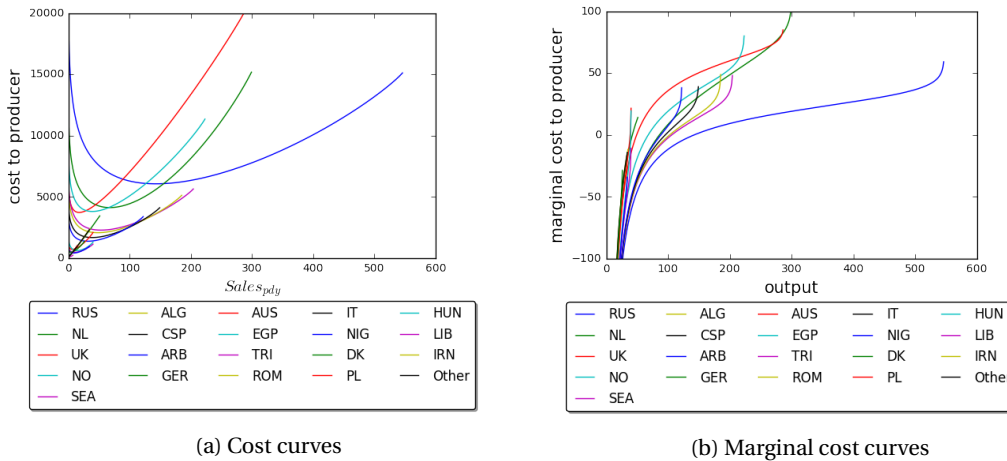


Figure C.12: Gabriels production curves

In order to parameterize the demand curve we try to find the relationship between price and quantity while keeping all other factors constant. One way to do this is to predict consumption based on known parameters. For example we predict for the factors among others economic growth and the inflation rate. The difference between predicted and observed could therefore be contributed to the missing variable, in this case the price.

$$\min \sum_{t=2000}^{2015} |P_{Consumption}^{real} - P_{Consumption}^{predicted}| \tag{C.27}$$

From this analysis over the past 15 years I assumed the demand elasticity of consumers in the heavy industry to be given by the formula:

$$Y(x) = 19.0 - 4.4 * x \tag{C.28}$$

X = Gas consumption in Bcm (Billion Cubic Meters) by the heavy industry

$Y(x)$ = The price paid on the TTF (spot market) per MWh gas

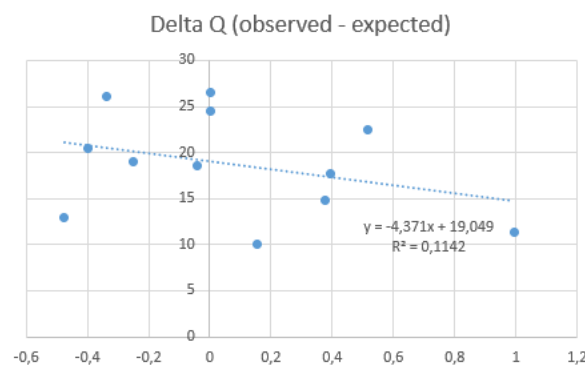


Figure C.13: Price elasticity of Industrial consumption

C.3. Net flow Model

Another approach is to address the model as a net flow model where major gas trades can be seen as a network of hubs with the different transport routes seen as arcs connecting these nodes. This will be especially suitable to explore how existing infrastructure impacts flows. It helps to reveal future bottle necks.

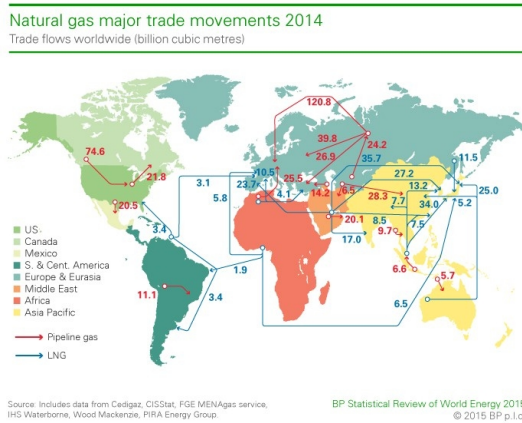


Figure C.14: Major natural gas (trade) movements in 2014

Optimization Problem (OP)

Minimize system costs

subject to:

Demand \leq production
 LNG shipments per year \leq Total shipment capacity
 $P_G \geq 0$
 $P_D \geq 0$

Figure C.15: The structure and components of the NetFlow optimization problem

C.3.1. LNG or natural gas

Natural gas and LNG are the same chemical component their state make them two different. In most cases however they are interchangeable products.

C.3.2. Demand and Production regions

By defining the arcs and nodes within the model we need to see the different demand and production regions. In a first effort the world is divided up by continent. However, a major demand region and one of the main price setters for LNG, namely the JKM is being added to the Asian pacific region. This does not reflect the market reality where this hub is one of the three main demand hubs.

To simplify transportation, we assume within a region gas can be traded at approximately zero transport costs.

North America

The production regions are the regions who are endowed with natural gas. In North-America, USA and Canada and Mexico, the shale gas revolution has opened up a lot production capacity. The region transformed from a net importer to a region in autarky. Politically the USA had decided to put a ban on exports. This is the reason practically no gas leaves the region to demand hubs in the pacific or Europe. Although the record low prices in the USA open up the economical possibility.

South America

South America is defined as everything that is not part of North America. Within this region the main player is Venezuela. Which had an output of 29 Bcm in 2014.

Europe

The European region is being defined by BP as everything not belonging specifically to either Asia or the Middle East.

Russian Federation

The gas flows coming from Russia would count as inter regional flows, which does not reflect the what we are expecting to see in the model. Within the European gas market the dependency on Russian gas and the related security of supply issues are a main concern for the European Union, as is reflected in the amount of papers being written on this subject [59, 63, 70, 72].

Asia

The Asian region consist of China and pacific region. Russia, Korea/Japan and Australia have been excluded from this geographical demarcation since they have their own characteristics.

Japan/Korea

Japan and Korea has been defined as a separate region, since this region has dominated the LNG market in the past years. This region has its own market and is being used as one of the three main world markers for gas prices. Combining this region with Australia, as done by BP in their statistical review (see figure C.14), would not make this major trade movement apparent.

Region	Production [bcm/year]	Demand [bcm/year]
North America	948	949
South America	175	170
Europe	423	1420
Russian Federation	579	410
Middle East	601	465
Africa	203	120
Mainland Asia	476	489
Japan/Korea	0	160
Australia	55	29

Table C.1: Parametrization of production and demand per region for 2014 (BP)

C.3.3. Transport routes

The above regions are connected by transport routes, these routes can either be by pipeline or by shipping routes of LNG vessels.

Russian Federation to Europe

The main transport capacity of the Russian federation to Europe is by means of pipelines either entering at the German border directly from Russia or through former soviet states, the most notably is the Ukraine. The pipeline capacity these pipes is being assessed by the Clingendael international Energy Programme [16] and they asses the import capacity as being: 309 Bcm where 130 Bcm was used in the year 2012. This includes the Nordstream pipeline who became fully operational in 2012.

Algeria pipeline into Europe has a capacity of 54 Bcm where 32.8 Bcm is used while other imports denote for 40 Bcm import capacity of which 16.9 was used.

North America LNG capacity

The North American region did not export a significant amount of gas in the past years. This is mainly due to a political ban on exporting gas. However the tide is shifting. The record low prices open up the opportunity to export gas to the pacific region. Regasification terminals once build for imports are now being transformed to liquefaction terminals and the region might soon be an significant player on the LNG market. The break even price of shale gas in the US is 4 dollar for the most efficient regions and 6 dollar per Mcf for the less efficient sites [87]. Converted to MWh a price range between 12 and 18 euro per MWh. At the moment (May 2016) gas is being traded at 6 Euro per MWh at the HH (2 dollar per MBtu). Please note that these are spot prices, long term gas contracts might be indexed differently. However for long term trends we are working with the low estimate of 12 euro per MWh.

LNG increment (shipping, liquefaction and regasification cost)

When gas is being transported from regions not connected by pipelines additional cost are being made to convert natural gas to LNG. In a simplification these cost can be seen as generic. The

C.3.4. Cost

Assessing production cost is extremely difficult since break-even costs of exploration is commercially sensitive information. Rystad provides a database with production costs per wellhead for all known sites. Articles written by experts from the industry refer to this database frequently. In assessing the costs of production and transportation estimates from scientific articles have been combined with company publications and articles written by experts.

The production cost at for the two main Russian regions Western Siberia and the Volga Urals region are between 1.32 - 1.60 per MWh. The Dutch Groningen field produces at a cost of 2.55 Euro per MWh and the Norwegian region between 2.55 and 4.33 and the the Brits are producing gas for the 5.48 Euro per MWh [68].

Parametrization of transport

Estimates range for 10 bcm/a pipes over land 1.13 - 2.26 per Euro/MWh*1000km and offshore a value of 4.52 euro per MWh*1000 km is used.

Apart from costs related to the transportation of gas other fees apply. One being the transit costs which is being levied by the transit country. The Ukraine, Tunisia and Morocco are between 0.2 and 1.5 euro per MWh, LNG tankers passing the Suez canal are charged 0.64 Euro per MWh. This costs should be added to the transportation costs.

The LNG costs are dependent on the tanker used, the cost of capital and labour at the production site for the liquefaction facility.

C.3.5. Preliminary conclusions

In a first exploration within the Netflow model we found it provided relief of one of the issues of the maximizing social welfare model, namely the ability to deal with multiple markets. Since every node can be seen as a market and the flows leading up to that market suppliers and or consumers. For this reason we see a lot of natural gas models in the scientific community being some sort of Netflow model for example Lochner[59].

However we lose the ability of the social welfare model to account elastic demand. Netflow models focus on the physical flow and do not internally shift consumer demand according to price. The quantity consumed is one of the questions we want to answer from exploring the scenarios. If consumption is independent of the price the analysis will be less valuable. Other drawbacks of not being able to model more complex behavior persist, for example with the model being able to anticipate the end and seemingly non-rational choices.

C.4. TTF Spot analysis

Within this file data about the TTF spot market (Day Ahead) and the closing price. The granularity of the data is daily. The purpose of this analysis is to find figures supporting supply or demand curve figures.

The construct demand and supply curves assumes only the price changes well all else remain constant. The excel-file 'TTFDA.xlsx' contains the Day Ahead data in daily traded volumes and closing price. This data is cleaned up so it can be used with pivot tables in excel in 'pythonoutput.xlsx'

Lastly the data is aggregated per year and a scatter plot is made and the trend line drawn. The figures are displayed on both semi-log axis and on linear axis.

C.4.1. Quantity sold on the TTF Day Ahead market

We observe declining market sales on the DayAhead market, which is contrary to what we would expect to happen. European policy was shaped to increase spot market sales. The figures of the DayAhead market however do not tell the whole story. Total sales did increase on the market, the fact that we observe a declining trend is perceiving. Due to a [64]

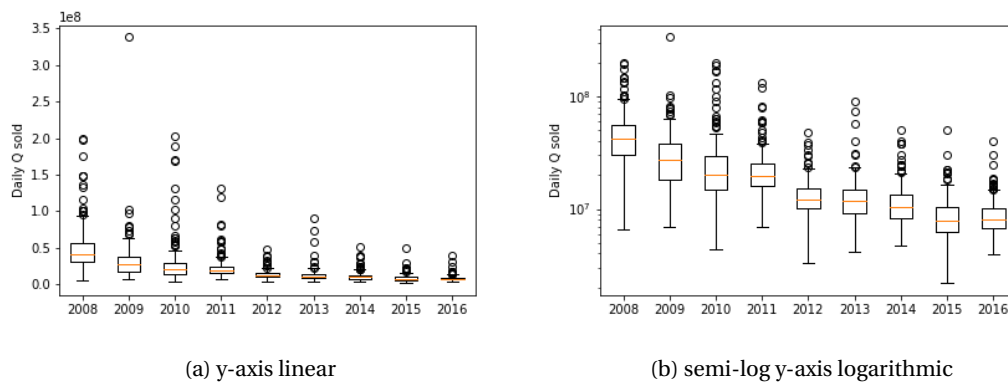


Figure C.16: Boxplot of Daily trading volume DayAhead sold on the TTF (MWh)

C.4.2. Finding a trend line

To find a QP relationship we observed data of the Day Ahead TTF and fitted a linear trend line to the yearly grouped data. We used the Least Square analysis of the SciPy package to fit the line to the past nine years. The figure below was the result of this analysis.

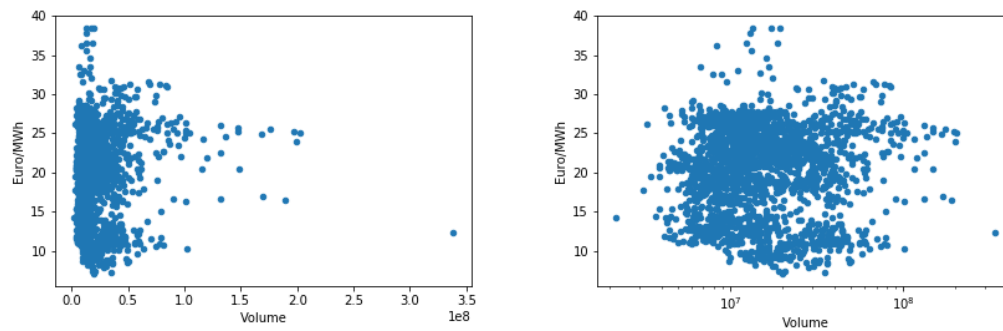


Figure C.17: TTF spot QP graph

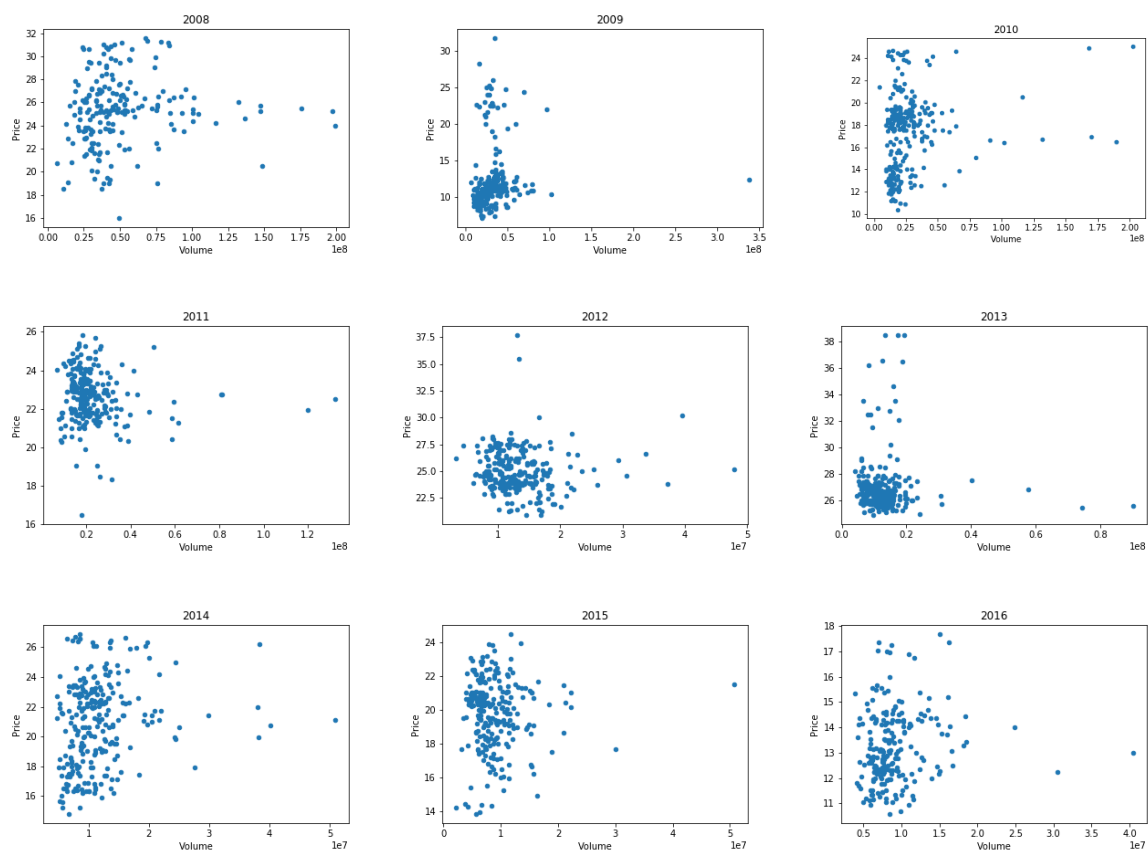
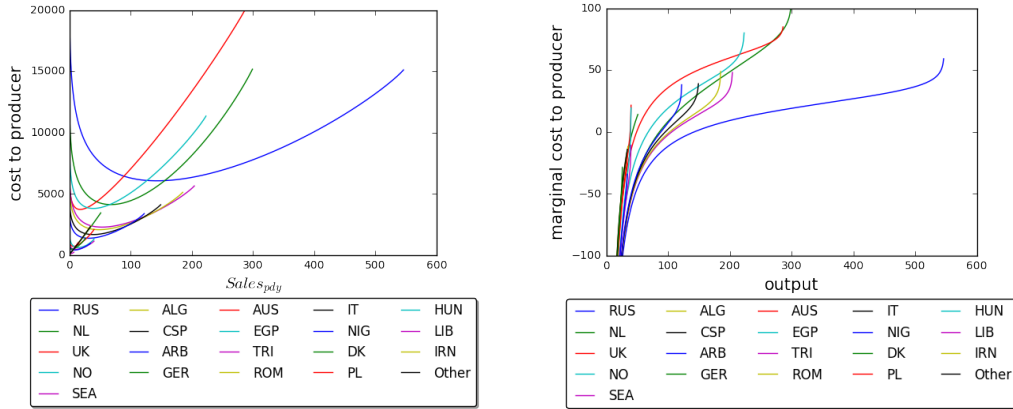


Figure C.18: TTF spot QP yearly graph

The main take away the above analysis is that spot market prices plotted against daily traded quantities are no useful tool in finding the the suppliers bidding curve or consumers demand equations.

C.4.3. Gas supply characteristics

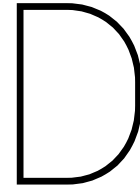
In other natural gas modeling studies the seasonal flexibility on the supply side is virtually non-existent. For example the production functions off the well-cited articles of Gabriel [33] [34] who wrote the book on (complementarity) Natural gas modeling are presented below, see figure C.19a and C.19b. We see a very narrow path for producers to swing their capacity. By these assumption the Groningen gas field for example would be losing money because of the stark reduction over the past years. In production rates from the US and Canada we observe a monthly production swing of roughly 10 percent, indicating that these figures



(a) Cost curves

(b) Marginal cost curves

Figure C.19: Gabriels production curves



Model requirements & codification

99 little bugs in the code
99 little bugs in the code
Take one down, patch it around
117 little bugs in the code

Tweet of Alexander (@irqed)

D.1. Requirements

The following steps have been considered to be requirements for the model in order to answer the research questions laid out in the research proposal. We want to model a market place in a generic form and expanding this model to fit the characteristics of the gas market.

1. one good, one seller, one buyer, one market. In the beginning, there is one market where one good is being sold by a seller and bought by a buyer. This is the most primitive form of a market.
2. one good, two sellers, one buyer. The model should be able to deal with one sellers trading one good to one consumer. The interaction of two sellers should make the model behavior more complicated.
3. one good, one seller, two buyers. This step consists of adding the compatibility to deal with multiple buyers in addition to a single buyer single seller model.
4. one good, two buyers, two sellers. This step is combining step two and three to construct a market of multiple sellers and buyers trading one homogeneous good.
5. Multiple goods, two buyers, two sellers. The gas market consists of multiple goods. Depending on the definition of goods one of the most obvious distinction is gas in its liquid in respect to gas in its gaseous form.
6. transformation of goods. In this step the two goods can be transformed into one another. When speaking about the gas in its liquid phase it will be called Liquefied Natural Gas (LNG). To convert natural gas to LNG a liquefaction plant has to cool the gas down. To convert LNG to its gaseous nephew a regasification plant has the heat up the gas.
7. Competition with substitute good coal. In the real world natural gas has to compete with coal as a primary energy carrier. Adding this substitute good to the model will add the real world competition between gas and coal as primary energy fuel in the heavy industry and the electricity sector.
8. Competition with substitute good electricity. In the household domain electricity is the main competitor for natural gas. Heat pumps and electric cooking replace the gas demand in the household sector.

9. Two period finite market, last mover advantages. In this step time is added to the model by adding an extra period. When constructing a multi-period model the phenomena “last mover advantage” comes into play, this is dealt with in the following step.
10. Two period continuous market, no last mover advantages. Last move advantage relates to irrational behavior in the last time step(s) by market participants because they “realize” the model is finite. In the real world this is not likely behavior and should be fixed.
11. Storage capacity added to the market (as constraints). Natural gas consumption is seasonal and production can consumption can be mismatched due to other (political) problems. Storage is a major part of the gas market and would allow inter-temporal trade.
12. Transportation costs will be addressed in this modeling step.
13. Alternative shipping, piping arrangements. Trade is largely determined by geographical centers of production and demand and how they are connected. Within this modeling step the piping arrangements and shipping routes and transportation capacity constraints will be looked at.

D.2. Non critical functions

The above are considered requirements of the model to answer the research questions posed in the thesis. However, more dynamics play a role in natural gas markets. The following points should be considered as addition to the model but are not critical (Nice to have).

1. Producers as price setters, back stop technology to stop actors from endlessly stocking up gas. A back stop technology is a dynamic that
2. Objectives of sellers as national actors. Some actors may behave non-economical; how do we model these actors.
3. Transportation problem, nodes and edges. Within the current market there can be a transportation problem. How do we get gas within the gas north western gas markets from sellers to buyers?
4. Long horizon. Extend the time frame of the model to incorporate trends in the energy market.
5. Policy changes, how do different policy changes affect the market? (e.g. subsidies, cap on emissions, global unrest)
6. World markets, other markets can be given as constants or they can interact with each other making the model a real world model

D.2.1. Major steps in the model

Below are the major model steps and there perceived difficulty.

Table D.1: Major model steps

Step	Category	Specific function	Completed	Difficulty
demand characteristics	1	-autarky -quantity -willingness to pay -buyer type -short term / long term -utility functions		***
supply characteristics	1	-quantity -quantity functions -willingness to sell		*
market clearance	2	-short term -long-term, contracts		*
taxes / tariffs	2	-emissions		*
exogenous factors	2	-oil price -economic growth -technological change		**
reserves	2	-economic availability		*
nationalized sellers	3			*
expectation/belief	3	-demand/ quantity -price		*
substitutes/fuel	3	-price -utility -amortization -availability		**
contracts	3	-length -price		*
location of market	3			*
manufacture	4	-conversion of product		*
intermediaries	4	-cost -capacity		*
transport by pipeline	4	-capacity, two way pip -terminal capacity		*
conversion (LNG)	4			*
multiple buyers Seller in network	5			*
market power	5			*

D.3. Code showcase

Within this section the codification of key concepts are presented. As mentioned before the full code is available at GitHub. Please see chapter 5 for 'quick starting' guide on getting the files running. We display code of the market agents clearing mechanism and market price determination.

```

1 def get_clearing_price(self):
2     # buyer drops their bids, sort to merit order
3     b = self.get_bids()
4     s = self.get_asks()
5     # highest to lowest
6     self.b=sorted(b, reverse=True)
7     # lowest to highest
8     self.s=sorted(s, reverse=False)
9
10    # More buyers or sellers?
11    # Drop the excess; they won't compete
12    n = len(b)
13    m = len(s)
14
15    # there are more sellers than buyers
16    # drop off the highest priced sellers
17    if (m > n):
18        s = s[0:n]
19        matcher = n
20    # There are more buyers than sellers
21    # drop off the lowest bidding buyers
22    else:
23        b = b[0:m]
24        matcher = m
25
26    count = 0
27    for i in range(matcher):
28        if (self.b[i] > self.s[i]):
29            count +=1
30            self.last_price=self.b[i]
31
32    # copy count to market object
33    self.count = count
34    return self.last_price

```

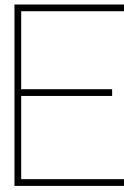
Code D.1: "get_clearing_price" function

```

1 def annotate_ledger(self, clearing_price):
2     ledger = self.book.get_ledger()
3
4     # logic test
5     # b or s can not be zero, market has to clear
6     b = self.get_bids()
7     s = self.get_asks()
8     if (len(s)==0 or len(b)==0):
9         new_col = [ 'False' for i in range(len(ledger['cleared']))]
10        ledger['cleared'] = new_col
11        self.book.update_ledger(ledger)
12        return
13    # end logic test
14
15    for index, row in ledger.iterrows():
16        if (row['role'] == 'seller'):
17            if (row['price'] < clearing_price):
18                ledger.loc[index, 'cleared'] = 'True'
19            else:
20                ledger.loc[index, 'cleared'] = 'False'
21        else:
22            if (row['price'] > clearing_price):
23                ledger.loc[index, 'cleared'] = 'True'
24            else:
25                ledger.loc[index, 'cleared'] = 'False'
26
27    self.book.update_ledger(ledger)

```

Code D.2: "annotate_ledger" function



Model output

Today's scientists have substituted mathematics for experiments, and they wander off through equation after equation, and eventually build a structure which has no relation to reality

Nikola Tesla

In this appendix the full model results will be presented. For the discussion of the results I would like to refer back to main text. The commentary provided in this appendix will be brief and will focus solely on being able to read the graphs. Values on the Y-axis are in the unit TWh when addressing absolute quantities like reserves or market volume or Euro per MWh when addressing prices. The main commentary will be provided at the market part of this appendix. In this 'market commentary' the figures E.3 and E.4 of the sellers production and reserves and figure E.2 of the buyers consumption of natural gas are taken into account.

In the first section 'Markets' we will discuss the results on the defined markets and how the markets are demarcated. This is largely done in order to define a major demand or supply region. When a region has an abundant supply of natural gas and is thus an exporting region it tends to have a high domestic demand as well, for this reason they can be seen as a separate market with their own dynamics. In this section we will provide 'raw' model output in a monthly granularity, which would help us to observe seasonal fluctuations. While on the right-hand side a yearly aggregation or average of the monthly values.

Buyers of natural gas reflect a demand region and/or a consumer group within such a region. In the absence of specific monthly data consumed by end-user group a representative demand group for the whole region has been used. Monthly values can be found on the left hand side and yearly summed quantities on the right.

Sellers represent a reserve region of natural gas likely to export to a demand region. These sellers are in general countries and aggregated to region if the countries by themselves are not significant to be modelled as separate entities. European reserves have been defined in a smaller granularity since it is the region of focus to the problem description. Again monthly values can be found on the left hand side and yearly summed quantities on the right hand side.

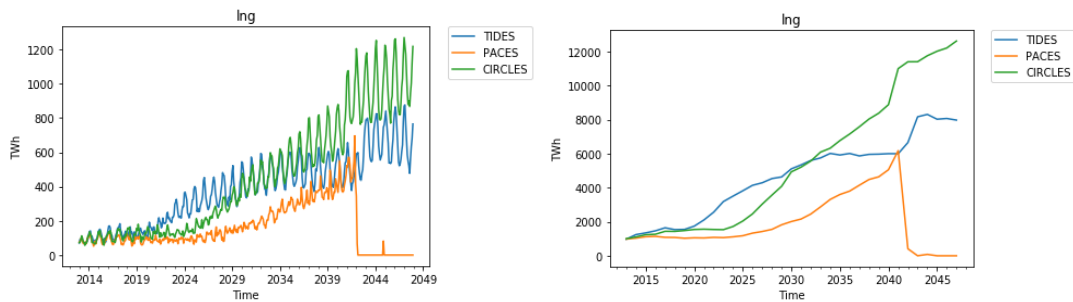
Reserves represent the finite amount of natural gas the sellers are endowed with, reflecting 'known' available resources which are economically and technically viable sources of exploration. Since in the different scenarios exploitable reserves differ these figures can have an upward trend. Since capacity and reserves are expected to be adjusted based on major investments or discoveries these figures are not added continuously but step-wise.

E.1. Markets

The markets are created around a big demand center. Since in general countries who are endowed with a lot of gas also use a lot of gas, they will have their own market and if applicable be connected to the markets they supply. The reasoning behind this construct can be found in chapter 5. On the left we observe monthly prices and quantities on the right side the yearly averages of prices and summed values when talking about quantities.

E.1.1. LNG

The LNG market is the global link between natural gas markets. The collapse of the LNG market in the paces scenario, has the basis in a growing demand of the originating countries limiting the availability of supply to the LNG market and to the major suppliers to the LNG market (e.g. Australia) run out of known supplies.



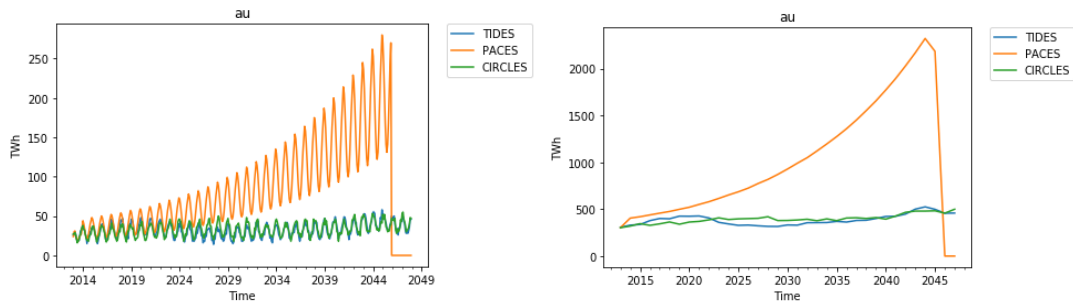
(a) results LNG market quantities



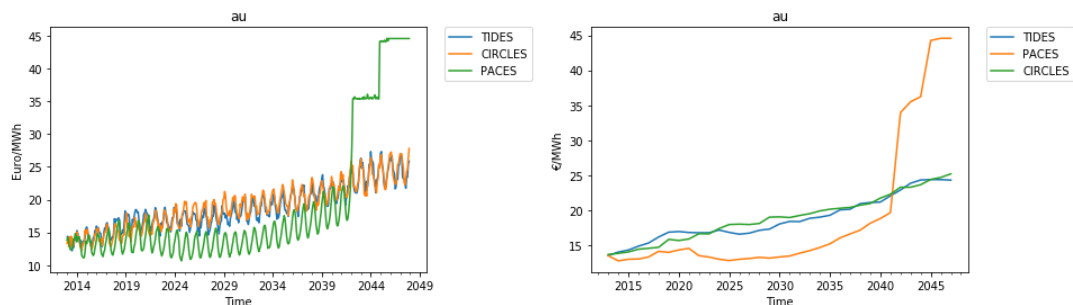
(b) results LNG market price

E.1.2. Australia

The region Australia should be seen as the whole region of Oceania. This region has been an exporter of natural gas in the form of LNG, the market Australia represent the consumption of natural gas by Australia.



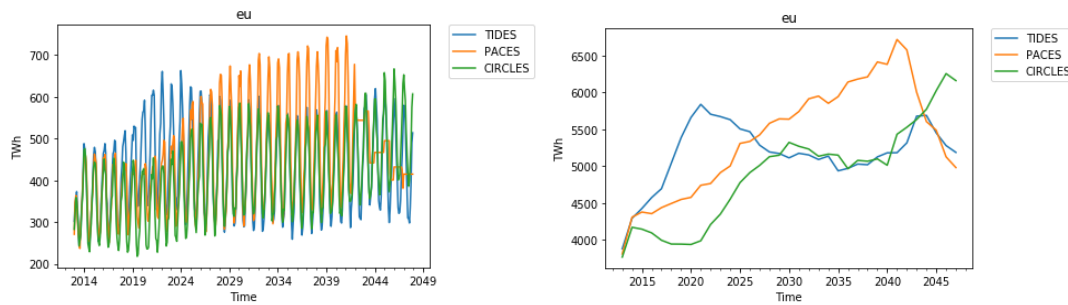
(c) results Australia market quantities



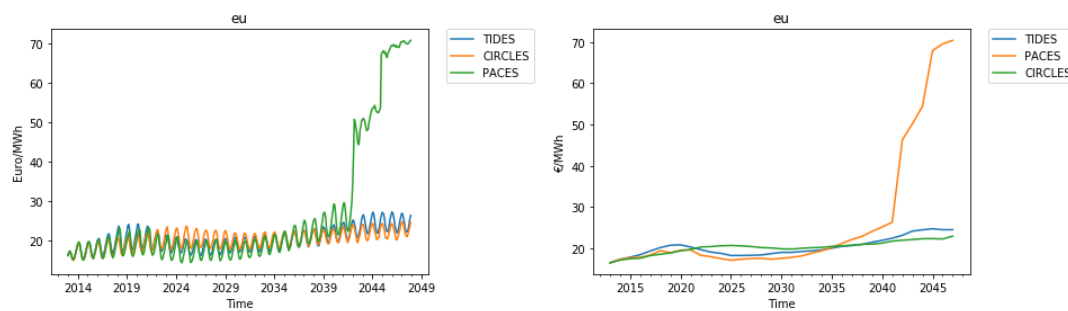
(d) results Australia market price

E.1.3. EU

The European region is defined as all countries who are part of the EU or are due to their geographical or economical position part of the same market. Hence this includes Norway, Switzerland and more recently the UK. A price spike is observed in the Paces scenario accompanied by a drop in quantities traded, indicating a shortage of supply.



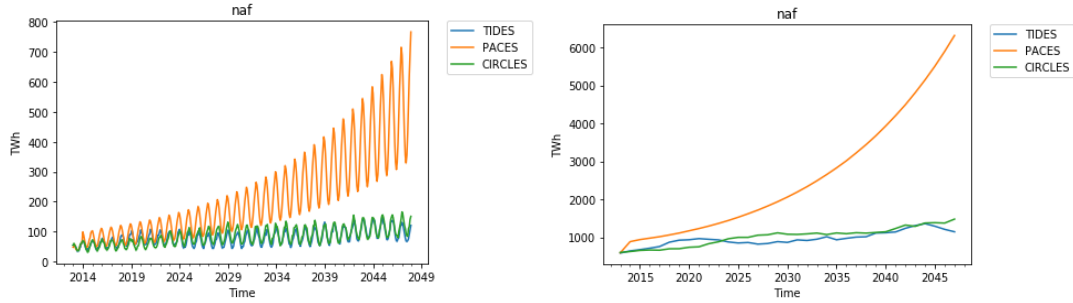
(e) results EU market quantities



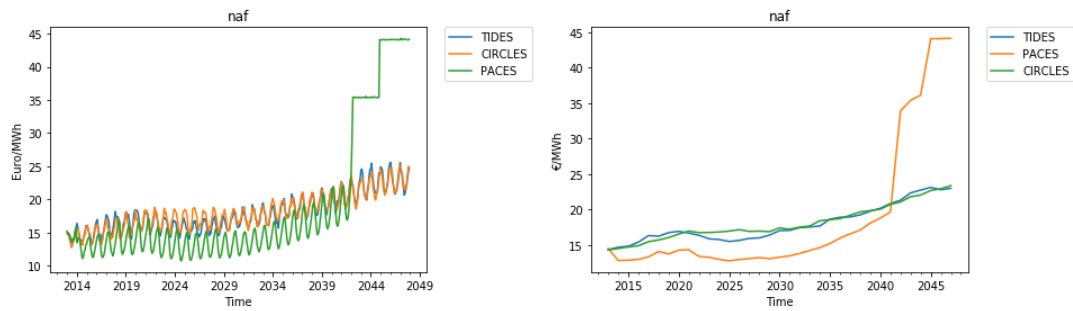
(f) results EU market price

E.1.4. North Africa

Northern Africa is defined as the African region above the Sahara, at present the region has a significant amount of reserves of natural gas which it is exporting to the EU via pipeline and LNG shipments. It stands out to other supply regions in the fact that it has a relatively low domestic consumption of natural gas. Within the paces scenario this increases significantly.



(g) results North Africa market quantities



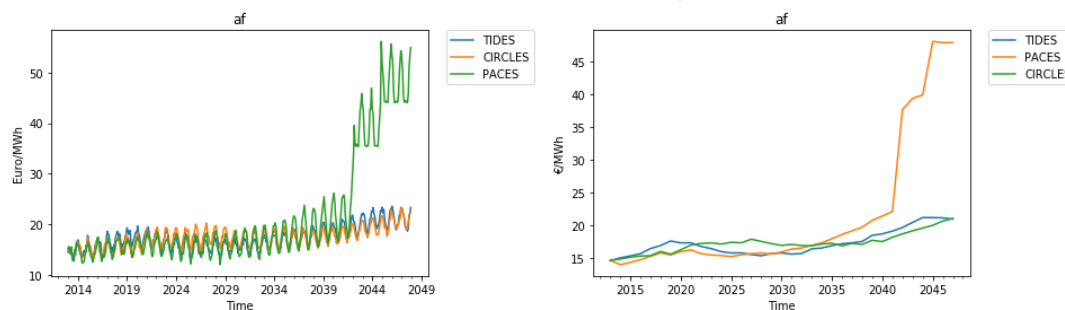
(h) results North Africa market price

E.1.5. Sub Sahara Africa

The Sub-Saharan African region consists as the name suggests all countries below the Sahara. These countries do not have major gas reserves known today for the exception of Nigeria. The sub-Saharan region is too far removed to any demand region thereby not having a direct region to export or import from and hence relying on the LNG market. It has little domestic consumption, in the process is changing leading to a shortage of supply in the final years of the model run.



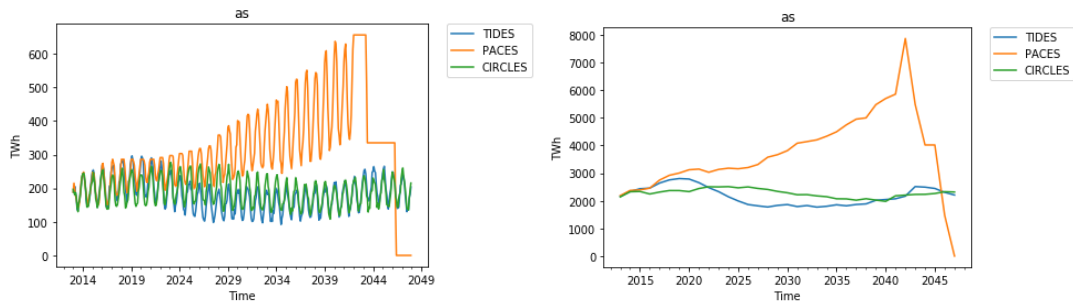
(i) results Sub Sahara Africa market quantities



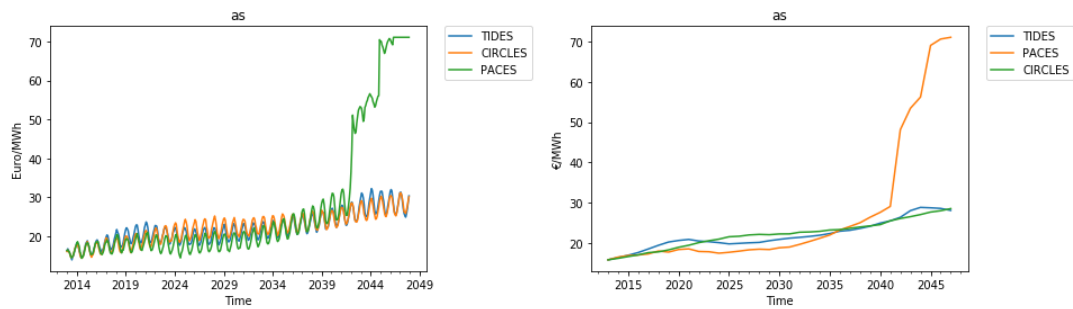
(j) results Sub Sahara Africa market price

E.1.6. Asia

The Asia region is all of Asia without the major producer China, which has its own market. It consist primarily of countries with reserves or consumption which was not significant by itself however combined could not be neglected.



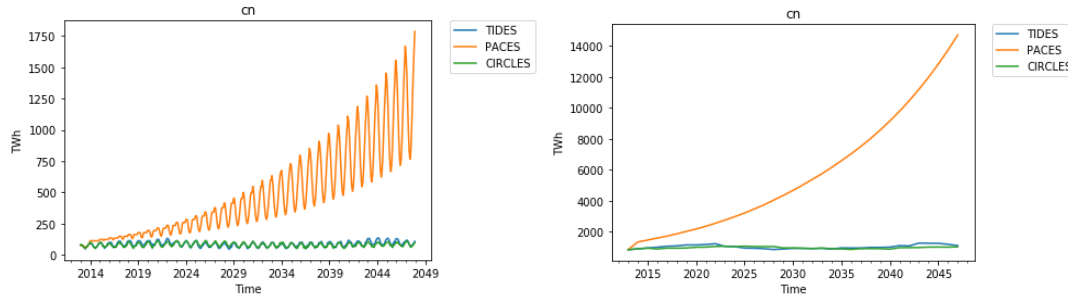
(k) results Asia market quantities



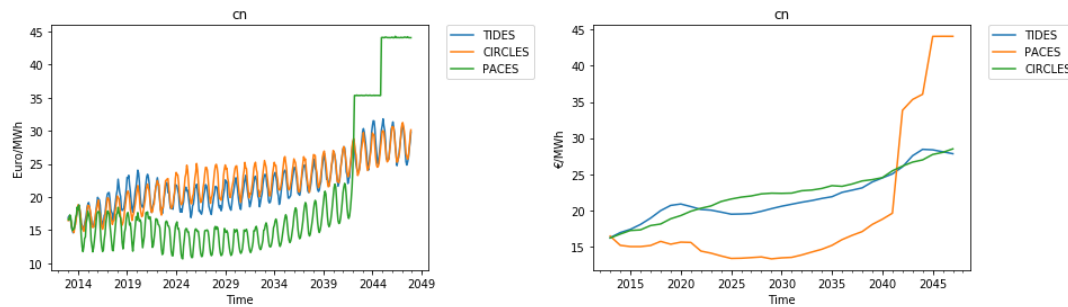
(l) results Asia market price

E.1.7. China

China is a major region with a lot of (shale) reserves, however at the moment it is an importing region. In the paces scenario in the final years of the model run, one might observe the lack of seasonal variety that is expected and observed throughout the previous years. This behaviour occurs when supply increases can not 'keep-up' with demand, leading to all supply bids being cleared throughout the months of the year.



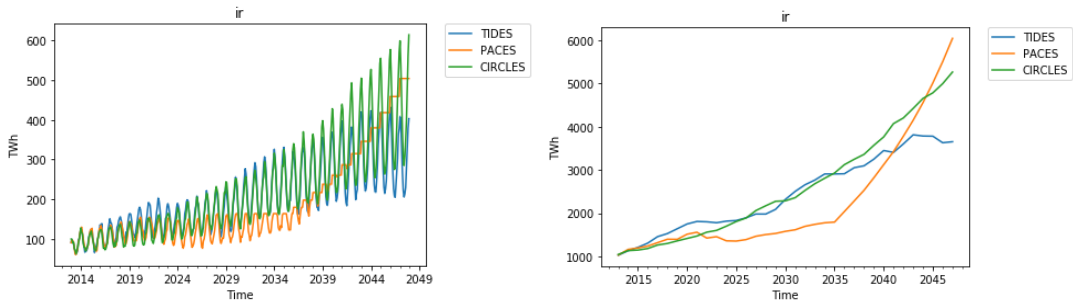
(m) results China market quantities



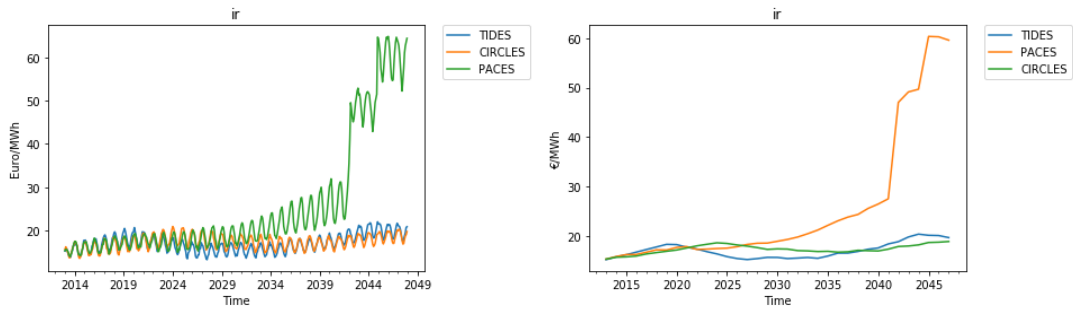
(n) results China market price

E.1.8. Iran

Iran has the biggest natural gas reserves of all countries in the world, it also has a high domestic consumption of natural gas. Iran will be a major supplier of natural gas to the LNG market and we see the domestic market price move in tandem with LNG market price.



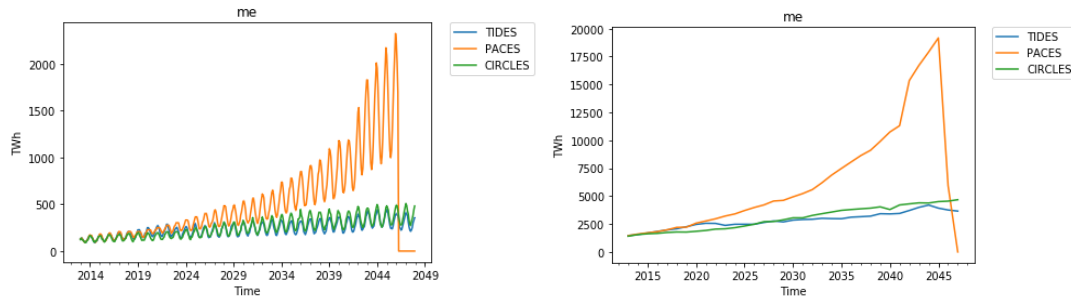
(o) results Iranian market quantities



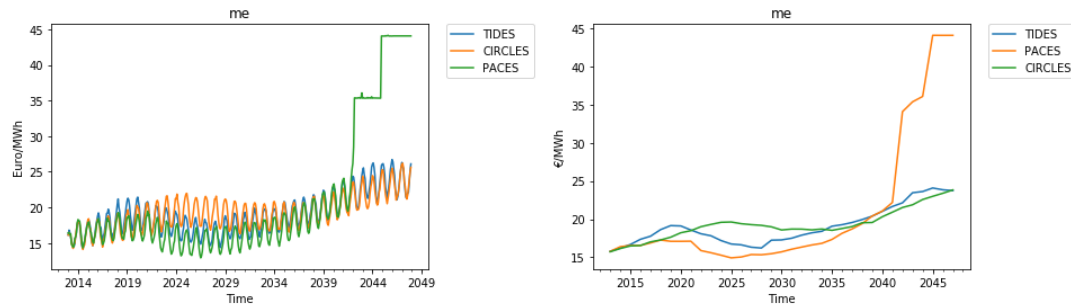
(p) results Iranian market price

E.1.9. Middle East

The Middle Eastern market entails all countries in the region with the exception of Iran. Qatar is part of this market since their lack of domestic consumption does not justify the existence of its own market.



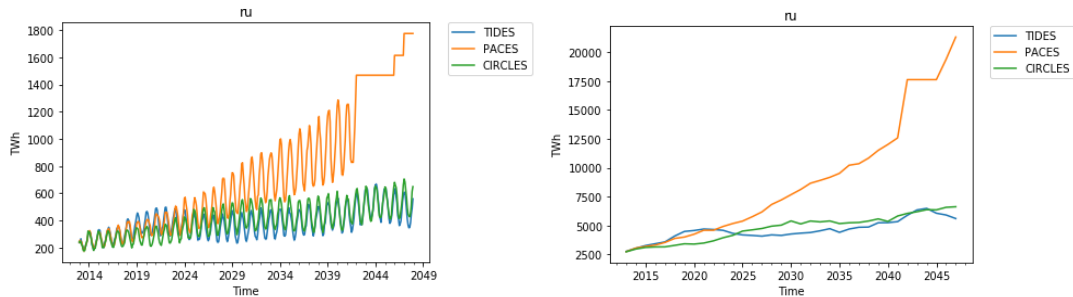
(q) results Middle-East market quantities



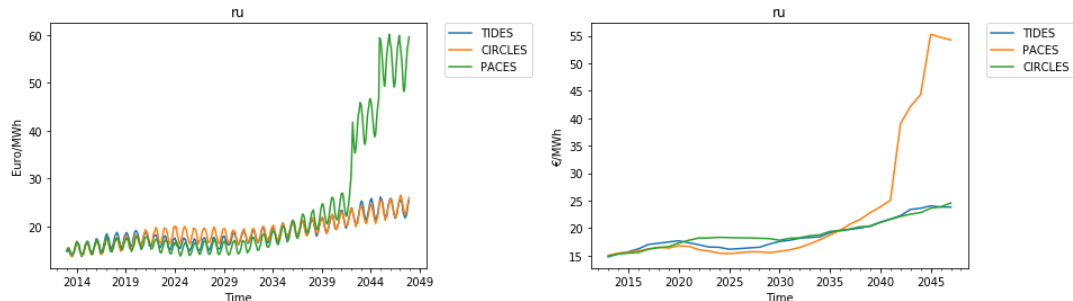
(r) results Middle-East market price

E.1.10. Russia

Russia has the second largest known reserves of natural gas and is a major exporter. There is a high inland consumption of natural gas which is simulated in this market. As we see in all other scenarios the world shortage of supply in the Paces scenario will impact Russia in the form of price spikes. Although it does not completely run out of reserves (see figure E.4, at the end of the model period the r/p ratio falls below 10 years. Form where the model assumes their will not be any significant investments to increase the production of natural gas.



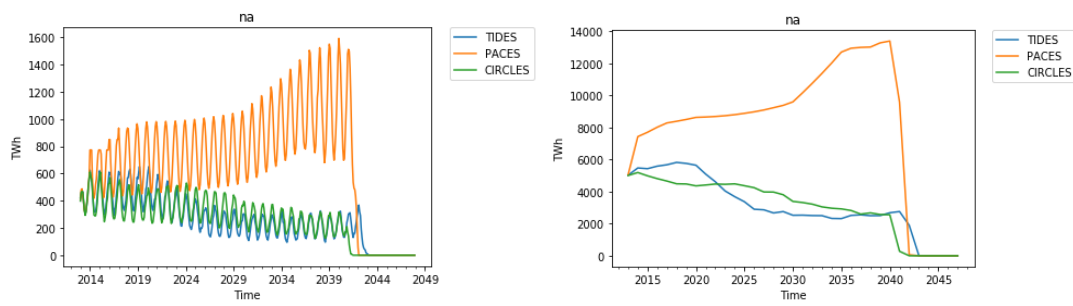
(s) results Australia market quantities



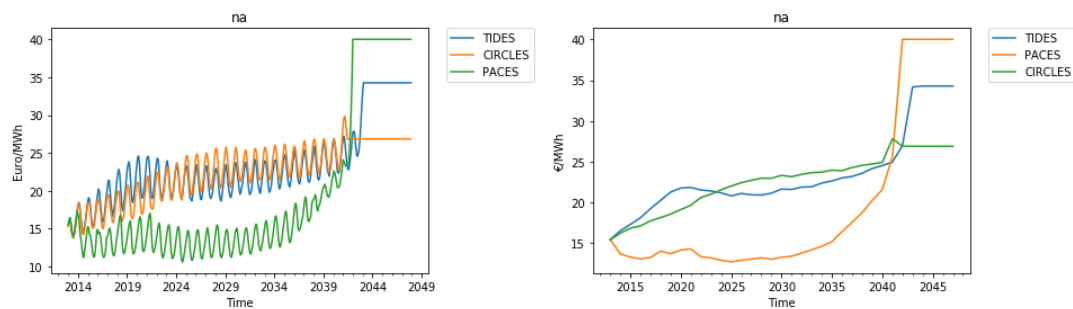
(t) results Russian market price

E.1.11. North-America

The North American market is defined as the North-American continent, where what is called Middle-America is divided over the North and South-American market. North-America consists of Mexico, USA and Canada. Mexico is an importer of natural gas while Canada is an exporter and the USA became more or less self sufficient because of the exploration of shale reserves. Within close to all scenarios we the common trend of a spiking market price in combination with a decline of market quantities traded, this is caused by the depletion of reserves on the continent (see figure E.4 for the sellers reserves).



(u) results North-America market quantities

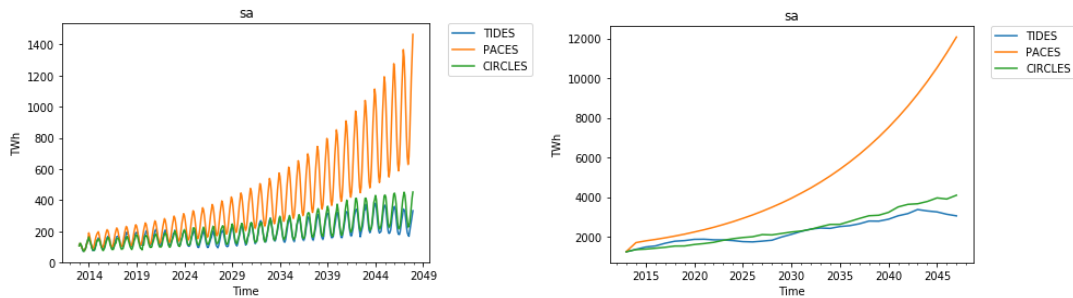


(v) results North America market price

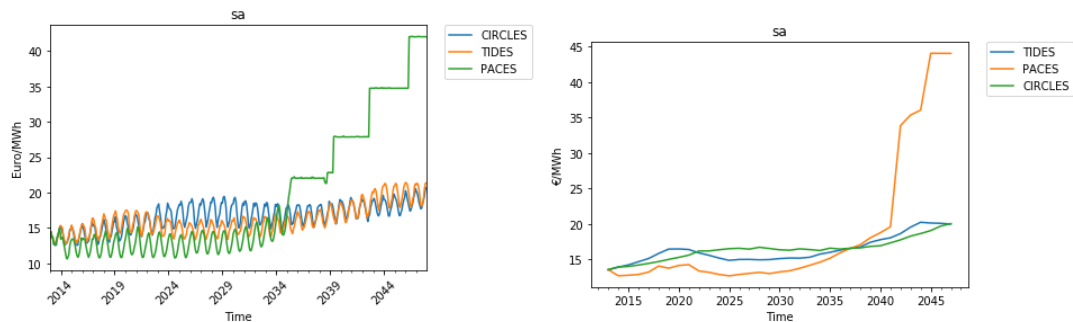
E.1.12. South America

South-America is defined as all countries in Middle and South-America not part of the Northern-American market, hence all countries South of Mexico. The characteristic of these market is the fact that it is a relatively isolated region in respect to the natural gas market. Around the region of Middle-America reserves are present which supply in general the surrounding region. There is a connection to the LNG market with modes trading quantities. If supply was to dry up these flows would be expected to become more significant. Within the Paces the link to LNG market becomes clear, in this scenario we observe an at first glance remarkable step-wise increase in price. This is caused by other regions running out of reserves and resorting to the LNG market thereby hiking the price. The lack of seasonal price variation can be explained by the fact that world regions peak demand is not synchronized leading to a close to constant demand on the LNG world market.

The figure C.14 visualizes the world trade flows and shows the dynamics of the internal South-American gas flows.



(w) results South-America market quantities

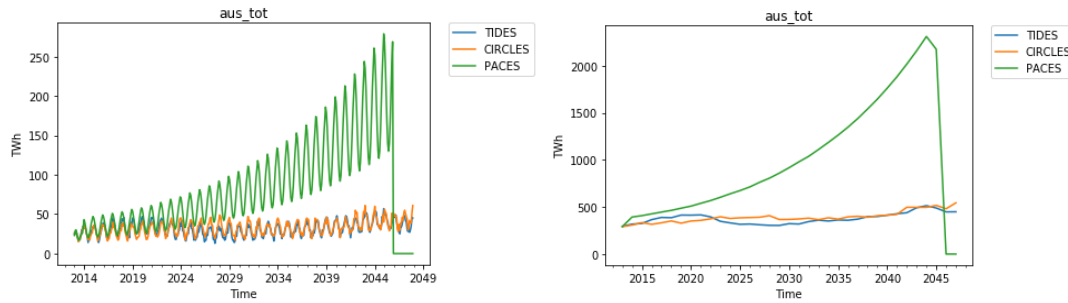


(x) results South-America market price

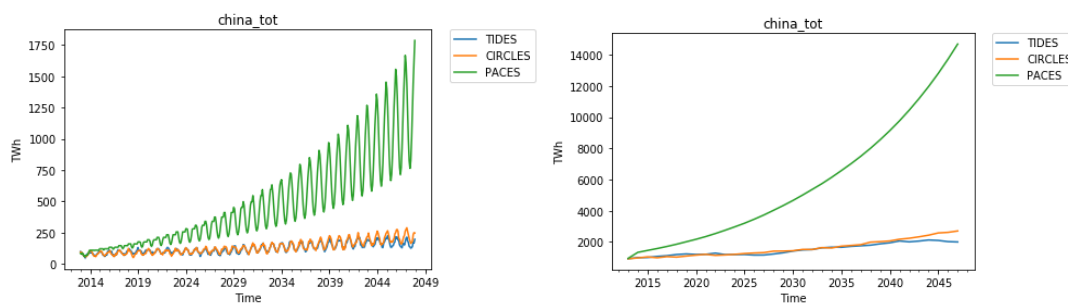
Figure E.1: Market quantities and prices

E.2. Buyers

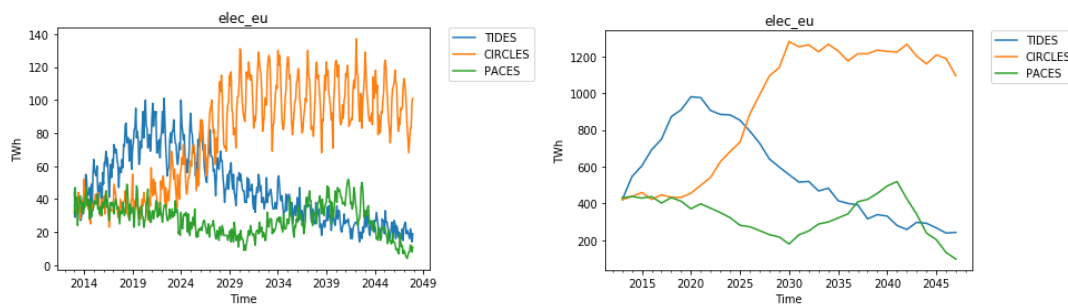
Buyers are defined as consumers of natural gas, in general countries or groups of countries representing around known demand hubs. For more information on the conceptualization of this group of agents I would like to refer to chapter 5. On the left we observe monthly bought quantities, these values have been summed on the right to provide some more insights.



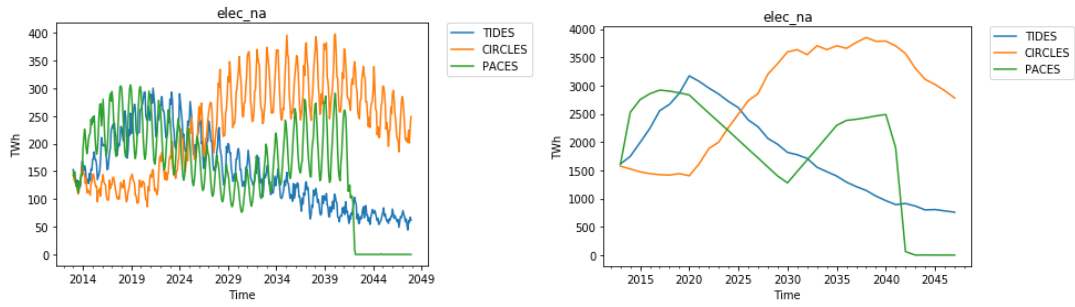
(a) results Australia buyer



(b) results China buyer



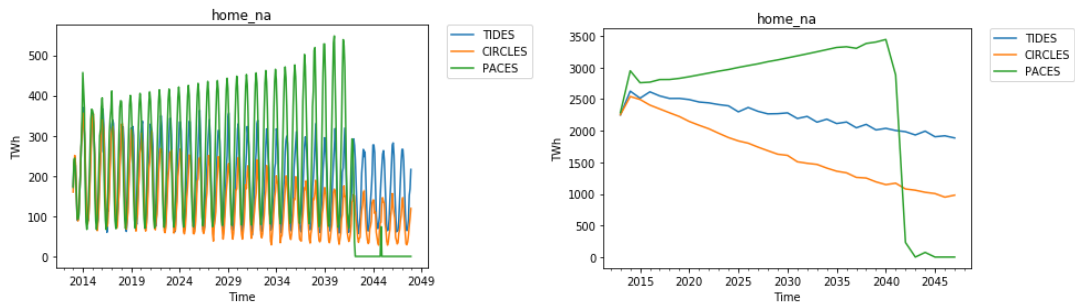
(c) results European electric power buyer



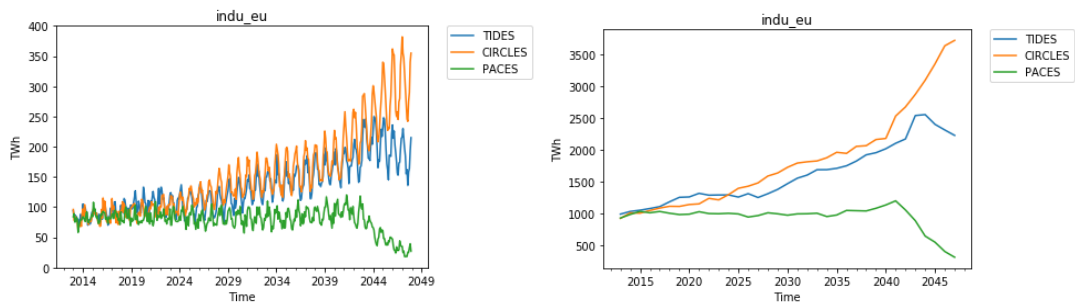
(d) results North-America electric power buyer



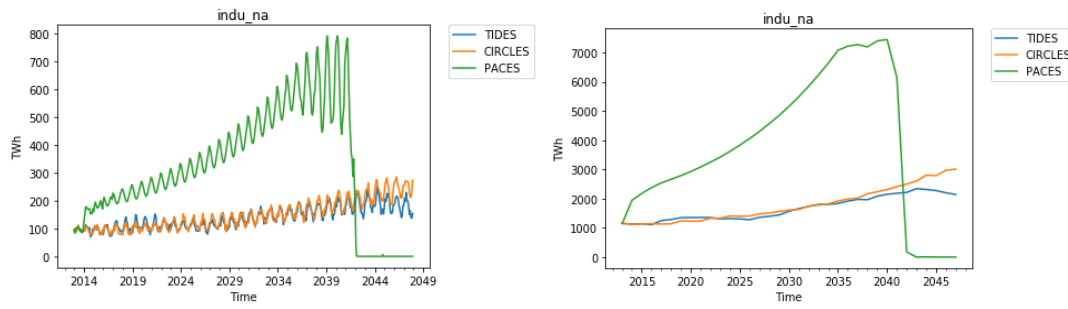
(e) results European consumption in the building environment



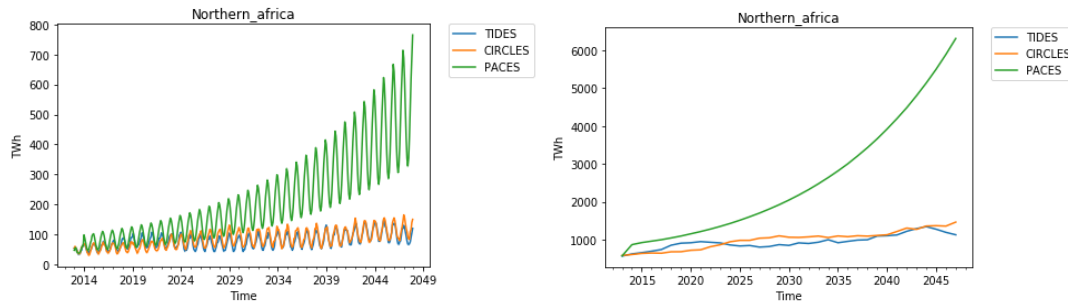
(f) results North-America consumption in the building environment



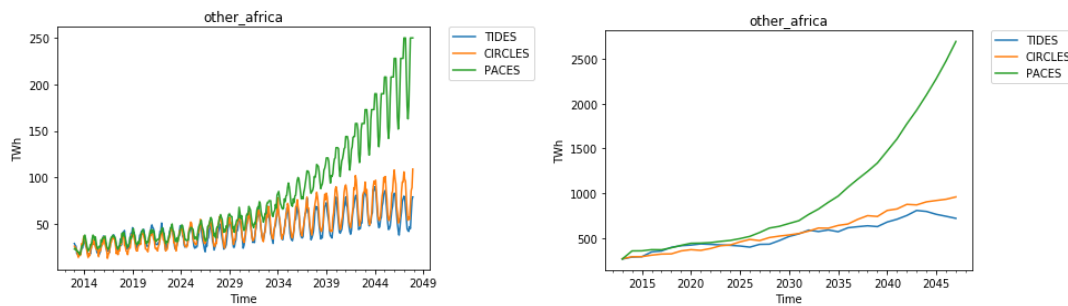
(g) results European heavy industrial buyers



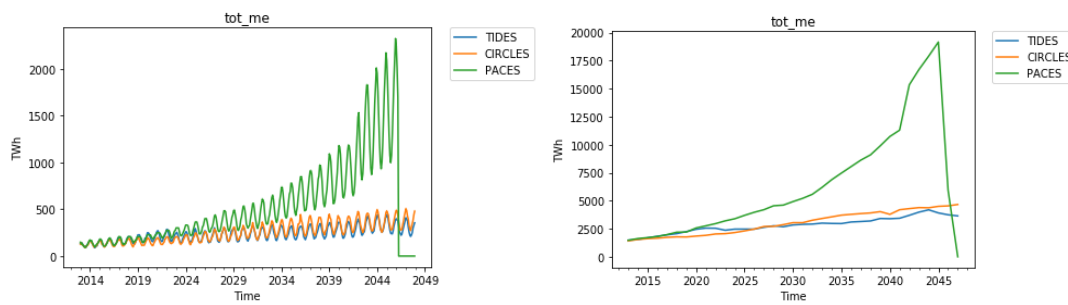
(h) results North-America heavy industrial buyers



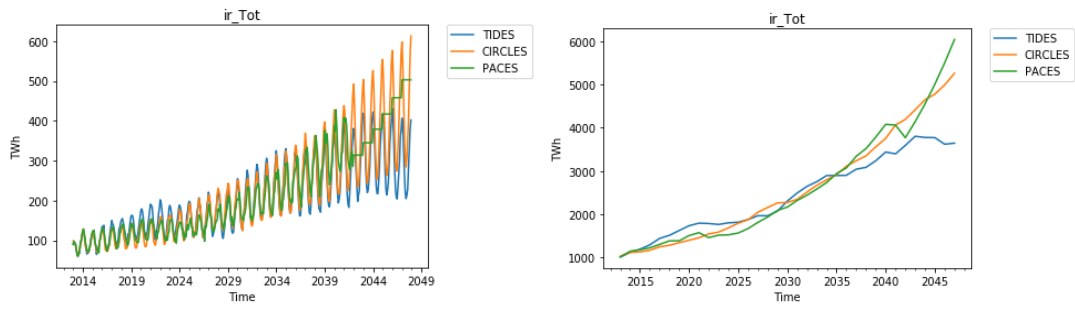
(i) results Northern Africa buyer



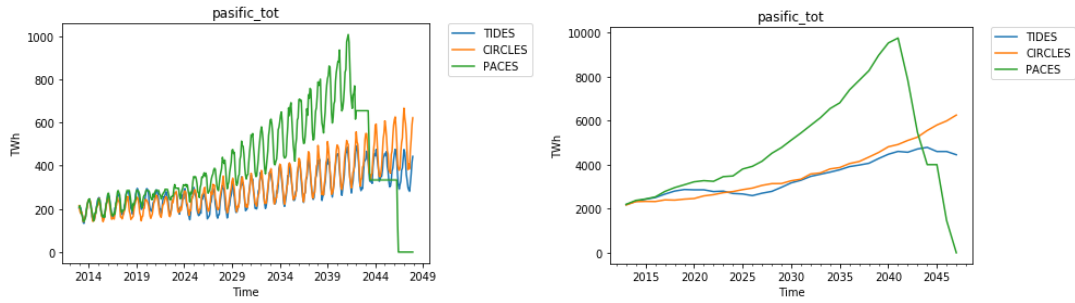
(j) results south of Sahara Africa



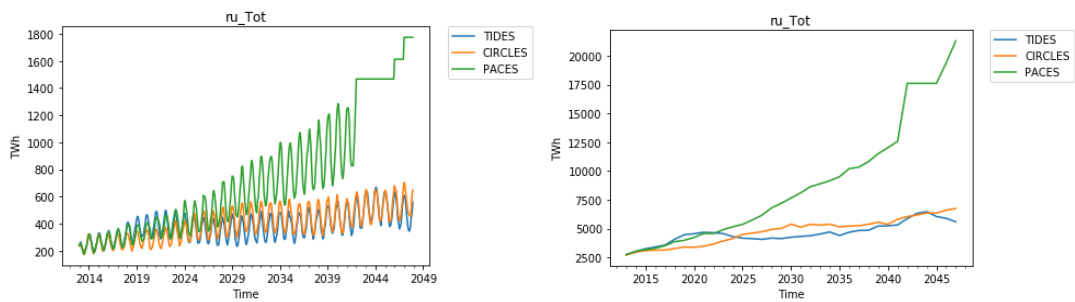
(k) results Middle-East (excluding Qatar and Iran) buyer



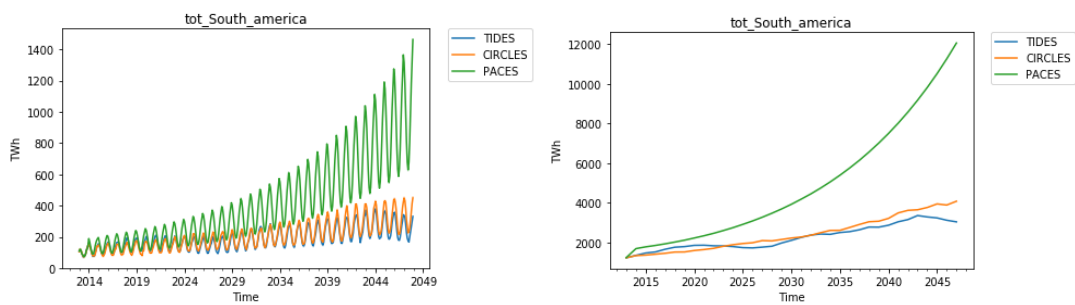
(l) results Iranian buyer



(m) results Pacific region buyer



(n) results Russian buyer

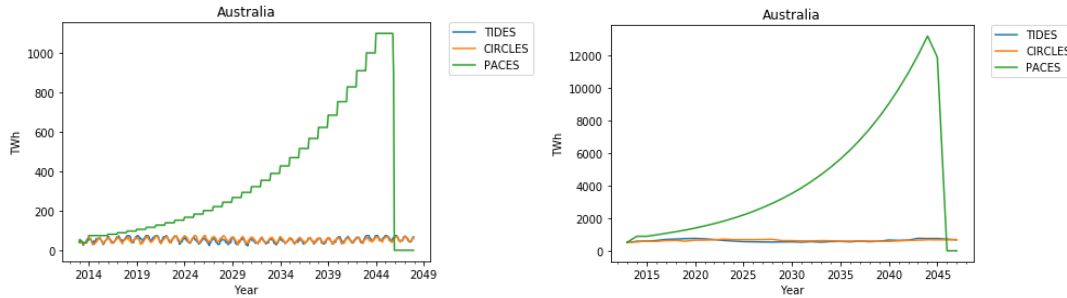


(o) results South-America buyer

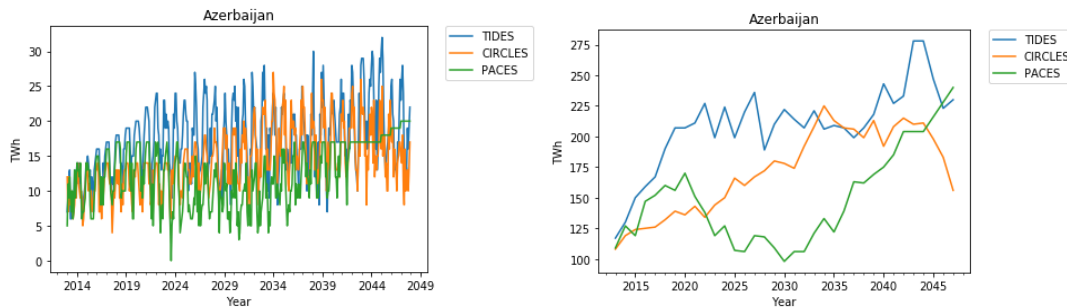
Figure E.2: Yearly and monthly quantities of buyers

E.3. Sellers

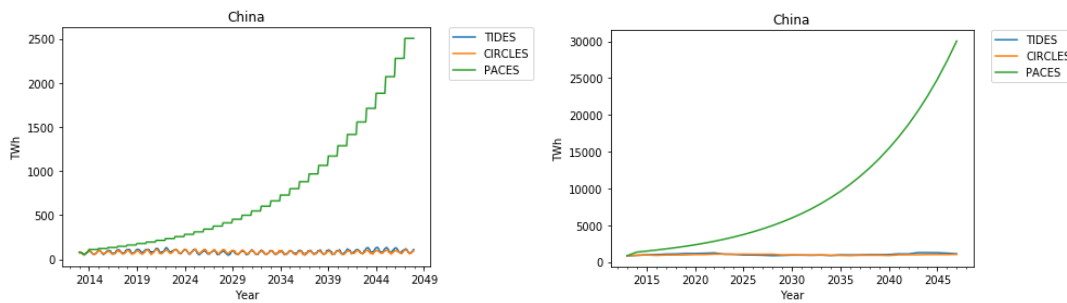
Sellers are defined as producers of natural gas, in general countries or groups of countries representing known reserves or expected reserves. For more information on the conceptualization of this group of agents I would like to refer to chapter 5. On the left we observe monthly sold quantities, these values have been summed on the right to provide some more insights.



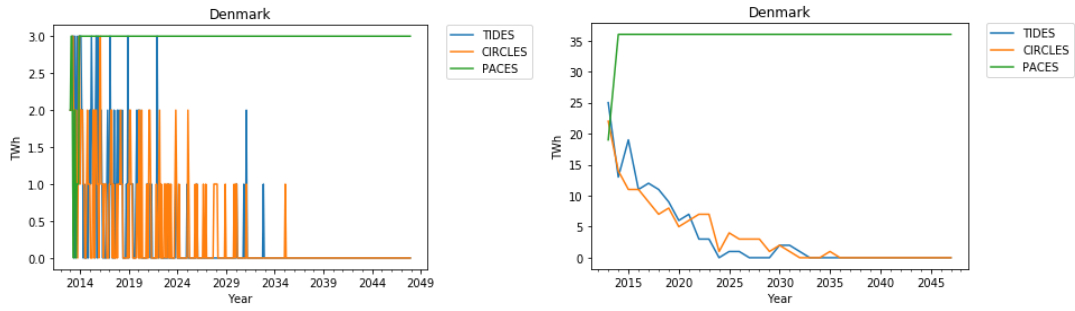
(a) results Australia seller



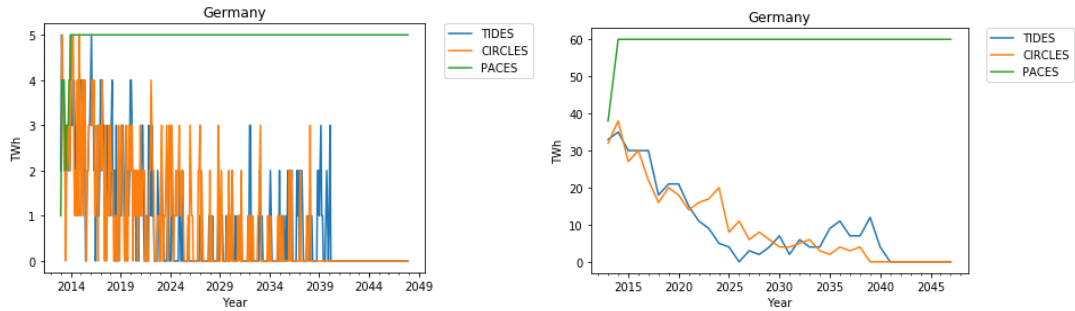
(b) results Azerbaijan seller



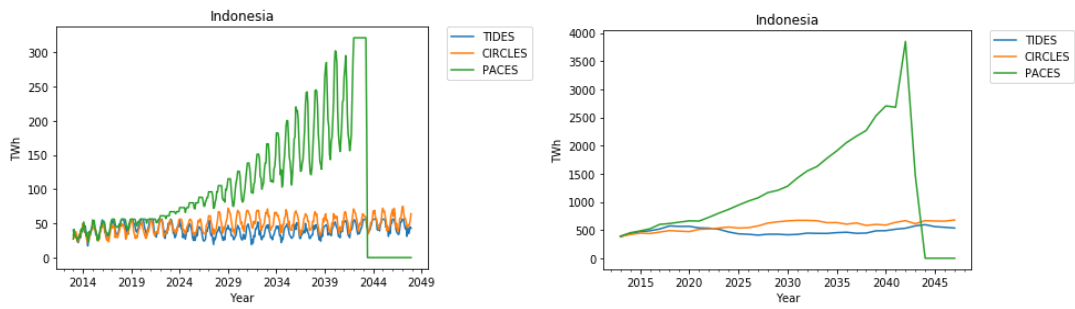
(c) results China seller



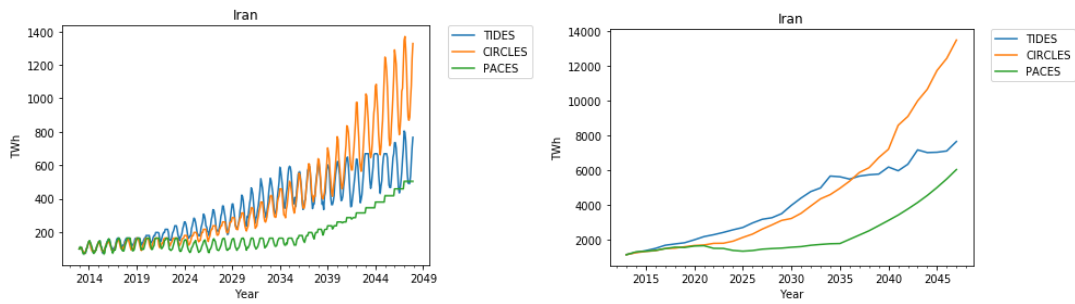
(d) results Denmark seller



(e) results Germany seller



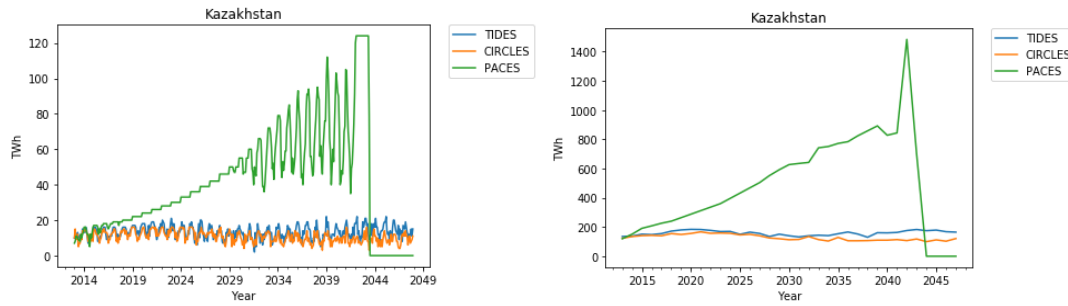
(f) results Indonesia seller



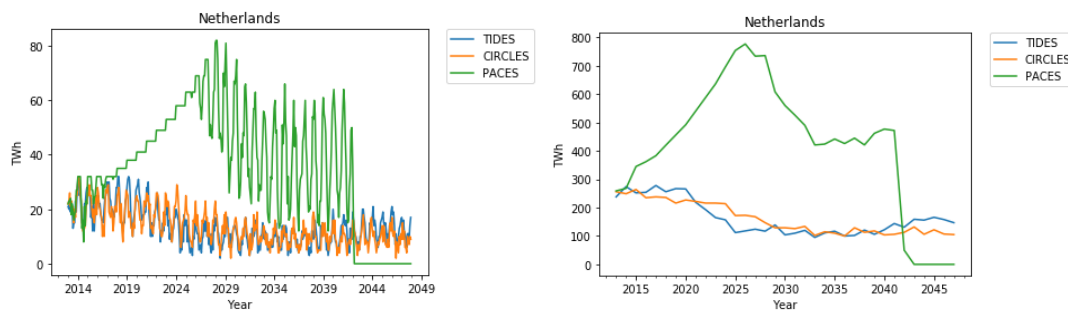
(g) results Iran seller



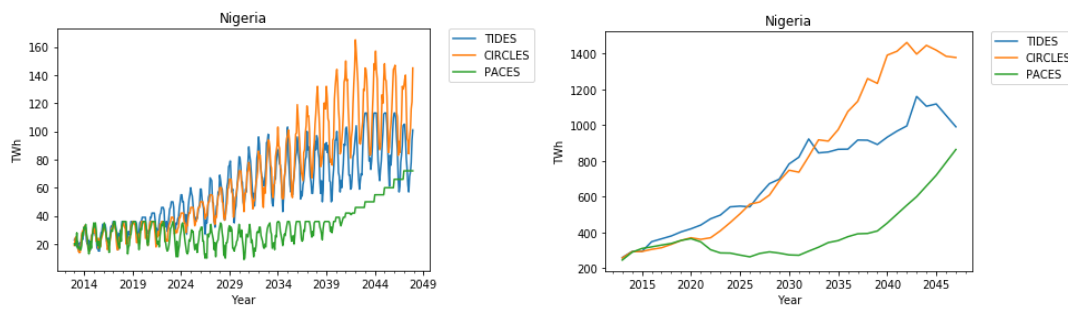
(h) results Italy seller



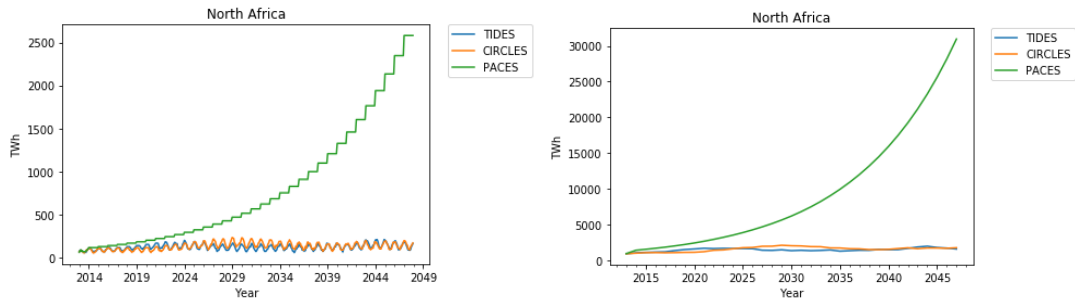
(i) results Kazakhstan seller



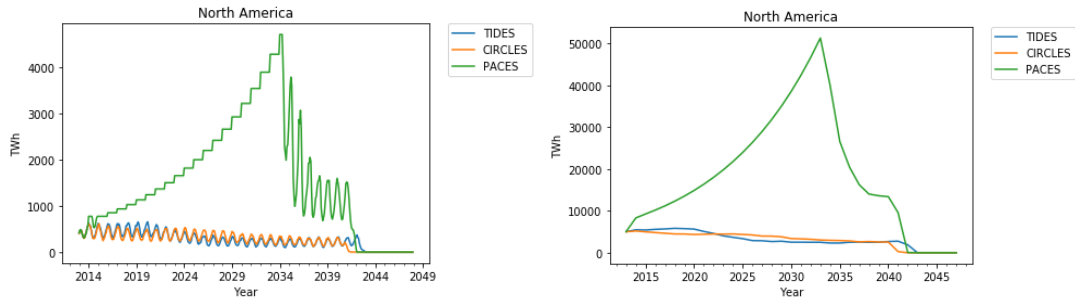
(j) results Netherlands seller



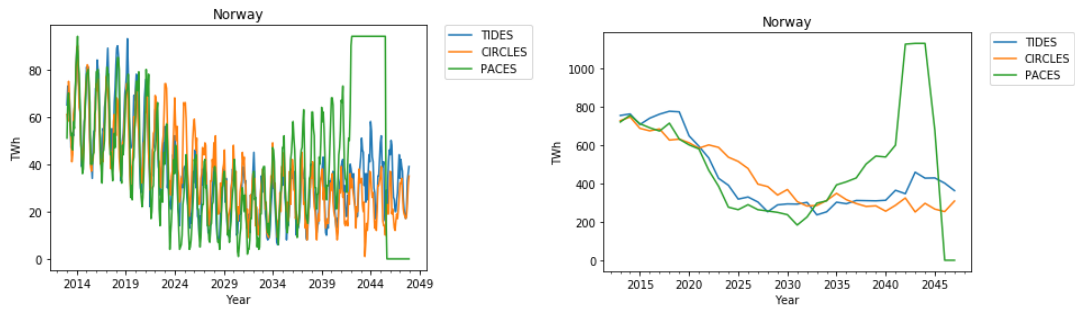
(k) results Nigeria seller



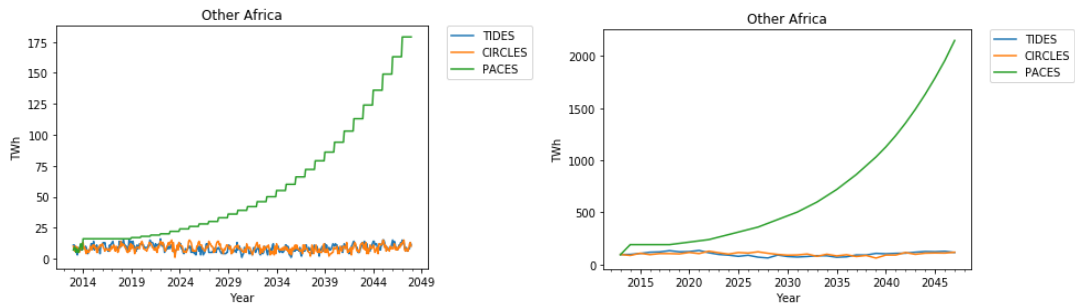
(l) results Northern-Africa seller



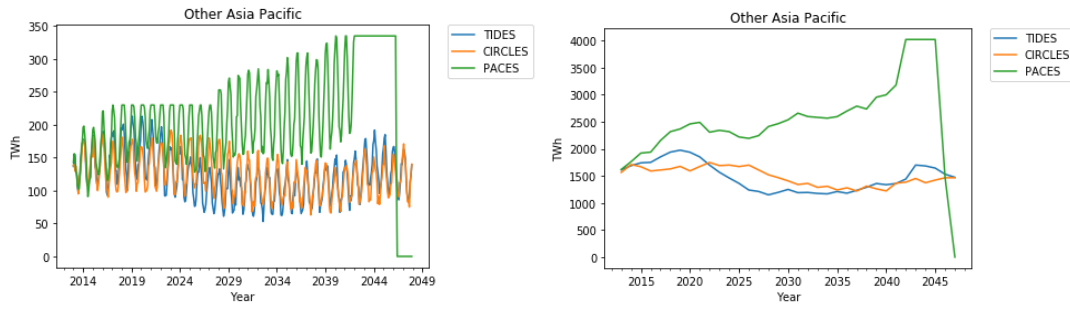
(m) results Northern-America seller



(n) results Norway seller



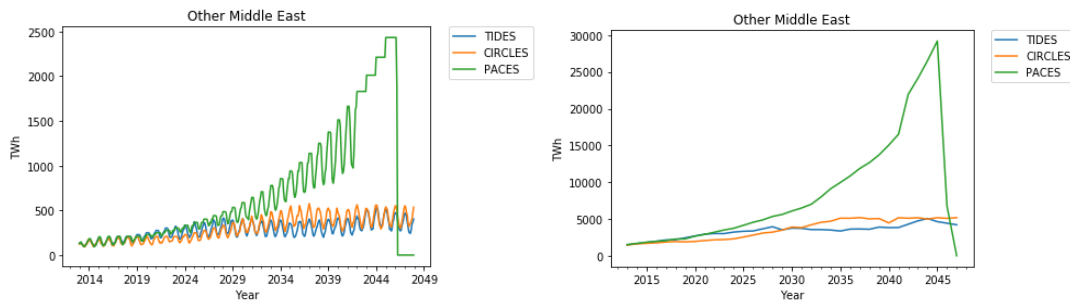
(o) results Other Africa seller



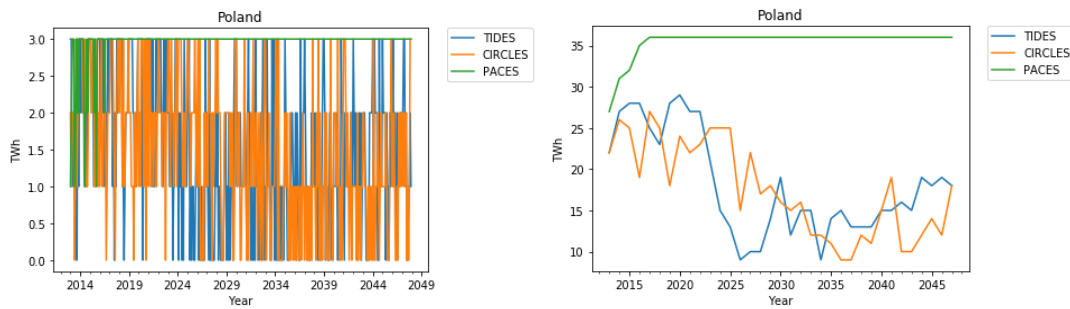
(p) results Other Asia Pacific seller



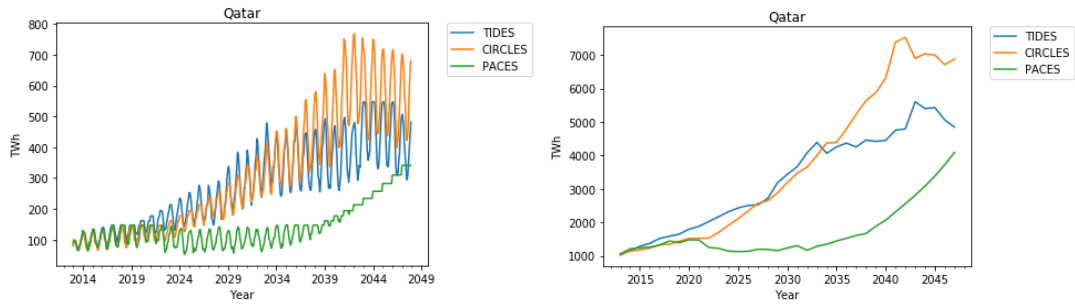
(q) results Other Europe Eurasia seller



(r) results Other Middle east seller



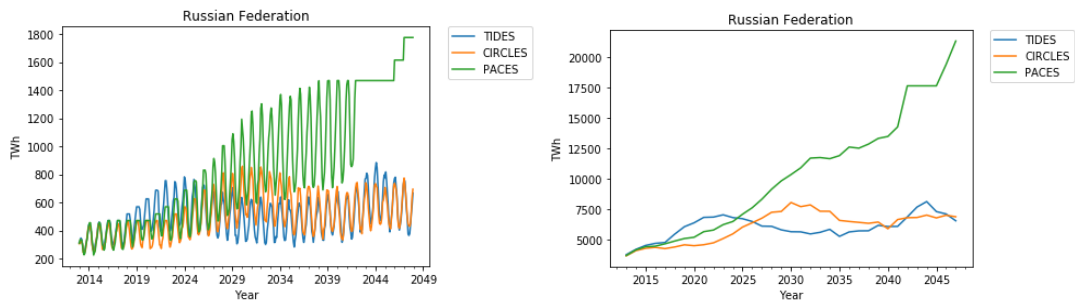
(s) results Poland seller



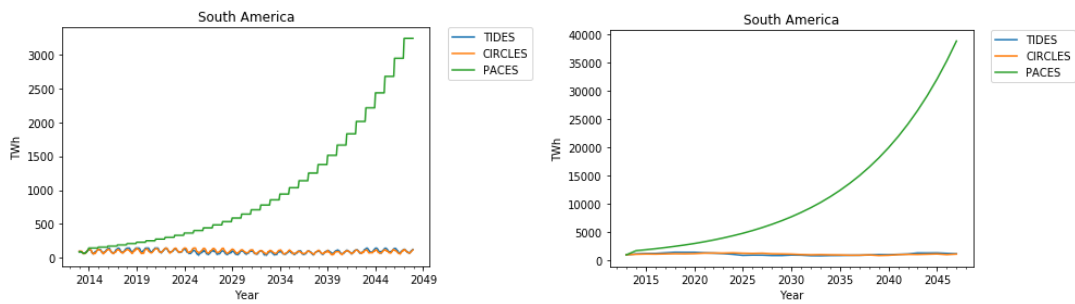
(t) results Qatar seller



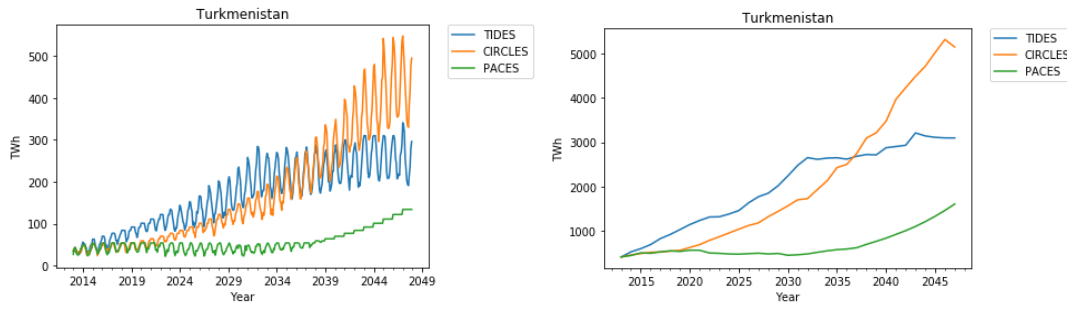
(u) results Romanian seller



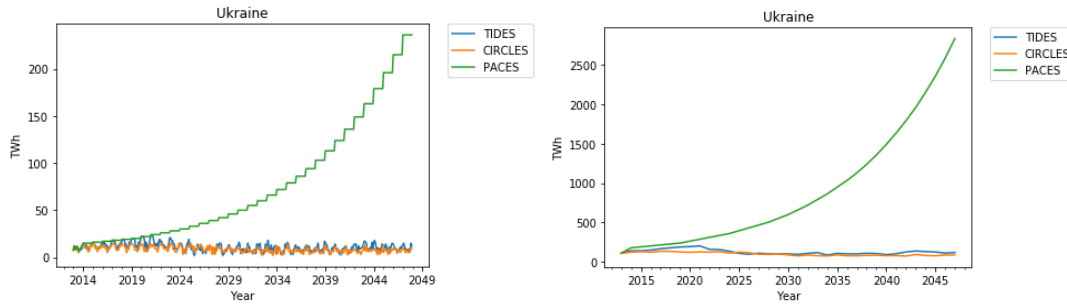
(v) results Russia seller



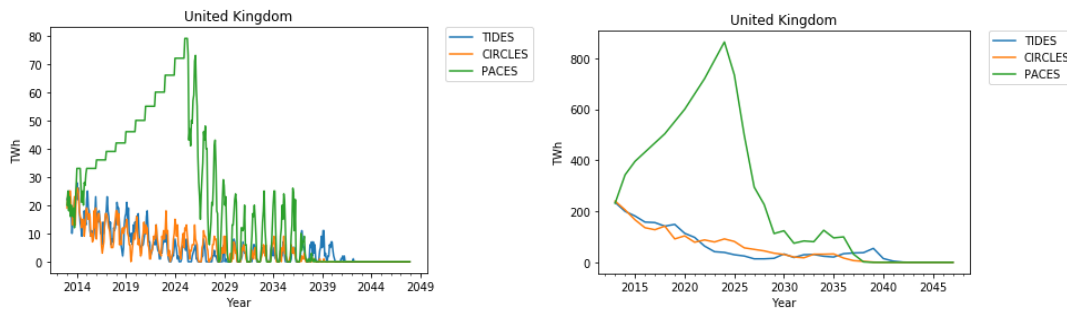
(w) results South America seller



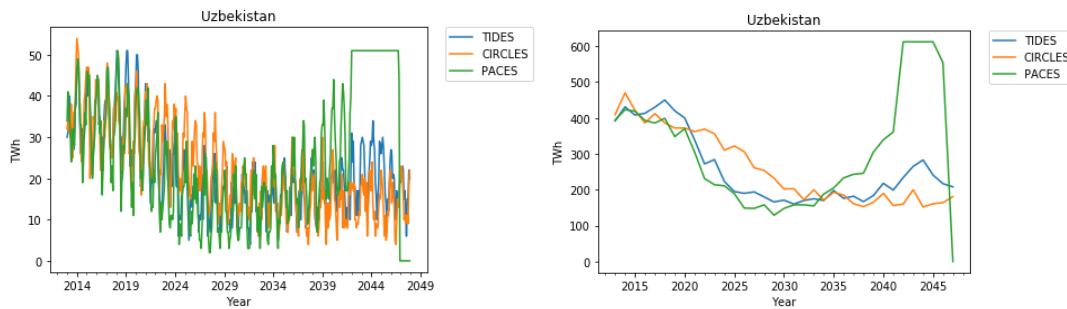
(x) results Turkmenistan seller



(y) results Ukraine seller



(z) results United Kingdom seller

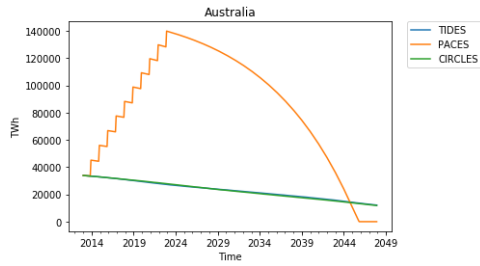


(aa) results Uzbekistan seller

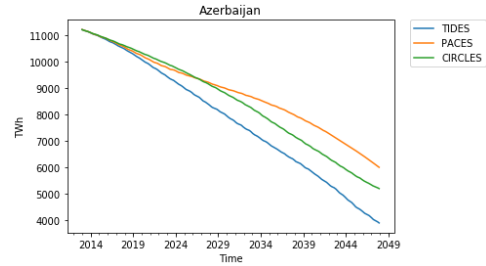
Figure E.3: Yearly and monthly quantities of sellers

E.4. Reserves

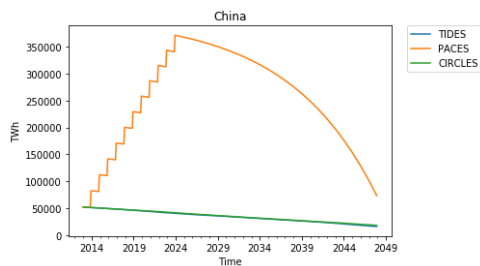
Reserves represent known reserves of natural gas to the producer in every model step. Increasing reserves represent newly discovered natural gas.



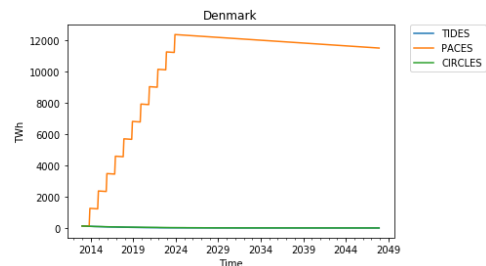
(a) results Australia seller reserve



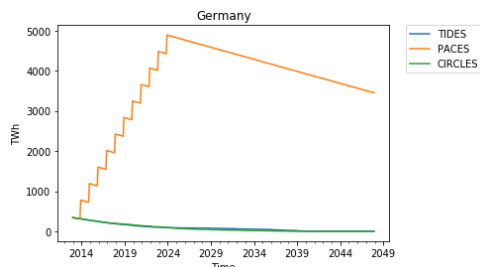
(b) results Azerbaijan seller reserve



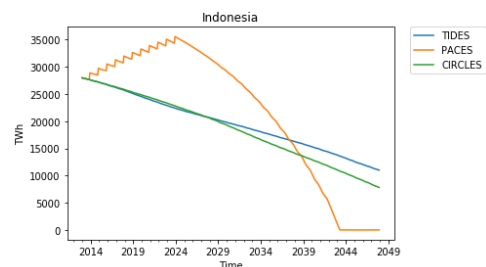
(c) results China seller reserve



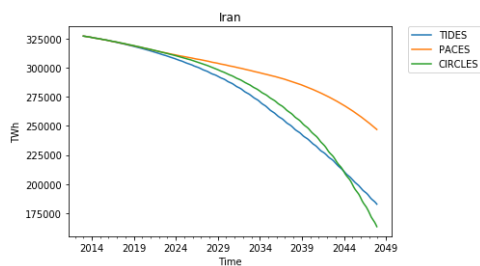
(d) results Denmark seller reserve



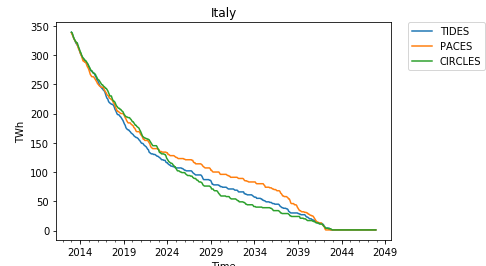
(e) results Germany seller reserve



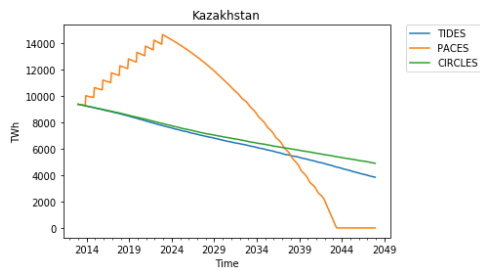
(f) results Indonesia seller reserve



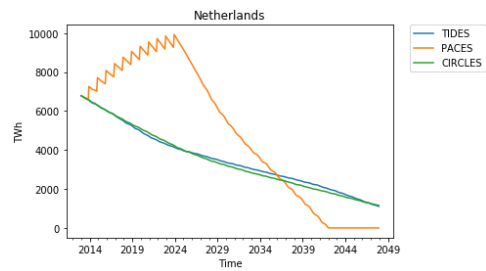
(g) results Iran seller reserve



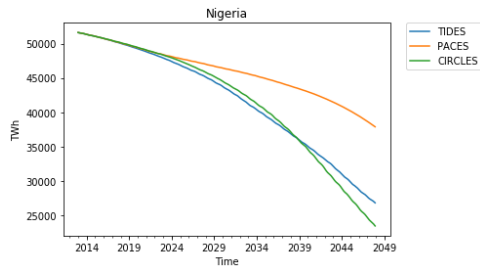
(h) results Italy seller reserve



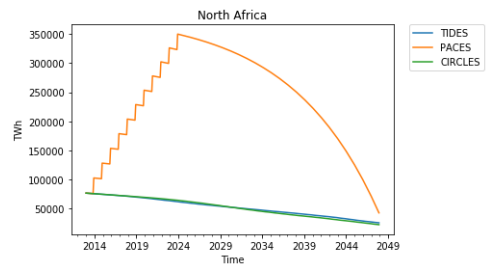
(i) results Kazakhstan seller reserve



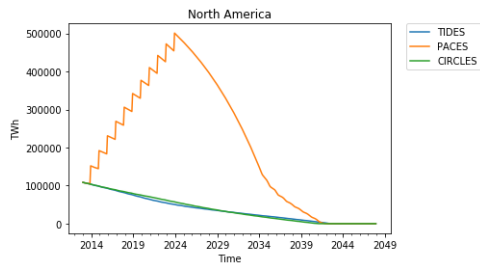
(j) results Netherlands seller reserve



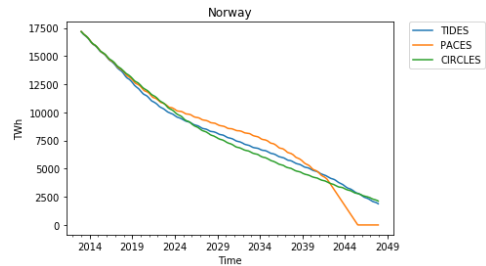
(k) results Nigeria seller reserve



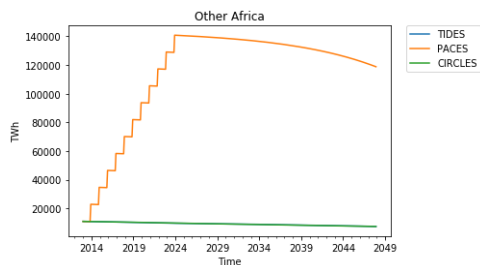
(l) results Northern-Africa seller reserve



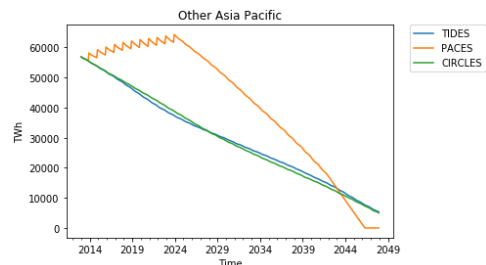
(m) results Northern-America seller reserve



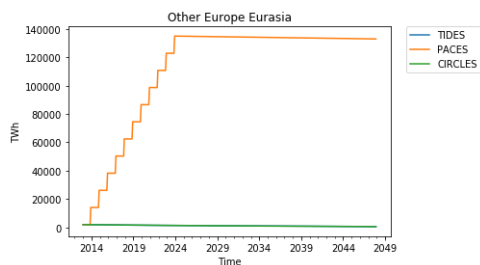
(n) results Norway seller reserve



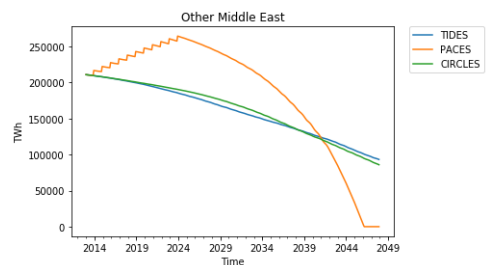
(o) results Other Africa seller reserve



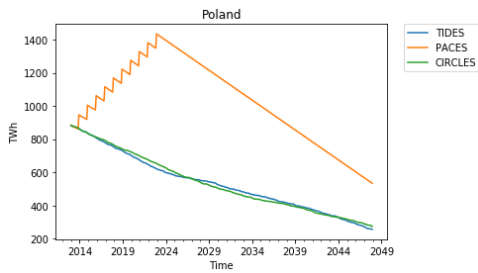
(p) results Other Asia Pacific seller reserve



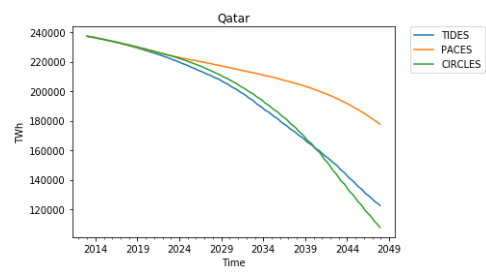
(q) results Other Europe Eurasia seller reserve



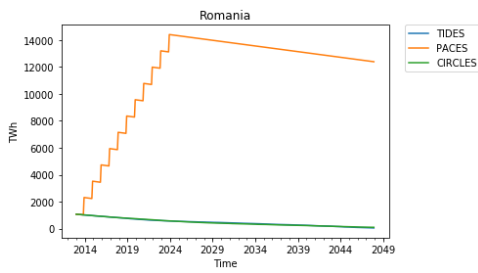
(r) results Other Middle east seller reserve



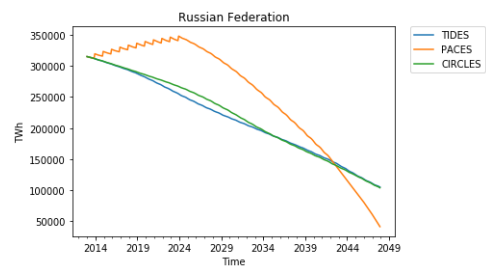
(s) results Poland seller reserve



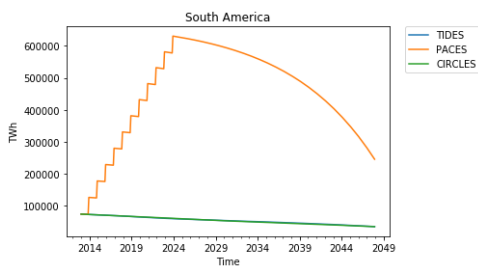
(t) results Qatar seller reserve



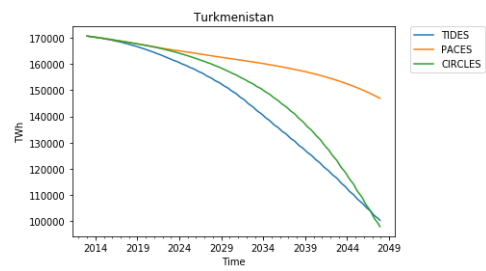
(u) results Romanian seller reserve



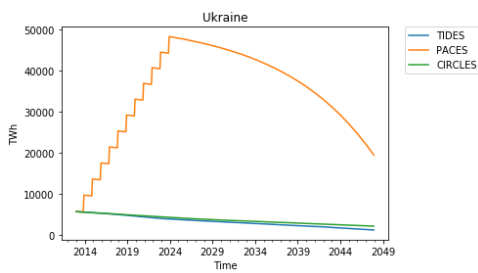
(v) results Russia seller reserve



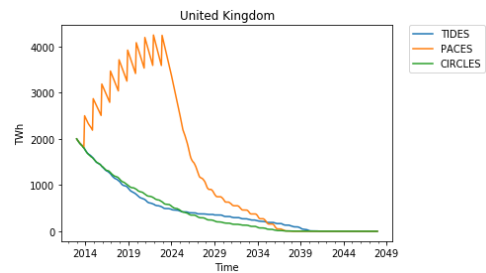
(w) results South America seller reserve



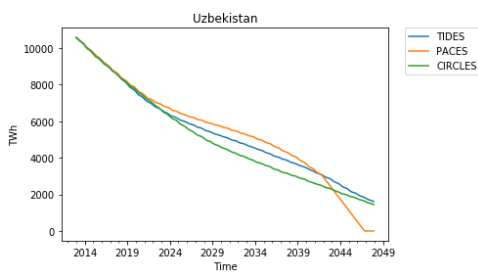
(x) results Turkmenistan seller reserve



(y) results Ukraine seller reserve



(z) results United Kingdom seller reserve



(aa) results Uzbekistan seller reserve

Figure E.4: Results seller reserves

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