Modelling the economic and political dimensions of the European gas market:

Evaluating the merits of co-simulation modelling

L. van den Buijs

Modelling the economic and political dimensions of the European gas market:
Evaluating the merits of co-simulation modelling

by

L. van den Buijs

to obtain the degree of Master of Science
at the Delft University of Technology

Student number:	4155947	
Thesis committee:	Dr. A. F. Correljé,	Values, Technology and Innovation, TU Delft
	Dr. ir. J. H. Kwakkel,	Multi-Actor Systems, TU Delft
	Dr. ir. W. L. Auping,	Multi-Actor Systems, TU Delft

TU Delft

Summary

In the beginning of 2018, Germany and Russia finalised their agreement to expand their gas transport capacity via the construction of the Nord Stream 2 gas pipeline (Witte & Beck, 2018). Eastern European Union (EU) member states have objected to the proposal as they fear it will make them more dependent on Russian gas (De Carbonnel, 2017). The commotion caused among EU member states by these plans showcases how conflicting economical and political interests divide the EU when it comes to the European gas market. Furthermore, it shows how the combination of political and economical dimensions shape the European gas market into a complex issue.

The essential interaction between the economic and political complexities form a system too complex to analyse via mental simulation (Sterman, 1994). Therefore, a quantitative simulation is necessary in order to gain a better understanding of the EU gas market. On the economical side it is important for such a simulation to model the regional energy markets (i.e. the interaction between energy demand, economic growth and the energy distribution over a variety of sources) and to account for the influence of the global energy market on energy prices. When it comes to the political side of the issue, it is important that the simulation is able to operationalise the different goals and perspectives of countries. Furthermore, the gas trade between countries has to be represented. In addition to both the economic and political dimensions, the quantitative simulation has to account for uncertainty that comes from technological developments affecting the gas market, uncertainty in the construction costs and time of transport capacity as well as the behaviour of the countries itself.

When it comes to a quantitative analysis of the EU gas market, several models have already been developed, most of which focus on the market mechanics of the gas trade. Most of these models do not simulate the impact of the world energy market on energy prices, with a few doing so exclusively with regards to gas prices. These models each take on of three different perspectives through which the gas trade is modelled: market agents (e.g. pipeline operators, producers, traders, liquefiers), current infrastructure and gas flows and countries themselves. Furthermore, while most of these models acknowledge the importance of regional demands and developments, non of the models actually simulate these developments and only specify regional needs via the used input data. Lastly, it is import to note that only a few of these models deal with uncertainty.

In general the existing models do not properly combine both market forces and political influences in their simulation. This is because the used formalisms limit their scope. For example, a network model simulating gas disruption within the EU gas supply is not able to capture regional energy market developments.

Co-simulation modelling can help solve this issue as it allows for different dimensions within a system to be included in different sub-models, using the appropriate formalism for each. In the case of the European gas market, both an economic and a political dimension have been identified. System dynamics (SD) (Forrester, 1961) is a well suited modelling method for the economic dimension, where as Agent-based modelling (ABM) (Epstein & Axtell, 1996) is more suitable for simulating the political dimension.

In order to explore the merits of using co-simulation to model the European gas market a rudimentary co-simulation model of the European gas market has been developed as a proof-of-principle. Combining the models is possible by defining an overarching model in Python (Van Rossum, 1995) which calls upon both system dynamics and agent-based models. One SD model, the SD Regional Energy model, models the energy markets on a national level and has been independently used for each country included in the model. A second SD model, the SD Energy Price model, uses information from the first sub-model to simulate the world energy prices. Lastly, an AB model, the AB Gas Market model, has be used to model the gas trade from the perspective of countries.

The synchronisation of the three sub-models forms an important challenge when developing a co-simulation model. First, the two SD models have been synchronised. The fact that both models are continuous in time is important when considering the synchronisation method. The two sub-models have been synchronised using the lock-step approach to co-simulation (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010). This approach runs both sub-models sequentially for set time steps after which the two sub-models exchange information. This time step has been set at one simulated year, as this offered a good balance between resolution and computational effort. Initialisation of both sub-models offered an additional challenge due to the dependency of the SD Energy Price model on data from the SD Regional Energy model to run. As a solution, the SD Regional Energy model performs a dummy run, which supplies its initial values to the SD Energy Price model, but dismisses the results after that.

Next the AB Gas Market model has been synchronised with both SD sub-models. The AB Gas Market model, however, is a discrete event model. The hybrid Discrete Event approach (Gomes et al., 2017) has been used in order to overcome the difference with the two continuous time sub-models. Discrete input signals for the AB Gas Market model are created out of the final values of the energy prices and trading needs of each region. Following a negotiation round in the AB Gas Market model, the resulting export and import values are considered to be a continuous time signal with discrete steps by the SD Regional Energy model. Furthermore, the same dummy run of the SD Regional Energy model used to overcome initialisation issues with the SD Energy Price model has been used to tackle the algebraic loop present at the initialisation of the AB Gas Market model.

Next, the developed co-simulation model has been used in a case study exploring the effects of an EU CO_2 tax and of an EU energy union on the CO_2 emissions of the EU and the dependency on Russian gas. The CO_2 tax policy has been implemented by adding a price per tonne CO_2 within the SD Regional Energy model. The energy union policy has been implemented by representing the EU as a single actor in the AB gas market model with a stronger negotiation position. Exploratory Modelling and Analysis (EMA) has been used to explore the effects of these policy levers upon the system under uncertain conditions.

From the exploration of the results it became clear that the energy union policy was able to significantly affect the behaviour of the co-simulated model. The CO_2 tax policy, on the other hand, only affected the CO_2 emissions of the EU. The reason for this difference was the significant difference in level of abstraction within the sub-models. As the energy union policy had been implemented within the AB Gas Market model (the model with the highest level of abstraction), the effect the policy can have on the system as a whole had become significantly higher than the CO_2 tax policy which had been implemented within the SD Regional Energy model.

All in all, co-simulation modelling offers significant benefits to the analysis of the European gas market, especially when it comes to the integration of multiple dimensions. Furthermore, the lock-step synchronisation approach makes it easy to use a single sub-model for many different iterations, which is especially useful to systems with a significant geographical component as is the case with the gas market. There will, however, always be some loss of information when using continuous time sub-models. Lastly, the different level of abstractions of the sub-models have to be carefully considered when using co-simulation modelling in policy analysis, as the case study showed that a significant difference therein will affect the impact policy levers make.

Contents

1

Introduction

In the beginning of 2018, Germany and Russia finalised their agreement to expand their gas transport capacity via the construction of the Nord Stream 2 gas pipeline (Witte & Beck, 2018). The new pipeline will offer Germany better access to a cheaper gas supply, as it eliminates transit fees and shortens the route (Russel, 2017). At the same time, the pipeline will help Russia to diversify their gas routes into the European gas market (Łoskot-Strachota, 2016), because Russia's contract with Ukraine is set to expire in 2019 (Shirov, Semikashev, Yantovskii, & Kolpakov, 2016).

Germany needs to ample supply of affordable gas in order to support its growing renewable energy production (Dohmen & Jung, 2012; Faas, Gracceva, Fulli, & Masera, 2011). Eastern European Union (EU) member states have objected to Nord Stream 2 as they fear it will make them more dependent on Russian gas (De Carbonnel, 2017). The reason for this is that the construction of Nord Stream 2 lowers economic incentives to invest in liquefied natural gas (LNG) in Eastern Europe (Luciana, 2016; Russel, 2017). Furthermore, the increased presence of Russian gas in Germany might prevent Germany from imposing potential sanctions in the future (Witte & Beck, 2018).

In order to prevent the plans for Nord Stream 2 to continue as planned, thirteen EU member states have expressed support to authorise the European Commission (EC) to negotiate with Russia on behalf of the EU (De Carbonnel, 2017; Wilson, 2018). The EC and the European Parliament (EP) have spoken out against Nord Stream 2 and are pursuing an extension to current EU gas laws (Wilson, 2018). Currently, EU law states that companies cannot own gas pipelines within the EU (Russel, 2017). It is because of this reason that Russia's previous efforts with regards to the planned South Stream pipeline was stopped in its tracks (Russel, 2017; Shirov et al., 2016). These rules do not seem to apply to Nord Stream 2 due to the fact that the pipeline is located in international waters (Keating, 2018; Russel, 2017). The proposals in question are meant to (retroactively) apply the same rules to the entirety of gas pipelines connected to the EU gas market (Keating, 2018; Wilson, 2018). However, while the proposal has passed the EP, it is far from passing through the European Council.

The commotion caused by the proposal of Nord Stream 2 showcases how conflicting economical and political interests divide the EU when it comes to the European gas market. Furthermore, it shows how the combination of political and economical dimensions shape the European gas market into a complex issue.

One of the reasons the EU gas market is complex from a political perspective, is the politicisation of gas itself. Several characteristics of the gas market have caused this to happen. First of all, the difficulty of transportation of natural gas over large distances has created regional gas markets. Secondly, National Oil Companies (NOCs) have substantial control over gas production. Thirdly, gas supply is very susceptible to political conflict, as conflicts have been shown to cause disruptions to the supply (Franza, De Jong, & Van der Linde, 2016; Ivanter et al., 2017).

A second reason for the political complexity of the EU gas market comes from the conflicting goals of the EU members states, with some prioritising climate goals, while others prioritise energy security (Austvik, 2016). Gas has an important role to play in order to reach the set climate goals, as gas can offer reliable support to renewable energy production (Dohmen & Jung, 2012; Faas et al., 2011). Furthermore, a coal-to-gas switch would enable the EU to reach the Paris climate goals, as gas is the cleanest fossil fuel (Faas et al., 2011; Franza et al., 2016).

Instead of climate goals, other EU member states make it a priority to increase energy security (Austvik, 2016). Energy security has become a more pressing issue for the EU over the last decade, following the gas crises in 2006 and 2009 as well as the expansion of the EU to include six countries fully dependent on Russian gas (Cotella, Crivello, & Karatayev, 2016; Faas et al., 2011; Luciana, 2016; Prahl & Weingartner, 2016). Dependency on Russian gas does not just hurt security-of-supply, but Russia has used natural gas as a political tool within the EU as well (Prahl & Weingartner, 2016). Diversifying the EU gas supply, by investing in LNG and new external pipelines like the Nabucco pipeline to Turkey (Arcuri, 2013), while maintaining relations with Russia is set to be a challenge (Cotella & Crivello, 2016). While diversifying, however, geopolitical developments have to be taken into account as conflicts pose a risk to the gas supply (Franza et al., 2016; Lombardi & O'Donnell, 2016). For example, in the Eastern Mediterranean gas market Italy, Cyprus, Egypt and Israel have the ambition to create a gas hub even though the fragile political relations in the region makes this even more difficult (Gürel, 2016). In addition to aiming to diversify the market the EU has introduced a regional approach in which countries ensure gas to their neighbours in case of future gas crises (European Union, 2010).

A third reason for the political complexity of the gas market is the fragmented approach EU member states take towards the gas market. Currently, negotiations on gas trade are done bilaterally by EU member states (Prahl & Weingartner, 2016). The conflicting priorities of the gas market within the EU (prioritising climate goals or energy independence) has prevented further political integration (Aalto & Temel, 2014; Austvik, 2016). In addition to this the preference of sovereignty of EU member states and support for national energy companies have prevented a common voice to develop as well (Aalto & Temel, 2014; Umbach, 2010). This is further supported by the differences in national energy policies, resources and social pressure (Cotella et al., 2016). One example of this can be found in the decision of the Netherlands to rapidly decrease gas production in response to safety issues (Luciana, 2016). Additionally, member states with fruitful relations with a gas supplying country are reluctant to give these up (De Jong, 2013).

The economic complexities of the European gas market can be found in the market mechanics itself as well as the changes that are occurring on the gas market, the biggest of which is the fact that LNG is turning the gas trade into a global endeavour (European Union, 2013). The use of LNG has increased over the past decade and will continue to grow (Chyong, 2016; Luciana, 2016). As LNG from the United States (US) on the EU market, will discourage Russia from raising their prices (Dohmen & Jung, 2012; Koranyi, 2016), consuming countries have been promoting the use of LNG as a means to open up the market (Franza et al., 2016).

The increased use of LNG has the potential to liberalise the EU gas market. In order to do so however, additional efforts will be required to further improve the connections between the member states (Prahl & Weingartner, 2016). Initial investments with this purpose have already been made after the gas crisis of 2009 (Luciana, 2016; Umbach & Nerlich, 2011). The liberalisation of the EU gas market is challenging this practice of long-term contracts as well, which signifies a change to gas negotiations (Le Coq & Schwenen, 2017; Łoskot-Strachota, 2016). This change can reduce the inter-dependence between supplier and buyer as it increases the number of potential trading partners for each (Minullin & Schrattenholzer, 2011).

Additional changes to the EU gas market come from technological advancements (e.g. ship-to-ship transfer), as they could offer even more flexibility to the market (Chyong, 2016; Le Coq & Schwenen, 2017; Lombardi & O'Donnell, 2016). The EU gas demand, however, will depend on alternating energy prices, economic growth in addition to developments in technology (European Union, 2013). Gas demand has been rising in Europe in order to replace oil and coal and as a result of a decreased domestic production (Götz, 2006; Luciana, 2016; Prahl & Weingartner, 2016). The fact that Russia might not be able to meet the future gas demand of the EU, further showcases the need to diversify the gas suppliers of the EU (Götz, 2006).

The political and economic dimensions interact and influence each other as well (Minullin & Schrattenholzer, 2011; Umbach & Nerlich, 2011). For example, the changing energy market could offer room for a more integrated external EU energy policy, however, the liberalisation of the market might further push the member states towards sovereignty instead (Aalto & Temel, 2014). Additionally, there is a fear that an integrated market will lead to foreign countries gaining from national subsidies (Valkenburg & Gracceva, 2016). Furthermore, the success of before mentioned energy infrastructure investments within the EU will affect the political will to move towards a common policy (Umbach & Nerlich, 2011). If these investment, however, conflict with policies regarding climate change, it could hurt the

EU economy (Kanellakis, Martinopoulos, & Zachariadis, 2013).

1.1. Gas Market Analysis

The essential interaction between economic and political factors form a system too complex to analyse via mental simulation (Sterman, 1994). Therefore, a quantitative simulation is required in order to gain a better understanding of the European gas market.

Each of the two identified dimensions require different dynamics to be included within a quantitative simulation. On the economical side it is important to model the regional energy markets. This includes the interaction between energy demand, economic growth and the energy demand distribution over a variety of sources. Furthermore, the global energy market has to be taken into account as it affects energy prices. When it comes to the political side of the issue, it is important that the simulation is able to operationalise the different goals and perspectives of countries and the negotiation process itself.

Previously developed models of the European gas market have mainly focused on the market mechanics of the gas trade and have neglected the significance of the combination of dimensions at play. Table 1.1 offers an overview of different models and approaches previously used to analyse the European gas market.

The included models each have their own focus when approaching an analysis of the European gas market. As none of the models include all world energy markets within their scope, the world energy prices of resources are not simulated. The World Gas Model (Egging, Holz & Gabriel, 2010) and the COLUMBUS model (Hecking & Panke, 2012; Schulte, 2018) are the exceptions. Both models encompass the global gas market and are therefore able to simulate the impact of global developments on the gas prices.

All of the models included in table 1.1 model gas trade in one form of another, the difference between them, however, comes from the perspective through which gas trade is modelled. Three different perspectives from which to model the gas market can be defined when comparing these models to each other. The first is to take the perspective of market agents (e.g. pipeline operators, producers, traders, liquefiers). The multilevel model (Grimm, Schewe, Schmidt, & Zöttle, 2018), the Gas Market Competition model (GASCOM) (Minullin & Schrattenholzer, 2011), the World Gas model (Egging, Holz & Gabriel, 2010) and the COLUMBUS model (Hecking & Panke, 2012; Schulte, 2018) all take this approach. This perspective is popular amongst models based on mathematical optimisation, as the network of market agents forms a suitable basis for this approach.

The second perspective that is taken is that of existing infrastructure and flows. This perspective is applied by models aimed at evaluating the gas supply itself. The TIGER model is aimed at evaluating the security-of-supply within the EU (Hecking & Weiser, 2017; Weiser, 2018) and the Security of Energy Supply Risk model (SES Risk) analyses the risk to energy supply as a result of political, economical, terrorist and technical challenges (Serbanescu, 2011).

The third perspective used by the models in table 1.1 is that of countries themselves. This perspective is used by models who prioritise the political dimension of the European gas trade. The clearest example of this is the game theory approaches applied by Popescu & Hurduzeu (2015), as it aims to evaluate the effects different approaches of both the EU and Russia would have on their gas trade in context of dependency on Russian gas. The security of supply (SoS) simulation, by the European network of transmission system operators for gas (ENTSOG), makes use of this perspective as well, though it does take the network of infrastructure into account (ENTSOG, 2017).

The next requirement for a fitting gas market model is the inclusion of the simulation of regional market developments. While most of the models in table 1.1 acknowledge the importance of regional demands and developments, non of the models actually simulate these developments and only specify regional needs via the used input data.

Lastly, it is important to note that only a few of the models provided in table 1.1 deal with uncertainty. The Multilevel model can be adapted to include data uncertainty regarding the demand functions (Grimm, Schewe, Schmidt, & Zöttle, 2018). The SoS Simulation makes use of a variety of scenarios in order to account for an uncertain input (ENTSOG, 2017). Lastly, the SES Risk model inherently deals with uncertainty due to the use of probabilistic risk assessment as its formalism (Serbanescu, 2011).

Table 1.1: Overview of gas market models

Model	**Created by**	**Formalism**	**Model Goal**	**Global Pricing**	**Gas Trade**	**Regional Energy Market**	**Uncertainty**
Multilevel Model	Grimm Schewe, Schmidt, & Zöttl	Mathematical Optimisation	Evaluating gas market design	No	By market agents	No	Data Uncertainty
GASCOM	Minulin & Schrattenholzer	Game Theory	Evaluating and optimising market strategies for all agents	No	By market agents	No	No
World Gas Model	Egging, Holz, & Gabriel	Mathematical Optimisation	Evaluating global gas market mechanics from the perspective of market participants	Gas prices only	By market agents	No	No
COLUMBUS	Hecking & Panke, EWI	Mathematical Optimisation	Simulating market developments based on country level characteristics	Gas prices only	By market agents	No	No
TIGER	EWI	Mathematical Optimisation	Simulating optimal gas flows in order to evaluate security of supply and potential bottlenecks	No	Based on infrastructure	No	No
SoS Simulation	ENTSOG	Network Modelling	Simulating the effects of gas disruption in the supply to European countries	No	By countries	No	Scenario input
SES Risk	Serbanescu	Probabilistic Risk Assessment	Analysing the risk to EU energy supply resulting from various challenges	No	Based on gas flows	No	Risk Assessment
	Popescu & Hurduzeu	Game Theory	Evaluating EU and Russian approaches to gas trade and how it affects EU's dependence on Russian gas	No	By countries	No	No

1.2. Super-formailsm, multi-formalism, and co-simulation

It is very understandable why the models in table 1.1 are not able to capture the required behaviour of the economic and political dimensions of the system. The reason for this is the inherent limitations each modelling formalism brings. Systems existing within multiple domains are therefore worth exploring via a combination of multiple simulation methods (Engel, Chakkaravarthy, & Schweiger, 2017). Three different approaches are available when integrating multiple formalisms: super-formalism, multi-formalism or co-simulation (Vangheluwe, H., De Lara, J., & Mosterman, P. J., 2002).

The clearest example of a super-formalism and how they can be used to include multiple domains within the model is bond graphs (Cellier, 1991). As very few formalisms are able to model multiple domains the use of super-formalism usually is not an option (De Lara & Vangheluwe, 2002).

The multi-formalism approach prescribes the different formalisms used by sub-models to be transformed into the closest common formalism. The AToM^3 tool has been developed in order to facilitate this approach (De Lara & Vangheluwe, 2002). The lowest common formalism will always be the trajectory level, focusing on the data exchange between formalisms, which results in the co-simulation approach (Vangheluwe, H., De Lara, J., & Mosterman, P. J., 2002).

Co-simulation allows for the different sub-models to be modelled in separate formalisms, using the accompanying simulators, only to be coupled via the trajectory level. The largest advantage of this approach is that each domain can be simulated via the most fitting approach (Gomes, Thule, Broman, Larsen, & Vangheluwe, 2017; Ni & Broenik, 2012), however, the submodels can not offer much insight on their own and the analysis will have to focus on the interaction between the models (Vangheluwe, 2000). Co-simulation has mainly been used in engineering projects covering multiple domains, where co-simulation offers a large advantage to the development process as different teams can work on their own domain (Gomes et al, 2017). The fields in which co-simulation has been used varies from the automotive industry to the maritime industry (Gomes et al, 2017).

In case of the European gas market, the co-simulation approach is most suitable, as the gap left by previous models can be found within the interaction between domains and the limitation single formalisms have on modelling different parts of the system.

Within the field of co-simulation there are different challenges that have to be tackled. The extend to which these challenges play a role, however, depends on the system in question and the characteristics of the to be included sub-models.

The most important challenges within co-simulation comes in the form of synchronisation of the different sub-models. In general there are two approaches to synchronisation. The first of which, optimistic co-simulation, runs the sub-models at the same time and includes a rollback mechanism in case the results of the sub-models affect each other (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010). The second approach is a lock-step co-simulation in which the sub-models are run at set time-steps, therefore forgoing the need of a rollback mechanism, but at the cost of performance (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010; Gomes et al., 2017).

Additional challenges related to synchronisation come from the presence of Discrete Event (DE) models and or Continuous Time (CT) models (e.g. causality, distribution, modular composition, algebraic loops, & compositional continuity (Gomes et al, 2017). It is also important to note that the survey on the state of the art of co-simulation performed by Gomes et al. (2017) does not have any discussion on uncertainty.

1.3. Research Question

The politicised nature of gas trade, conflicting political goals and national interests affect the approach taken towards the gas market, while increasing amount of available LNG on the gas market alters the political discourse within the EU (Minullin & Schrattenholzer, 2011; Umbach & Nerlich, 2011).

Previous quantitative approaches towards the EU gas market have mainly focused on the development of market mechanics and on security-of-supply. In general the existing models do not properly combine both market forces and political influences in order to evaluate its interaction, as this requires multiple modelling formalisms to be combined.

Several approaches available for the integration of multiple formalisms have been discussed out of which co-simulation has been identified as the most fitting approach in order to fulfil the gap left by previous models of the European gas market. Within the use of co-simulation, however, several challenges surrounding the synchronisation of the different sub-models occur depending on the characteristics of the sub-models in question. Thus, the following research question has been developed:

What are the merits of using co-simulation to include the interaction between the economic and political dimensions affecting the European gas market in order to analyse the effects of EU policies on the ambitions of its member states?

Approaching this research question will be done in several steps guiding the development process of a rudimentary co-simulation model of the European gas market. First, the sub-models have to be defined, including their respective formalisms. Next, the challenge of synchronisation the sub-models has to be addressed. Lastly, the developed model will be used in a case study analysing the effects of several EU policies on the ambitions of its member states. The generated results can in turn be used to discuss the advantages and drawbacks of the applied method. Thus, the following three sub-research questions have been formulated:

- RQ1: Which sub-models have to be included and which formalisms are best suited for them?
- RQ2: How will the sub-models be synchronised?
- RQ3: Given the case study, what are the advantages and drawbacks of using co-simulation to model the European gas market?

1.4. Thesis Structure

Chapter 2 will address the methodology of the research. Within this chapter, first, a discussion will be held on the sub-models that will have to be included within the co-simulation model of the European gas market. Secondly, the goals and methods used to perform the case study will be discussed.

Next, chapter 3 offers a description of the developed co-simulation model. It does this by discussing the conceptual model, specifying the relations between the sub-models, followed by a description of the implementation of the sub-models. Next, the synchronisation of the sub-models will be elaborated upon. Lastly, the validation process of the model will be discussed.

Chapter 4 focuses entirely on the case study. The chapter will start by defining the implementation of the co-simulation model in the XLRM framework, after which the experimental set-up used in the case study will be discussed. Next, the generated results will be explored, followed by the conclusions that can be drawn based upon them.

Lastly, chapter 5 draws a conclusion on the merit of co-simulation modelling in context of the European gas market. Next, the discussion elaborates upon still undiscussed development challenges and improvements that can be made upon the developed co-simulation model.

2

Methodology

The research of this thesis can be divided into two distinct parts. First, the required sub-models are discussed, as well as the formalism that will be used for each. Secondly, the methodology used within the case study will be elaborated upon.

2.1. Sub-models

For a quantitative analysis on the impact of EU approaches to the gas market on the political goals of its member states, both the gas market mechanics as well as the political dimension will have to be included in the model. Co-simulation allows both of these dimensions to be included in the model via domain specific sub-models.

The first sub-model has to model regional energy markets. In order to achieve that it is essential to include the gas demand, production, transport capacities, and local energy mixture. These different elements all affect each other constantly and create feedback loops. Taking this into account the use of system dynamics (SD) (Forrester, 1961) is appropriate as this method is well suited to model feedback loops (Sterman, 2000). This sub-model will have to be used to represent each European country separately. Furthermore, while the focus of the model will be on the European gas market, the interaction with the rest of the world is essential to include, and thus this sub-model will represent regions outside of Europe as well. Thus the first required sub-model is the SD Regional Energy Market model.

Secondly, as the SD Regional Energy Market model simulates different world regions separately, an additional sub-model is required which simulates the development of energy prices around the world. System dynamics is suitable for this sub-model as well, as the relations between supply, demand and energy prices are part of the seem feedback loops. Therefor, the second sub-model will be included in the form of the SD Energy Price model.

Lastly, the political dimension of the European gas market has to be included in a sub-model as well and will have to operationalise negotiations on gas trade, while considering the politically charged bargaining positions of countries. The focus on negotiations makes it difficult to be included in the system dynamics model suggested based on the gas market mechanics. Instead an Agent-Based (AB) model (Epstein & Axtell, 1996) would be a better fit, as AB models are especially suitable for the modelling of social networks (Marchi & Page, 2014). The third sub-model to be included will thus be the AB Gas Market model.

Python (Van Rossum, 1995) will be used to create the infrastructure through which the interactions between the sub-models are managed. The required SD models will be developed using Vensim (Ventana Systems Inc., 2011). Next, the PySD module will be utilised to run these models from Python (Houghton, 2018). Similarly, Netlogo (Wilensky, 1999) will be used to develop the agent-based model. PyNetlogo will be used within the overarching python model to connect to the AB model (Kwakkel, 2018).

2.2. Case Study

The developed model will next be used in a case study in order to gain insight into the advantages and drawbacks of using co-simulation when modelling the European gas market. In this case study, several EU policies will analysed. The policies that are to be analysed will have to address the identified political goals of limiting CO_2 emissions and lowering the dependence on Russian gas. The first policy approach that aims to tackle one of these issues is an EU wide CO_2 tax, which the EU has not been able to implement in previous attempts and will face a multitude in barriers if it were to be implemented (Kanter, 2010; Weishaar, 2018). It is, however, a clear example of an EU centralised approach to the issues at hand. The second policy of interest regards the formation of an energy union within the EU. The EU has launched their energy union strategy in 2015 and is slowly building towards its goals of improving energy security, integrate the energy market and lower CO_2 emissions (European Commission, n.d.). As the energy union policy regards a centralised approach towards both political goals, the effects of the policy will also be explored.

Both the CO_2 tax and the energy union will be included as policy levers to the developed model. Exploratory Modelling and Analysis (EMA) will be used to explore the effects of these policy levers upon the system under uncertain conditions. EMA is a research method designed to analyse uncertainty in systems (Kwakkel, 2012). Particularly the EMA-workbench has been developed in order to support the analysis of uncertainty in system dynamic and agent-based models (Kwakkel, 2012). However, the EMA-workbench is also capable to support models defined in Python and can thus support the developed co-simulation model.

The generated results will first be explored in case no policies are enacted. This will offer a better understanding of the behaviour of the model as well as the effects the proposed modelling structure has on the results. Next, the change in behaviour as a result of the two implementations of the CO_2 tax will be explored, followed by an exploration of the effects of an energy union. Lastly, a brief discussion will be held on the effects the combination of the policy options has on the behaviour of the model.

3

Model Description

3.1. Conceptual Model

Figure 3.1 shows the relations between the sub-models and how, together, these sub-models are able to cover the necessary elements when modelling the European gas market. The SD Regional Energy Models simulates the energy markets of each included region. The regional changes in the supply and demand of energy resources are in turn used by the global SD Energy Price Model to simulate price fluctuations for the different energy sources. These energy prices feed back into the SD Regional Energy Models. The SD Regional Energy Models also output the trading needs of each country (i.e. how much gas they want to import/export). The AB Gas Market Model uses this information as its input in order to simulate gas trade deals. In turn, the results of these negotiations feed back into the SD Regional Energy Models.

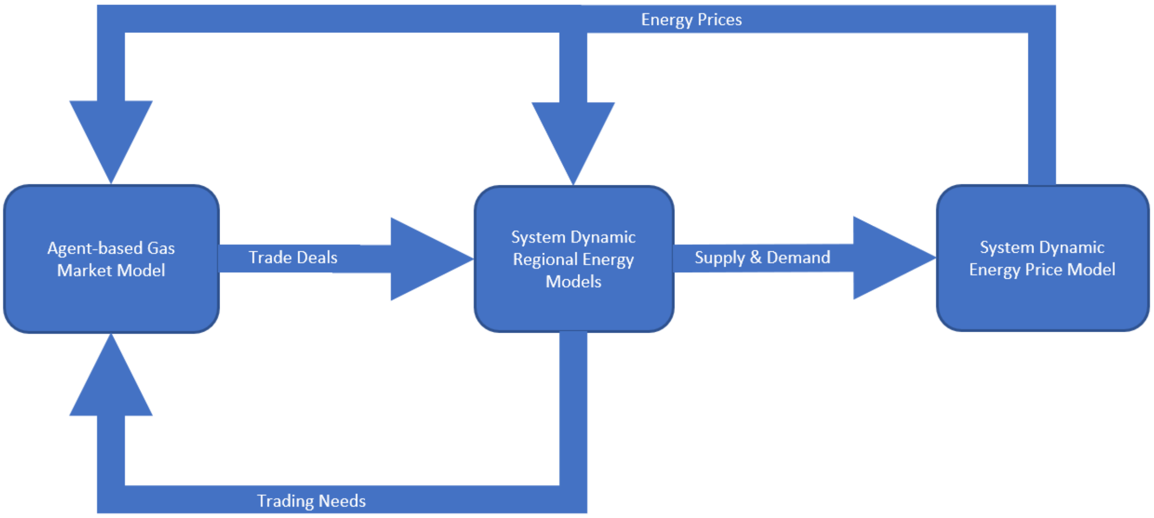


Figure 3.1: Integrated Model Structure

3.2. Model Specification

3.2.1. Assumptions

The first assumption that has been made for the purpose of this model, is that countries themselves negotiate between each other with regards to trade. Gas trade negotiations are done by a complex set of actors, varying between companies active in all aspects of it from extraction to transportation. It would not, however, be fair to dismiss the influence of governments on trade all together. Governments approve the construction of extraction capacities and the construction of pipelines between countries.

As the model has a focus on the political goals of EU member states (i.e. decreasing CO_2 emissions and decreasing the dependency on Russian gas) the model will negotiate gas trade from the perspective of the countries themselves, similarly to the analysis of Popescu & Hurduzeu (2015) and the SoS Simulation (ENTSOG, 2017).

The second assumption is that all trade negotiations are being held every 5 simulated years. In reality, negotiations are both continuous as well as set for longer and varying periods of time. Including this dynamic within the overarching model structure would, however, add a level of complexity to the model structure that does not appear to offer sufficient additional insights over the proposed structure in order to warrant it.

Third, for the purpose of the overarching model, the important information of each gas trade deal is the size of each deal and which two countries made the deal. The negotiated gas price within each deal is not of importance, as it is not a goal of the model to gain insight into the financial profits of gas trade. The price of gas, however, will play a significant role in the consideration of trading partners, but it is the relative price to other trading partners that is deciding. Furthermore, while the route traded gas takes is relevant when it comes to available capacity within pipelines, which trade deal uses which pipelines is not vital information.

The fourth assumption is that it is the priority of each country to satisfy its own gas trading needs, before considering to serve as a transit country between two trading nations. As a result the trade negotiations algorithm has been subdivided between the trade with neighbouring countries and the trade negotiations with non-neighbouring countries.

Lastly, as the research focuses on the European gas market, several regions of the world are represented as a single entity (i.e. North America, South & Central America, the Middle East, Africa and Asia-Pacific). The same simplification has been used for the Commonwealth of Independent States, however, Russia, Ukraine and Belarus have been included separately due to their geographical location and relevance to the research. Neighbouring non-EU European countries have been grouped together as well, resulting in a single agent representing the non-EU Balkan and a second agent representing both Turkey and Georgia. Lastly, European micro states have been grouped with their nearest neighbour, regardless if their neighbour is a member of the EU or not.

3.2.2. Agent-Based Gas Market Model

The AB Gas Market model can be described following the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006). The purpose of the AB Gas Market Model comes from the required interaction with the other elements of the integrated model structure. The SD Regional Energy Models serve to inform the AB Gas Market Model of the need in gas trade (i.e. whether countries are looking to import or export gas and how much they would like to trade). The AB Gas Market Model in turn has to use this information as its input and output information on the made trade deals. Additionally, the AB Gas Market Model models the trade of other resources (i.e. coal, oil and biofuels).

The AB Gas Market model makes use of agents to represent the different *countries* and three different types of links to model the connections between these countries. Each *country* receives a positive or negative *gas surplus* (depending on their need to export or import gas), as well as a *bargaining position. Bargaining positions* are used to influence the gas price between two countries. The three link-breeds have been defined as *border pipes*, *LNG routes* and *transfer routes. Border pipes* are predefined and represent the total of pipelines between two countries. *LNG routes* link together two countries with the capacity to export and import Liquefied Natural Gas. Lastly, *transfer pipes* are virtual links to represent the connection between two countries and consist of *border pipes* and *LNG routes* connected to other countries. Each *Border pipe* has a variable tracking its available capacity. The capacity of *LNG routes* is dependent on the *LNG export capacity* and the *LNG import capacity* of the *countries* the link is connected to.

Every time the AB Gas Market model is run, the gas trading algorithm is called upon first. Figure 3.2 offers a high-level flowchart of the designed trading algorithm. The flowchart depicts the order in which different functions are called upon within the AB model. The gas market algorithm relies on an iterative process which starts by resetting the links (i.e. the *transfer routes* created in the previous iteration are dismissed). Next, new *transfer routes* are created between countries connected via other countries who have satisfied their gas trading needs. Next, all links are asked to determine the gas trading price between its connected countries based on the regional gas prices and the *bargaining positions* of the two countries. The price is further altered depending on the use of *transfer routes* and

Figure 3.2: Flowchart Gas Market Algorithm

LNG routes. Once the prices have been determined, each country considers the determined trading price of all links it is connected too. Exporting countries will prefer to receive the highest price for their gas, while importing countries prefer lower prices. Each country makes proposals based on these prices. Each link checks to see if both countries it is connected to have made an offer. If this is the case, a deal is struck between the two countries. The size of the deal is determined by the lower offer. The needs of the countries are updated as a result of the made deals. The same goes for the available capacity within each link. If there is still potential for trade, the algorithm will loop back around. If this is not the case, the algorithm ends. An example of the algorithm can be found in appendix B.

Once the gas trading algorithm has been completed, the trade of coal, oil and biofuel starts. As these resources do not share the same logistical challenges as gas, they are proportionally traded between all regions. Next, *border pipes* used at full capacity plan to expand a set amount in a set number of years. If enough time has passed since an expansion was planned, the capacity of the *border pipe* in question is updated. The same process is used to expand *LNG import & export capacities* of *countries*.

The design of the AB Gas Market model has been based on a few key concepts. The first of which is the fact that countries pay different prices for gas from the same partners (Mazenva, 2018). Therefor, unique prices between countries are determined at the start of each negotiation round based on their respective *bargaining positions.* The calculation of the *bargaining positions* have been included in appendix A. The second key concept is the network of gas pipelines that limit potential trading partners (International Energy Agency, n.d.) and that transporting gas via multiple countries or via LNG routes, require additional costs (BP Statistical Review of World Energy, 2018). Two key assumptions within the AB Gas Market model are that exporting countries want to maximise their profit and that importing countries want to minimise their costs. Lastly, the assumption was made that *countries* are only willing to facilitate trade between neighbouring countries if their needs have been met.

Initialisation of the AB Gas Market model occurs at the start of the overarching model. During the initialisation 41 different *countries* are created, as well as the *border pipes* that connect them. If the energy union policy option is enabled, only 14 *countries* will be created.

The AB Gas Market model uses input from both the SD Regional Energy models and the SD Energy Price model, as shown in figure 3.1. Each time the AB Gas Market model is called upon the gas prices of each region are updated as well as the trading needs of each *country.*

A more detailed overview of the sub-models of the AB Gas Market model can be found in appendix C.

3.2.3. System Dynamics Regional Energy Model

The System dynamics energy model aims to model the energy markets of each country. As depicted in figure 3.1, the model uses energy prices from the energy price model and the made trade deals from the gas market model as input. The output the model has to generate comes is the amount of resources the country in question would like to trade.

The structure of the SD Regional Energy model has largely been inspired by the Energy Price Scenario Model as described by De Jong, Auping and Govers (2014).

Figure 3.3 depicts the causal loop diagram (CLD) of the SD Regional Energy model. Within the model there is a strong causal relation between the size of the economy and the energy demand of a country. This relation takes shape in the form of two balancing loops: *Limited Economic Growth* and *Decoupling Economy.* The loop *Limited Economic Growth* depicts overall energy demand growing along with the economy which in turn, affected by the limitations of supply, will increase the shortage in energy. As a result of a shortage, economic growth is limited and the size of the economy decreases. The loop *Decoupling Economy* regards the impact the size of the economy has on the overall energy demand. Similar to the previous loop, an increase in demand creates an increase in energy shortage. An energy shortage encourages the decoupling of the economy in order for it to become less energy intense and thus lowering the energy demand.

The CLD further depicts several balancing loops with regards to the capacity of energy production: *Balancing Capacity Gas Production*, *Balancing Capacity other Fossil Fuels* and *Balancing Capacity Renewables.* The CLD shows a highly aggravated depiction of the relations within these loops. All three loops display the balancing effects an increase of supply has on its profitability due to a shortage. An increase in supply, decreases the energy shortage and thus discourages further investments in supply capacity.

As mentioned before, the trade of resources and the associated price of each resource are inputs to this model and thus, as seen in the CLD are not affected by the behaviour of other variables.

A detailed description of the various sub-models included in the SD Regional Energy model can be found in appendix D.

3.2.4. System Dynamics Energy Price Model

While the supply and demand of different energy sources can be modelled for countries separately, the energy prices do not stop at the border of a country. In order to account for this a separate system dynamics model has been designed. Within the model a distinction is made between resources that are are relatively easy to transport around the world (i.e. oil, coal and biofuel) and region bound resources (i.e. gas, nuclear energy, and other renewable energy). One sub-model structure is replicated multiple times within the energy price model. Once for every world bound resource price and once per region for each regional bound resource. this sub-model structure has been based on the Energy Price Scenario Model designed by De Jong, Auping, and Govers (2014).

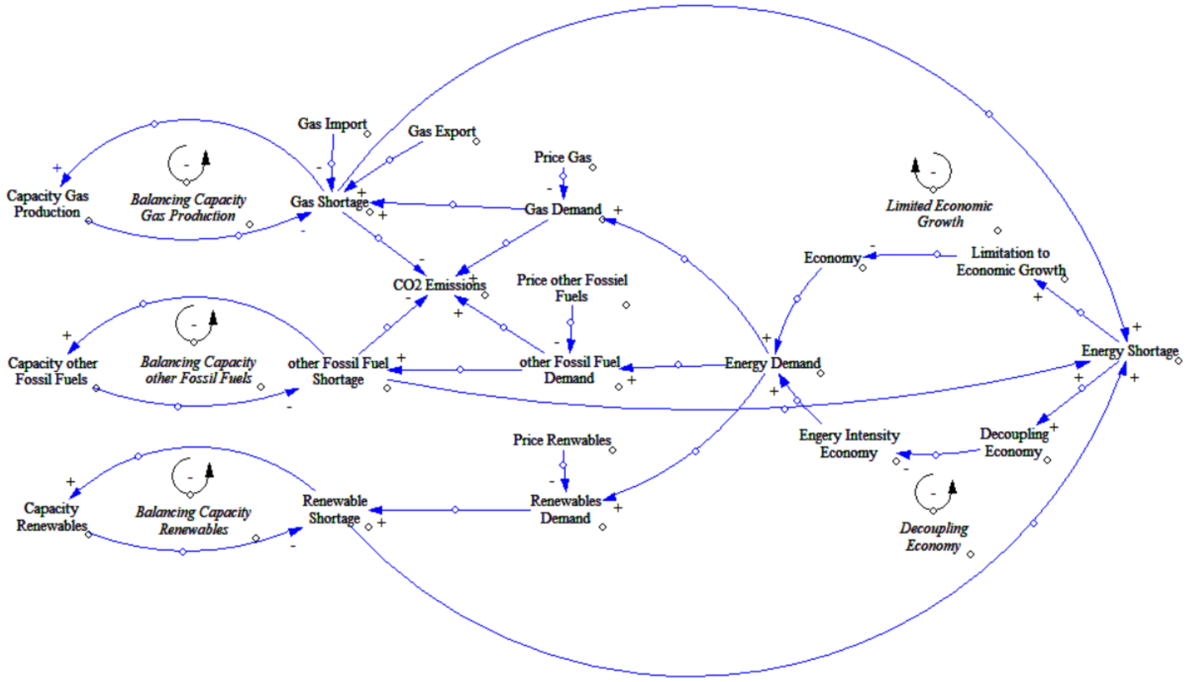


Figure 3.3: Aggregated closed Loop Diagram SD Regional Energy model

3.3. Synchronisation

The three sub-models each have unique characteristics. The SD Regional Energy model and the SD Energy price model result in a continuous output over time. The AB Gas Market model on the other hand, serves as a discreet signal and models a single point in time. Furthermore, the SD Regional Energy model serves to model the energy markets on a national level with duplicates modelling other countries. This stands in contrast with the SD Energy price model and the AB Gas Market model, both of which aim to model the entire world. An overview of these characteristics can be seen in table 3.1.

Table 3.1: Overview of the characteristics of the different models

	National Level	**International Level**
Continuous Time	SD Regional Energy Model	SD Energy Price Model
Discrete Event		AB Gas Market Model

The difficulty from connecting the two continuous time models (i.e. the SD Regional Energy model and the SD Energy Price model) comes from their interaction. If, for example, the SD Energy Price model would not have been included, there would not be any direct interaction between the different iterations of the SD Regional Energy model. Defining the same start and end times would suffice in order to run them in parallel. The interaction with the SD energy price model, however, require both models to interact with each other as continuously as possible.

There are two approaches available to synchronising sub-models: optimistic co-simulation and lock-step co-simulation (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010). Optimistic co-simulation runs the sub-models parallel to each other, allowing mismatches between the sub-models to occur. When this happens a roll back is initiated correcting the error (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010; Carothers, Perumalla, & Fujimoto, 1999). Lock-step co-simulation simulates the sub-models independently from each other for a set time step after which the sub-models communicate (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010; Gomes et al., 2017).

Considering the characteristics of the SD Regional Energy model and the SD Energy Price model, lock-step simulation is the better fit. The first reason for this is the fact that the SD Regional Energy model is used for 41 different regions. This would results in 42 sub-models having to run at the same time if optimistic co-simulation were to be applied. Lock-step simulation allows the SD Regional Energy model to simulate each energy market sequentially for a limited time step. Secondly, the lack of need for a roll back mechanism simplifies the design of the system.

The next factor affecting the synchronisation between the two SD sub-models is the time step set between moment of communication. Essentially, the output signals of the SD sub-models are sampled to become the input signals of the other SD sub-model. Therefore, the smaller the time step the closer the sampled signal represents the original continuous signal. This is, however, a trade off with the performance of the co-simulation model, as smaller time steps increases the number of computations (Gomes et al., 2017). Based on this trade off the decision was made to set the time steps at one simulated year, as this resulted in both a reasonable resolution and a reasonable computation time.

One of the challenges that come with synchronising two continuous models, as identified in the survey by Gomes et al. (2017), that also occurs in this case is the initialisation of simulators. This issue of initialisation is a result of the algebraic constraint present at the initial conditions of the two SD sub-models. While the initial energy prices are input values of the co-simulation model, the supply and demand of each energy resource are not. Thus, the SD Energy Price model can not initialise without an input signal from the SD Regional Energy model. As a solution to this problem the SD Regional Energy model performs a dummy run for each region. Next, the initial conditions of the supply and demand of each energy resource are used as the missing input values to the SD Energy Price model. The results of the dummy run are then dismissed at both SD sub-models are able to initialise.

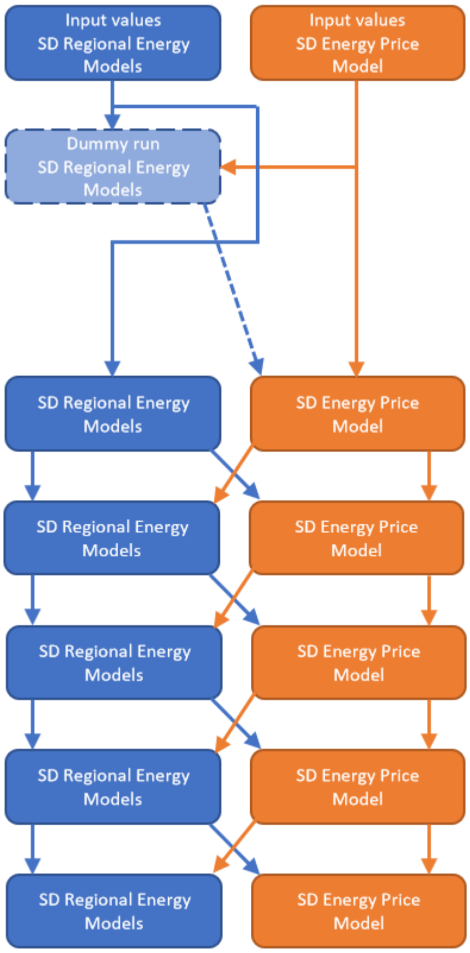


Figure 3.4: Synchronisation of the continuous time sub-models

Figure 3.4 depicts the synchronisation of the SD Regional Energy Model and the SD Energy Price model based on the previous discussion. The figure depicts the run of each sub-model as a block, with a different colour for each sub-model. The arrows indicate a transfer of information in which the results of a sub-model are used as the input of a different one. The colours of the arrows correspond with the sub-model of origin. The figure shows the synchronisation of the sub-models over a simulated time of five years, with a moment of communication after each year.

Next, the AB Gas Market model has to be synchronised with the SD sub-models as well. The fact that the AB Gas Market model is a discrete event model, however, makes the interaction between the sub-models inherently different. Generally speaking, there are two approaches available when integrating discrete event and continuous time models: the hybrid DE approach and the hybrid CT approach (Gomes et al., 2017). The hybrid DE approach transforms continuous signals into discrete signals in order to effectively model the system as a set of DE models, while the hybrid CT approach does the opposite (Gomes et al., 2017).

In order to find which of these approaches is most suitable, it is important to consider that the AB Gas Market model simulates separate events without propagating the simulated time. As a result, the moments of interaction between the AB Gas Market model and the two SD sub-models can be considered to be a discrete event in and of itself. Therefore, the hybrid DE approach is most suitable.

Following the hybrid DE approach, discrete input signals for the AB Gas Market model are created out of the final values of the energy prices and trading needs of each region. Following a negotiation round in the AB Gas Market model, the resulting export and import values are considered to be a continuous time signal with discrete steps by the SD Regional Energy model. Furthermore, an algebraic loop between the AB Gas Market model and the SD Regional Energy model creates issues with the initialisation of both sub-models. The loop exists as the AB Gas Market model requires the trading needs of the regional energy markets as an input, while the SD Regional Energy market requires the initial import and export values of resources in order to calculate these trading needs. The dummy run of the SD Regional Energy model offers the solution once again, as the initial trading needs of the dummy run can be used to initiate an initial negotiation round.

As specified in the assumptions of the model (section 3.2.1) the negotiation rounds are held at fixed moments in time every 5 simulated years. Figure 3.5 depicts the fully synchronised system. Once again, the different colours are used to indicate the different sub-models.

3.4. Validation

3.4.1. Validation Sub-Models

The most important validation of the AB Gas Market model came in the form of *behaviour reproduction tests*. *Behaviour reproduction tests* compare the generated results with the data the model should have produced (Forrester & Senge, 1980). These were especially well suited to validate the implementation of the designed gas trading algorithm in Netlogo. During these test, a variety of input scenarios were applied to both the AB Gas Market model and calculated by hand using the gas trading algorithm in order to see if the generated behaviour was conform expectations. Appendix B showcases the gas trading algorithm, but it also works as an example of the way in which the validation technique was applied. These tests have been applied to every development stage of the algorithm and combined with *behaviour anomaly tests*, in which the effects of changing assumptions are evaluated (Forrester & Senge, 1980), have guided and informed the algorithm design.

Family member tests have been performed during the development of the AB Gas Market model as well. In *family member tests* a model is tested by applying it to a different case in order to see if the behaviour of the model adjusts appropriately (Forrester & Senge, 1980). In case of the AB Gas Market model these tests were done by using different combinations of fictional countries. Lastly, *extreme conditions tests* have been applied to the AB Gas Market model as well. In *extreme conditions tests* variables are set to extremely high or low values in order to see if the model still behaves logically (Sargent, 2010). These test took the developed model of the gas market and tested to see the behaviour of countries under extreme conditions, for example, if Russia does not want to export gas. While behaviour of countries were logical, the *extreme conditions test* did show one limitation. One of the assumptions made for the purpose of the algorithm was that countries only become willing to facilitate gas trade between its neighbours once it has fulfilled their own demands. One of the *extreme conditions tests* displayed the limit this assumptions imposes, as an unfulfilled gas demand of the United Kingdom, will completely cut off Ireland from the gas market.

A variety of validation techniques have been applied to the SD Regional Energy model as well. The first of which comes in the form of *family member tests*. In the case of the Regional Energy model these

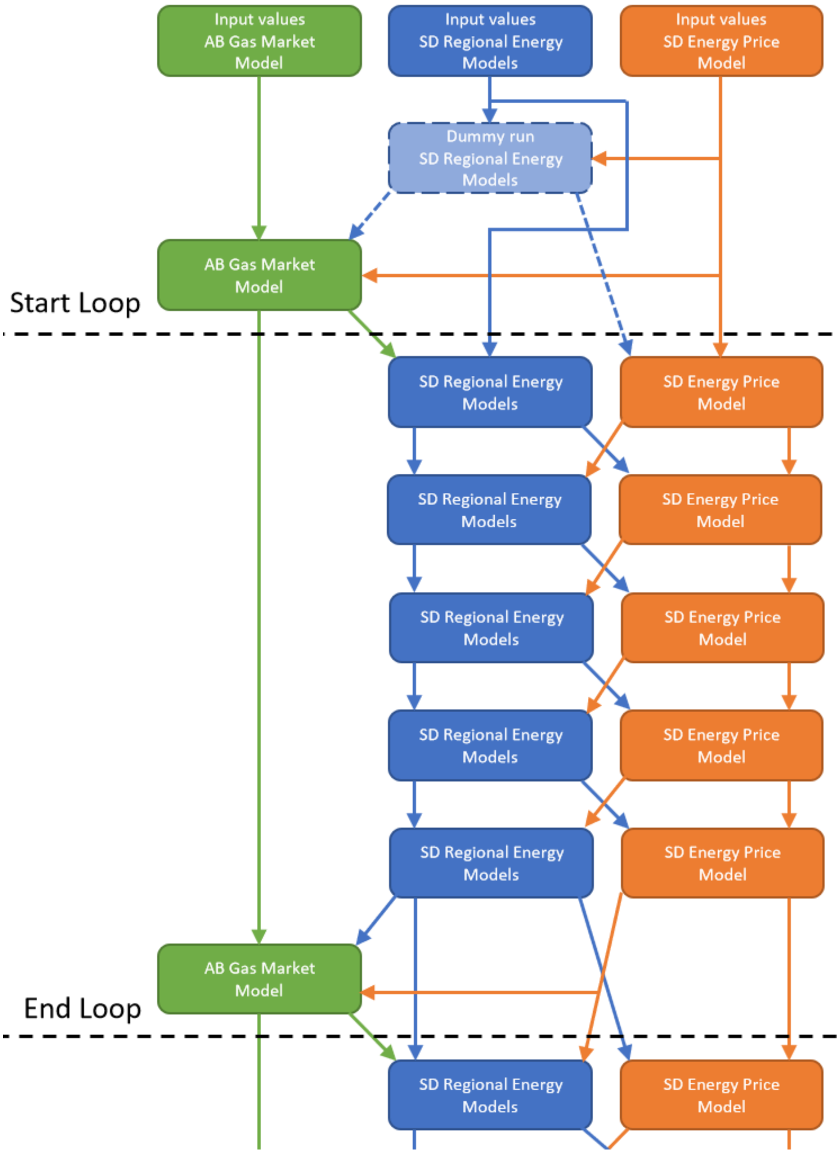


Figure 3.5: Synchronisation of all three sub-models

were especially important as the Regional Energy model has to be used for 41 different regions with different conditions. During these tests the input conditions of different regions were run within the model in order to see if the generated behaviour made sense for the region in question.

Next,*extreme conditions tests* have been done showing the behaviour of the model does not show unexpected behaviour when entering extreme values to a wide variation of variables.

Lastly, *behaviour-sensitivity tests* have been done as well. These tests aim to see if realistic changes within the input values have an unwanted impact on the behaviour of the system (Forrester & Senge, 1980). While, the *behaviour-sensitivity tests* displayed numerical sensitivity under most conditions, the distribution of consumption over the different energy sources showed to be very sensitive to the energy price. While the behaviour itself seems logical and to be expected, the result is that the starting values of the consumption of each energy sources can vary heavily when a broader range of energy prices is applied simulations.

The SD Energy Price model is such a small model, that it does not show any change in behaviour without input of the SD Regional Energy model. Therefore, a separate validation of the SD Energy Price model is not possible and will the function of the sub-model will have to be validated via the full co-simulated model.

3.4.2. Validation Co-Simulated Model

The validation of the integrated model focused primarily on *surprise-behaviour tests.* In *Surprise-behaviour tests* unexpected behaviour in the model is checked to see if it is plausible or not (Forrester & Senge, 1980). Initial runs with the integrated model showed a lot of unexpected behaviour as a direct result of the integration. Results showed unexpected spikes, as a result of integration errors, the amount of resources still in the ground appeared to grow, renewable energy underwent extreme growth in some countries and Russia appeared to stop exporting gas early on in the simulation. As it turned out, these errors were a result of using the same PySD model for 41 different iterations, while switching between these iterations constantly. While each variable was communicated to the next input as well as the final value of each stock, this was not yet the case for delay functions with an initial value.

Next, an *extreme policy test* has been performed on the integrated model. Similar to the *extreme conditions test*, the *extreme policy test* checks the behaviour of the model once a policy option has been implemented in an extreme way (Forrester & Senge, 1980). This test was done by implementing the CO_2 tax at the start of the model and at a rate of 100 dollar per tonne CO_2. The resulting CO_2 emissions of the EU showed two broad bands of results, with the results undergoing the extreme policy forming the lower band of results. This test reiterated the already identified large behavioural sensitivity of the SD Regional Energy model to starting energy prices. Once again, this showed a clear limitation of the designed model. In order to work within these limitations the CO_2 tax has been implemented with a low starting value which incrementally increases, under two different rates, over time, as described in section 4.1.1.

4

Case Study

4.1. XLRM framework

The EMA-workbench applies a wrapper around the co-simulation model in order to run the model as a function (Kwakkel, 2017). This function follows the XLRM framework (Lempert, Popper, & Bankes, 2003). The XLRM framework defines external factors (X), policy levers (L), the relationships in the system (R) and the performance metrics (M). Doing so allows the model to define M to be the result of a function using X and L as its inputs. Figure 4.1 offers a depiction of the XLRM framework of developed co-simulation model in context of the case study.

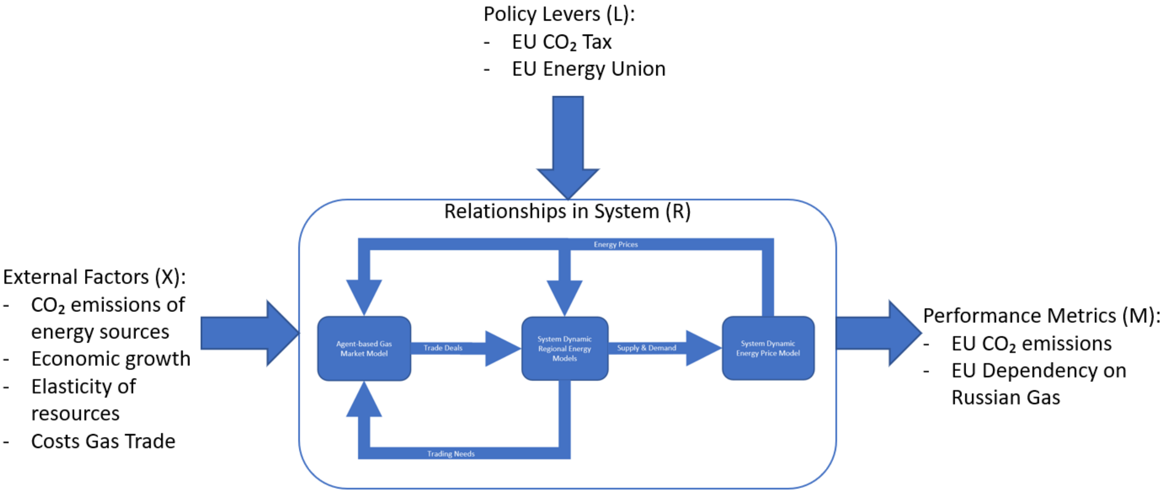


Figure 4.1: The XLRM framework of the co-simulation model

In the designed model the external factors are defined by the uncertainties that will be selected for the application of the EMA-workbench. These uncertainties affect economic growth, operationalised costs for LNG and transferring gas through multiple countries and CO_2 emissions per resource. The relationships within the model are defined via the SD sub-models and AB sub-model, as seen in figure 3.1. The policy levers are contain the options of an energy union and an EU wide CO_2 tax. The performance metrics of the model consist of the CO_2 emissions of the EU, the share of Russian gas of the EU gas supply and the share of Russian gas of the EU energy supply.

4.1.1. Policy Levers

Two different policy related to the energy market the European Union could take have been included in the developed model: A EU-wide CO_2 tax and an energy union. For the purpose of this research it is assumed that the United Kingdom joins EU in implementing these policies, whether they remain a member of the EU or not.

CO_2 tax

The CO_2 tax has been included via the SD Regional Energy Model. When the policy is enabled, a price per tonne CO_2 is added to the functional price of each fossil fuel. As a result, the preference for fossil fuels will decrease. Note that the prices themselves are not increased, as this would have increased the profitability of the resources. From the validation of SD the Regional Energy model (section 3.4.1), the initial distribution of the consumption of the different energy sources is very volatile. Including the CO_2 tax as an immediate measure from the start would therefore alter the scenarios over which policy options can be compared (section 3.4.2). In order to circumvent this issue, the CO_2 tax is not implemented until after the first year of the simulation, after which the CO_2 price will incrementally increase. Furthermore, two different sizes for these incremental increases have been included, resulting in a relatively slow and fast implementation of the CO_2 tax

Energy Union

As the term "energy union" is rather vague, it is important to clarify the made assumptions. For the purpose of this research, the energy union policy has been defined to do three things. First of all, negotiations on gas trade are done from the perspective of the European Union. Secondly, the *bargaining position*, as defined in the AB Gas Market model, of the European Union on the gas market increases. Thirdly, the European Union prioritises fulfilling the energy needs of the member states over exporting resources. The energy union policy has been modelled by grouping together the member states of the EU in a single actor within the AB Gas Market model. For this purpose a second version of the Agent-Based Gas Market Model is used in which EU is represented by a single agent, with a high *bargaining position*, and the EU as a whole uses a single version of the System Dynamics Regional Energy Model.

It is important to note that, as this implementation of the energy union requires a hefty structural change in the overarching modelling structure, the policy can only be enabled at the start of the simulation.

4.2. Experimental Set-Up

The EMA-workbench (Kwakkel, 2012) has been used in order to create and perform a large number of experiments on the developed model. The experiments are formed by combining a set of scenarios, based on selected uncertain values in the model, and a set of policy combinations. These uncertainties take the place of the external factors (X) within the XLRM-framework (figure 4.1). The selection of uncertainties and the implemented value ranges is depicted in table 4.1.

When selecting these uncertainties, the size of the developed model had to be taken into account. As every variable within the SD Regional Energy model is used differently 41 times, the selection of uncertainties can easily grow out of proportions. Thus, a large selection of sensitivity analyses (Kleijnen, 1997) have been performed on the SD Regional Energy Model.

From these sensitivity analyses *Autonomous Economic Growth Factor*, *Initial Energy Intensity GDP*, & *Demand Balance Supply Energy Price* showed to be behaviour sensitive. The variables regarding the supply elasticity and CO_2 emissions of resources showed having a large numerical impact on the *Gas to trade* variable within the SD Regional Energy model. A large numerical sensitivity of*Gas to trade* will likely have a behavioural impact on the overarching modelling structure.

Out of the two lists of variables only the *Autonomous Economic Growth Factor* and the *Initial Energy Intensity GDP* differ per region. As mentioned before, including a different uncertainty for every region would result in too many uncertainties to include. Therefor, both uncertainties have been included in the shape of scenarios. Three scenarios have been included for each, with a lower, medium and higher data set.

The AB Gas Market model only has a small set of variables to consider. These variables (i.e. *power factor*, *LNGprice*, *transferprice*, *(LNG)Capincrease*, and *(LNG)Capincreasetime*) affect the conditions and behaviour shown within the AB Gas Market model. The defined ranges in table 4.1 have been defined as an extension of the underlying assumptions of the used algorithm.

The policy levers (L) from the XLRM-framework, were defined as an EU CO_2 tax and the formation of an energy union. The CO_2 tax has been implemented at two different speeds. The combination of

Table 4.1: Selection of external factors (X)

Variable	Value Range	Unit	Source
Economic Growth Scenario	1, 2, 3	Scenario Input	"World Bank Open Data", n.d.
Economic (Energy) Intensity Scenario	1, 2, 3	Scenario Input	BP Statistical Review of World Energy, 2018
Demand Balance Supply & Energy Price	0.4 - 0.7	Dmnl	
Supply Elasticity Gas	0.06 - 0.07	1/year	De Jong, Auping, & Govers, 2014
Supply Elasticity Oil	0.1 - 0.2	1/year	De Jong, Auping, & Govers, 2014
Supply Elasticity Coal	0.1 - 0.2	1/year	De Jong, Auping, & Govers, 2014
Supply Elasticity Nuclear	0.007 - 0.017	1/year	De Jong, Auping, & Govers, 2014
Supply Elasticity Biofuel	0.1 - 0.2	1/year	De Jong, Auping, & Govers, 2014
Supply Elasticity OR	0.15 - 0.3	1/year	De Jong, Auping, & Govers, 2014
CO_2 emissions coal	95 - 105	t/BBTU	De Jong, Auping, & Govers, 2014
CO_2 emissions oil	65 - 95	t/BBTU	De Jong, Auping, & Govers, 2014
Variance power	-5.0 - -0.1	Dmnl	De Jong, Auping, & Govers, 2014
Autonomous Energy Intensity Decrease	0 - 0.02	Dmnl	
powerfactor	15 - 25	Dmnl	
LNGprice	200 - 1000	$/BBTU	
transferprice	50 - 300	$/BBTU	
Capincrease	1000 - 3000	BBTU	
Capincreasetime	1 - 2	Scenario Input	
LNGCapincrease	1000 - 3000	BBTU	
LNGCapincreasetime	1 - 2	Scenario Input	

both leavers thus results in 6 policy combinations. Combined with 200 scenarios resulting from the uncertainty ranges over the external factors, a total of 1200 experiments will be done. Latin Hypercube sampling (LHS) will be used to sample the uncertainties (Stein, 1987). The policy levers will be sampled via Full Factorial sampling (FFS), as it is required to explore every combination.

4.3. Results Exploration

200 scenarios have been run under 6 different policy combinations, resulting in a total of 1200 experiments. As the two identified goals EU member states have when it comes to the European gas market were lowering CO_2 emissions and lowering the dependence on Russian gas, the three key performance indicators (KPIs) of the experiments are the CO_2 emissions by the EU, the proportion of Russian gas to the gas supply in the EU and the proportion of Russian gas to the total energy supply of the EU.

Figure 4.2 depicts the EU CO_2 emissions that resulted from 200 experiments in which none of the policy options have been enabled. Looking at these results a few things stand out. First of all, the CO_2 emissions in 2015 already show a broad range. The reason for this range is a direct result of the uncertainty ranges applied to the CO_2 emissions of coal and oil, as discussed in section 4.2. Additionally, the uncertainty regarding economic growth & energy intensity scenarios further alters the levels of energy consumption within the EU, and thus affects the range of starting CO_2 emissions as well.

The second thing that stands out in figure 4.2 is the visible discrete steps shown within the results. This behaviour is a direct result from the integration of multiple distinct sub-models. Small discrete steps can be seen every year simulated by the model. These steps indicate an interaction between the SD Regional Energy models and the SD Energy Price model. The input the SD Regional Energy model receives from the SD Energy Price model is essentially sampled once a year. Larger discrete steps in the results can be seen every five years modelled. These steps result from the interaction between the SD Regional Energy model and the AB Gas Market model and indicate a change in the export and import of gas, coal, oil and biofuels for each member state, which directly influences the consumption of each resources as well as the resulting CO_2 emissions.

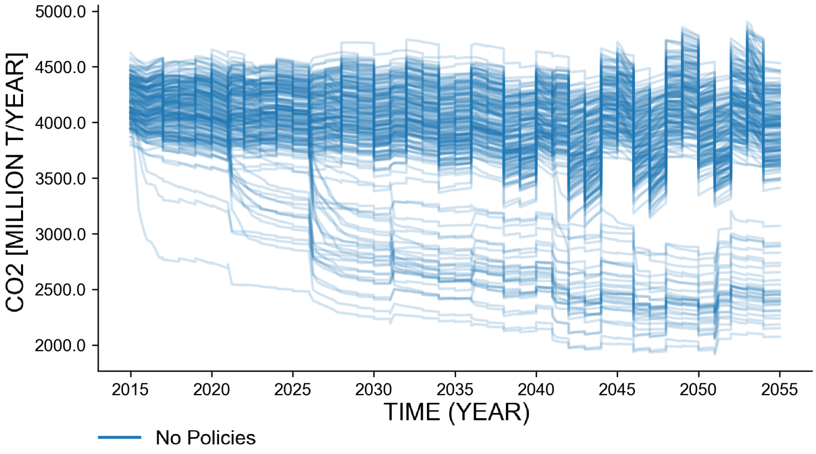
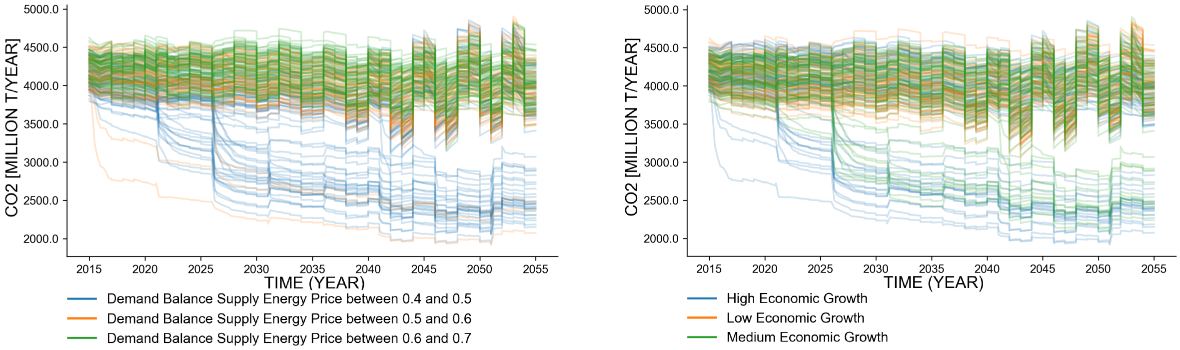


Figure 4.2: EU CO_2 emissions without policies



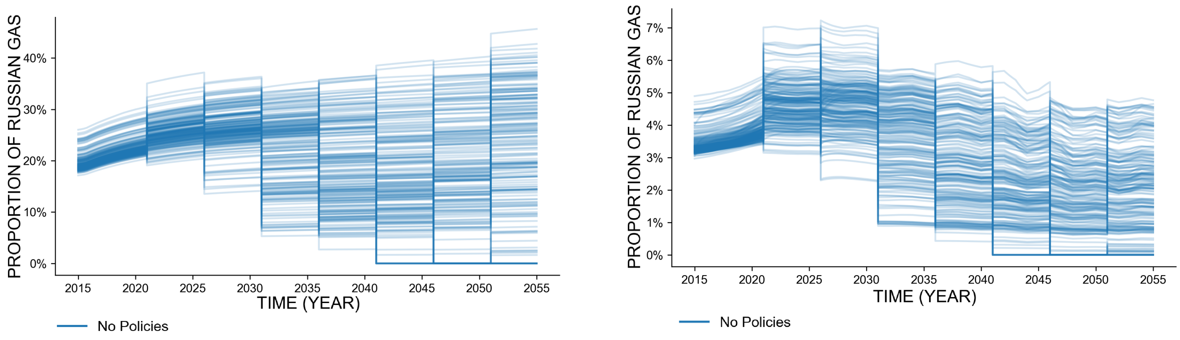
(a) (b)

Figure 4.3: EU CO_2 emissions without policies grouped by (a) *Demand Balance Supply Energy Price* & (b) Economic Growth Scenario

The third noticeable behaviour can be found in the bifurcation visible within the results. Figure 4.3(a) shows the same generated results, but sorted based on the factor *Demand Balance Supply Energy Price*. The figure shows that virtually only a low *Demand Balance Supply Energy Price* allows the bifurcation to occur. *Demand Balance Supply Energy Price* is the distribution of energy demand over the different resources prioritise the previous distribution of energy supply over the preferences based on energy prices. At first glance this might seem counter intuitive, as it seems to suggest that slow change speeds up the energy transition. However, it is important to note that the factor takes the supply of resources as input. Combined with the discrete manner in which the import of each resource is added to the SD Regional Energy models, the behaviour that occurs is that when a trading negotiation does not meet the demand of a country, the supply of the resource in question possibility decreases significantly. With the supply forming the main factor for the demand distribution, this will instantly decrease the demand for the resource in question as well. Figure 4.3(b) depicts the CO_2 emissions of the EU grouped by the used economic growth scenario. The figure shows that the bifurcation is most prevalent under a high economic growth scenario. The higher economic growth increases the domestic energy demand for coal exporting regions and therefore there is less coal available to import. Combined with the dynamic created by the low *Demand Balance Supply Energy Price*, as described above, the identified bifurcation in CO_2 emissions occurs.

Figure 4.4 depicts the results of the second performance metric, the dependency of the EU on Russian gas. Figure 4.4(a) depicts the proportion of Russian gas to the EU gas supply and figure 4.4(b) depicts the proportion of Russian gas to the total EU energy supply.

Similarly to figure 4.2, the first thing that stands out from both images is the broad range of initial values. This range is once again the result of the uncertainty range placed over economic growth and



(a) (b)

Figure 4.4: Proportion of Russian Gas to (a) the Gas Supply & (b) total Energy Supply of the EU without policies

energy intensity of the economy, resulting in a different level of energy demand and therefore causes a different proportion of Russian gas.

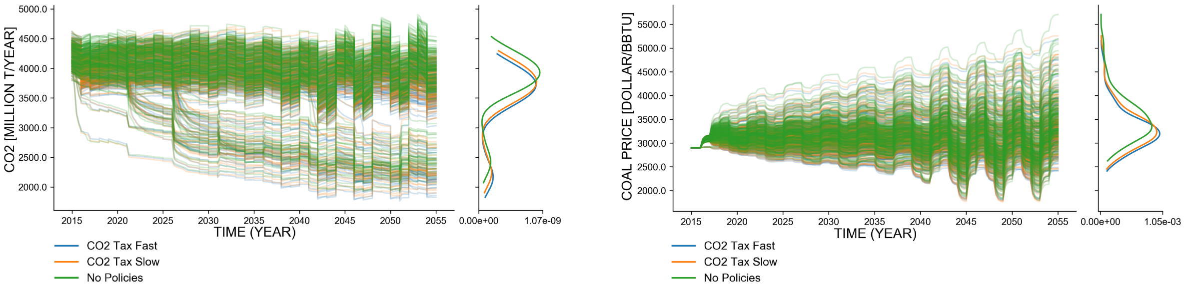
Furthermore, both images show behaviour more indicative of a discrete signal rather than a continuous result. To understand this behaviour it is important to note that the AB Gas Market model is only called upon every five years of modelling. Therefore, every five years the gas trade between countries (including Russia) is suddenly readjusted to the updated regional energy needs. When comparing both figures, figure 4.4(a) shows significantly less fluctuations between the negotiation rounds than figure 4.4(b). The reason for this is the fact that it is relatively easy for countries to adjust the proportion of gas within their own energy supply.

4.3.1. Effects of Policy Options

Two different policy options have been implemented in the model (i.e. two versions of an EU-wide CO_2 tax and the introduction of an energy union). The implementation of these policy options has been discussed in section 4.1.1. This section will explore the generated results based on these policies.

CO_2 Tax

Figure 4.5(a) depicts the generated CO_2 emissions by the EU grouped by the implementations of an EU CO_2 tax. Both implementations of the tax start at 10 dollar per tonne CO_2. Next the slow implementation increases with one dollar per year, growing towards 50 dollar per tonne CO_2, and the fast implementation increasing with 2 dollar per year, growing towards 90 dollar per tonne CO_2.

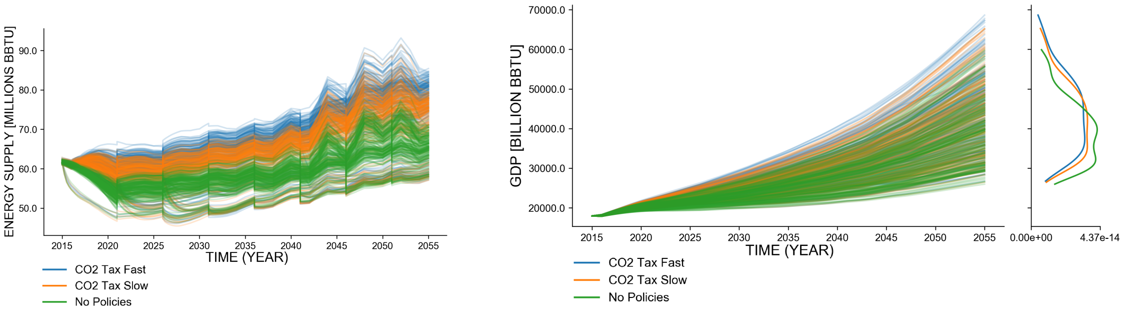


(a) (b)

Figure 4.5: Effects of CO_2 tax implementations on (a) EU CO_2 emissions & (b) Coal price

While the density plot in figure 4.5(a) shows a shift towards a decrease in CO_2 emissions, the effect itself is perhaps lower than expected. One of the reasons for this is the incremental implementation of the CO_2 tax.

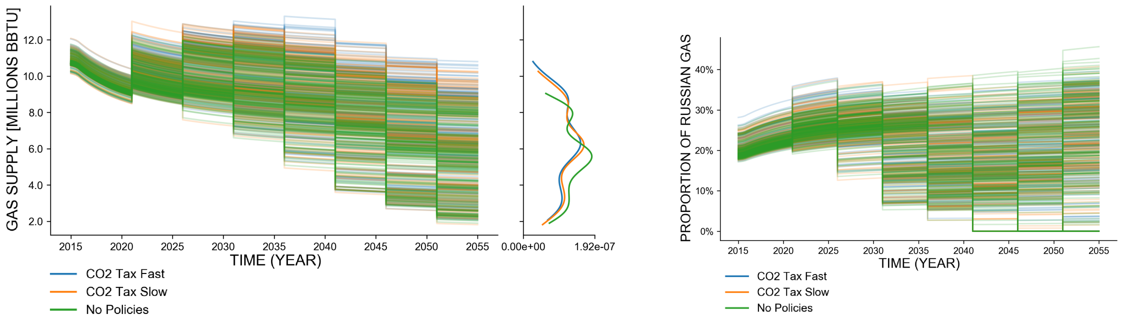
The second reason for the dynamic is the balancing effect the energy price for coal has on CO_2 emissions. When a CO_2 tax lowers the consumption of coal, stockpiles of coal rise. As a result, the price for coal decreases and becomes more appealing to use. Figure 4.5(b) depicts the generated prices for coal grouped by the CO_2 tax. The density plot of these results shows a downward shift as a result of the policy. This supports the proposed explanation of a correcting effect a CO_2 tax has.



(a) (b)

Figure 4.6: Effects of CO_2 tax implementations on (a) the EU energy supply & (b)the GDP of the EU

The third reason for the limited reduction in CO_2 emissions is that it is not just coal whose stockpiles increase, but that same holds true for oil. Figure 4.6(a) shows a significant increase in EU energy supply as result of the CO_2 tax. In turn, a larger energy supply is able to facilitate more economic growth, as seen in figure 4.6(b). Next, a larger economy results in an increase in energy demand, which leads to an increase in consumption of fossil fuels and thus increases the CO_2 emissions of the EU.



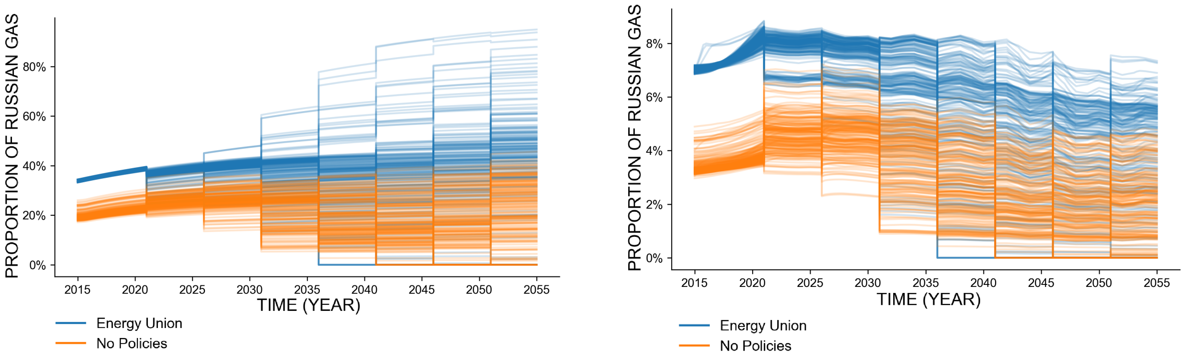
(a) (b)

Figure 4.7: Effects of CO_2 tax implementations on (a) the EU gas supply & (b) the proportion of Russian gas to the EU gas supply

The increase in energy supply and demand, as result of the CO_2 tax, can also been seen in the gas supply of the EU. Figure 4.7(a) displays this behaviour. The increase in gas available within the EU has to come from somewhere. Figure 4.7(b) shows the proportion of Russian gas to the EU gas supply and does not a clear behavioural trend as a result of the tax. Thus, it can be concluded that the increased gas demand, as a result of the CO_2 tax, is supplied via the established distribution over the different sources (i.e. trading partners and local extraction).

Energy Union
Figures 4.8(a) and 4.8(b) show a comparison between the introduction of an energy union with a no policy option with regards to the proportion of Russian gas to the gas supply of the EU and the total energy supply of the EU respectively. The first thing stands out in these graphs is the bifurcation present at the start of the simulated period. Due to the chosen implementation of the energy union policy option, it is not possible for the policy to be enacted anytime after the initiation of the model. The reason for this is that the resulting model structure differences, in the sense that regions within the EU are aggregated together within a single iteration of the SD Regional Energy model. Furthermore, the simulation starts with a negotiation round, as seen in figure 3.5, in the AB Gas Market model and thus results in an immediate change in the outcome of the simulation.

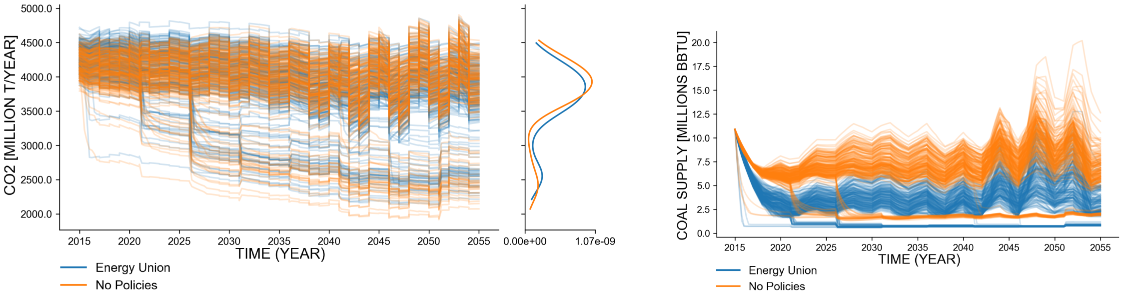
The next thing that stands out is the clear increase in the proportion of Russian gas. This behaviour



(a) (b)

Figure 4.8: Effect of an Energy Union of the Proportion of Russian Gas to (a) the Gas Supply & (b) total Energy Supply of the EU

is quite logical considering the mechanics used to model the policy. First, the joint **bargaining position** of the EU under an energy union is higher, which results in a lower price for Russian gas making it more attractive. Secondly, the energy union allows the EU to consider a broader range of potential trading partners than countries do by themselves. Therefore, North African countries, Norway, Russia and LNG exporting countries are all compared to each other by a single EU agent.



(a) (b)

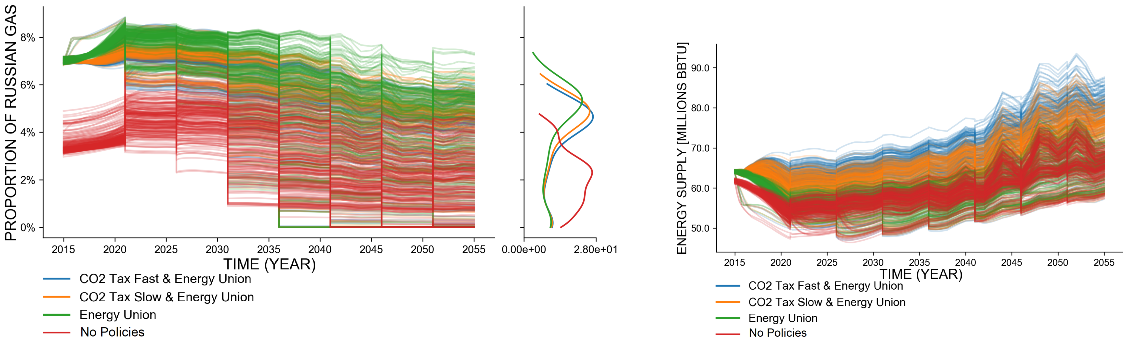
Figure 4.9: Effects of an energy union on (a) the CO_2 emissions of the EU & (b) the coal supply in the EU

Figure 4.9(a) shows the effect the energy union has on the CO_2 emissions of the EU. In the corresponding density plot, a slight decrease in CO_2 emissions can be noticed. The cause of this decrease is a result of a decrease in the coal supply. Figure 4.9(b) shows the effect of the energy union of the coal supply within the EU. The figure shows that the initial supply decreases faster and further with an energy union than in the base case. Soon a balance is reached within the system in a similar fashion as the "no policy"-case. The energy union allows member states to overlook their own borders when considering the use of coal and thus initially increases its use. These depletes the EU coal supply at a faster rate, which encourages the use of other resources resulting in the decrease in CO_2 emissions visible in figure 4.9(a).

Combination of Policy Options

Two sets of experiments have been run in which both the energy union and (one of the implementations of) the EU CO_2 tax are enabled. Figure 4.10(a) shows the effects of the combination of a CO_2 tax and an energy union. From the figure it becomes clear that implementing both a CO_2 tax and the energy union, results in a lower increase in the proportion of Russian gas to the EU energy supply than the energy union policy on its own achieves. Note that the previous discussion on the effects of a CO_2 tax showed that stockable resources grew. Figure 4.10(b) shows the effects of the combination of both policies on the EU energy supply. The figure shows a similar increase in energy supply, which directly leads to the proportion of Russian gas to the EU energy supply to become lower.

The proportion of Russian gas to the EU energy supply is, however, the only performance metric in



(a) (b)

Figure 4.10: Effects of a CO_2 tax in addition to an energy union on (a) the proportion of Russian gas to the energy supply of the EU & (b) the energy supply in the EU

which the combination of the policy options offers additional insights. With regards to the other KPI's, the effects of the policy levers do not add to each other, nor do they negate the effects sole policies have shown.

4.4. Conclusions

Creating an energy union leads to an increased dependence on Russian gas for the EU. The reason for this is the increased bargaining position of the EU resulting in a lower import price for Russian gas. Furthermore, the centralised approach towards outside trading partners encourages the EU to retrieve gas from Russia, where as without an energy union southern EU countries would first consider North African countries for their gas import. However, it should be noted that the model implementation of the energy union, does not account for capacity limitations within the EU. Therefore, the impact of the policy would realistically be smaller than the model prescribes. It is clear to conclude that the energy union would not decrease the dependency on Russian gas. Furthermore, the energy union showed to have a decreasing effect on the CO_2 emissions of the EU, as it encouraged the use of coal depletes the stockpile of coal in the long run.

It is, however, important to note that, while the discussed results of the energy union do have merit, the implementation of the energy union simplifies multiple key relations. First, and most important, of all, the pipeline network within the EU (along with the capacity limitations this brings) is not accounted for under the energy union. This makes it much easier for the EU to fulfil union wide gas needs with gas from Russia. Secondly, both the demand and supply of each resource are re-distributed over the EU. As a result, the coal supply in the EU depletes much faster than expected, decreasing the consumption of the resources in the long term and decreasing the CO_2 emissions of the EU. The shown trends in the results should not be dismissed, but the numerical impact should be interpreted with more nuance.

An EU wide CO_2 tax encourages a decrease in CO_2 emissions within the EU, even though the effect is limited due to an increase in stocked supply. Furthermore, a CO_2 tax appears to increase the energy demand of the EU as increased resource stocks help sustain economic growth, resulting in a higher energy demand. It should be noted however, that the implementation of the CO_2 tax in question comes in the form of an incrementally increasing tax. The reason for this is how sensitive the distribution of energy demand over different energy sources to a change in energy prices. Once the energy demand sub-model within the SD Regional Energy model is improved, as further discussed in section 5.2.2, higher and more sudden implementations of an EU wide CO_2 tax can be explored. The CO_2 tax does not have a clear effect on the EU dependency on Russian gas.

5

Conclusions & Discussion

5.1. Conclusions

Previous models of the European gas market have been limited in scope due to the limitations the used formalism brings with. The use of co-simulation allows for multiple dimensions of a system to be modelled within the most fitting formalism. In order to explore the merits of co-simulation, when modelling the European gas market for the purpose of policy analysis, a rudimentary co-simulation model has been developed. Three different sub-models were defined for this model: a system dynamics model of regional energy markets, a system dynamics model of world energy prices, and an agent-based model of gas trade negotiations. The system dynamics sub-models have been synchronised via the lock-step approach (Ni & Broenik, 2012; Broenik, Ni, & Groothuis, 2010). The agent-based model has in turn been synchronised using the hybrid DE approach (Gomes et al., 2017). Next, the developed co-simulation model has been used in the in a case study in which the effects of an EU CO_2 tax and of an EU energy union on the CO_2 emissions and dependency on Russian gas of the EU. The development of this co-simulation model and the application within the case study has created insight into the merits of the applied method.

The largest benefit of co-simulation modelling is that it is able to include relations between different dimensions of a system. In case of the European gas market, this becomes especially clear when comparing the developed co-simulation model to the previous gas market models as discussed in table 1.1. Thanks to the inclusion of both system dynamics and agent-based sub-models, the developed model is able to simulate gas trade, regional energy market developments, and global influence on energy prices. Furthermore, the co-simulation model has shown to work well with the ema-workbench (Kwakkel, 2012), which allows the analysis to account for uncertainty.

Furthermore, the development of the model has shown that the lock-step approach makes the integration of sub-models relatively easy, as it circumvents most co-simulation challenges highlighted in the survey by Gomes et al. (2017). Additionally, the lock-step approach is uniquely capable of utilising the same sub-model for multiple entities within the co-simulation model. As the run times for each iteration of the sub-model is set, the sub-model can sequentially simulate the different entities for the duration of this time step.

An important downside to co-simulation, however, is the inherent loss of information that comes from the inclusion of continuous time sub-models. Within the developed model this effect is visible in the interaction between the SD Regional Energy model and the SD Energy Price model. As the continuous time signals used to communicate between the sub-models have to sample the signals at a set frequency, there will always be a loss of information.

The largest downside to co-simulation, however, is the potential difference in abstraction level of the included sub-models. A different level of abstraction does not have to be a problem in co-simulation itself, however, when co-simulation is used for the purpose of policy analysis it does become a problem. Policy levers implemented in the sub-model with the higher level of abstraction will inherently have a larger impact on the system, than policy levers implemented in sub-models with a lower level of abstraction. This conclusion can be drawn based on the performed case study on the effects of EU gas market policies. The AB Gas Market model is at a very high level of abstraction, especially when compared to both SD sub-models. The energy union policy was implemented in the AB Gas Market model, while the CO_2 tax policy was implemented in the SD Regional Energy Market model. From the results exploration it becomes clear that the energy union policy makes a significant impact on the behaviour of the entire co-simulation model, while the effects of the CO_2 tax are only visible in the SD Regional Energy model itself. This effect becomes particularly apparent when considering the fact that the implementation of the energy union policy, because of the high level of abstraction of the sub-model, forgoes capacity limitations within the EU and creates an instant redistribution of both energy demand and supply within the EU.

All in all, co-simulation modelling offers significant benefits to the analysis of the European gas market, especially when it comes to the integration of multiple dimensions. Furthermore, the lock-step synchronisation approach makes it easy to use a single sub-model for many different iterations, which is especially useful to systems with a significant geographical component as is the case with the gas market. There will, however, always be some loss of information when using continuous time sub-models. Lastly, the different level of abstractions of the sub-models have to be carefully considered when using co-simulation modelling in policy analysis, as a significant difference therein will affect the impact policy levers make.

5.2. Discussion

5.2.1. Development Challenges

During the development of the co-simulation model unique challenges arose which should be addressed via tooling improvements, in order to better facilitate the use of co-simulation in future policy analysis.

The biggest developmental challenges are a direct result of the interaction between the sub-models, as the number of interactions adds a lot to the complexity of a model using multiple formalisms (Vangheluwe, H., De Lara, J., & Mosterman, P. J., 2002). Each interaction is susceptible for errors, both due to potential mistakes in the code managing the data streams and due to the re-initialisation of the sub-models. As co-simulation modelling focuses on the data exchange on the trajectory level, surprising behaviour in the results will likely start after a sub-model interaction. Once the model has completed a run, however, the number of interactions and the amount of gathered data has grown significantly to the point where it is very difficult to discover the origin of the error. In order to better deal with this issue, the code managing the sub-models should include a debug mode in which the co-simulation model easily be run step by step, while providing intermediate results along the way.

Another set of challenges are a direct result of the limitations of the PySD module, which was used to run the system dynamics sub-models. The key limitation is the fact that PySD does not support the use of subscripting. Subscripting would have prevented the need of using the same sub-model for multiple regions, as it would allow each region to be included within a single iteration of the SD Regional Energy model. While the lock-step approach was able to facilitate the required behaviour, only using a single iteration of the SD Regional Energy model would result in 40 fewer sub-models interacting with the rest of the sub-models every simulated years. Furthermore, subscripting the countries within the same SD Regional Energy model would also forgo the need for transforming the results of each iteration of a country's energy market in the sub-model into the input values of the next iteration of the country's energy market. Moreover, when using large number of versions of the single sub-model, a lot of separate data sets have to be combined towards the end of the co-simulation run. In case of the 41 different iterations of the SD Regional Energy model, this resulted in a memory error. The error was only solved when the number of output variables was severely limited. As subscritping would allow for a single version of the SD Regional Energy model to suffice, this issue would be circumvented altogether.

5.2.2. Model Improvements

Dynamic Energy Demand

The designed sub-model regarding energy demand within the System Dynamics Regional Energy Model. While the simulation of the total energy demand works well, the distribution between different energy sources should be improved.

The problem with the current sub-model structure is that the demand distribution is too dependent on the fluctuations of the resource energy prices. Originally, the goal was to set the factor "Demand Balance Supply Energy Price" lower, in order to simulate relatively slow changes within the demand distribution. However, due to the interaction with the AB Gas Market Model it is possible for a country to import a significantly lower quantity of a resource than wanted. As a result, the demand distribution could shift radically after each negotiations round. It would also be impossible for the demand for fossil fuels to readjust in a meaningful way. Increasing the dependence on energy price circumvented this issue and offered reasonable results. The biggest limitation to this method, however, is that the starting values for the demand distribution can vary significantly, especially when analysing the effect of the CO_2-policy option.

Worth exploring would be to model the demand for each resource in separate stocks. The overarching energy demand calculations can still be used, as the change in total energy demand can inform the how much of the demand per resource requires redistribution. It would also be possible to change the potential rate for change per resource.

Modelling Gas Trade

The biggest improvements that can be made on the developed co-simulation model relates to the way in which trading negotiations are performed. The developed trading sub-model limits the capabilities and realism of the method. Furthermore, the high level of abstraction hurts the quality of the policy analysis significantly, as discussed in section 5.1.

The first of these improvements would be include variations in the time commitment within each deal. In order for this dynamic to be included in the model, the dynamic between the System-Dynamics models and the Gas Market Model will have to become significantly more complex. Furthermore, the trading algorithm will have to be revised in order to account for preferred time commitments of each country. This dynamic is significant when researching the gas market though, as the liberalisation of the market is changing average contract times and in term the negotiation process (Le Coq & Schwenen, 2017; Łoskot-Strachota, 2016; Minullin & Schrattenholzer, 2011).

The second improvement regarding trade negotiations demands an even further redesign of the AB Gas Market Model, as it entails the inclusion of a complex network of stakeholders. Even though the negotiations by countries was an important assumption and fit within the purpose of this research, a more complex actor dynamic is worth exploring. This is especially worthwhile because it would lower the level of abstraction of the sub-model.

Internal Capacity Energy Union

The Energy Union policy has been modelled by replacing the EU member states for a single actor. Doing so allowed the negotiating position to be centralised, however, transportation capacity limitations within the union are not well accounted for. One way of solving this issue would be to separate the negotiations from the pipeline network. This would significantly increase the complexity of the AB Gas Market model, as, in addition to a separate negotiation network, an optimisation algorithm will have to be designed and included. The EU-agent would have to be able to consider different scenarios while attempting to fulfil the needs of each member states. The same structure of multiple regions being represented by a single negotiating agent, could further be applied in order to focus on different regions within a single country. Furthermore, this structure would open up the possibility to model the trading process from the perspective of the operators rather than countries.

Regional Energy Prices

There are two significant improvements that can be made with regards to the regional energy prices. The first would be to reevaluate the defined regions. In the current iteration of the model the gas price in Europe does not show a lot of behavioural change. The reason for this is that this price does not take outside influence on supply and demand into account. The current regional approach works best for regions defined by a continuous network of gas pipelines (e.g. South and Central America). A region like Europe is connected well to other regions which dilutes the realism of the simulation.

The easier solution would to define the region containing the EU to include the Commonwealth of Independent States as well as Northern Africa. A more interesting solution would be to create smaller overlapping regions (i.e. countries can be part of multiple regions). Each region could determine its regional energy prices in original manner with countries adopting the average energy prices of the regions it belongs to.

Profitability Export

The revenue gas creates is calculated by multiplying the sum of the export of gas and the national demand with the gas price. As a result, the exported gas is considered to be sold at the local price, even though this might differ. The profitability of exporting gas from Russia to Europe, for example, should be higher than currently simulated as the price for gas is higher in Europe. In order for this approach to be implemented properly, however, requires a more detailed breakdown of the recipients of the exported gas to be communicated between the AB Gas Market model and the SD Regional Energy model.

Expended Political Dimension

Within the developed model for this research, political influence has been modelled via the *bargaining positions* of countries as well as recognising political motivation within the goals regarding the energy market of EU member states. One way to achieve this would be to create unique *bargaining positions* between each set of countries. Additionally, the *bargaining positions* could be made to become dynamic and change based on developments. For example, the *bargaining position* of North America could decrease when the Russian share of gas on the European market grows.

Regional Energy Union

Other than an EU CO_2 tax and a full energy union, there are other possible policies for the EU to explore. The most important of which is the proposal the EU has made regarding a regional approach in which countries ensure gas to their neighbours in case of future gas crises (European Union, 2010). The current model would be able to simulate this regional approach by using different agent defining the sub-regions of the EU, but only if they form a smaller energy union. In order to model the commitment to step in in case of a gas crisis the algorithm used in the AB Gas Market Model will have to be revised. After that, it would be possible to use to model to research with regional groupings makes for the most effective policy.

National Policies

Other than EU policy, the model can be used to explore effects of policies taken on a national level as well. A clear example would be the planned end of gas extraction in the Netherlands. Another possibility would be to explore the effects of countries deciding to implement a CO_2 tax on their own.

Adaptive Policy Pathway

Within the current research each policy can either be enforced or not from the start of the simulation. The model could be used to explore different moments in time to start with the implementation of the policies. This research would result in a Dynamic Adaptive Policy Pathways while identifying tipping points after which policies would have the largest effect.

Increasing Resolution

As the performed research focused on the European gas market, regions outside of the continent have been simulated at a very high resolution. The developed model does allow for individual countries to be included outside of Europe as well. Therefore, the same model can be used to explore the effects of energy policies implemented in other regions or countries in the world. Another option would be to keep the focus on Europe, but explore ways to react to energy policies implemented in other parts of the world.

6

References

Aalto, P. & Temel, D. K. (2014). European energy security: Natural gas and the integration process. *Journal of Common Market Studies, 52*(4), 758-774. doi:10.1111/jcms.12108

Arcuri, A. (2013). *The rise of a new superpower: Turkeys key role in the world economy and energy market.* Heidelberg: Springer International Publishing. doi:10.1007/978-3-319-00431-0

Austvik, O. G. (2016). The Energy Union and security-of-gas supply. *Energy Policy, 96*, 372-382. doi:10.1016/j.enpol.2016.06.013

BP Statistical Review of World Energy. (2018). *BP Statistical Review of World Energy 2018.* Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

Broenink J.F, Ni Y., & Groothuis M.A. (2010). On Model-driven Design of Robot Software using Co-simulation. In E. Menegatti (Ed.), *SIMPAR, Workshop on Simulation Technologies in the Robot Development Process.*

De Carbonnel, A. (2017, June 26). Thirteen EU nations back plan for talks with Russia over gas pipeline. *Reuters.* Retrieved from https://www.reuters.com/ article/eu-gazprom-nordstream/update-1-thirteen-eu-nations-back-plan-for-talks-with-russia-over-gas-pipeline-idUSL8N1JN3KB

Carothers, C. D., Perumalla, K. S., & Fujimoto, R. M. (1999). Efficient optimistic parallel simulations using reverse computation.*ACM Transactions on Modeling and Computer Simulation, 9*(3), 224-253. doi:10.1145/347823.347828

Chyong, C. (2016). On the future of global LNG trade and geopolitics. In S. Colombo, M. E. Harrak & N. Sartori (Eds.), *The future of natural gas: Markets and geopolitics* (pp. 41-62). The Netherlands: Lenthe

Cellier, F. E. (1991). *Continuous System Modeling.* Springer-Verlag, New York

Cotella, G. & Crivello, S. (2016). The macroregional geopolitics of energy security: Towards a new energy world order?. In P. Lombardi & M. Gruenig (Eds.), *Low-carbon energy security from a European perspective* (pp. 81-108). London: Academic Press

Cotella, G., Crivello, S. & Karatayev, M. (2016). European Union energy policy evolutionary patterns. In P. Lobardie & M. Gruenig (Eds.). *Low-carbon energy security from a European perspective* (pp. 13-42). London: Academic Press

Dohmen, F. & Jung, A. (2012, May 18). Europe's failed natural gas strategy: Gazprom hopes to build second baltic sea pipeline. *Spiegel.* Retrieved from http://www.spiegel.de/international/business/gazprom-eyeing-second-pipeline-as-nabucco-faces-failure-a-833501.html

Egging, R., Holz, F. & Gabriel, S. A. (2010). The world gas model: A multi-period mixed complementarity model for the global natural gas market. *Energy, 2010*(35), 4016-4029. doi:10.1016/j.energy.2010.03053

Engel, G., Chakkaravarthy, A. S., & Schweiger, G. (2017). A General Method to Compare Different Co-simulation Interfaces: Demonstration on a Case Study. In M. S. Obaidat, T. Ören, & F. De Rango (Eds.), *Simulation and Modeling Methodologies, Technologies and Applications* (pp. 351-366). Cham, Switzerland: Springer. doi:10.1007/978-3-020-01470-4

Epstein, J. M., & Axtell, R. L. (1996). *Growing Artificial Societies: Social Science From the Bottom Up.* Washington, D.C.: Brookings Institution Press.

European network of transmission system operators for gas (2017). *Union-wide simulation of gas supply and infrastructure disruption scenarios (SoS simulation)*

European Commission (n.d.). *Building the energy union.* Retrieved from https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/building-energy-union

European Union (2010). *Concerning measures to safeguard security of supply.* (Regulation 994/2010). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010R0994&from=EN

European Union (2013). *Roadmap EU-Russia energy cooperation until 2050.* Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/2013_03 _eu_russia_roadmap_2050_signed.pdf

Faas, H., Gracceva, F., Fulli, G. & Masera, M. (2011). European security - A European perspective. In A. Gheorghe & L. Muresan (Eds.), *Energy security: International and local issues, theoretical perspectives, and critical energy infrastructures* (pp. 9-22). Dordrecht: Springer

Forrester, J. W. (1961). *Industrial dynamics.* The M.I.T. Press.

Forrester, J. W., & Senge, P. M. (1980). Tests for building confidence in system dynamics models. *TIMS Studies in the Management Sciences*, 14, 209-228.

Franza, L., De Jong, D. & Van der Linde, C. (2016). The future of gas: The transition fuel?. In S. Colombo, M. E. Harrak & N. Sartori (Eds.), *The future of natural gas: Markets and geopolitics* (pp. 25-40). The Netherlands: Lenthe

Gomes, C., Thule, C., Broman, D., Larsen P. G., & Vangheluwe, H. (2017). *Co-simulation: State of the art*

Götz, R. (2006). Russia's energy strategy and the energy supply of Europe. In H. G. Broadman, T. Paas & P. J. J. Welfens (Eds.), *Economic liberalization and integration policy: Options for Eastern Europe and Russia* (pp. 185-200). Berlin: Springer

Grimm, V., Berger, U., Deangelis, D. L., Polhill, J. G., Giske, J., & Railsback, S. F. (2010). The ODD protocol: A review and first update. *Ecological Modelling, 221(23)*, 2760-2768. doi:10.1016/j.ecolmodel.2010.08.019

Grimm, V., Schewe, L., Schmidt. M. & Zöttle, G. (2018). A multilevel model of the European entry-exit gas market. *SSRN Electronic Journal.* doi:10.2139/ssrn.2978135

Gürel, A. (2016). Eastern Mediterranean gas: Source of prosperity for the region?. In S. Colombo, M. E. Harrak & N. Sartori (Eds.), *The future of natural gas: Markets and geopolitics* (pp. 117-138). The Netherlands: Lenthe

Hecking, H. & Panke, T. (2012). *COLUMBUS - A global market model* (EWI working paper, No 12/06) Retrieved from http://www.ewi.uni-koeln.de/fileadmin/ user_upload/Publikationen/Working_Paper/EWI_WP_12-06_Columbus_global_gas _market_model.pdf

Hecking, H. & Weiser, F. (2017). *Impacts of Nord Stream 2 on the EU natural gas market* (Rep.). Cologne, Germany: Ewi Energy Research & Scenarios gGmbH. Retrieved from https://www.ewi.research-scenarios.de/cms/wp-content/uploads/2017/09/EWI-1163-17-Studie-Impacts-of-Nord-Stream-2-web.compressed.pdf

Houghton, J. (2018). *PySD Documentation Release 0.9.0.*

International Energy Agency (2018). *Gas trade flows in Europe.* Retrieved from https://www.iea.org /gtf/#

Ivanter, V. V., Panfilov, V. S., Nekrasov, A. A., Uzyakov, M. N., Sinyak, Y. V., Moiseev, A. K.,... Semikashev, V. V. (2007). Russia and Europe: Energy union or energy conflict? *Studies on Russian economic development, 18*(2), 115-122. doi:10.1134/s1075700707020013

De Jong, S. (2013). The EU's external natural gas policy - Caught between national priorities and supranationalism (Doctoral dissertation). Retrieved from https://lirias2repo.kuleuven.be/bitstream/handle/123456789/393181/PhD_Sijbren _de_Jong_Final.pdf;jsessionid=440B3FECAF3DD513B83B FA3D257801D8?sequence=1

De Jong, S., Auping, W., & Govers, J. (2014). *The Geopolitics of Shale Gas: The Implications of the US' Shale Gas Revolution on Intrastate Stability within Traditional Oil- an Natural Gas-Exporting Countries in the EU Neighborhood* (Rep. No. 17). The Hague: The Hague Centre for Strategic Studies & TNO.

Kanellakis, M., Martinopoulos, G. & Zachariadis, T. (2013). European energy policy - A review. *Energy Policy, 62*, 1020-1030. doi:10.1016/j.enpol.2013.08.008

Kanter, J. (2010, June 22). Europe Considers New Taxes to Promote 'Clean' Energy. *The New York Times.* Retrieved from https://www.nytimes.com/2010/06/23/business/energy-environment/23carbon.html?_r=2&ref=cap_and_trade

Keating, D. (2018, March 27). Don't expect new EU gas rules to solve Russian pipeline impasse, say experts. *Forbes.* Retrieved from https://www.forbes.com/ sites/davekeating/2018/03/27/dont-expect-new-eu-gas-rules-to-solve-russian-pipeline-impasse-say-experts/#13d86781147a

Kleijnen, J. P. C. (1997). Sensitivity analysis and related analyses:A review of some statistical techniques, *Journal of Statistical Computation and Simulation, 57*(1-4), 111-142, DOI: 10.1080/00949659708811805

Koranyi, D. (2016). The United States as a new gas exporter. In. S. Colombo, M. E. Harrak & N. Sartori (Eds.), *The future of natural gas: Markets and geopolitics* (pp. 63-78). The Netherlands: Lenthe

Kwakkel, J. H. (2012). Exploratory Modelling and Analysis (EMA) Workbench. Retrieved June 6, 2018, from http://simulation.tbm.tudelft.nl/ema-workbench/contents.html#exploratory-modelling-analysis-workbench

Kwakkel, J. H. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software, 96,* 239-250. doi:10.1016/j.envsoft.2017.06.054

Kwakkel, J. H. (2018). *pyNetLogo Documentation Release 0.None.3*

De Lara, J. & Vangheluwe, H. (2002) *AToM^3: A Tool for Multi-formalism and Meta-modelling*

Le Coq, C. & Schwenen, S. (2017). *Challenges for natural gas in the context of the energy union.* Retrieved from http://www.cerre.eu/sites/cerre/files/170307 _CERRE_GasChallenges_final.pdf

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the next one hundred years new methods for quantitative, long-term policy analysis and bibliography.* Santa Monica, CA: RAND.

Lombardi, P. & O'Donnel, B. (2016). Towards a low-carbon citizens-driven Europe's energy security agenda. In P. Lombardi & M. Gruenig (Eds.), *Low-carbon energy security from a European perspective* (pp. 258-263). London: Academic Press

Łoskot-Strachota, A. (2016). Winds of change: Challenging future for Russia's gas. In S. Colombo, M. E. Harrak, & N. Sartori (Eds.), *The future of natural gas: Markets and geopolitics* (pp. 159-180). The Netherlands: Lenthe

Luciana, G. (2016). The EU and LNG as a flexible tool for energy security: Constraints and opportunities. In S. Colombo, M. E. Harrak & N. Sartori (Eds.), *The future of natural gas: Markets and geopolitics* (pp. 101-116). The Netherlands: Lenthe

Marchii, S. D. & Page, S. E. (2014). Agent-Based Models. *Annual Review of Political Science, 17*(1), 1-20. doi:10.1146/annurev-polisci-080812-191558

Mazenva, E. (2018, April 25). *German $10 Billion Gas Bill Shows Perks of Close Russia Ties.* Retrieved April 26, 2018, from https://www.bloomberg.com/news/articles/2018-04-25/germany-s-10-billion-gas-bill-shows-perks-of-close-russia-ties

Minullin, Y. & Schrattenholzer, L. (2011). Lessons learned for regional and global energy security. In A. Gheorghe & L. Muresan (Eds.), *Energy security: International and local issues, theoretical perspectives, and critical energy infrastructures* (pp. 55-70). Dordrecht: Springer

Ni, Y. & Broenink, J. F. (2012). Hybrid systems modelling and simulation in DESTECS: a cosimulation approach. In M Klumpp (eds), *26th European Simulation and Modelling Conference, SM 2012, Essen, Germany*, (pp 32-36), Ghent, Belgium, EUROSIS-ETI.

Popescu, M. & Hurduzeu, G. (2015). Energy challenges for Europe - Scenarios of the importance of natural gas prices form a game theory perspective. *Journal of Game Theory, 4*(2), 26-35. doi:10.5923/j.jgt.20150402.02

Prahl, A. & Weingartner, K. (2016). A study of Russia as key natural gas supplier to Europe in terms of security of supply and market power. In P. Lombardi & M. Gruenig (Eds.), *Low-carbon energy security from a European perspective* (pp. 43-79). London. Academic Press

Van Rossum, G. (1995) *Python tutorial*, Technical Report CS-R9526, Centrum voor Wiskunde en Informatica (CWI), Amsterdam.

Russel, M. (2017). *Gazprom's controversial Nord Stream 2 pipeline.* (PE 608.629). Retrieved from http://www.europarl.europa.eu/RegData/etudes/ATAG/ 2017/608629/EPRS_ATA(2017)608629_EN.pdf

Sargent, R. G. (2010). Verification and validation of simulation models. *Proceedings of the 2010 Winter Simulation Conference.* doi:10.1109/wsc.2010.5679166

Schulte, S. (2018) *COLUMBUS: A long-term simulation model for the global gas market.* Retrieved from http://www.ewi.research-scenarios.de/en/models/columbus/

Serbanescu, D. (2011). Modeling and evaluation of security of energy supply in regional environments. In A. Gheorghe & L. Muresan (Eds.), *Energy security: International and local issues, theoretical perspectives, and critical energy infrastructures* (pp. 177-234). Dordrecht: Springer

Shirov, A. A., Semikashev, V. V., Yantovskii, A. A. & Kolpakov, A. Y. (2016). Russia and Europe: Energy union or energy conflict? (Eight years after). *Studies on Russian economic development, 27*(2), 127-137.
doi:10.1134/s1075700716020143

Stein, M. (1987). Large Sample Properties of Simulations Using Latin Hypercube Sampling. *Technometrics, 29*(2), 143-151. doi:10.1080/00401706.1987.10488205

Sterman, J. D. (1994). Learning in and about complex systems. *System Dynamics Review, 10*(2-3), 291-330. doi:10.1002/sdr.4260100214

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world.* Boston: Irwin

Umbach, F. (2010). Global energy security and the implications for the EU. *Energy Policy, 38*(3), 1229-1240. doi:10.1016/j.enpol.2009.01.010

Umbach, F. & Nerlich, U. (2011). Asset criticality in European gas pipeline systems - Increasing challenges for NATO, its member states and industrial protection of critical energy infrastructure. In A. Gheorghe & L. Muresan (Eds.), *Energy security: International and local issues, theoretical perspectives, and critical energy infrastructure* (pp. 273-304). Dordrecht: Springer

Valkenburg, G. & Gracceva, F. (2016). Towards governance of energy security. In P. Lombardi & M. Gruenig (Eds.), *Low-carbon energy security from a European perspective* (pp. 207-229). London: Academic Press

Vangheluwe, H. L. (2000). DEVS as a common denominator for multi-formalism hybrid systems modelling. In Varga, A., (eds), *IEEE International Symposium on Computer-Aided Control System Design*, (pp 129-134). IEEE Computer Society Press. Anchorage, Alaska

Vangheluwe, H. L., De Lara, J., & Mosterman, P. J. (2002). An introduction to multiparadigm modelling and simulation. In *Proceedings of AIS2002 (AI, Simulation & Planning)*, (pp. 9-20). SCS

Ventana Systems Inc. (2011). *Vensim Systems Manual* (Tech. Rep.)

Weiser, F. (2018). *TIGER: Precise simulation of European gas flows.* Retrieved from http://www.ewi.research-scenarios.de/en/models/tiger/

Weishaar, S. E. (2018). *Carbon Taxes at EU Level: Introduction Issues and Barriers* (Working paper No. 556). Vienna: Österreichisches Institut für Wirtschaftsforschung. Retrieved from https://www.wifo.ac.at/jart/prj3/wifo/main.jart?content-id=1454619331110&publikation_id=60973&detail-view=yes

Wilensky, U. (1999). NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. http://ccl.northwestern. edu/netlogo/

Wilson, A. B. (2018). *Common rules for gas pipelines entering the EU internal market* (PE 614.673). Retrieved from http://www.europarl.europa.eu/RegData/ etudes/BRIE/2018/614673/ EPRS_BRI (2018)614673_EN.pdf

Witte, G. & Beck, L. (2018, April 25). How a proposed Russian pipeline to Europe is dividing the West. *The Washinton Post*. Retrieved from https://www.washingtonpost.com/world/europe/a-giant-gas-pipeline-raises-the-spectre-of-russian-influence-in-europe/2018/04/24/415a63f0-4199-11e8-b2dc-b0a403e4720a_story.html?noredirect=on&utm_term=.38ef89b360cf

World Bank Open Data (n.d.). Retrieved November 25, 2018, from https://data.worldbank.org/

A

Determining Bargaining Positions

The *bargaining positions* of countries have been based on the different prices countries pay the Russian Gazprom for gas (Mazenva, 2018).

The AB Gas Market model operationalises the trading price of gas as follows: the fist step is to take the average of both regional gas prices at hand which defines the base gas price. The *bargaining position* variable has been defined in order to capture the negotiation positions of countries. Each country receives a *bargaining position*. These *bargaining positions* are then used to alter the market gas price as follows:

Trading_Price = ((bargaining_position_Supplier - bargaining_position_Buyer) / power_factor + 1) * base_gas_price

Using this formula the gas prices each country has payed Gazprom (Mazenva, 2018) can be used to determine the bargaining positions. Assuming the power factor to be 20, the pricing formula can be simplified to:

Trading_Price = Factor * base_gas_price

Factor = ((BP_Russia - BP_Country) / 20 + 1)

As the paid prices all approach 200 USD per 1000 cubic meters of gas, the base_gas_price is set at 200. Next, as the United Kingdom pays the lowest price for gas, their bargaining position has been set at 10. From there, the bargaining position of Russia can be determined, which results in the bargaining position to be 7.4. With the bargaining position of Russia set, the bargaining positions of other countries can be determined. An overview of these calculations can be found in table A.1. Countries not included in the overview provided by Mazenva (2018) have been assumed to have bargaining positions similar to neighbouring countries.

Table A.1: Overview of calculations bargaining positions

	Paid Price	**Price**	**Factor**	**Factor - 1**	**BPR-BPC**	**BPR**	**BPC**
Germany	192	200	0.96	-0.04	-0.8	7.4	8.2
Italy	207	200	1.035	0.035	0.7	7.4	6.7
U.K.	174	200	0.87	-0.13	-2.6	7.4	**10**
France	199	200	0.995	-0.005	-0.1	7.4	7.5
Austria	208	200	1.04	0.04	0.8	7.4	6.6
Czech R.	190	200	0.95	-0.05	-1	7.4	8.4
Poland	197	200	0.985	-0.015	-0.3	7.4	7.7
Netherlands	199	200	0.995	-0.005	-0.1	7.4	7.5
Hungary	203	200	1.015	0.015	0.3	7.4	7.1
Slovakia	201	200	1.005	0.05	0.1	7.4	7.3
Bulgaria	180	200	0.9	-0.1	-2	7.4	9.4
Greece	193	200	0.965	-0.035	-0.7	7.4	8.1
Finland	209	200	1.045	0.045	0.9	7.4	6.5
Latvia	186	200	0.93	-0.07	-1.4	7.4	8.8
Denmark	196	200	0.98	-0.02	-0.4	7.4	7.8
Lithuania	201	200	1.005	0.005	0.1	7.4	7.3
Romania	202	200	1.01	0.01	0.2	7.4	7.2
Estonia	197	200	0.985	-0.015	-0.3	7.4	7.7
Croatia	196	200	0.98	-0.02	-0.4	7.4	7.8
Slovenia	210	200	1.05	0.05	1	7.4	6.4

B

Example trade negotiations

Figure B.1 depicts a case of six countries looking to trade with each other and the gas prices between them based on their power positions.

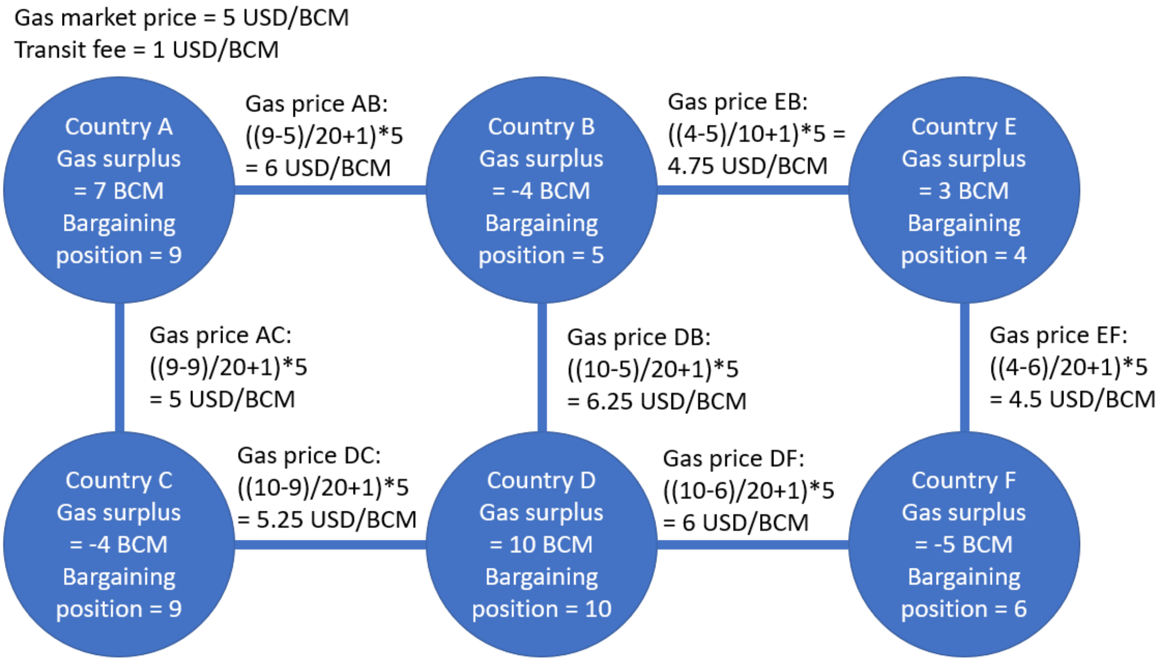


Figure B.1: Example Case Trade Negotiations : Round 1

In the first state of negotiations each country makes proposals to the countries they are connected to, based on their needs and their preferred gas price out of the available options. A non of the countries are able to form a trade hub, countries are only considering there neighbours. This results in the following proposals:

- Proposals country A:
  - Export 4 BCM to country B
  - Export 3 BCM to country C
- Proposals country B:
  - Import 3 BCM from country E
  - Import 1 BCM from country A

- Proposals country C:
  - Import 4 BCM from country A
- Proposals country D:
  - Export 4 BCM to country B
  - Export 5 BCM to country F
  - Export 1 BCM to country C
- Proposals country E:
  - Export 3 BCM to country B
- Proposals country F:
  - Import 3 BCM from country E
  - Import 2 BCM from country D

In the second state of negotiations the proposals are compared and finalised where they overlap. This results in the following deals to be made:

- Country A exports 1 BCM to country B
- Country A exports 3 BCM to country C
- Country E exports 3 BCM to country B
- Country D exports 2 BCM to country F

Figure B.2 depicts the new states of the countries with updated gas surpluses. Because there is still potential for gas trade, a new round of negotiations is initiated. The gas surpluses of countries B and E have both reached 0 BCM, thus these two countries start to facilitate trade within their network. As countries B and E are connected themselves, they form a joint trade hub. Countries A, D and F are connected to the newly formed trade hub, with countries A and D looking to export and country F looking to import. As countries D and F are already connected, the only transfer connection that is established via the trade hub is between countries A and F.

From the updated gas surpluses and connections the following trade proposals follow:

- Proposals country A:
  - Export 3 BCM to country F
- Proposals country C:
  - Import 1 BCM from country A
- Proposals country D:
  - Export 3 BCM to country F
  - Export 1 BCM to country C
- Proposals country F:
  - Import 3 BCM from country D

The second state of negotiations results in the following deals to be made:

- Country D exports 3 BCM to country F

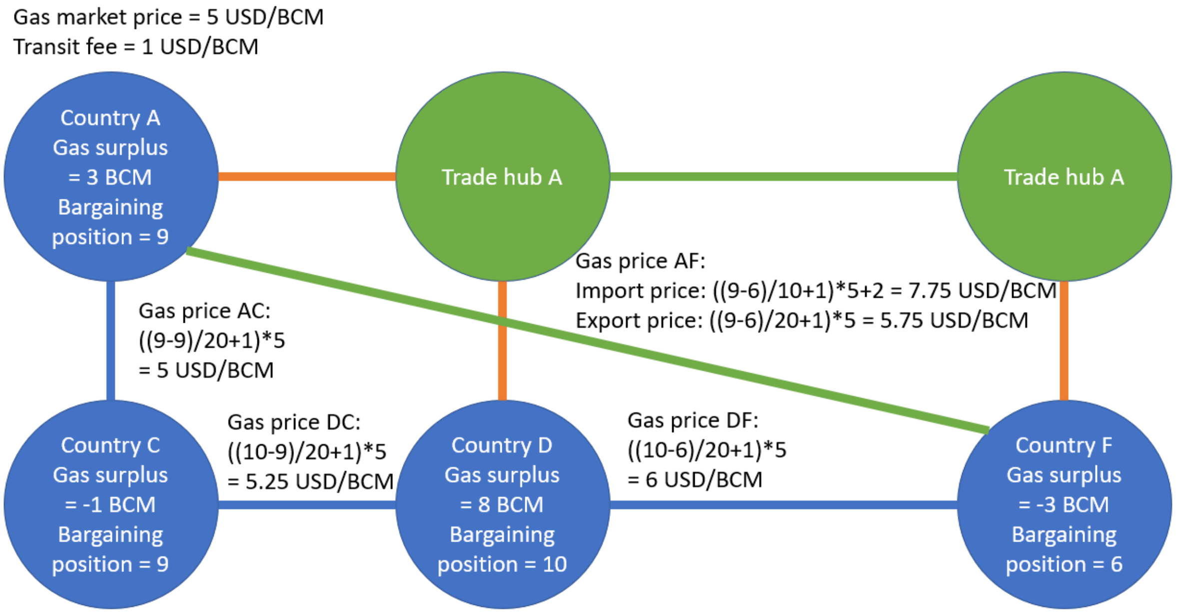


Figure B.2: Example Case Trade Negotiations: Round 2

Figure B.3 depicts the next states of the countries with updated gas surpluses. As countries B, E and F have all reached a gas surplus of 0 BCM and are directly connected to each other, they form a united trade hub. Connected to this trade hub are countries A and D, however, as both of these countries are looking to export gas no new connection is established.

From the updated gas surpluses and connections the following trade proposals follow:

- Proposals country A:
  - Export 1 BCM to country C
- Proposals country C:
  - Import 1 BCM from country A
- Proposals country D:
  - Export 1 BCM to country C

The second state of negotiations results in the following deals to be made:

- Country A exports 1 BCM to country C

Figure B.4 depicts the next states of the countries with updated gas surpluses. As there is no more potential for trade between neighbouring countries, negotiations end here.

The complete gas trade deals between the countries are thus:

- Country A exports 1 BCM to country B
- Country A exports 4 BCM to country C
- Country E exports 3 BCM to country B
- Country D exports 5 BCM to country F

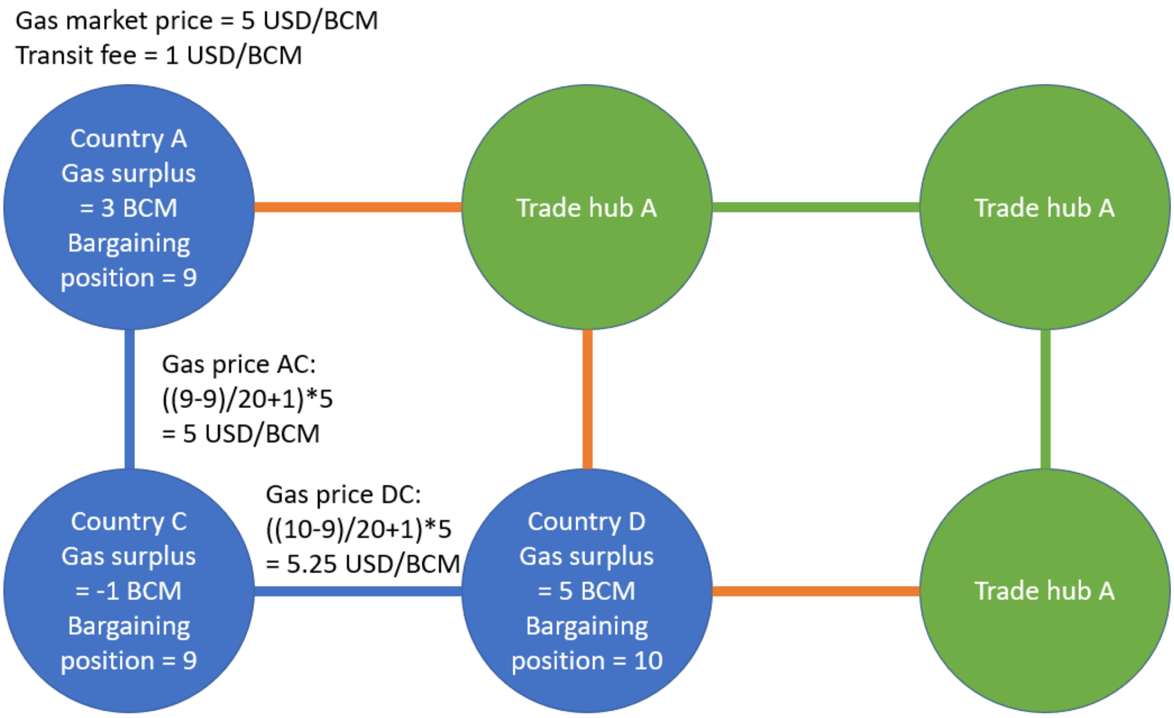


Figure B.3: Example Case Trade Negotiations: Round 3

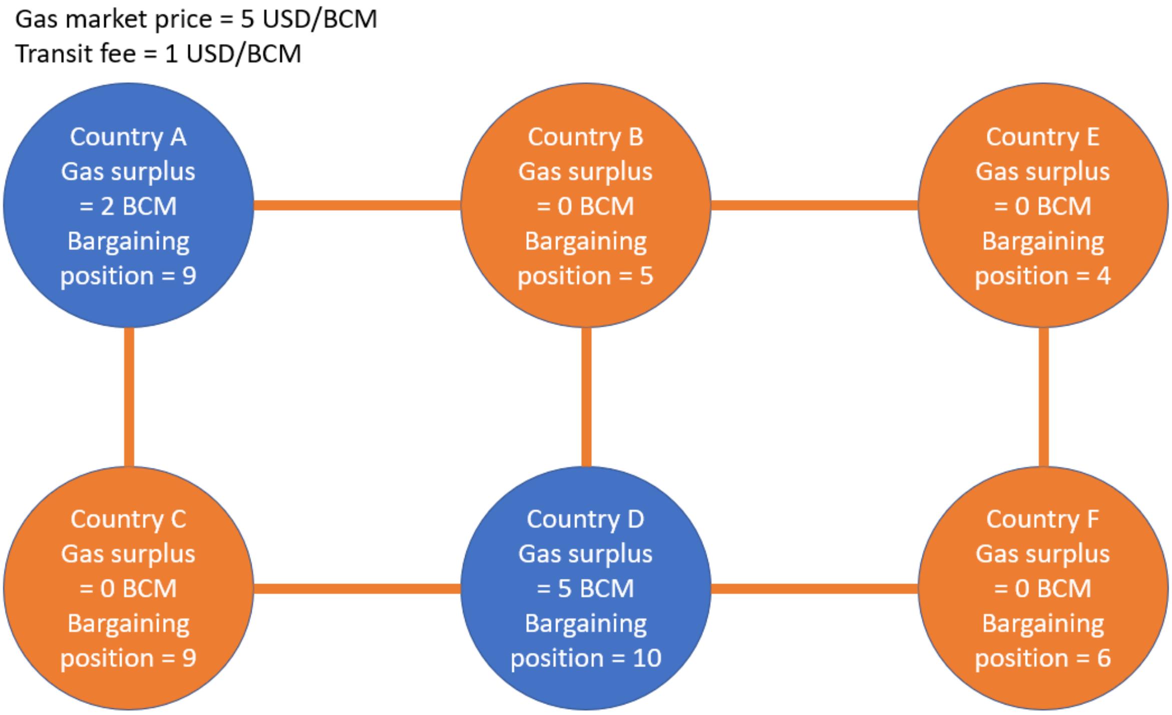


Figure B.4: Example Case Trade Negotiations: Final Results

C

AB Gas Market model sub-models

C.1. Determining Gas Prices

In any trade negotiation the price paid for trade forms a key aspect. The trading prices of gas are especially important when modelling the gas market, due to the regional price differences of gas, the potential for LNG trade and the differences that occur due to different *bargaining positions*.

Having countries negotiate on gas prices, while also considering alternate trading partners would soon becoming to complex for the purpose of the this research. Instead, in order to operationalize differing gas prices within the gas market model, fixed prices between countries are calculated at the start of each negotiation round. These prices revolve around two key aspects: a base gas price for each market and the political positions of the involved countries.

When the price for gas between two countries is to be determined, the fist step is to take the average of both regional gas prices at hand which defines the base gas price. The *bargaining position* variable has been defined in order to capture the negotiation positions of countries. Each country receives a *bargaining position*. These *bargaining positions* are then used to alter the market gas price as follows:

Trading_Price = ((bargaining_position_Supplier - bargaining_position_Buyer) / power_factor + 1) * base_gas_price

The size of price variations can be tweaked via the power factor within the formula. The *bargaining positions* of countries have been based on the different prices countries pay the Russian Gazprom for gas (Mazenva, 2018). The calculation of the *bargaining positions* can be found in the appendix A.

The next step is for the trading price to become unique for each of the two countries. The price is to be altered based on the use of LNG and the lack of direct connections between the countries in question. The use of LNG, with regards to both importing and exporting, is a costly endeavour. As the importing country is considering costs, a set input variable *LNG price* is added to their trading price. Seeing as the exporting country is looking for the highest price the same variable is subtracted from their trading price. Additionally, it isn't free to transport gas via different countries, therefore, an additional set input variable (*transfer price*) is added to the trading price of the importing country if this is the case.

C.2. Proposing and Completing Gas Trade Deals

Using the gas prices between countries, every country has a clear overview of the potential trading partners they share one of the three link-breeds with (i.e. *border pipes*, *LNG routes* and *transfer route*). In order to model the negotiation process the negotiations go through different rounds which are repeated until there are no potential deals left.

In the first state of the negotiation process each country expresses their preferred trade deals. Countries either have the need to export or to import based on their gas surplus being positive or negative respectively. An exporting country would prefer to trade with the country offering the highest price for its gas, while an importing country would prefer to buy gas for the lowest possible price. A country will allocate their needs based on these prices, being limited by the absolute size of the needs

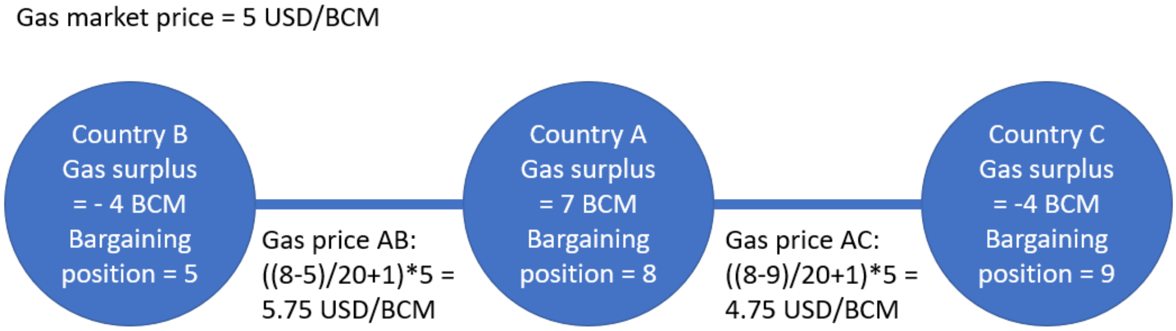


Figure C.1: Example Case Trade Negotiations Neighbouring Countries

of their neighbours. In the second state of the negotiation process, the different proposals between countries are compared to each other and an initial trade deal is at the volume equal to the smaller proposal made between countries. In the third state of negotiations the model is to check whether there is still potential to trade between countries, i.e. are there still neighbouring countries with a need to import and export gas respectively. If this is the case negotiations start a new round by going back to the initial state.

Figure C.1 depicts a simple case in order to demonstrate the principle. In this case three different countries are looking to trade, country A wishes to export while country B and C are looking to import gas. Furthermore the power factor has been set at 20. Note that the values used in this example don't aim to realistic, but have been chosen to simply explain the algorithm.

In the first state of the negotiation process country A prefers to trade with B over C as B offers a higher price. As the size of B's import needs is lower than A's, country A can only offer to trade 4 BCM with country B. The other 3 BCM are than offered to country C for the lower price. As countries B and C only have the possibility to deal with country A, they both offer to import 4 BCM from A.

In the second state of negotiations in the example the deals are compared which results in an agreement of 4 BCM between countries A and B and an agreement of 3 BCM between countries A and C.

In the third state, the potential for trade is measured. As only country C is still looking to trade, but doesn't have any potential trading partner, there is no further potential for trade in this system and the negotiation process ends.

A more extensive example of the algorithm can be found in appendix B.

C.3. Establishing Transfer Routes

Where as *border pipes* are predefined and *LNG routes* are created in a straightforward way, the creation of *transfer routes* is a more complicated process.

Once a country has fulfilled their own trading needs, they open up the possibility to facilitate gas trade between their neighbours. When this happens, first, a trade HUB is created out of a group of connected countries in this position. The next step is for *transfer routes* to be created between all countries connected to the established trade HUB.

The trading algorithm, as a result of the made assumptions at the start, only considers the net results of international gas trade. With the inclusion of capacity limitations, the path between these countries has become necessary to uncover when a *transfer route* is used rather than a direct *border pipe* or *LNG route*. A three step algorithm was designed aimed at finding a viable route between countries, as well as register the available capacity.

In the first step of the algorithm every country is asked to set a variable i to zero. The exporting country asks his neighbours to switch this zero to a one if there is still capacity available between the two. These countries ask their neighbours to switch their i to a three. This process continues until the importing country's i becomes non-zero. At this point, any viable route between the two countries is characterised by a series of countries with ascending values for i. Because the trading algorithm keeps repeating until their are no potential deals left, the assumption was made that the route itself isn't as important as the trading capacity in use over all made deals. Once a viable route has been found, the second step of the algorithm, the last step of the algorithm compares the available capacity between the countries in the found route and sets the potential size of the deal to the lowest value found.

C.4. Trade of Additional Resources

Besides gas, the trade of other energy resources between countries is included as well, i.e. oil, coal and biofuels. As it is much easier to transport these resources compared to gas, it is assumed that the world market will clear. The algorithm checks to see the difference in supply and demand of each of these resources and distributes them evenly over the importing countries.

C.5. Capacity Limitations and Expansion

As trading capacity forms an important limitation to the gas trade between countries it has to be included within the trading model. In order to simulate this limitations, each pipeline was assigned a variable containing the capacity of the pipeline and a second variable referring to the amount of unused capacity. Countries aren't able to offer a deal larger than the available capacity in the pipeline. After each deal the available capacity is updated. LNG trade routes are limited by capacity as well, but come from the liquifying capacity of the exporting country and the deliquifying capacity of the importing country.The available capacity is updated via available (de)liquifying capacities assigned to the countries in question.

At the end of each trade negotiation, each country and *border pipe* is asked to evaluate the use of their capacities. If a country's liquifying or (de)liquifying capacity is fully in use, or a *border pipe's* capacity is fully in use, an expansion of the relevant capacity is planned. The year this decision was made is recorded and at the start of every negotiation each country and *border pipe* planning to expand checks to see if sufficient time has passed since the decision. If this is the case, the relevant capacity is expanded by a pre-defined amount. Both the time it takes to expand capacity as well as the size of the capacity expansion are input values to the Gas Market model.

D

SD Regional Energy model sub-models

D.1. Extraction Capacity

The energy supply sub-model consists of smaller sub-models for each energy source. These sub-models are build with the same building blocks, but not all of these are applicable to each source. The basic set-up for each extraction capacity sub-model can be seen in figure D.1.

The first of these building blocks surround the installed extraction capacity. In the short term, the installed extraction capacity can be mothballed when not in use, from where the capacity in question will either deteriorate over time or be recommissioned when the demand rises. In the long term new extraction capacity is proposed and prepared via a procurement delay. Both *new long term supply* and *Change in short term supply* are determined within the energy costs sub-model.

The second building block models the discovered resources reserve base. The discovered resources reserve base grows by discovering more of the resource and technological advancements in recoverable of the resources. The third building block models the available energy stocks. The extracted resources and import increase the stock, while consumption and export decrease the stock.

As mentioned before, this set-up isn't directly applicable to each energy source. Oil and coal are the only energy sources which uses each of the described building blocks, as they are extractable resources which are fairly easy to store.

The gas supply sub-model only uses the extraction capacity and discovered resource reserve base building blocks, as it is very difficult for gas to be stored effectively.

The biofuels sub-model doesn't use the discovered resource reserve base elements, but uses its extraction capacity to produce biofuels in order to increase the energy stocks.

Lastly, both the nuclear energy sub-model and the sub-model regarding other renewable sources, solely relay on their respective extraction capacities.

D.2. Energy Demand

As shown in the CLD in figure 3.3 and discussed in section **??** the size of the economy and the energy demand of a country relate to each other in two different ways. First of all, a growing economy warrants a growing energy demand, however, an energy shortage impedes on economic growth. Secondly, the energy intensity of the economy is encouraged to decrease when there is an energy shortage, resulting in a lower energy demand and thus lower shortage. An overview of the energy demand sub-model, which encompasses both relations, can be seen in figure D.2.

In the sub-model shown in figure D.2 the *Energy Demand* is defined by the product of the *GDP* and the *Energy Intensity GDP* of a country. The *GDP* has been modelled to grow based on *Autonomous Economic Growth* and *Limitations Economic Growth due to Energy Shortage. Limitations Economic Growth due to Energy Shortage* is defined as the product of the *Relative Energy Shortage* and the *Factor limiting Economic Growth due to Energy Shortage* which is an uncertain input value as well.

The *Energy Intensity GDP* has been modelled to decrease via a *decrease factor* which has been defined as the sum of the modelled *Effect of Supply Shortage on Decoupling* and *Autonomous Energy*

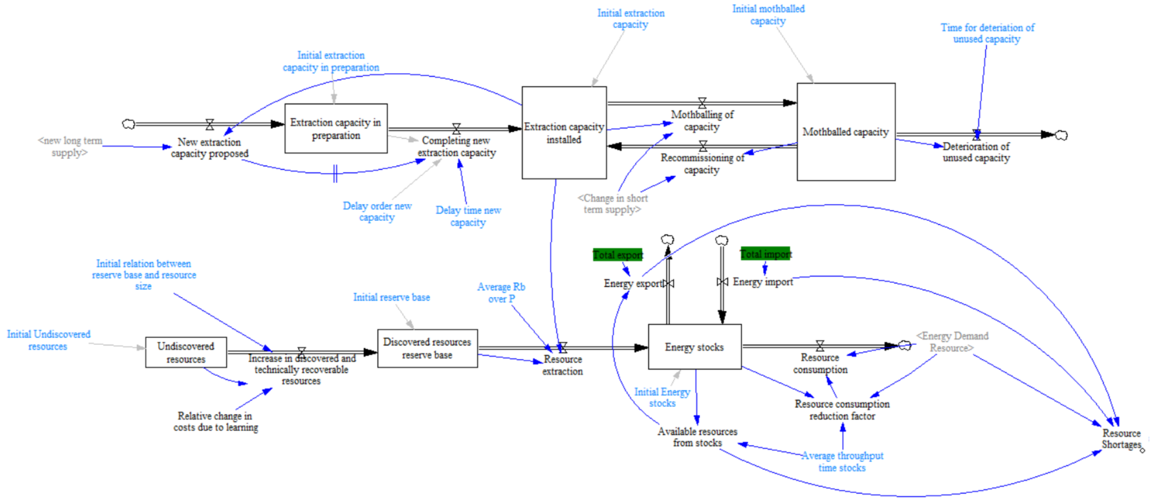


Figure D.1: Basic Set-Up Extraction Capacity

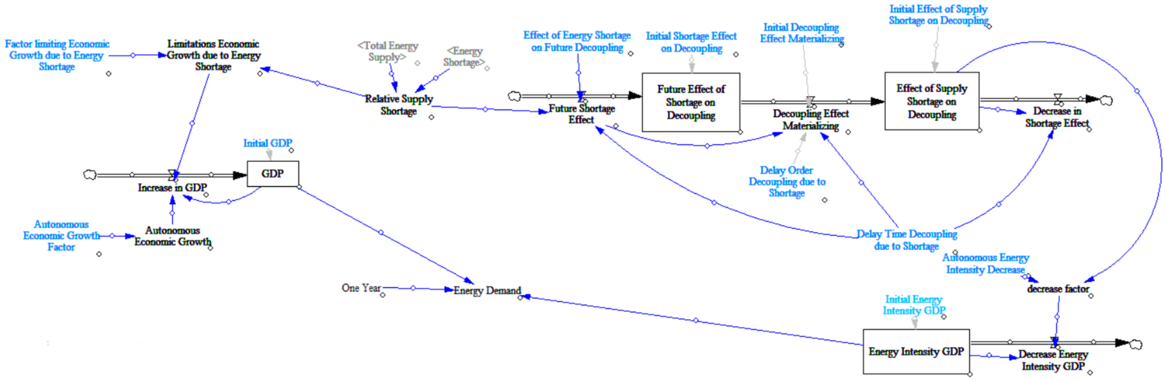


Figure D.2: Sub-model Energy Demand

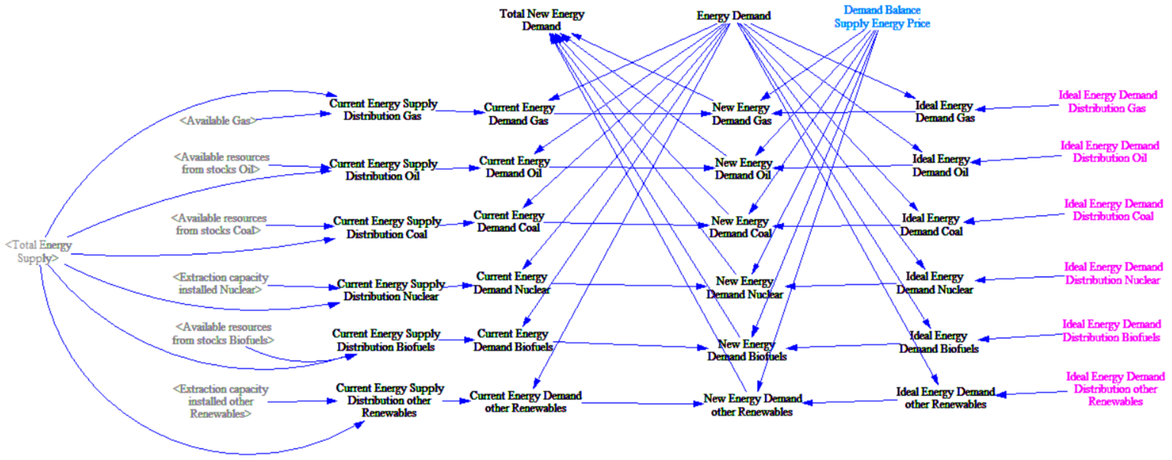


Figure D.3: Sub-model Energy Demand Distribution

Intensity Decrease. A procurement delay has been used to model *Effect of Supply Shortage on Decoupling* as the decoupling of the economy isn't an instantaneous phenomena, but takes time and planning before it occurs.

D.3. Energy Demand Distribution

As the model has the goal of outputting the resource trading needs of the country in question, the model has to distribute its demand over the different resources included in the model. This distribution is based on the *Current Energy Supply Distribution* and the *Ideal Energy Demand Distribution* of each resource. Figure D.3 shows the described modelling structure. The uncertain input factor *Demand Balance Supply Energy Price* balances the influence of the current supply distribution and the preferences based on energy prices on the demand distribution, as the *New Energy Demand* of each resource has been defined as (1 - *Demand Balance Supply Energy Price*) * *Current Energy Demand* + *Demand Balance Supply Energy Price* * *Ideal Energy Demand*.

The *Ideal Energy Demand Distribution* is based on the *Energy Price* of each resource and is simulated via the modelling structure depicted in figure D.4. The *Energy Price* is summed with their respective *Costs* CO_2 *emissions*. *Costs* CO_2 *emissions* itself can be seen as a CO_2 tax in order to discourage the use of fossil fuels and can be considered to be a policy lever. Inversely correlated to the resulting *Functional Energy Price* is the *Preference for* each resource, as a higher energy price discourages the demand of that resource. Next, the *Preference for* each resource is normalised which results in the *Ideal Energy Demand Distribution*.

D.4. CO_2 Emissions

In order to model the CO_2 emissions of a country, the consumption of gas, oil and coal are all multiplied by the equivalent emission size and summed together to get the overall CO_2 emissions. The resulting sub-model can be seen in figure D.5. The CO_2 emissions of each source are treated as uncertain input values.

D.5. Energy Costs

The *unit costs* of each resources develop over time and hinge on the *cumulative extracted fuel* of each resource. Depending on the resource the *cumulative extracted fuel* influences the *unit costs* differently. The model structure for each fossil fuel has been included in figure D.6. The change in *unit costs* of fossil fuels results from the effect the *cumulative extracted fuel* has on the availability of the resource

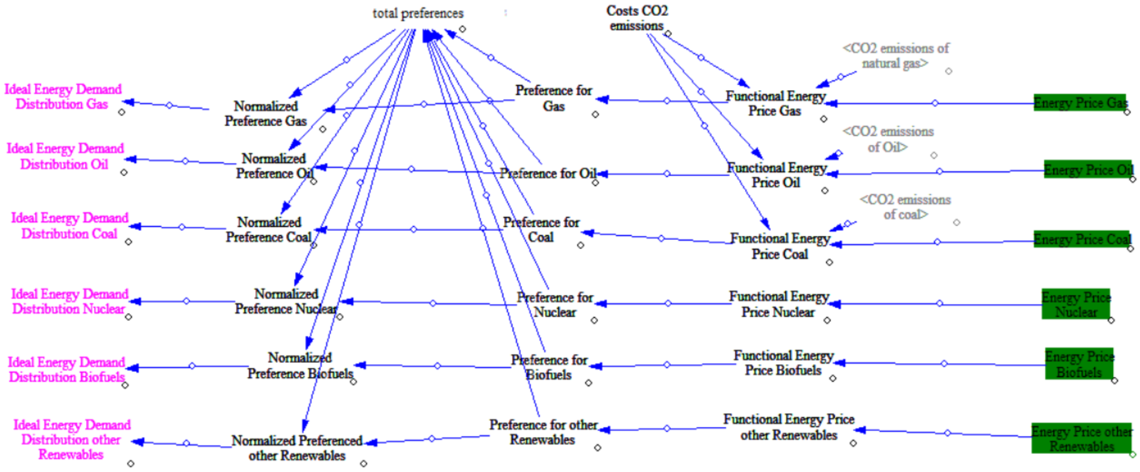


Figure D.4: Sub-model Ideal Energy Demand Distribution

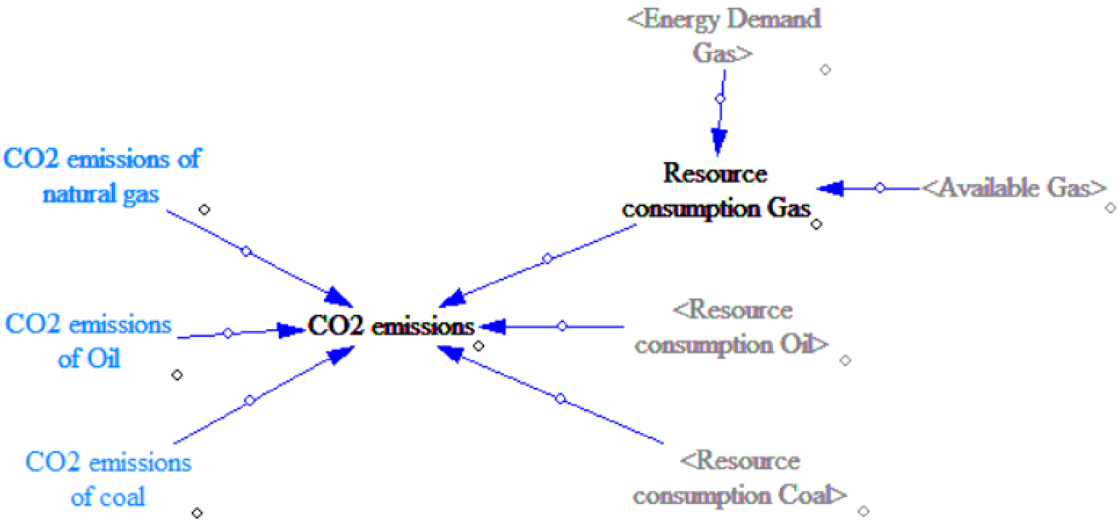


Figure D.5: Sub-model CO_2 Emissions

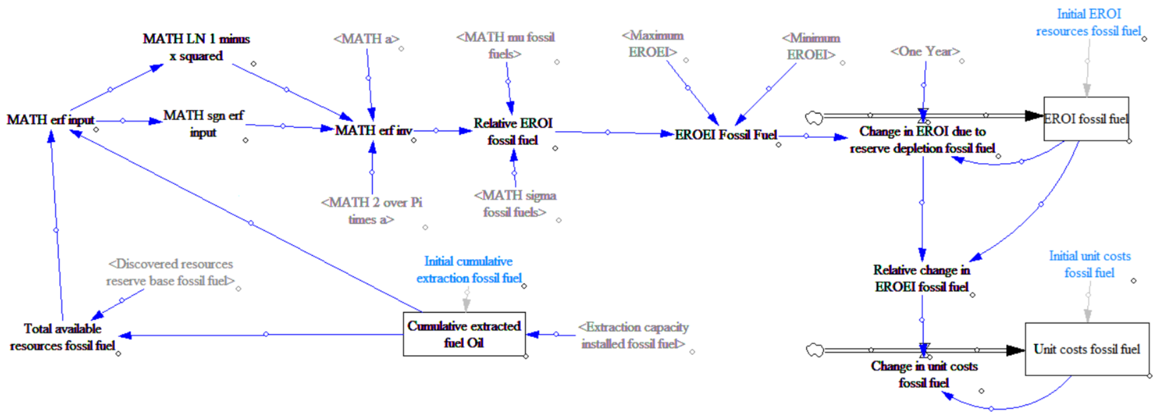


Figure D.6: Sub-model Unit Costs Fossil Fuels

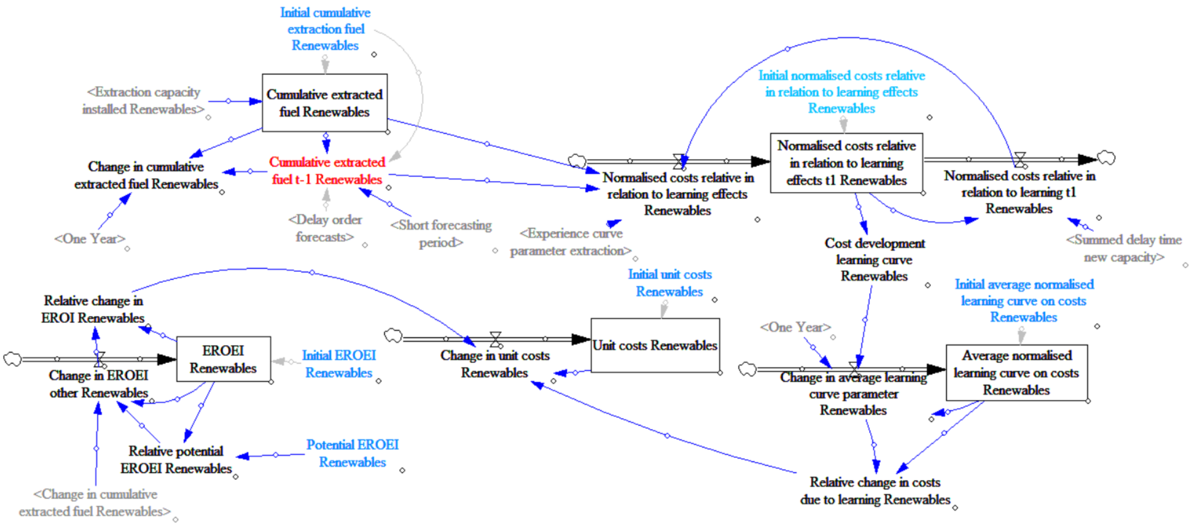


Figure D.7: Sub-model Unit Costs Renewable Sources

and in turn affects its Energy Return On Energy Invested (EROEI).

As renewable energy sources aren't dependent on a depleting source, their EROEI is instead dependent on the change in *cumulative extracted fuel* and the *relative potential EROEI* of the resource in question. Furthermore, as these sources of energy are still relatively new, a learning effect has been included lowering the costs over time. The used model structure for renewable sources can be seen in figure D.7.

D.6. Long Term and Short Term Supply

The final sub-model determines the *Change in short term supply* and the *new long term supply* which affect the mothballing and proposals of new capacity respectively within the extraction capacity sub-model. The basic set-up of the sub-model, as shown in figure D.8, has been adapted to each resource. The sub-model determines the *Total income energy supply* and the *Total costs energy supply* in order to determine the profitability of the resource in question. If this results in a positive *Change in short term supply*, mothballed capacity will be recommissioned, while a negative result will have installed capacity be mothballed. As planning for additional capacity warrants a more long term perspective, *Long term normalised profits* has been modelled via a stock in order for it to be resilient against sudden fluctuations.

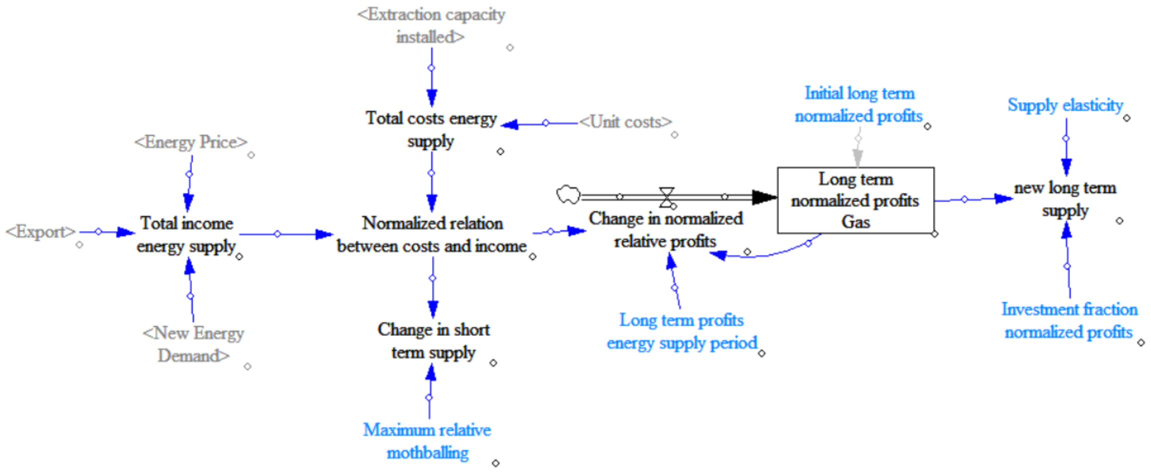


Figure D.8: Basic Set-Up Long and Short Term Supply