Exploring the effects of shale gas development on natural gas markets: a multi-method approach

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Abstract

Now that conventional gas resources are rapidly declining in many industrialised regions, national governments are considering the exploration and production of unconventional resources, with shale gas in particular. Large-scale development of these resources could significantly lower import dependency of the gas supply of many countries. The complexity of gas markets and the uncertainties affecting it make that simulation modelling is required to assess these economic implications of global shale gas development. In this study, System Dynamics and Agent-based Modelling are deployed in parallel to discover scenarios for the effects of shale gas development on regional gas markets, while accounting for method uncertainty. It is shown that the gas market is mainly demand-driven, hence economic growth is likely to have a larger impact on gas import dependency than the actual size of shale gas resources. The use of a multi-method approach provided additional insights in the behaviour of gas markets. Future work should focus on the inclusion of additional structural uncertainties in order to obtain a more complete view on plausible economic implications of global shale gas development.

Keywords: shale gas, method uncertainty, agent-based modelling, System Dynamics, multi-method research

1. Introduction

During the coming decades the global energy system will be confronted with the challenge of keeping up with increasing demand, as global energy demand is projected to increase by 25-45% by 2030 compared to the 2010 level (BP, 2013; International Energy Agency, 2012). Since the global energy mix changes only very slowly, experts consider it likely that fossil fuel will continue to play an important role in the future (Bradshaw, 2009; International Energy Agency, 2012; Kolb, 2011). However, climate change urges for a lower carbon footprint of energy consumption. Given these developments, natural gas as primary energy source could play an important role in the next decades due to its relatively low CO_2 emissions, high energy density and widespread applicability. But as high gas consumption in many industrialized nations has caused conventional gas resources to rapidly decline over the past decades, these resources are becoming depleted (International Energy Agency, 2012).

The recent developments in the exploration and production of unconventional energy resources – in particular shale gas – could significantly extend the role of natural gas as one of the primary energy sources. In the United States, so far the only country to have exploited their shale gas resources on a large scale, shale gas is regarded as a revolution, having caused large drops in the price of natural gas (Energy Information Administration, 2014). The effects of the lower price and the belief in natural gas as the prevailing cheap energy resource for the coming decades are illustrated by the fact that the chemical industry in the United States is considering a switch from naphtha to natural gas as their main feedstock (Snow, 2014).

In spite of these positive effects, the United States' shale gas revolution has not yet spread to other parts of the world. The vast experience with (energy) resource extraction, the well-developed energy infrastructure, the open market and the way property rights are set up all contributed to a rapid development of shale gas in the United States . While in other countries conditions are likely to be less favourable, exploitation of shale gas resource might offer significant advantages. As shale gas resources are more evenly distributed over countries than conventional gas resources, many national governments may be inclined to pursue the opportunity to reduce import dependency by producing a larger share of their energy demand domestically (Medlock, 2012). This is especially the case in Europe, where for many countries the gas crises of 2006 and 2009 painfully confirmed their dependence on Russia for their natural gas supply (Kovacevic, 2009). But decision-making processes are stalled, mainly because of uncertainty regarding the potentially negative environmental effects of shale gas exploration, which resulted in a provisional ban on test drillings in various countries like the Netherlands, Belgium, France and South Africa (International Energy Agency, 2012). In addition to the environmental concerns, it is uncertain how large-scale shale gas extraction could affect global gas markets in terms of supply, demand, prices and transport infrastructure, though quantitative information on these effects is critical for policymakers to assess the advantages and disadvantages of shale gas.

In 2012, the Henry Hub gas price dropped so rapidly that energy companies who just started producing their shale gas fields already had to suspend production because the price dropped below their marginal costs (Natural Gas Intel, 2012). This development illustrates the complexity of gas markets, as clearly the market analysts of these multinational energy companies have failed to predict the low gas price. The complexity of gas markets is caused by number of factors. Firstly, there are many different actors active on the market, i.e. base load suppliers, peak suppliers, consumers, gas-fired power plants, LNG traders and gas storage operators. In addition, gas is traded not only on spot markets but also by means of medium and long term contracts. Investments in production and transport capacity create internal dynamics. Important external dynamics are formed by economic growth, energy substitution and weather patterns. The geological aspects of the gas fields add to complexity. Finally, congestions in transport infrastructure make that gas markets are hard to understand.

For systems characterised by a high degree of complexity, simulation models could help in understanding its observed behaviour. Moreover, it offers a way to perform what-if analyses to see how the system could respond to certain impulses given a set of assumptions and parameters. Various modelling methodologies have been deployed to model the gas market. Many studies formulate the gas market as a mixed complementarity problem (de Joode, Plomp, and Ozdemir, 2012; Gabriel *et al.*, 2013; Hecking and Panke, 2012; Huppmann *et al.*, 2011; Lochner and Bothe, 2009), in which clearing of the gas market is seen as mathematical optimization. Although this modelling method is widely used, it fails to fully capture the dynamics of the gas market. Often exogenous trends are used, instead of modelling the interdependencies between system components such as demand and supply, as is the case in de Joode *et al.* (2012). Other attempts at modelling the gas market take a more rigid approach by modelling the relations between system components endogenously. These studies use either the System Dynamics modelling method (SD) (Forrester, 1994) or the agent-based modelling method (ABM)(Macal and North, 2009). Examples of SD studies include the work of Jingchun, Ding, and Fan (2010), Eker and Daalen (2013) and Olaya and Dyner (2008). Examples of relevant agent-based studies include Bunn and Martoccia (2008), van Dam and Chappin (2010) and Benthem (2010).

Although both modelling methods are often applied to similar topics, SD and ABM are operationally different. SD and ABM are conceptualised and formalised differently, which to some extent determines the behaviour that could be modelled. In SD the model elements are made up of the system observables, i.e. flows and states, and the model is described using mathematical equations, linking factors together. In ABM, the model elements are made up of individuals (agents) who are decision-making entities and are described by algorithms (van Dam *et al.*, 2009). Due to these methodological differences, the choice of method might affect the outcomes of the simulation modelling effort. It would be more desirable not to make a choice for either ABM or SD, but rather create models using both methods and treat them as equally valid.

Exploratory Modelling and Analysis (EMA) is a plausible and useful methodology that allows to incorporate both modelling methods and treats other uncertainties consistently. First introduced by Bankes (1993), EMA was developed as a way to analyse systems for which no predictive model can be built due to the various uncertainties that dominate the behaviour of the system. Instead of trying to predict future states of a system, in EMA, the future is explored by studying the effects of these uncertainties, mainly parametric uncertainties and uncertainties about the structure of the model. EMA will be used in a scenario discovery approach. The scenario discovery methodology used for this study is provided by Bryant and Lempert (2010). It involves generating a set of data from a simulation model or an ensemble of simulation models, preferably using Latin Hypercube sampling (Stein, 1987). The Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) is used to find areas in the input space that are responsible for the observed behaviour. Kwakkel, Auping, and Pruyt (2013) describe seven clearly defined steps for engaging in a scenario discovery exercise from an EMA perspective, which have been reduced to six steps for this study. Adaptations have been made to this methodology to match the multi-method approach of this study. An overview of the adapted scenario discovery methodology is provided in Table 1, while Figure 1 shows how both models are combined in this study.

Table 1: research methodology

Step	Description	Explanation
1.	Conceptualise the decision problem and associated uncertainties	This phase consists of determining the scope and goals of the study, setting the boundaries of the problem to be modelled and by mapping the key processes and mechanisms of the system for both methods. In addition, the uncertainties associated with the decision problem are defined and described in the first phase.
2.	Develop an ensemble of fast and simple models of the system of interest	During this phase the conceptualisations of phase 1 are implemented to create two simulation models, one developed from an ABM perspective and the other from a SD perspective.
3.	Specify the uncertainties that are to be explored and generate a set of experiments and outcomes	In this phase a range of values is specified for each uncertainty. Next, using Latin Hypercube Sampling (LHS) (Stein, 1987) experiments are run and a set of outcomes is generated. Using Latin Hypercube Sampling (LHS), the experiments are sampled from the uncertainty space. The advantage of LHS over random sampling methods (e.g. Monte Carlo) is that the number of experiments required to establish a reasonable distribution over the uncertainty space is significantly less, thus reducing the time required for simulation.
4.	Analyse the behavioural landscape	In this phase the outcomes are studied, and undesired or interesting scenarios are selected for further analysis. To explore the merits of the multi-method approach, in this study the analysis phase focuses on identifying regions in which both models deviate from each other.
5.	Identify the combinations of uncertainties from which regions of interest in the behavioural landscape originate	In this phase the goal is to identify which uncertainties are responsible for the behaviour observed in the relevant scenarios that have been identified in the previous phase. A machine learning technique called the ‘patient rule induction method’ (PRIM) will be applied to identify these uncertainties (Friedman and Fisher, 1999).
6.	Qualitatively or quantitatively communicate typical futures in these regions of interest	Here the outcomes of the analysis are presented in a way that they can be easily understood.

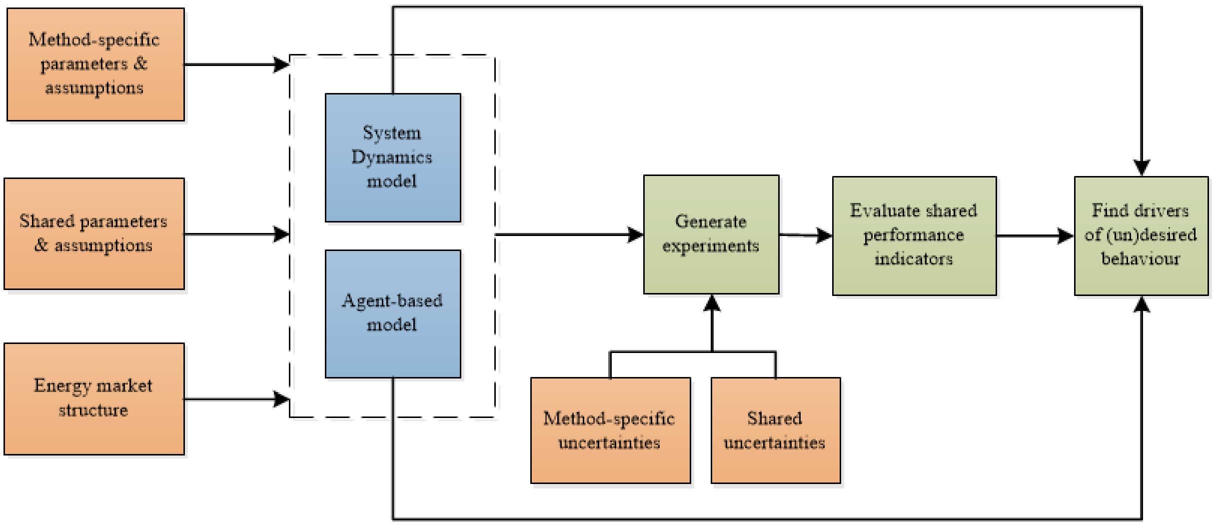

Figure 1: research design

The aim of this study is to discover scenarios for the development of the global gas market up to 2050. Although a fully global gas market has not yet developed, regional markets are linked through LNG, hence they can be analysed as a global market with infrastructure limitations. The four regions that are identified for this study include Greater Europe, which consists of Europe the former Soviet Union (the Commonwealth of Independent States) and the Middle East and North Africa, the Far East, North America and the rest of the world. These areas cover the main demand and supply centres and possess the infrastructure necessary to transport gas. The main uncertainty that will be explored is the technically recoverable resource (TRR) of shale gas. The analysis phase aims to answer two questions. Firstly, how does shale gas development affect import dependency? Secondly, through which mechanisms can the observed behaviour be explained? The article will conclude with a reflection on the added value of the multi-method approach and make recommendations for the development of this methodology.

2. The models

Two models are used to analyse the effects of shale gas development on the global gas market, one SD model and one AB model. The SD model is a modified version of the model discussed in De Jong, Auping & Govers (2014). The agent-based model has been developed specifically for this study. Figure 2 displays the general flowchart for the agent-based model. Both models share similar mechanisms for some parts of the system, though for other system components the characteristics of each method require a different implementation. This section describes the conceptualisation and formalisation for both models, concluded by an overview of the case-specific differences between both models.

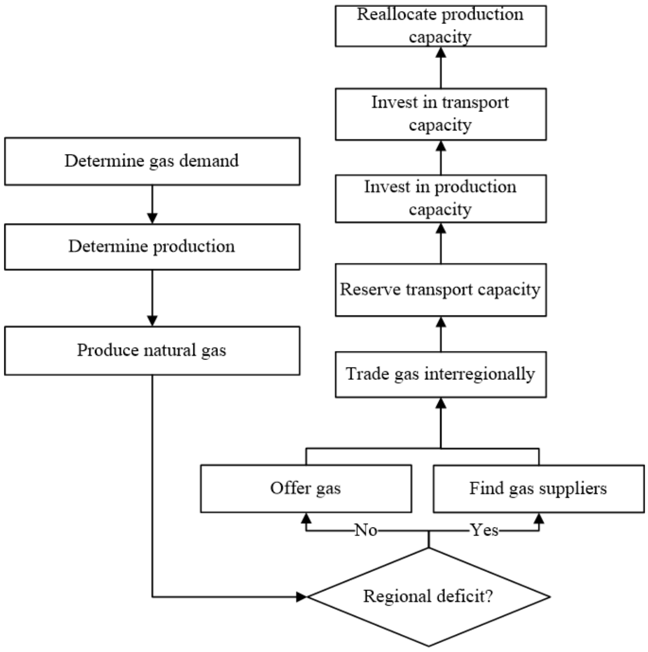

Figure 2: General flowchart for the agent-based model

2.1 General modelling choices

The gas market consists of production, trade, transport and consumption. The interplay between these aggregate-scale components determines the gas-price, which on its turn influences how the system develops.

The TRR consists of conventional gas resources and shale gas resources. A paradigm of exhaustible resources as described in Tilton (1996) is used to model resource depletion. This paradigm assumes a fixed resource base, from which resources can be extracted using current technology. The production capacity determines how much of the TRR can be extracted annually. Investments in production capacity are based on profit margins.

The costs of resource extraction are influenced by two main determinants, i.e. a learning effect and a resource depletion effect. The learning effect decreases costs because extraction processes become more efficient as more experience is gained and technological advances are applied, while the resource depletion effect increases costs due to the decreasing pressure in gas fields as more gas is withdrawn and because new fields are likely to be further away from demand centres and harder to develop.

Economic growth is the main determinant for the level of gas demand. Fluctuations in price however induce substitution of gas demand by other forms of energy. As energy consumption is usually preceded by significant up-front investments in equipment – e.g. central heating systems, power plants, combustion ovens – the amount of energy that can be substituted each year is limited. In addition to the income effect and the substitution effect, price changes also lead to changes in energy demand in general.

In order for demand to be met by supply, gas is traded through pipelines and via LNG terminals, limited by their annual throughput capacity. For LNG, the infrastructure is made up of gasification (receiving/import) terminals and liquefaction (export) terminals. Investments in infrastructure are based on their usage. A high average use induces upgrades in the throughput capacity of pipelines and LNG terminals.

2.2 Differences between models

The SD model and the AB model differ on a number of aspects. Some of these differences are method-induced, meaning that the specifics of the modelling method forces a different implementation, whilst others are the result of modelling decisions. This is however not an issue; the goal of this study is not to compare or benchmark SD and ABM, but to use them in parallel to obtain a richer set of scenarios for the gas market. The most important differences will be discussed briefly.

Price

For both models the price is dependent on the balance between supply and demand, as well as the costs of extraction and transport. The price is calculated as a cost-plus price, in which the actual costs of extraction and transport form the basis, supplemented by a profit based on the ratio of supply and demand. This ratio includes supply and demand of other regions over the transport infrastructure. In the AB model a distinction is made between the profit of gas sold within the region and gas that is exported to other regions. Shortages increase this profit margin, while oversupply decreases the profit margin.

Substitution

The SD model makes use of the subscripting feature in the software environment of Vensim to simulate not only the gas market, but also the markets of oil, coal, hydro, nuclear and renewables. This way, sophisticated substitution can take place based on the relative price differences. The AB model assumes that the price of other energy carriers remains constant and uses a price elasticity to reflect substitution due to gas price changes.

Physical infrastructure

The modelling software Netlogo, used for creating the AB model, allows for the integration of a physical network. For the gas market, this physical network consists of pipelines connecting regional gas networks. Including this physical network makes it easy to include transport limitations. The SD model only includes the LNG infrastructure, assuming no pipeline transport will take place between the defined regions.

Trade

Both models take the intraregional supply as the basis for its gas demand. For some regions this is not sufficient, hence import from other regions is required to meet its gas demand. The algorithms used to trade gas are implemented differently across the two models. The SD model makes use of Vensim’s built-in allocation functions. As NetLogo does not offer such functions, gas is traded in a two-step procedure. First, all regions offer their excess supply on the global market. Next, in random order, regions with gas shortages will buy gas from the global market, constrained by its import capacity. This will reduce the amount of gas available to other regions. Due to this stochastic element in the model the experimental design contains multiple repetitions of each run.

3. Model behaviour

The EMA workbench (Kwakkel, 2014), developed in Python, is used to run experiments with both models. A total of 10.000 experiments (runs) is carried out, 5.000 for each model. Since the AB model contains probabilistic functions, each run is repeated five times and averaged. These 5.000 experiments are partly identical, i.e. the parameterisation of the shared uncertainties is equal in both models. This allows for a pairwise comparison of simulation outcomes, providing insight into the differences across the two models. For each experiment the shared uncertainties are complemented with model-specific uncertainties to create a complete sample of uncertainties for each model. The simulation runs result in two datasets, one containing the parameterisations of uncertainties for each experiment, the other containing the values of performance indicators over time (outcomes), grouped by the model that generated these outcomes.

3.1 United States and Canada

Figure 3 shows the import dependency of the USCA region. Both models show that in many scenarios import dependency will remain below 20%. However, there are a few scenarios in both models that show considerably higher import dependencies. In the SD model, a number of scenarios show a rapid increase in import dependency around 2025-2030, resulting in an import dependency of over 50% by 2050. The AB model shows scenarios with a steep increase of import dependency as early as 2015, which further increase to an import dependency of over 90% by 2050. When looking at these scenarios, the first question that comes to mind is: under which circumstances could import dependency in the USCA region become that high? A second question that arises is: why does import dependency in particular scenarios increase so rapidly?

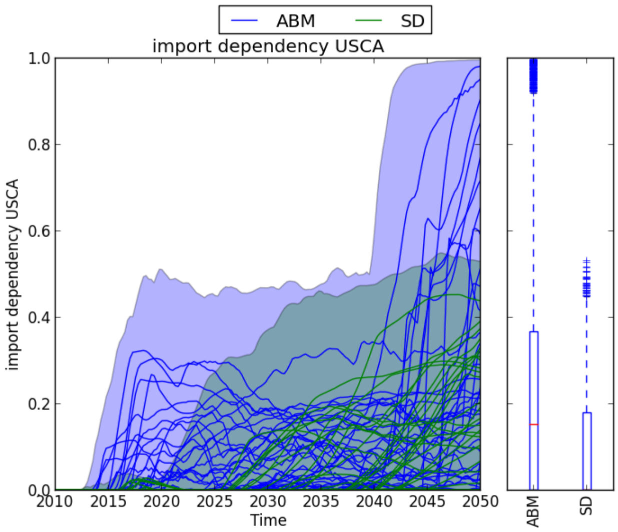

Figure 3: import dependency in the USCA region

Explaining high import dependency scenarios

In order to answer the first question, PRIM is applied to find the uncertainty space that explains the high import dependency scenarios. For the AB model all scenarios with an import dependency of over 80% by 2050 are selected. The analysis shows that these scenarios are explained by four uncertainties: the *averaging period for energy prices*, the *depletion parameter*, the *initial shale resources USCA* and the scenarios for economic growth.

Firstly, as shale gas resources are a substantial part of total gas resources, low shale gas resources make that total gas resources are low too. This causes domestic gas production to be insufficient to cover demand, hence imports are required. A high *depletion parameter* causes production costs and thus prices to rise sharply when resources are becoming scarce, making imports more attractive and thus import dependency is likely to rise. This is fuelled by a low *averaging period for energy prices*, which makes that actors base their decisions to a larger extent on short-term prices than on long-term prices. A *low averaging period for energy prices* effectively decreases the smoothing of energy prices, making the gas market more volatile and responsive to changes such as a rapid increase in the costs of regionally produced gas. Finally, the scenarios for economic growth that are linked by the PRIM algorithm to high import dependency are all scenarios that include strong economic growth for the USCA region. Economic growth causes gas demand to rise, and given the low domestic gas resources and high costs of production, regional production is insufficient to supply the higher levels of gas demand.

Although the SD model does not show import dependency scenarios of over 80%, it does include scenarios which could pose a threat to energy security in the USCA region. Hence, for the SD model all scenarios with an import dependency of over 35% by 2050 are selected. Here the PRIM analysis indicates that two economic growth scenarios largely explain the high import dependency scenarios. Similar to the PRIM analysis of the AB model, these scenarios show high economic growth over the simulated period, resulting in increased demand and hence increased prices. The second uncertainty linked to the high import dependencies in the SD model is a low *effect of long term regional prices on economic growth*, which enables the economy to grow despite the high gas prices. This limits the strength of the negative feedback loop in the economy, where economic growth results in higher demand and hence increased prices, which in turn should slow down the economy.

Rapid increase in import dependency

In the AB model scenarios two rapid increases in import dependency are visible: the first increase occurs around 2015, while the second increase occurs around 2045. In order to explain these increases, additional KPIs are required. Firstly, Figure 4 displays the gas demand in the USCA. This graph shows that gas demand scenarios are not volatile, and no peaks in demand are visible around 2015 or 2045. If demand is stable, then the increase in import dependency arises from a collapsing domestic gas production. Figure 5 and Figure 6 display the total production for the import dependency scenarios characterized by a peak around 2015 and 2045, respectively. Based on these graphs, the rapid increase in import dependency around 2015 and 2045 can be linked to a rapid decrease in total domestic gas production. The rapidly declining production in 2045 can be explained by the depletion of gas resources and consequent exponentially increasing production costs, but the early decrease in production is less easily understood. Using PRIM, the uncertainties linked to these scenarios can be found. It appears that a high *divestment threshold* and a high *averaging period for energy prices* are related to these scenarios. A high *divestment threshold* means that nearly all production capacity has be used within a year, or else any excess capacity will be removed. Further analysis shows that this is exactly the

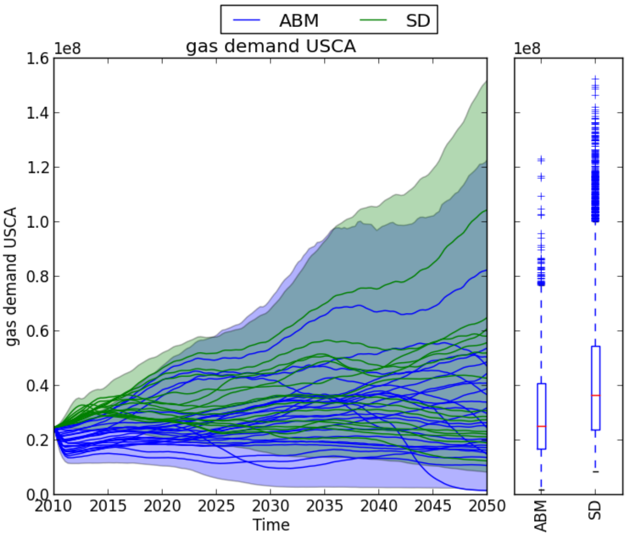

Figure 4: gas demand USCA

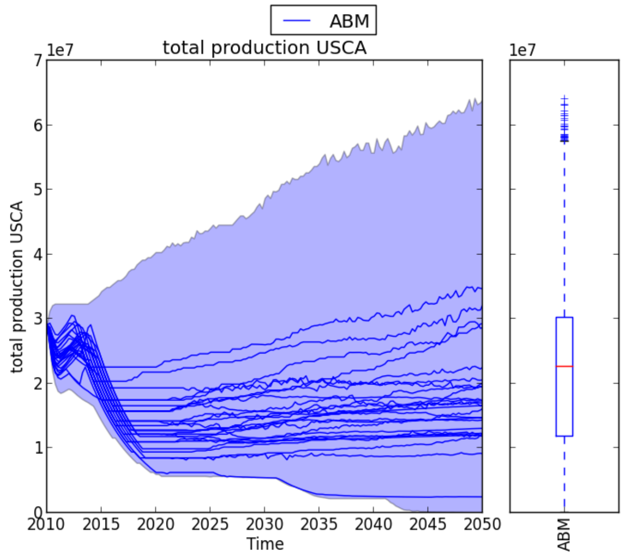

Figure 5: total production USCA for specific scenarios (2015)

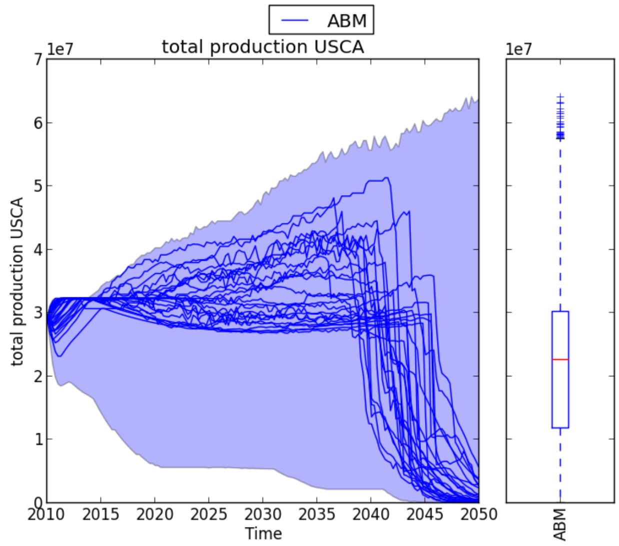

Figure 6: total production USCA for specific scenarios (2045)

case. In these scenarios some overcapacity exists on the global gas market during the 2010-2020 period, and due to the limited export options of the USCA region both via pipeline and LNG tankers, the excess capacity in this region is likely to remain unused. The high *divestment threshold* makes that this capacity is removed from the system. In addition, the high *averaging period for energy prices* causes divestment to continue even after the capacity utilisation rate goes up, because of the long-term trend of overcapacity.

The SD model shows scenarios in which import dependency rapidly increases between 2020 and 2030. PRIM analysis links scenarios of high economic growth and a low *lead time for LNG facilities* to the peak in import dependency. As high economic growth is directly related to gas demand, an increase in gas demand should be visiible around 2030. Figure 7 shows that this is actually the case, as for some scenarios, gas demand nearly doubles between 2025 and 2035. Domestic production is incapable of keeping up with demand, hence imports are required to supply the increased demand. As the USCA region is due to its geographical location not connected by pipeline to any of the other regions, the domestic supply gap can only be filled by importing gas in the form of LNG. This is where the second uncertainty linked to the import dependency increase plays an important role. A low *lead time for LNG facilities* allows the quick ramp-up of infrastructure required to import LNG, enabling import dependency to increase.

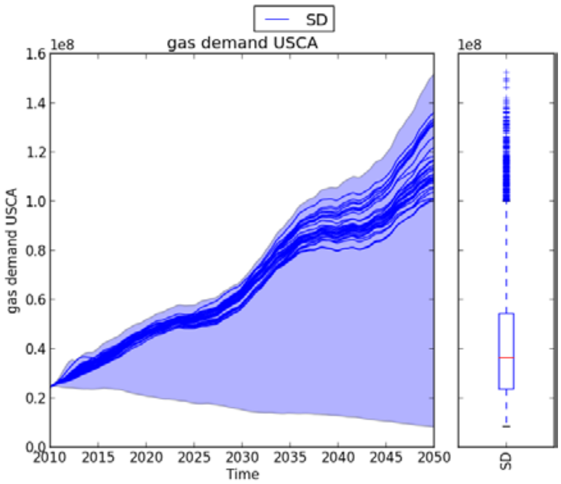

Figure 7: gas demand USCA for specific scenarios (2030)

Low import dependency

Considering figure 3, there is a large number of scenarios that show that import dependency remains below 10% during the simulated period. PRIM analysis shows that the uncertainties related to these scenarios are mostly opposite to those related to the high import dependency scenarios: low economic growth and high *shale gas resources USCA*. In addition, in the SD model also a low *amplifier relation demand and supply* is linked to low import dependency scenarios, which prevents that prices rise quickly in the USCA region when the supply demand ratio decreases. High prices would make imports from other regions more attractive.

3.2 The Far East

Figure 8 displays the import dependency of the Far East region. It can be seen that import dependency in this region could develop in very diverging ways. Departing from the current high level of import dependency, it could decrease quickly or slowly, stay at a high level, or even increase. In addition, the dynamics of these scenarios are also interesting, with both rapid and dramatic changes in import dependency over time. In order to inform policy-making processes on energy security in the FE region, it is relevant to evaluate which uncertainties are linked to scenarios of both high and low import dependency over the simulated period.

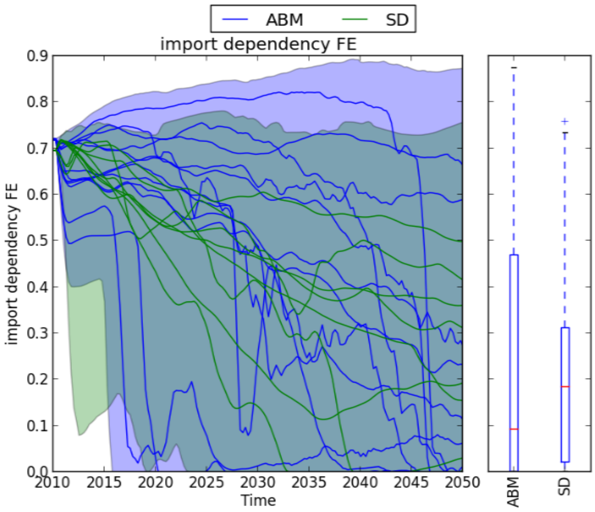

Figure 8: import dependency in the FE region

High import dependency

High import dependency is, for this particular region, defined at 60% percent or higher by 2050. In figure 9 these scenarios are displayed in solitude. They effectively maintain the status quo of this region, in which a large majority of the natural gas demand is met by imports. With the use of PRIM the uncertainties can be found that are linked to these scenarios. For the AB model, it has been found that three uncertainties are linked to high import scenarios in the FE region. Firstly, a high economic growth makes that gas demand will be higher too, and could create a situation where an increase in domestic production is offset by the increase in demand. This is confirmed by figure 10, in which it is visible that in these scenarios at least a doubling of gas demand by 2050 is expected. Secondly, large shale gas resources in the USCA region are also related to

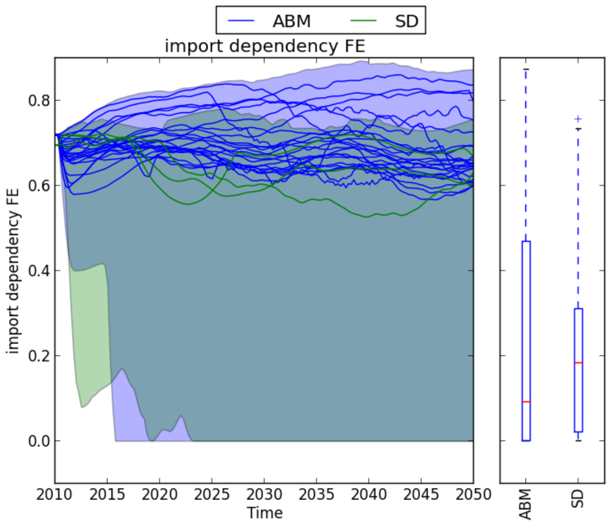

Figure 9: high import dependency scenarios in the FE region

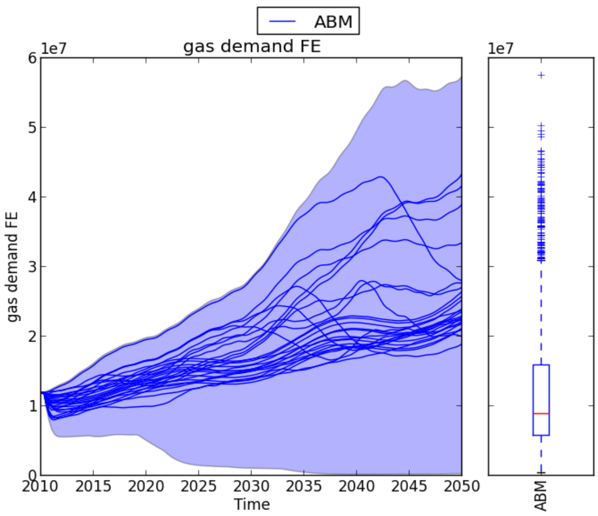

Figure 10: gas demand FE for high import dependency scenarios

high import dependency scenarios in the FE region. The wide availability of shale gas resources implies a wide availability of cheap natural gas in the USCA region, which could be exported to other regions. Thus, the global gas market in general and the FE region in specific is provided with an option to meet domestic gas demand without having to invest in regional production capacity. Moreover, importing gas from the USCA region might even be cheaper than producing gas domestically. This is studied in more detail in the next section. The third uncertainty related to high import dependency in the FE region is a high *delay time for new capacity*. This makes that it takes too long for suppliers to respond to an increase in demand and that production cannot keep up with demand growth.

PRIM analysis on the SD model provides a partially different explanation for the high import dependency scenarios. Firstly, a low *supply elasticity* is associated with these scenarios. A low *supply elasticity* makes that large changes in gas price result in only small changes in production capacity. Hence, when prices are increasing in the FE region, domestic production increases only with a fraction of the increase in price. This way, domestic production will not come to a point where it is large enough to reduce import dependency. Secondly, scenarios of medium economic growth in the FE region are linked by PRIM analysis to the high import dependency scenarios. The same economic growth scenarios also cause low economic growth in the GE region. Being the largest region in terms of gas consumption, the developments in this region have a large impact on the global availability of gas. Limited economic growth here means that gas demand in the GE region is limited, which makes that a sufficient amount of gas is available for export to other regions, in particular the FE. Hence, the FE is provided with an option to import gas from the GE region against relatively low prices, similar to how high gas resources USCA are linked to the high import dependency scenarios generated by the AB model.

Low import dependency

Low import dependency is defined as 20% or less by 2050. Figure 11 displays a number of scenarios that satisfy this definition. These scenarios are very relevant to the FE region, as they allow for a dramatic decrease in import dependency compared to the current situation, in which over 70% of all gas comes from imports. Hence, the circumstances under which these scenarios emerge are very relevant to policymakers trying to reduce import dependency in the FE region.

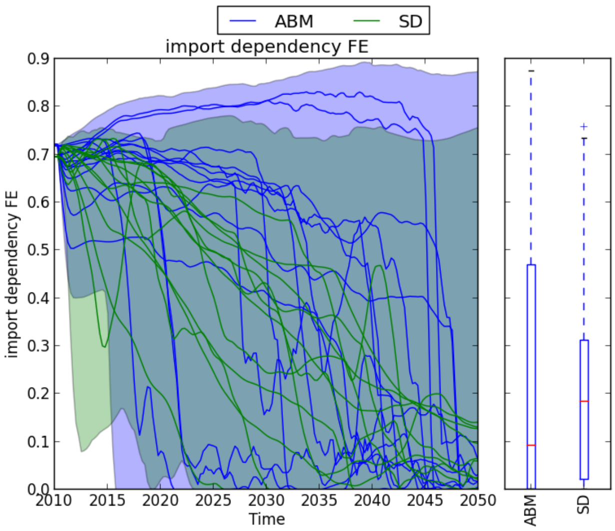

Figure 11: Low import dependency scenarios in the FE region

Firstly, the uncertainties that are linked to the low import dependency scenarios in the AB model will be revealed using PRIM. It appears that again an economic growth scenario largely explains these high import dependency scenarios. The specific scenario shows limited economic growth in the FE region, which is confirmed by figure 12, in which it is visible that low import dependency scenarios go together with low gas demand scenarios. In addition, this scenario also causes high economic growth in the USCA region. High economic growth here causes high gas demand, which makes gas produced in the USCA region unavailable for import by other regions, in specific the FE region. Hence, the FE region is forced to increase its own production in order to supply the domestic gas market. PRIM analysis with the SD model relates the highest economic growth scenario in the FE region to the low import dependency scenarios. This appears to be in sharp contrast with the outcomes of the same analysis with the AB model, where limited economic growth was linked to low import dependency in the FE region. However, despite the high economic growth scenario linked to low import dependency in the SD model, no relation between a high gas demand and a low import dependency could be found for the FE region. In figure 13 it is visible that a low import dependency is possible for varying levels of demand. Coincidentally, the high economic growth scenario in the FE region also creates high economic growth in the GE region and

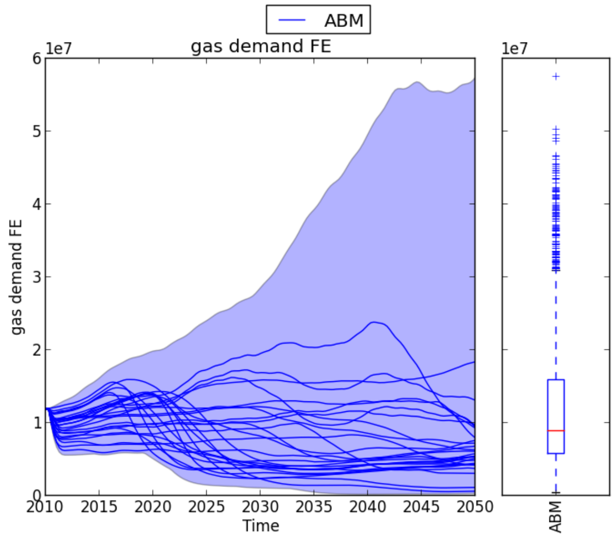

Figure 12: gas demand in the FE region for low import dependency scenarios (ABM)

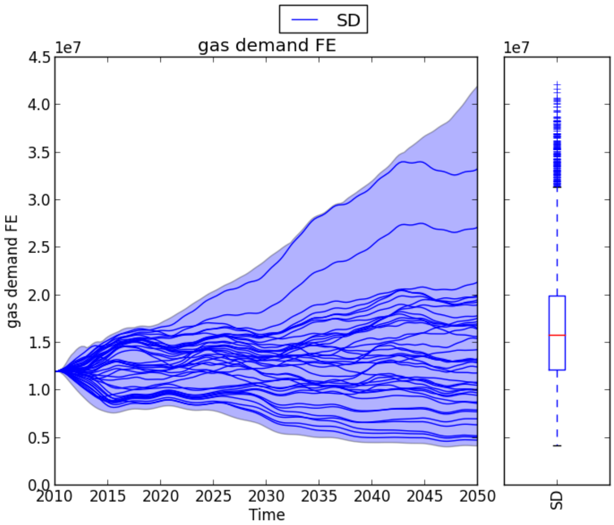

Figure 13: gas demand in the FE region for low import dependency scenarios (SD)

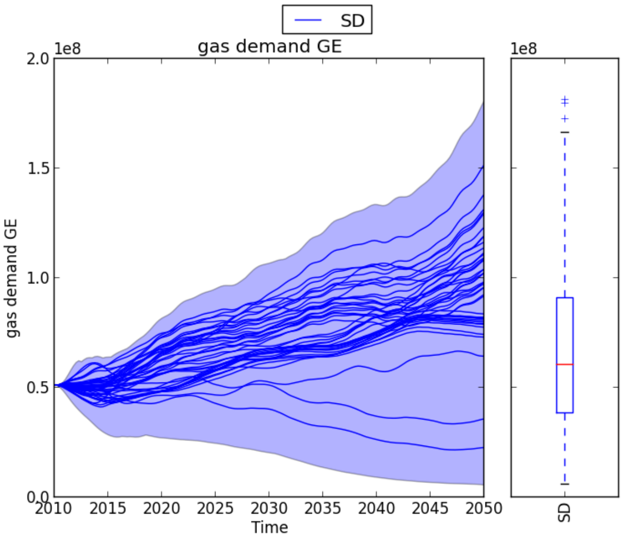

Figure 14: gas demand GE for low import dependency scenarios in FE

corresponding high gas demand. It appears that high gas demand in the GE region is strongly related to low import dependency in the FE region, as is shown in figure 14. A high gas demand in the GE region increases pressure on the global gas market, reducing the amount available for export to the FE region and thus forcing the FE region to increase domestic production to satisfy their demand. Similarly, high gas demand in the USCA region is found to be related to low import dependency in the FE region.

The gas sourcing algorithm is price-driven for all regions, which means that the price of gas forms the main criterion when regions are deciding on how to satisfy their domestic gas demand. The high costs of domestic production in this region make that as long as a sufficient amount of gas could be imported from other regions, increasing domestic production is inefficient from an economic point-of-view. Thus, it is expected that scenarios of low import dependency in the FE region come at a cost in the form of higher gas prices, compared to the high import dependency scenarios. However, when considering figure 15 and figure 16, the opposite appears to be true. Although the difference is small, the price scenarios associated with low import dependency in figure 12 show lower gas prices during the first 20 years of the simulation. A similar but stronger relation exists between the low import dependency scenarios in the FE region and the gas prices in the GE and USCA region, as also here low gas prices are associated with low import dependency in the FE region. The causal mechanism through which this works is simple: less imports from the FE region means a lower global supply-demand ratio, reducing gas prices in other regions.

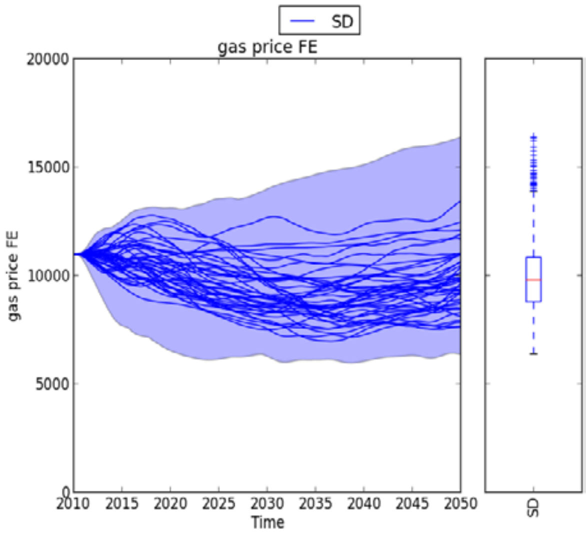

Figure 15: gas price scenarios FE

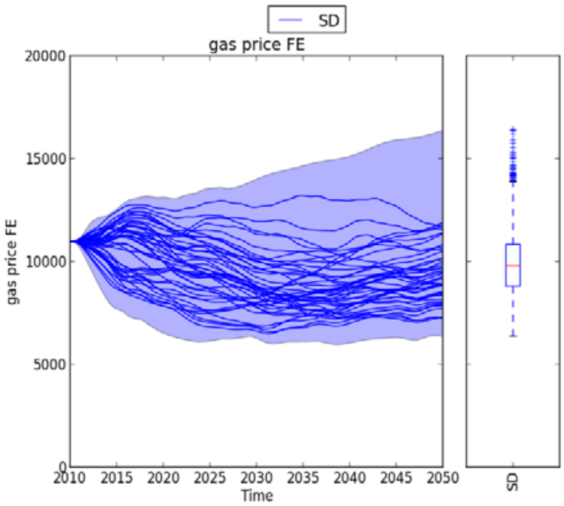

Figure 16: Gas price FE for low import dependency scenarios

3.3 Greater Europe

Figure 17 displays the import dependency scenarios for the region of Greater Europe, from which it could be concluded that in most scenarios, import dependency will remain below 10%. The difference between both models is explained by differences in the way gas sourcing is implemented in both models, as described in section 2.2. Nevertheless, the AB model shows a few scenarios in which import dependency is higher, increasing to over 50% by 2050 for the most extreme import dependency scenario in the GE region. The highest import dependency scenario generated by the SD model remains below 15%, and is therefore not considered for further analysis. PRIM analysis points out that uncertainty in the size of gas resources in the CIS region is related to the high import dependency scenarios. Being the largest producer of natural gas, the resources of the CIS region are important for the total gas production of the GE region in general. If actual gas resources turn out to be on the lower end, the GE region could import up to 50% of its natural gas, when no additional policies are implemented aimed at keeping import dependency low.

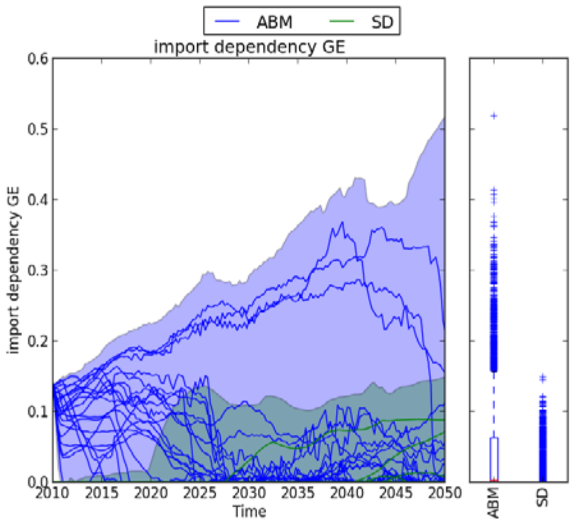

Figure 17: import dependency in the GE region

Low import dependency

As is visible in figure 17, the majority of scenarios in both models predicts an import dependency for the GE region of nearly zero. Given the large gas resources in mainly the CIS and MENA region, this is no surprise. Due to the large number of low import dependency scenarios, no specific uncertainties can be found using PRIM that are related to these scenarios.

4. Conclusion and discussion

4.1 Synthesis

Section 3 provided the import dependency scenarios per region. With the use of PRIM, the uncertainties related to both high and low import dependency have been revealed. Table 2 summarises the outcomes of the PRIM analyses. What can be concluded by looking at this table, is that economic growth plays the largest role in explaining import dependency, as each performed PRIM analysis included at least one economic growth scenario. Since economic growth is strongly related to natural gas demand growth, it can be stated that import dependency across all regions is strongly demand-driven. In general, low demand growth is associated with low import dependency, and high demand growth is associated with high import dependency. This relation can be observed in both models, and the causal mechanism explaining this relation is relatively simple: a lower demand makes it easier for regions to obtain a higher degree of self-sufficiency, because the gap between demand and domestic supply is smaller. Similarly, in high demand scenarios, demand growth could outpace growth in domestic production, resulting in increased import dependency.

Table 2: uncertainties related to import dependency scenarios

	AB model		SD model	
	Low dependency	**High dependency**	**Low dependency**	**High dependency**
USCA	Low domestic economic growth, high shale gas resources	High domestic economic growth, low shale gas resources, high depletion parameter, low averaging period for energy prices	Low domestic economic growth, low amplifier relation demand and supply	High domestic economic growth, low feedback effect of gas prices on economic growth
FE	High economic growth USCA	High domestic economic growth, high shale gas resources USCA, high delay time for new capacity	Low amplifier relation demand and supply, high economic growth GE	Low supply elasticity, low economic growth GE
GE	N/A	Low global economic growth, high shale gas resources USCA	N/A	N/A

An exception to this rule is found in the explanation of import dependency in the SD model, for the FE region. Here, high demand is linked to low import dependency, but this demand is not the domestic demand. Instead, the relevant demand uncertainty is that of the GE region. Strong demand growth in the GE region forces the FE region to produce more gas domestically, as the global gas market becomes undersupplied. Conversely, low global demand growth makes that gas is widely available against low prices, which does not create an incentive for the GE region to produce more gas domestically. The differences between the effects of economic growth in the USCA region versus the FE and GE region emphasises that multiple mechanisms are at work in the gas market, and complex, nonlinear relations exist between system components. Depending on the specific assumptions and uncertainty parameterisation, the system could develop in different ways.

Another observation that could be made based on Table 2 is that in some cases, the explanation for either high or low import dependency in a specific region is found outside the region itself. For example, this is the case for the high import dependency scenarios generated by the SD model for the FE region, where low economic growth of the GE region is found to be crucial in explaining these scenarios. Also the high import dependency scenarios of the FE region generated with the AB model are explained by an uncertainty related to a different world region, i.e. the shale gas resources of the USCA region. Here, wide availability of cheap shale gas from the USCA region makes it attractive for the FE region to continue relying on imports for its gas supply. The same logic goes for the GE region, for which its high import dependency scenarios are also partially explained by the high shale gas resources in the USCA region.

4.2 Towards the design of policies

The fact that in some cases scenarios are explained by uncertainties linked to other regions, does not directly imply that no effective policies can be designed. However, for policies to be effective, they should be robust for both models, meaning that the policy yields good results, regardless of the model in which the policy is implemented. Moreover, a perhaps even bigger challenge is to find policies that can be implemented in both models. This requires that the system component or variable used as application point for the policy measure exists in both models, or that at least an equivalent exists in the other model. Looking at Table 2, the economic growth scenarios are pointed out by both models as being of crucial importance for lowering future import dependency. There are, however, numerous issues with using the economy as a whole as a leverage point for reducing import dependency. First and foremost, slowing down economic growth to reduce import dependency would have enormous negative side effects and most likely will inflict enormous costs on national and regional governments. Secondly, the economy of a region is an extremely large and complex system on its own, which cannot simply be steered in a direction. Thirdly, the economy moves only very slowly, hence the effects of policy measures implemented here can take decades to materialise.

Moving closer to the gas market, policies aimed at reducing or increasing gas demand may have more direct effects on import dependency. For the USCA region, policies aimed at reducing gas demand may decrease import dependency. With the use of subsidies and taxes, consumers of gas, whether industrial, commercial or household, may be stimulated to switch to other energy sources that are more widely available within the USCA region. However, natural gas currently is the cheapest and cleanest fossil fuel in the USCA, implying that a switch away from gas as the most important fuel could come at significant costs, both financially and environmentally. In addition, the positive effects on energy security – the higher goal of import dependency – might be limited as this policy increases dependence on a different energy source and makes the energy supply less diversified.

A better way would be to reduce gas demand sustainably, without the need to replace the loss in gas demand by other energy sources. One way to do this is to focus on increasing energy efficiency, as when less energy is lost, less energy is needed in general. There are many ‘locations’ where natural gas can be saved, for example in the built environment by improving on isolation, or in large-scale power plants where natural gas is converted to electricity. A second way to lower gas demand is by making the economy less energy-intense; switching from an energy-intensive manufacturing economy with goods as the main output to a knowledge economy with services as the main output would also decrease energy demand. Given the important role of natural gas in chemical and industrial processes, gas demand would decrease proportionally if such a switch were to occur.

Though, also policies aimed at reducing gas demand sustainably have their downsides. Reforming the economy puts large requirements on education of the workforce, which changes only slowly over time. Also the effects of policy measures aimed at increasing energy efficiency could potentially take a long time to materialise, because of the large investments that are associated with gas-consuming equipment. Replacing gas-fired power plants and residential heating appliances before their end-of-life might be costly, and only the availability of more efficient equipment could be insufficient for convincing consumers to replace their equipment. A positive side effect exists in the form of reduced carbon emissions due to the reduced energy demand, an issue of global importance. The goal of lowering import dependency could be combined with the goal to reduce carbon emissions, making the case for increasing energy efficiency stronger.

For the FE region policies aimed at reducing domestic demand are less effective, as PRIM analysis pointed out that import dependency here is mainly dependent on gas demand in the GE region. Even if the FE region could influence gas demand, it would still be uncertain in which region gas demand should change, since the AB model links high gas demand in the USCA region to low import dependency FE, whereas the SD model links high gas demand GE to low import dependency FE. In both cases, the developments in the GE region affect the domestic production level in the FE region, which forms the direct cause for the lower import dependency scenarios. Hence, policies aimed at the supply side might be more effective in the FE region. Here, increasing domestic production provides an opportunity to reduce import dependency regardless of the developments elsewhere in the world. The FE region possesses sufficient shale gas resources to reduce import dependency, but the initially high costs of producing these resources is holding back the build-up of production capacity. A policy that helps overcoming these initially high production costs could spur the production of shale gas, thus reducing import dependency. Another indication for why policies should be aimed on the supply side, is the high *delay time for new capacity* that is listed in Table 2 as one of the causes for the high import dependency scenarios generated by the AB model. A policy aimed at reducing this delay time, for example by shortening the licensing process for new drillings, could hence reduce import dependency. Finally, the low *supply elasticity*, listed as a cause for high import dependency scenarios generated by the SD model, forms another indication that policy measures on the supply side might be beneficial for the FE region.

Also the GE region might benefit from policies aimed at increasing domestic gas production. The import dependency graphs provided in section 3.3 show that a low import dependency is technically possible in this region, but in some scenarios the incentive to increase domestic production is missing, i.e. when a global oversupply of gas exists or when a large amount of low-priced shale gas from the USCA region is available. The policy here should be aimed at providing an incentive to source gas regionally instead of importing it from other regions, which could be done in multiple ways. One option is to make regionally produced gas more attractive, for example with the use of subsidies. Another option would be to discourage the import of gas, by applying extra levies on them.

There are a few variables listed in table 2 linked to low import dependency that cannot be used by policymakers as leverage points for policy measures, mainly because these uncertainties are characteristics of the gas market. For example, the uncertainty *amplifier relation demand and supply* is linked to low import dependency scenarios in both the USCA and FE region, but refers to the amplifying effect of the supply-demand ratio on prices. A low amplifier means that gas prices are relatively insensitive to changes in the supply-demand ratio. However, there is no way for policies to directly affect the price-setting mechanism, as this is done by the market. Also the *depletion parameter, averaging period for energy prices* and *feedback effect of gas prices on economic growth* are not suited for policy measures to be applied on.

In order to test the effectiveness of the proposed policies for lowering import dependency, they should be implemented in both models. A policy that lowers the *delay time for new capacity* could be directly implemented in both models, which also goes for policies that either subsidise or enact levies on the import of gas. The proposed policies that work on the demand side of the gas market cannot be directly implemented, but require more detail in the way demand is modelled. A breakdown of gas demand into industrial, commercial and residential demand is necessary in order to implement and test these policies.

4.3 Limitations & recommendations for improvement

The models that have been used in this analysis have complemented each other on multiple aspects. The SD model features interaction with other energy sources, makes use of sophisticated demand allocation functions for trading energy, and contains detailed pricing mechanisms. The AB model includes the interregional pipeline network, maintains a lower aggregation scale, and is more detailed in the costs of transport. Despite the complementarity of the models, they still are limited in the extent to which they accurately describe the gas market. The limitations regard the scope of the model and the level of detail, as well as the way experiments are set up and iterated. This section discusses these limitations, and provides suggestions on how to improve gas market research.

Decrease aggregation scale

The agent-based model currently consists of six regions, whereas the SD model contains four regions. These regions more or less reflect the main gas trading markets. In the AB model, these regions are represented by agents. These region agents hence represent all gas producers, consumers, traders, storage and transport capacity operators. A more disaggregated model would include these actors as individual agents, which will provide insight in the inter-actor dynamics. It is likely that a lower aggregation scale will also affect system level behaviour, as each agent pursues its own goals. In a similar fashion, decreasing the aggregation scale from region to nation will affect system level behaviour, because each nation is different in terms of resources, production capacity, the share of gas in the energy mix et cetera. Also, the market is organised differently per nation, with regard to the pricing mechanisms, the amount of governmental influence and the extent to which (gas sourcing) decisions are made on a central level, and trading contracts.

Decreasing the aggregation scale to the level of individual producers and consumers is possible for the AB model, but would become quite complicated in the SD model. Similarly, decreasing the aggregation scale to the level of nations would become complicated in the SD model, though it is not impossible. ABM is suited for low aggregation scales, but it would create additional data requirements. Accounting for differences in the organisation of national gas markets is possible with both methods, but requires a lot of effort to create such a detailed model.

Improve contracting procedures

The current AB model allocates gas demand on an annual basis, in contrast with the SD model, where gas is traded continuously. In reality, gas is traded via various types of contracts, including complex contracts spanning over multiple decades with periodical contract revision. Including these more detailed contracts in the models could affect the dynamics of the gas market and would offer a more realistic representation of gas trade. Long term contracts effectively create delays in the system, whereas spot market trading makes the system more flexible and volatile.

Include intraregional gas networks

Both models simulate only the interregional transport network and assume that within each region gas can flow freely without limitations. In reality, also intraregional networks are limited in terms of transport capacity and congestions could occur. For example, natural gas produced in Egypt might be unable to flow to Northern Europe due to transport limitations within Europe, even if sufficient interregional capacity exists between Europe and Egypt.

Improve exploration of uncertainties

The current set of uncertainties includes 46 variables. Although the initial set of uncertainties included over 150 variables, 46 is still too many to fully explore the impact of these uncertainties. An iterative approach should be applied in which the uncertainties that appear to have a large influence on the results are further explored, filtering out the uncertainties that have no significant effect on model outcomes. For example, more detail in the economic growth scenarios would make it easier to reveal which growth scenario in which specific region is related to high or low import dependency. The current approach, in which a single global scenario in fact entails 6 scenarios, one for each region, makes it difficult to assess which regional scenario is related to the observed behaviour.

Include investment costs

In the current AB model, the costs of investment in transport and production capacity is not considered. Currently, capacity is upgraded according to the rate of utilisation, and investment costs are integrated into the price per unit of gas sold. In reality, these large investments are made based on a detailed cost-benefit analysis, accounting for the time value of money. Breaking down costs into operational costs and investment costs would provide a more realistic insight into the actual costs of the gas production system. If policies are to be implemented and evaluated, a more accurate view on the costs of gas supply is critical.

Include social aspect

One of the major points of improvement concerns the inclusion of social factors. In the current models, gas resources can be exploited without any limitations. In reality, there are a plethora of factors that make that only a limited amount of these resources can be exploited. In many countries in Europe, the lack of public acceptance for fracking, the process associated with the extraction of shale gas, has resulted in a provisional ban on test drillings for shale gas. Although the conditions might change in the future, not taking into account the limitations in (shale) gas production is insufficient.

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