A SUPPLY DEMAND MODEL FOR EXPLORATION OF THE FUTURE OF THE DUTCH GAS SECTOR

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Abstract: *Import dependency and the extent of renewable gas production are two outcomes of interest concerning the future of gas supply in the Netherlands. Due to the complexity of internal mechanisms and uncertainties associated with the natural gas production, the production of renewable gases, and the demand for gas, the future of these two outcomes of interest cannot simply be projected. In this study, a system dynamics model is built to investigate the dynamics of import dependency and the renewable gas production, and an uncertainty analysis is conducted by using this model to explore the possible futures of these two outcomes of interest in numerous scenarios. The results show that import dependency is above 80% in 2060 in the majority of the scenarios, but there are few favourable cases in which it is below 20%. The ratio of renewable gas to the total consumption is not expected to exceed 10% in short term and to remain around this value although there are cases in which it reaches 40%. In future studies, the import mechanism of the model can be extended, different behavior patterns observed in the scenarios can be identified and analysed, and the results can be used for policy recommendations.*

Keywords: *System dynamics, exploratory modeling and analysis, uncertainty, natural gas, unconventional gas, biogas, green gas, power-to-gas, power generation*

1. Introduction

Natural gas is the third most prevalent primary energy source in the world, with a 24% share in the total energy consumption in 2011 (BP, 2012), and this share is expected to significantly (40-60%) grow by 2040 (IEA, 2012; ExxonMobil, 2012). The dependency on natural gas as the primary energy fuel is much higher, namely 47% (CBS, 2013), in the Netherlands, which is the largest natural gas producer and the only net exporter in the European Union (EUROSTAT, 2011). However, there is much uncertainty about whether this dependency will create challenges or opportunities in the future, depending on the balance between the supply and demand dynamics of gas.

On the supply side, decreasing conventional natural gas reserves, and recently revealed increasing risk of seismic activity, point out an inevitable decrease in the domestic supply, to be possibly substituted by imported gas. However, high dependency on import is a desirable situation due to the economic disadvantages and possible disruptions. Shifting to another energy source as an alternative solution is not favorable, too, due to the investments locked in the gas infrastructure. Therefore, new gas types such as unconventional natural gas or renewable gases that can be injected into the grid are seen promising to compensate the decreasing natural gas production. However, the contribution of these new gas types is dependent on many uncertain factors, such as the resource availability, societal acceptance, market price and the costs of production.

On the demand side, the sectors that consume gas in the Netherlands are aggregated into five, being households and buildings, industry, agriculture, transport and electricity generation. Mainly due to the factors like efficiency measures, economic activity and market penetration, the future demand of the first four sectors is highly uncertain. As for the electricity generation, the future demand is dependent on the internal dynamics of the energy system, namely the competition between the various technologies and the eventual share of gas-fired generation in the electricity supply. Besides, new technologies in the electricity sector, such as decentral co-generation of heat and power, power-to-gas systems, and carbon capture and storage bring the gas and electricity sectors closer and affect the role of gas in the future energy system.

Given such uncertain developments both in the supply and demand side, there are two outcomes of interest that concern the main actors in the gas sector. The first one is the import dependency, which is desired to be low due to the abovementioned reasons. Secondly, the share of renewable gas types in the total supply is important as it maintains the domestic production and the utilization of the network. The targets for the natural gas replacement by renewable gas are set to be 10% by 2020, to be increased by 2050 (Dumont, 2010).

The objective of this paper is to investigate the dynamics of these two outcomes of interest with a close look at the co-evolution of supply options, in the presence of uncertainties which stem from the lack or ambiguity of information. The presence of such uncertainties associated with the system itself or with the model prevents reaching plausible 'best-estimate' dynamics. Therefore, an 'exploratory' approach is adopted in this study to generate numerous possible future dynamics so that the decision making can be based on a wide range of possibilities rather than a single one.

In the remainder of this paper, first, the system dynamics model developed for this purpose will be described, and the base run output of this model will be briefly discussed in Section 3. In Section 4, the possible future dynamics of the two outcomes of interest will be explored, and the uncertain factors which yield favorable outcomes will be investigated. Following that, the paper will end with conclusions in Section 5.

2. Model Description

Figure 1 depicts the overview of the model, which aims at investigating the balance of gas supply and demand. On one side of the balance, the model includes various demand groups, and various supply options are included on the other side. What brings complexity to this balance is the competition between supply options and the interconnections between the demand groups and supply options. In this study, the mechanisms that affect the gas demand are kept beyond the model boundaries, except for the demand of the power sector, and the supply side of the balance is represented in more detail.

The model is designed as a composition of six sub-models. The first sub-model is built to represent the gas demand at a high aggregation level, whereas in the second one power generation is modeled in detail due to the significant links between the power and gas sectors. The other three sub-models represent the three main technologies that currently contribute or have the potential to contribute to the gas supply. These technologies are natural gas extraction, biogas and green gas production, and the power-to-gas systems. Lastly, these demand and supply sub-models are linked in the market segment. In the following sections, these sub-models will be described one by one, and some common structures present in several of them will be explained in Section 2.7.

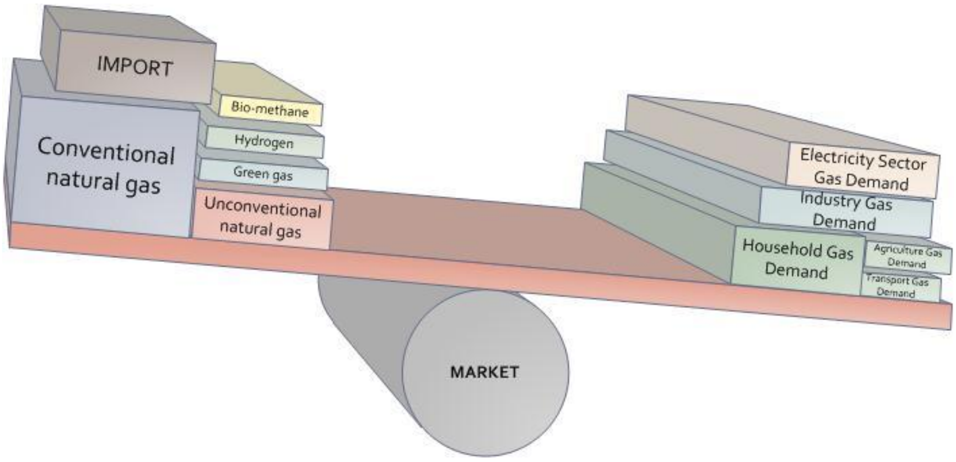

Figure 1 The Overview of the Model

2.1. Demand

The demand of each of the four sectors, namely the households, industry, agriculture and transport, is represented as a stock variable which fractionally varies over time. The fraction of change is assumed to be an external time dependent variable which is based on published demand forecasts (EFNL, 2011). This simple demand formulation is denoted as follows, where D_i is the demand of sector *i*, and f_i is the corresponding annual change fraction which is assumed to be a stepwise function over time :

$$D_i(t) = D_i(0) + \int_0^t f_i(\tau) D_i(\tau)\, d\tau \qquad (1)$$

$$f_i(t) = f_{i,2010} + STEP\left(f_{i,2030}, 2030\right) + STEP\left(f_{i,2050}, 2050\right) \qquad (2)$$

The total of the individual demand of these sectors is to be satisfied via the supply in the gas grid. However, alternative locally implemented technologies decrease the amount of gas consumed via the grid. Namely, the heat generated as a side product of the decentral electricity production, the amount of biogas directly used for heating, and the amount of green gas used for mobility are subtracted from the total of sector demands, to determine the annual domestic gas demand excluding the power sector. Hence, the total gas demand is formulated as in the following equations:

$$TDeP(t) = \sum_i D_i(t) - GG_m(t) - m\, BG_h(t) - P_h(t)$$

$$TD(t) = TDeP(t) + D_p(t)$$

TDeP(t)	*Total domestic gas demand except power*
$GG_m(t)$	*Green gas used for mobility*
$BG_h(t)$	*Biogas used for heating*
m	*Methane content ratio of biogas to natural gas*
$P_h(t)$	*Natural gas equivalent of the heat generated by the power sector*
TD(t)	*Total domestic demand*
$D_p(t)$	*Gas demand of the power sector*

Uncertainties in the demand sub-model

Being based on forecast studies, the demand change fraction (f_i) of each sector is highly uncertain. The methane content of biogas varies according to the production conditions, but still it is kept in a certain range. Therefore, the parameter *m* which enables the comparison of biogas to natural gas in terms of the energy yield has a low uncertainty level.

2.2. Electricity Generation

The power sector lies at the core of the energy transition, since a large share of the energy consumption is in terms of electricity, and the prevalent renewable energy systems are developed to produce electricity. In the Netherlands, the power sector is currently dominated by gas-fired generation because natural gas has been an abundant and reliable source in the Netherlands so far, and the gas demand of the power sector constitutes an important element of the total gas demand. However, while the transition to a renewable energy system is expected to moderate the share of the natural gas in the power sector on the one hand, the intermittent nature of renewable energy production requires a flexible backup source on the other hand. Gas-fired electricity generation is considered as a strong candidate to be the substitute of renewable electricity due to its relatively low CO_2 emissions and flexible operation, which may give a different role to gas in the future. However, coal-fired and nuclear power technologies are still important competitors of gas, due to lower fuel prices and almost zero CO_2 emissions, respectively. The intermittency of renewable electricity generation is expected to result not only in shortages that require a complementary source, but also in surpluses that can be stored for further use instead of wasting. Producing hydrogen and methane with this excess electricity and injecting them into the gas grid is a promising technology that builds another connection between the gas and power sectors. Thus, due to such developments in the power sector which are important for the future of gas demand and supply, electricity generation is explicitly modeled in this study.

The total power generation capacity installed in the Netherlands in 2010 is reported as 25.4 GW, which yielded 123.8 GWh electricity in that year (Energiezaak, 2011). This current capacity contains a wide variety of technologies and resources, although their shares in the power mix significantly differ. Table 1 lists the technologies included in the model and their installed capacity, and capacity under construction values in 2010.

Table 1 Current Electricity Generation Capacity in the Netherlands

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

All these 10 technologies are assumed to have the same capacity installation, market and operation structure with different parameter values, and the model is based on the two negative feedback loops demonstrated in Figure 2. The *Capacity Installation* loop represents commissioning new capacity according to the discrepancy between current supply level and the expected demand and the score of each technology, which is calculated based on the Return on Investment (RoI) under the current market conditions and the societal acceptance level. The second loop, *Capacity Adjustment*, represents the adjustment of the capacity utilization factor according to the share in the power mix, which determines the desired production of each technology based on the expected demand value.

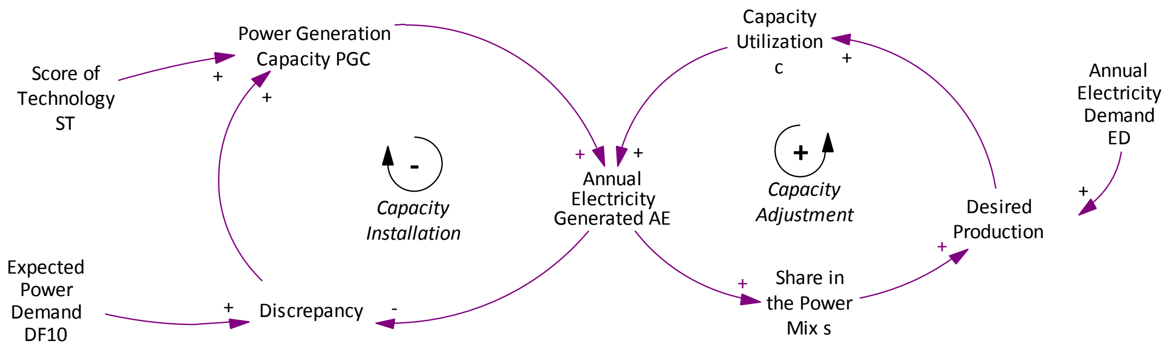

Figure 2 Causal Loop Diagram of Electricity Generation Model - Capacity

The score of each technology, which distributes the expected supply discrepancy among the technology options for capacity installation, is assumed to be the weighted average of the RoI and the societal acceptance of each technology, with uncertain weights which depend on the preferences of the decision makers. RoI is determined by costs and the market price of each technology as will be explained in Section 2.7. However, both the costs and price are expected to decline depending on the production, due to the learning effect and the basic laws of supply and demand, respectively. As for the societal acceptance, it is assumed that only the controversial technologies, namely coal, CCS (both coal and gas) and nuclear have variable societal acceptance levels. The societal acceptance of other options is assumed to be constant at their current high values. Among the controversial technologies, CCS and nuclear are opposed to because of the safety risks, whereas coal (without CCS) is objected to because of high CO_2 emissions. As the cumulative production increases and safety issues unfold, it is assumed that the societal acceptance of CCS and nuclear energy decreases. Regarding the CO_2 emissions, as the discrepancy between the current CO_2 emissions and the target level expands, the societal acceptance of CCS and nuclear is assumed to increase, while that of coal decreases. Another factor that positively affects the acceptance of all these controversial technologies is assumed to be the scarcity of electricity supply, which is measured by the ratio of the total national electricity demand to the total domestic supply. The causal loop diagram that summarizes these relations that determine the score of each technology can be seen in Figure 3 and Figure 4.

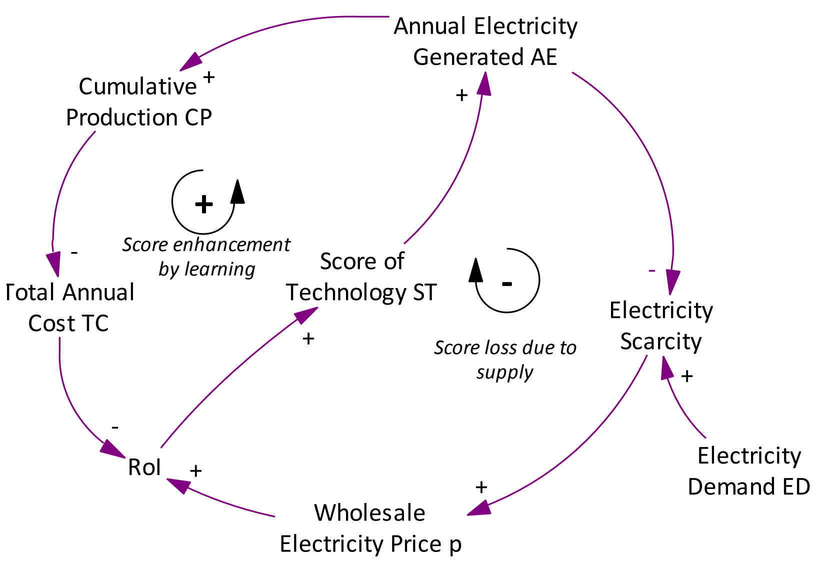

Figure 3 Causal Loop Diagram of Electricity Generation Model - RoI

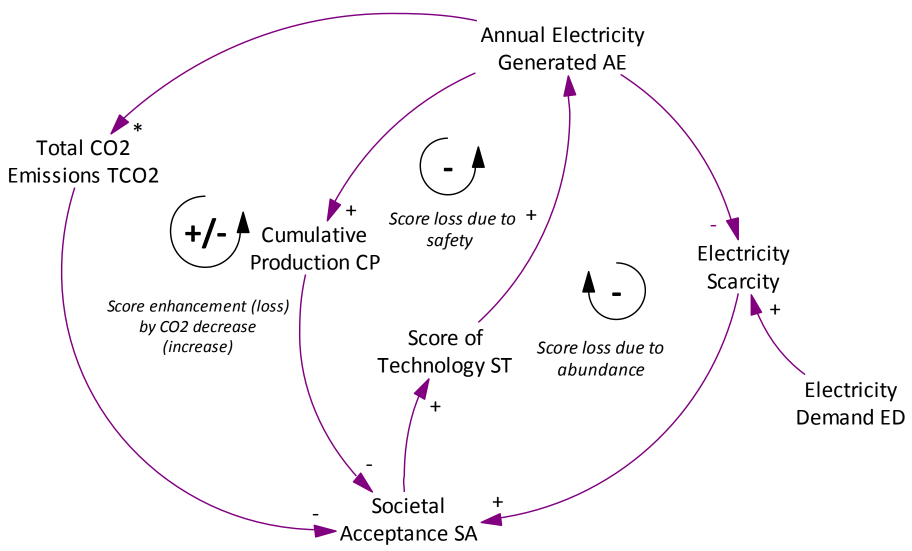

Figure 4 Causal Loop Diagram of Electricity Generation Model - Societal Acceptance

For the capacity installation mechanism, the production capacity module of the generic commodity market model (Sterman, 2000, 798-800) is adapted, as shown in Figure 5, since there are long delays between the capacity ordering and commissioning of power plants with most of the generation technologies. The equations of this part of the model is not presented here, since they are the same as in the generic model, but it is worthwhile to mention that the capacity is associated with the power that can be generated, hence the operational capacity depends on the available operating hours per year. This capacity installation mechanism is triggered by 'Desired Additional Capacity'. The entire equation list of the rest of the electricity generation sub-model can be seen in Appendix 1.

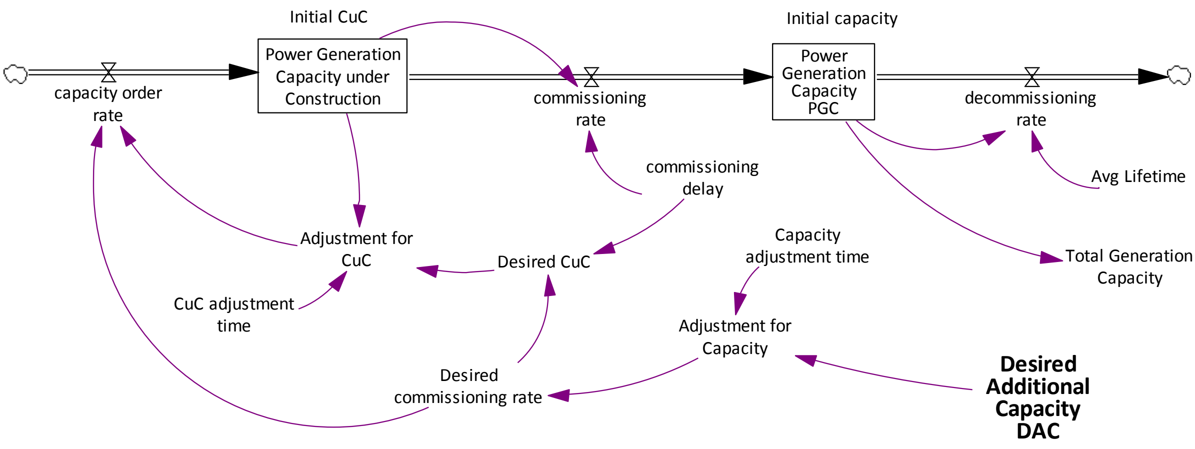

Figure 5 Stock-Flow Diagram of the Power Generation Capacity Installation

This sub-model eventually generates the effect of electricity production on the gas demand. In the meantime, it enables monitoring the power mix and the CO_2 intensity of the electricity generation, which provides valuable insights about the energy transition.

Uncertainties in the electricity generation sub-model

Several equations in this model are based on the physical facts of energy generation and the basic laws of economics. Still, many assumptions have been made in order to simplify and quantitatively represent the real structure. The variability of price based on the ratio of demand to supply, the effects of safety, scarcity and CO_2 targets on societal acceptance are such assumptions that could have been formed differently. Uncertainties are present in the parameter values of this sub-model, too. Initial costs, initial societal acceptance levels, fuel efficiency values, unit CO_2 emissions and fuel prices are subject to uncertainty due to the unavailability or ambiguity of data.

2.3. Natural Gas Production

Natural gas production is the main source of gas supply in the Netherlands currently, which meets 47% of the total energy consumption in the country (CBS, 2013). In 2010, the production volume was recorded as 83.9 billion m^3 (bcm) which was much higher than the domestic production of 51.9 bcm (Energiezaak, 2011). However, this was reported as the peak production, and the remaining reserves and resources which maximally sum up to 1890 bcm (EBN, 2012) are expected to be gradually depleted before 2050. Although the industry tries to maximize the production by improving the technologies used, and the government supports the industry by ensuring that the gas produced from small fields will always be purchased at favorable prices (small fields policy), the eventual depletion is the unavoidable end, since no new additions to the resource base are expected. Nevertheless, unconventional gas, which is basically the natural gas extracted from more challenging reservoirs and known by the most common type shale gas, may be an option to maintain high production rates. The actual amount of unconventional gas resources in the Netherlands is not known yet, and the societal controversy around unconventional gas makes its possible production more uncertain. The opposition to unconventional gas production is mainly due to the seismic risk created by the production technology called fracturing, the water contamination risk and the landscape damage. The seismic risk is also a current issue regarding the ‘conventional’ natural gas production although it has long been known that the production causes subsidence in the region since earthquake occurrences have been more frequent and considerable. Therefore, the societal acceptance of natural gas production, conventional or unconventional, has emerged as an important issue that affects the future of gas.

Given this current situation of the gas production, a sub-model is built in order to investigate to what extent it can contribute to the gas supply in the future. Several system dynamics models that investigate natural gas or petroleum resources exploration and production exist in the literature (Davidsen *et al.*, 1990; Dyner *et al.*, 1998; Olaya and Dyner, 2008; Chi *et al.*, 2009), which originate from Naill (1974). The model developed in this study is similar to these models, in terms of the relation between the exploration and production activities and the corresponding investments, and the factors that affect investments. However, this model is different than those in terms of the fundamental assumption that consumption directly affects production. Since the energy system is highly dependent on natural gas in the Netherlands currently, and the natural gas industry is determined to produce as much as available with the support of government policies, the production amount is assumed to be independent of demand. Hence, the capacity plays a more important role in production than demand. Due to this, this model includes a more detailed structure of construction of wells, which assist the industry to estimate the resources and reserves, and constitute the total production capacity. Having the production as a ‘push’ system also means that there is no reason for competition between the two types of gas, conventional and unconventional, in the market. Also, the production lifecycle of the two types are the same; the differences in the technologies used, yield volume and the societal acceptance levels can be represented by different parameter values on this structure.

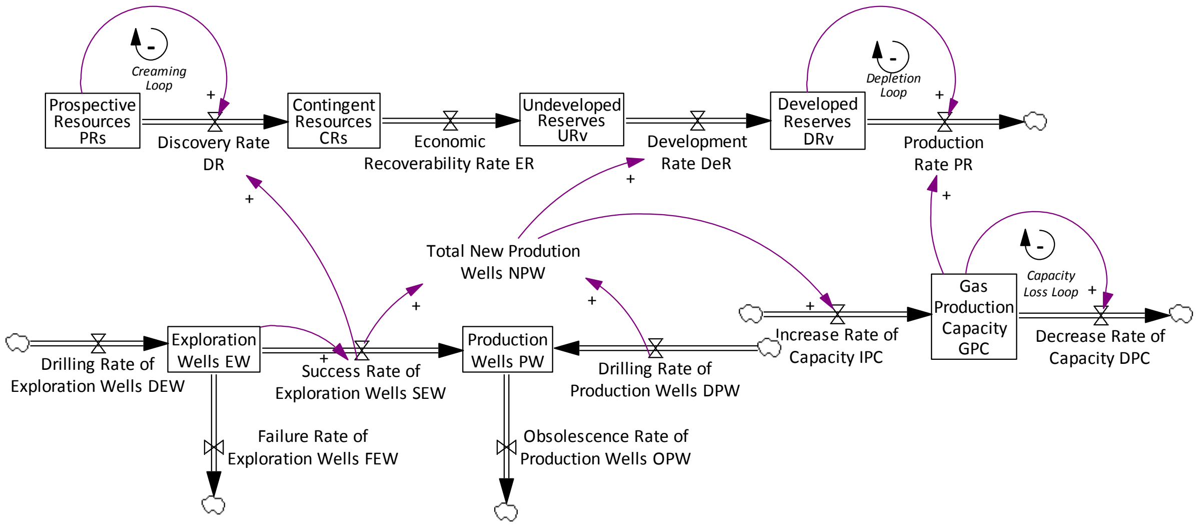

Figure 6 Stock-Flow Structure of the Natural Gas Production Sub-model

Figure 6 Stock-Flow Structure of the Natural Gas Production Sub-model shows the stock-flow structure of this natural gas production model. The first chain represents the lifecycle of different categories of resources and reserves that starts with the Prospective Resources, flows forward as they are confirmed by exploration drilling and ends with the Production Rate. The discovery of resources, the development of reserves and the production capacity are triggered by the drilling activity, which is represented in the second chain. Drilling activities start with the construction of exploration wells. The exploration wells which result in discoveries are converted to production wells, and the drilling of new production wells is stimulated. As new production wells are drilled, the development of fields is realized and the Gas Production Capacity is increased, which results in a higher Production Rate. Three single feedback loops in this stock-flow structure play important roles in the mechanism. The *Creaming Loop* points out the declining amount of new discoveries as no undiscovered (Prospective) resources remain. The *Depletion Loop* represents the depletion of Developed Reserves as production continues, which restricts further production. This loop is important also because depletion means reduced pressure in the reservoirs and higher production costs. The *Capacity Loss Loop* demonstrates the loss of capacity as production wells reach the end of their lifetime.

The driving factor behind the drilling activity is certainly the investment, which is also affected by the Production Rate. The four of the six feedback loops that govern this relationship between the Production Rate and the Effective Capital Expenditure (CAPEX) in Production can be seen in Figure 7. The *Economies of Scale* is a balancing loop which represents well-known phenomenon of decreasing unit cost as the production amount increases, which result in price decrease and makes the investments in production less attractive. Next to that, the *Economies of Depletion* is a reinforcing loop, which means that depletion due to increasing Production Rate increases the unit cost, leading to price increase which makes the investments in production more attractive. The investments increase as the Possibility of maintaining the current Production Rate with the Undeveloped Reserves increase. However, this possibility declines as the Production Rate increases and forms the *Promising Investment Loop*. The fourth loop, *Urge for Investments*, demonstrates the increase in investments as a shortage of gas supply occurs. However, this shortage is covered by further production which is stimulated by investments.

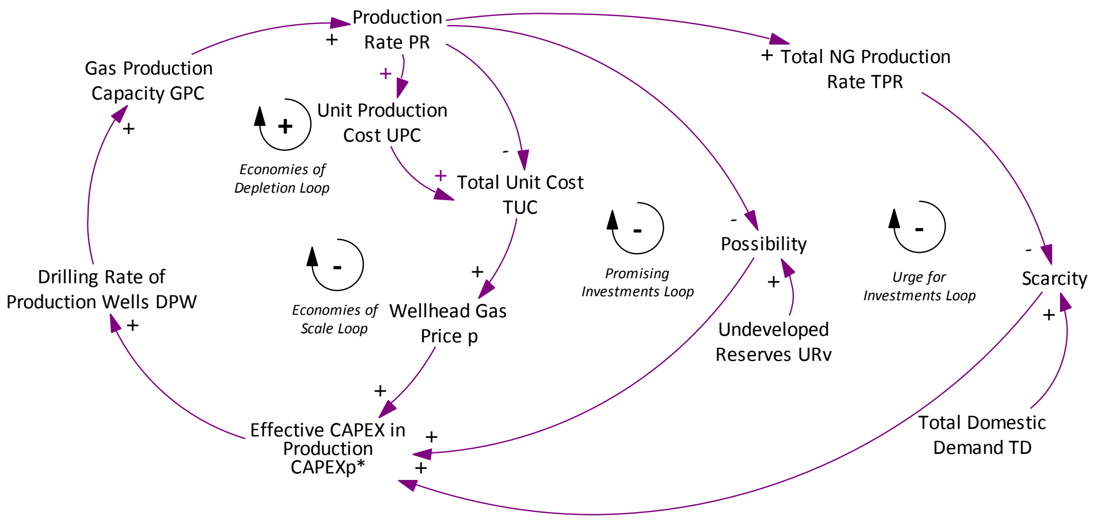

Figure 7 Causal Loop Diagram of Investment Making in the Gas Production

The other two of the feedback loops between the Effective CAPEX in Production and the Production Rate are related to the Societal Acceptance. The societal acceptance of natural gas production (of both types) is formulated as a variable between 0 and 1, similarly to the societal acceptance of power technologies. The increase fraction of societal acceptance is assumed to increase as the domestic production is not sufficient to satisfy the demand, whereas the decrease is based on the assumption that the increase in the cumulative production reveals the safety issues and raises opposition. The causal loop diagram of these relations, where the former relation leads to the *Lack of Urgency* loop and the latter forms the *Increased Risks* loop, can be seen in Figure 8.

The entire equation list of this sub-model can be seen in Appendix II.

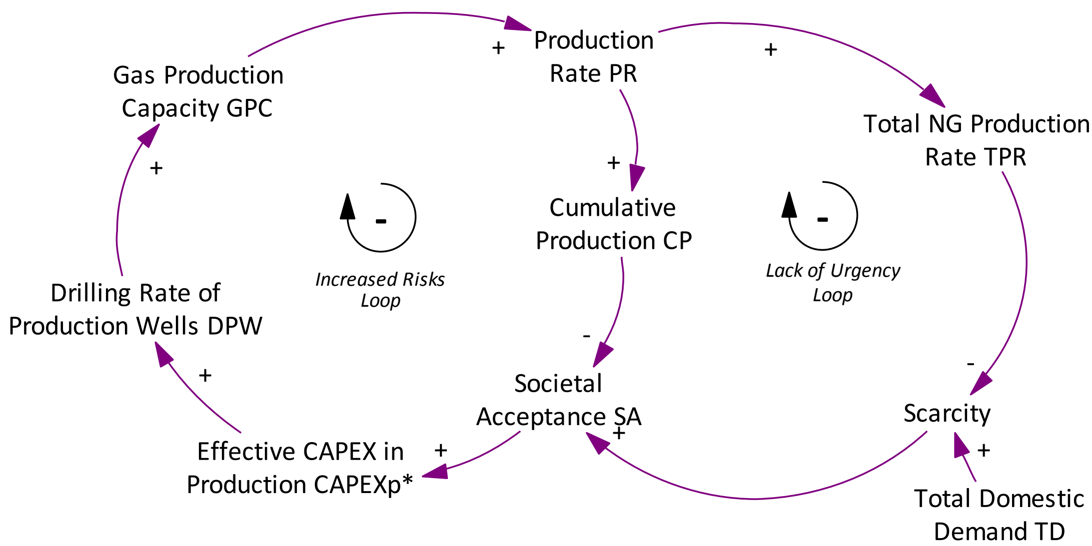

Figure 8 Causal Loop Diagram of the Societal Acceptance of Gas

Uncertainties in the natural gas production sub-model

Several uncertainties in the parameters of this sub-model exist, regarding the initial values of resources and reserves, technical characteristics of the resources and the cost values. It is important to note that these uncertainties are at a low level for conventional gas compared to the unconventional, since conventional gas production is a mature industry in the Netherlands which yields reliable data. However, the absence of data for unconventional gas which is not yet produced brings a significant uncertainty to this analysis.

2.4. Biogas and 'Green Gas' Production

One of the new technologies that may significantly affect the gas sector is the production of biogas. Biogas is produced from biomass mostly by using digestion technology, however gasification is emerging as a new option which provides higher amounts of gas yield. In addition to the maturity level and the installed capacity of the production technology, the availability of biomass plays an important role in the biogas production. The availability depends on the government policies, since not every type of biomass is allowed for combustion, and on the competition between electricity production, direct heating and biogas production for the allocation of biomass. Once biogas is produced, it has a 40-60% methane content, whereas the methane content of natural gas in the gas grid is 89.4%. Therefore, biogas is either used for heating or electricity generation locally, or upgraded to the natural gas methane level and injected to the grid, which is called 'green gas' in this case. The use of green gas instead of natural gas is a promising way to reduce CO_2 emissions, and the Dutch government has plans to achieve 8-12% natural gas replacement by green gas and other renewable gas types in 2020 (Dumont, 2010) as stated before.

With this sub-model, the contribution of green gas to the gas supply is investigated. Similar to the electricity generation sub-model, the competition of the two production technologies and the capacity installation is assumed to be based on the RoI, but unlike the electricity generation, capacity installation is driven by the raw material availability instead of demand, because the goal of biogas production is to utilize the biomass. Societal acceptance is not taken into consideration in this model, since there is no commonly known opposition to these green technologies. Unlike the electricity generation, capacity installation is not formulated as a chain structure in this sub-model, because the installation delay is a few months and negligible on an annual basis.

Figure 9 demonstrates the stock-flow representation of this storyline. First of all, available biomass is distributed among electricity generation, heating and biogas production according to their predetermined scores and the demand of each sector. In the case of electricity and biogas production, demand is dependent on the installed capacity. This biomass amount allocated for biogas production not only determines the annual biogas production rate, but also triggers the installation of new capacity. Since the installed capacity is a measure of biomass demand, a positive feedback loop, the *Biomass Allocation* loop, is formed between the capacity and allocated biomass. Following the production, biogas is distributed among three sectors, namely heating, electricity generation and upgrading to the natural gas quality, according to the market price of the end product. For upgrading, the allocated biogas amount triggers the installation of new upgrading capacity, which stimulates the green gas production in return. The green gas produced is either injected to the grid, which is the final outcome of interest in this sub-model, or used for mobility. The injectable amount also depends on the injection capacity, which is the physical availability of connection to the grid and stimulated by the production of green gas.

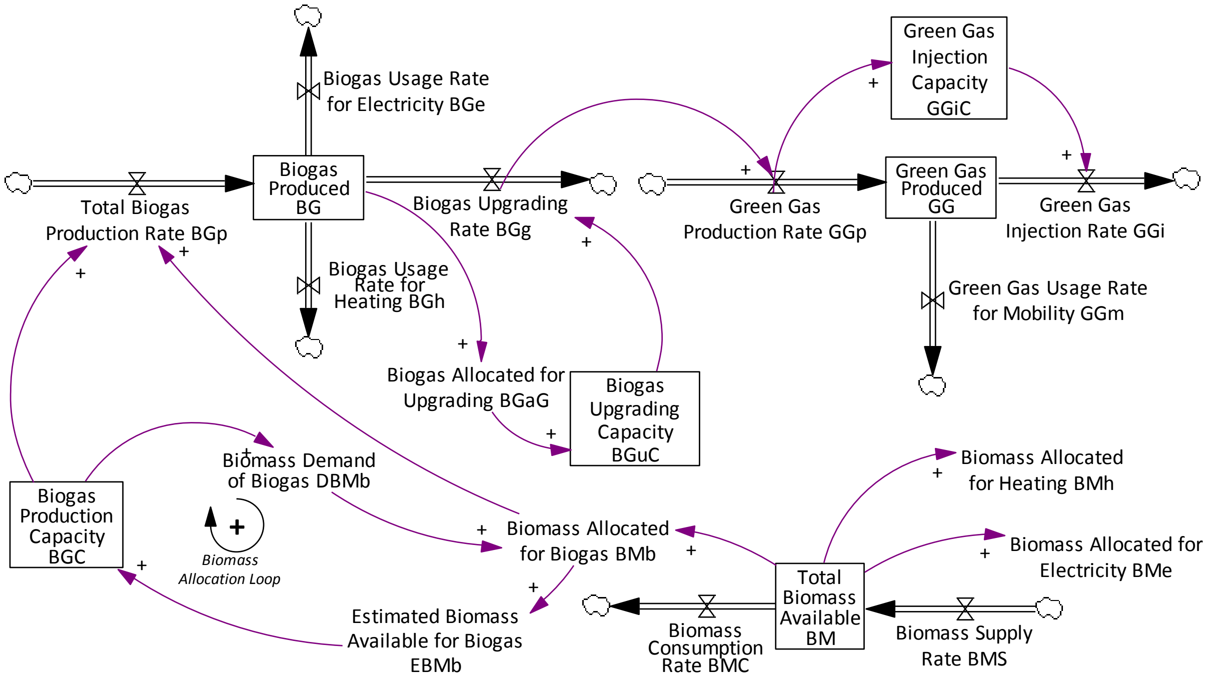

Figure 9 Stock Flow Structure of the Biogas and Green Gas Production Sub-model

As mentioned before, the RoI of capacity installation is the other major factor that affects biogas and green gas production. Given the high costs of these new technologies, the price they can be sold at is highly important to make the production profitable. Currently, green gas production is subsidized in the Netherlands for 12 years following the installation, however biogas production and the electricity generation from biogas is not. Due to this, it is assumed that the biogas price is positively linked to the green gas price, and the green gas price stimulates the production both directly and indirectly via biogas production. Increasing green gas production means a larger market share, hence the adaptation of market price with a higher effect of the green gas price. This positive causal link seems contradicting with the inverse relationship between supply and price in microeconomics, but it must be emphasized that it is to indicate the effect of each supply option's own price on the average market price. Since the market price determines the price of green gas in the absence of subsidies, these two reinforcing financial stimulation loops depicted in Figure 10 can enable the survival of green gas in the market. However, these reinforcing loops can as well impede the production of green gas, as the market price is lowered by cheap imports or natural gas production. Hence, this structure actually represents the dilemma of import capacity installation versus the green gas stimulation for the future gas supply.

The model equations of the Biogas and Green Gas Production are listed in Appendix III.

Uncertainties in the biogas and green gas production sub-model

The important parameter uncertainties in this sub-model are related to the biomass availability, subsidy duration, cost values and the average gas yield of biomass. Costs are uncertain, either because of the absence of data since the production has not reached a large scale as in the case of gasification technology, or because the local figures are not collected and aggregated as in the case of digestion and upgrading.

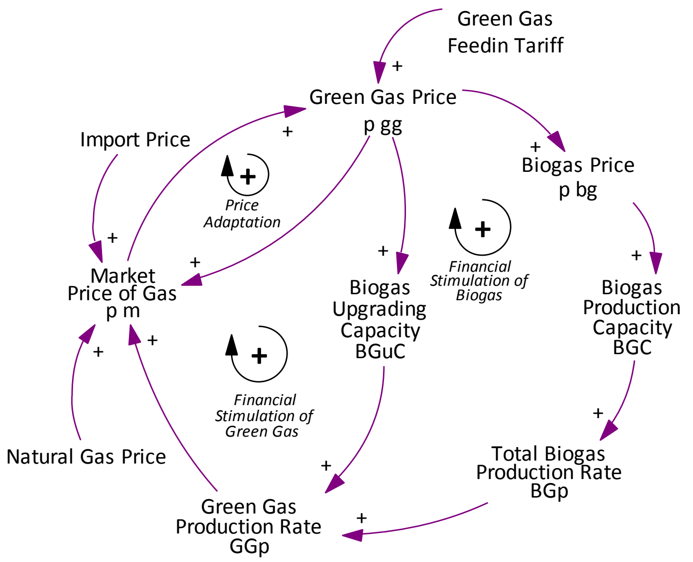

Figure 10 Causal Loop Diagram for the Market Dependency of Biogas and Green Gas

2.5. Power-to-Gas

As mentioned in the Electricity Generation section, the eager installation of renewable energy systems in order to reduce CO_2 emissions is expected to result in electricity surplus due to the intermittent nature of renewable energy and variations in demand. Power-to-gas technologies have emerged as an option to store this surplus electricity instead of wasting it and in addition to storing it in electric cars. With this technology, the electricity is used to produce hydrogen from water by electrolysis. The resulting hydrogen (H_2) can be directly injected to the natural gas grid, or can be further processed to produce methane (CH_4) according to the Sabatier reaction, which is shown in Equation 3. Methane produced in this way is called bio-methane, and has the same qualities of natural gas. Therefore, bio-methane is another renewable gas option that may contribute to the gas supply as it is injected to the grid. Besides, the use of CO_2 emitted during electricity generation in this methanation process provides a secondary opportunity for the reduction of emissions in addition to the storage.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{3}$$

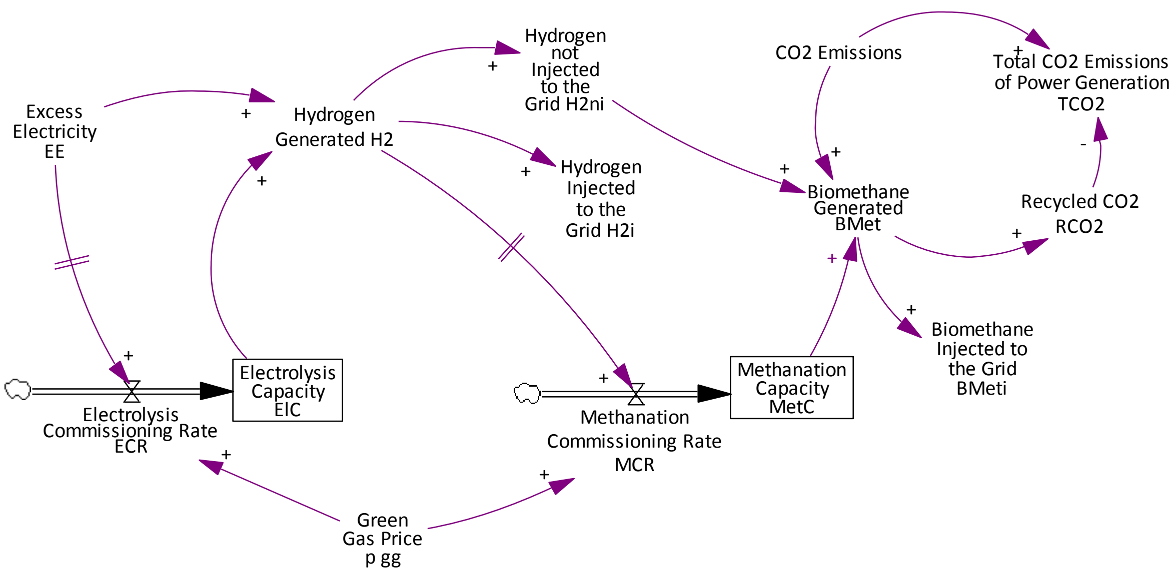

Figure 11 Stock Flow Diagram of the Power-to-Gas Sub-model

Figure 11 depicts the stock-flow structure of this sub-model. Both electrolysis capacity and methanation capacity are installed according to the estimates of excess electricity and hydrogen, respectively, which they can process. The RoI values which determine the commissioning of these technologies are assumed to be based on the Green Gas Price, since there is no institutional structure yet that defines the price of these new gases in the gas market. It must be noted that the financial loops of Green Gas Production (Figure 10) are present here, too, which stimulate or impede the production of these new types of gases.

Uncertainties in the power-to-gas sub-model

The uncertain elements in this sub-model, mostly in the parameter form, are related to the amount of excess electricity which depends on the highly uncertain weather conditions, the injectable amount of hydrogen which depends on the gas appliances used, price of these new gases due to the absence of institutional structure, and the costs of production due to the lack of data.

2.6. Import

When the domestic supply options are not adequate to cover the domestic demand, importing natural gas from the international market is the only remaining option. Natural gas can be imported in two forms: gaseous via pipelines or liquid via LNG (Liquefied Natural Gas) tankers. For the purpose of this model, the two mechanisms are represented by the same model structure, which is briefly depicted in Figure 12, but two different parameter settings. The amount imported by each mean annually, Imports, depends on the demand for that type of import (Desired Import), the volume available for the Netherlands in the international market (Available Gas) and the installed Import Capacity of the Netherlands. Desired Import of each mean is a fraction on the total shortage of domestic supply, depending on the relative price of importing by each mean (Import Price). Certainly, the price asked to the Dutch shippers in the international market increases as the Desired Import increases, which actually decreases the demand in return. These two relationships form the *Demand-Price Loop*.

The price in the Dutch market, which is influenced by the import price and volume as explained in the following section, is an important factor to attract natural gas to the Netherlands together with political factors. Therefore, Available Gas, the volume available for the Netherlands in the international market, is formulated as a fraction of total important potential, depending on the political availability and the effect of the relative market price. Available Gas is certainly different for pipelines and LNG, and long term estimation of Available Gas is a main driver of further Import Capacity installation, together with the expected Domestic Supply Shortage. To determine the installation of more capacity for each import mean, the costs are also important.

The full list of equations of this sub-model can be found in Appendix IV.

Uncertainties in the import sub-model

The major uncertainties in this sub-model are related to the costs of installation, political effects on the available gas, and the parameters used to compute the effect of demand change on price.

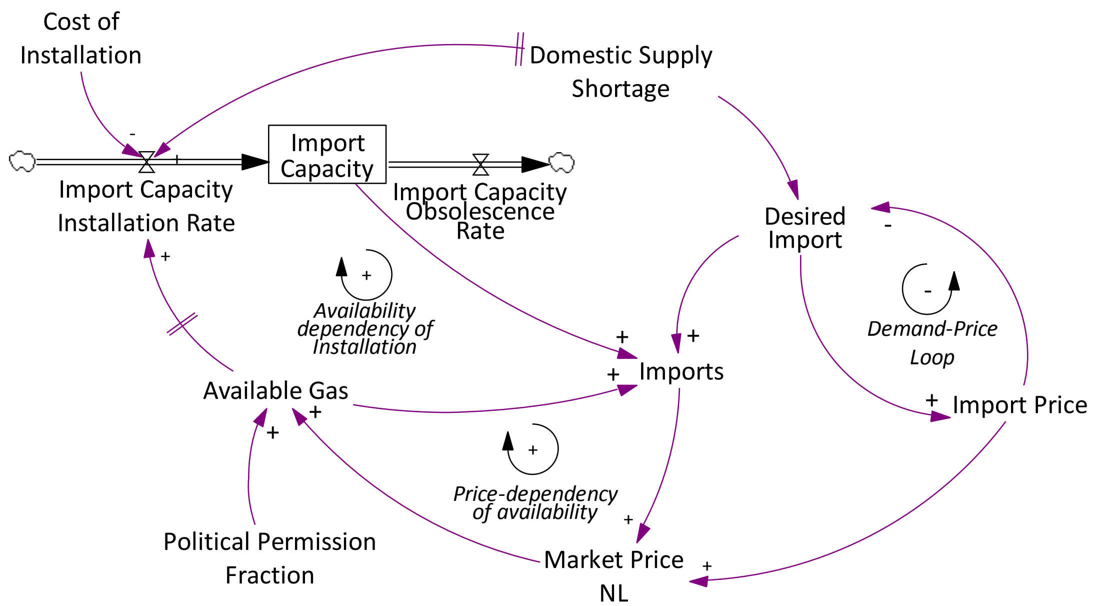

Figure 12 Stock flow diagram of the import mechanism

2.7. The Market

As shown in Figure 1, the market is what keeps the supply and demand in balance. The sub-model constructed to represent the market mechanism is based on the price-setting mechanism of the generic commodity market model (Sterman, 2000, pg. 813). In this sub-model, the market price is dependent on the interactions between three parties: traders, producers and consumers. Traders' expected price is formulated as a stock variable since it is constantly adjusted to the market price with a first order information delay. Traders adapt their expectations continuously, and market price is tried be made equal to the cost by covering the difference between traders' expected price and costs. The Costs, which is actually a virtual variable that represents the average economic value of gas in the network, is assumed to be the weighted average of the individual costs of all supply options. If one of the supply options is dominant, Costs, hence the market price, is closer to its cost value, and if it is cheap, the other expensive ones may be left out since they are not profitable at that market price.

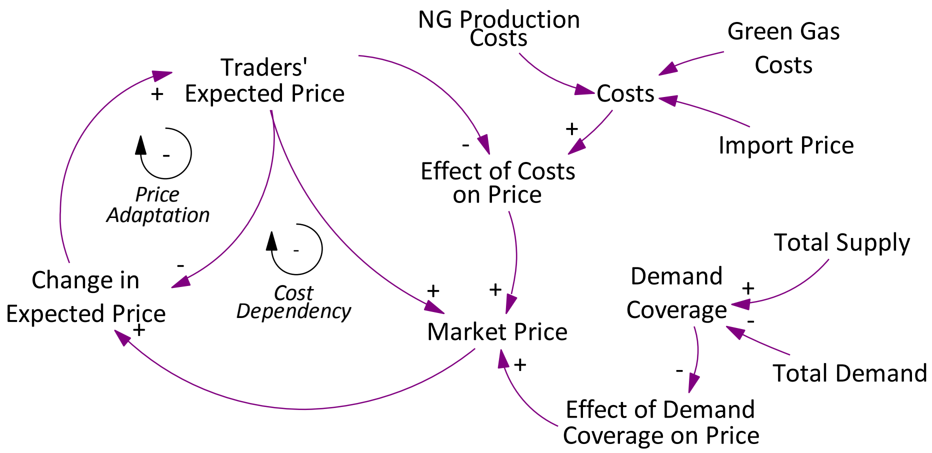

Figure 13 Causal Loop Diagram of the Price-setting Mechanism

Additionally, the two outcome measures, *Import Dependency (ID)* and *Renewable Gas Ratio (RGR)* are computed in the market segment, which are formulated as in the Equations 4 and 5 below:

$$ID(t) = \frac{MAX\left(G_{im}(t), 0\right)}{G_c(t)} \tag{4}$$

$$RGR(t) = \frac{BMet_i(t) + H2_i(t) + GG_i(t)}{G_c(t)} \tag{5}$$

The equations of this model segment are listed in Appendix V.

Uncertainties in the market sub-model

The two major outcomes in this sub-model are in the price-setting mechanism, related to the sensitivity of price to the costs and to the demand coverage.

2.8. Common Structures

One of the main assumptions of the model which resulted in a repeated structure is that new capacity installation for each type of technology is dependent on the return on investment (RoI) of this technology given the current market conditions. The RoI for technology *i* and the 'RoI response' which shows if this RoI value is acceptable or not is computed in the following way:

$$RoI_i(\text{t}) = \frac{P_i(t)}{EAC_i}$$

$$EAC_i = \frac{C_{k,i}\, r\,(1+r)^{T_i}}{(1+r)^{T_i} - 1}$$

$$P_i(t) = TC_i(t) - R_i(t)$$

$$R_i(t) = p_i(t) EQ_i$$

$$TC_i(t) = C_{k,i} + C_{f,i}(t) + C_{v,i}(t) EQ_i$$

$$RoIr_i(t) = RoI_i(t)\, f_{RoI}(RoI_i(\text{t}))$$

$P_i(t)$	*Expected annual profit of technology i at time t*
EAC_i	*Equivalent annual cost of capital of technology i*
r	*Interest rate*
T_i	*Average lifetime of the technology i*
$TC_i(t)$	*Total Annual Cost of technology i at time t*
R_i	*Expected revenue*
p_i	*Price of the product of the technology*
EQ_i	*Expected annual production*
$C_{k,i}$	*Investment cost*
$C_{f,i}$	*Annual fixed cost*
$C_{v,i}$	*Variable cost*
$RoIr_i$	*Return on Investment response*

where $f_{RoI}(RoIr_i)$ is a graphical function which enables taking only the options with a RoI value greater than 1 into account substantially.

The fixed operating cost (C_f) and the variable production cost of (C_v) of new gas production technologies (biogas, green gas, hydrogen and bio-methane) and electricity generation technologies are assumed to decrease over time due to the learning effect. Assuming a logarithmically declining experience curve, the effect of learning on the cost is formulated based on the ratio of cumulative production to the initial total production as follows:

$$L_j(t) = \left(\frac{CP_j(t)}{CP_j(0)}\right)^{-n_i}$$

$$C_{f,j}(t) = C_{f,j}(0) L_j(t)$$

$$C_{v,j}(t) = C_{v,j}(0) L_j(t)$$

$L_j(t)$	*Learning effect on the cost of technology j at time t*
$CP_j(t)$	*Cumulative production of technology j at time t*
$CP_i(0)$	*Initial/Threshold Total Production*
n_i	*Strength of the learning curve*
$C_{f,i}(0)$	*Initial fixed cost*
$C_{v,i}(0)$	*Initial variable cost*

Uncertainties in the common structures

In the calculation of RoI, the capital costs, the initial value and learning curve strength of the fixed costs, and those of the variable production cost as well as the fuel and CO_2 costs are uncertain. The reasons for these uncertainties are either the confidentiality or unavailability of the market data, or the potential changes in the future values due to policy changes, or the immaturity of the market to provide sufficient data especially for the new technologies. Attributable to the third reason, the levels of these uncertainties vary among the technologies. For instance, natural gas extraction and gas-fired power generation are proven technologies for which data is commonly available, and the uncertainty of the costs of these is low. However, there is deeper uncertainty in the cost measures of technologies such as green gas production and bio-methane production from electricity, which could not reach a large scale yet. Moreover, the modeling approach used to represent price change according to the demand and supply creates an important structural uncertainty.

3. Base Run

Although this model is not intended to generate a single trajectory, the output of the base run is presented in this section to obtain a preliminary insight about the relation between the model structure and behavior. The model is initiated with 2010 values, quantified with values which can be seen in Appendix VI, and run for 50 years between 2010 and 2060. Below, the output of this base simulation for the two outcomes of interest, namely import dependency and renewable gas ratio, is discussed.

3.1. Import Dependency

According to the base run results, 2036 is the year when the Netherlands becomes a net importer of gas, in other words, the total domestic gas production is not adequate to meet the demand. As it can be seen in Figure 14, the rapid but decelerating increase in the imports in the first two years tends to drop slightly after a stagnation around 45%. This little drop is attributed to the investments made to increase the production capacity against this undesirable high import dependency. However, increased investments are not sufficient to keep import dependency declining due to the depletion of the reserves. Hence, import dependency increases again till 65% and stabilizes around this.

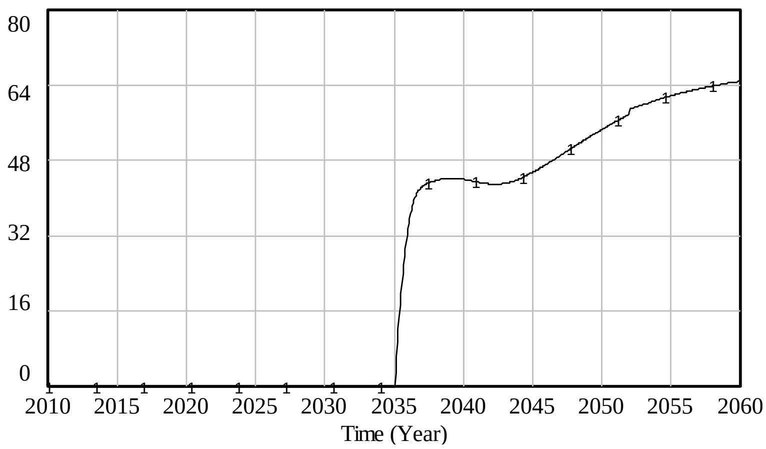

Figure 14 Import Dependency in the Base Run

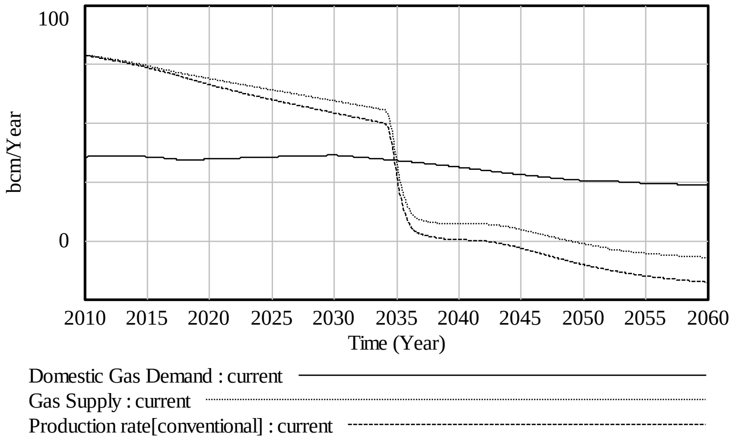

Figure 15 Gas Demand, Supply and Conventional Natural Gas Production in the Base Run

Besides the moderating effect of declining demand, this behavior of import dependency is mostly attributed to the supply, which follows the dynamics of conventional natural gas production due to the very small contribution of renewable gases, as Figure 15 shows. In Figure 15, conventional natural gas production is shown to have a sharp decline in 2034, which causes the total gas supply to fall below the demand. The reason for that is the inadequacy of gas in the reservoirs to yield the volume that the installed production wells can actually produce. However, this sharp decline doesn't continue, but is expected to be mitigated by increased investments in production (development of new fields), as the three balancing loops in Figure 7, that is the *Economies of Scale, Promising Investments and Urge for Investment*, govern the behavior. The sharp increase in the effect of demand and price in Figure 16 indicates these balancing efforts. Still, the insufficiency of remaining resources and reserves to maintain the current production amount impedes investments and the production activities, resulting in almost zero production rates by 2060.

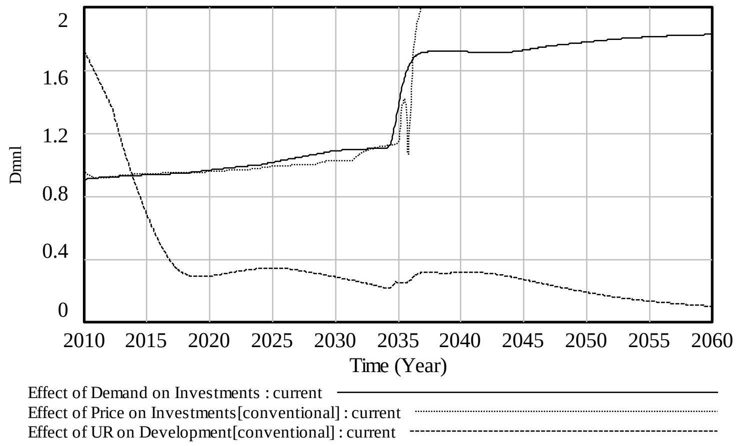

Figure 16 The Effect of Demand, Price and Undeveloped Reserves on Production Investments

3.2. Renewable Gas Ratio

The dynamics of the renewable gas ratio in the base simulation are presented Figure 17. According to this, the maximum renewable gas ratio in the gas grid is expected to be 3.5%, which is far below the 10% target, desired to be achieved by 2020. As Figure 18 shows, the major contribution to the renewable gas supply is in the form of green gas, since bio-methane never becomes profitable to produce and the volume of hydrogen produced is very low, which becomes even zero after 2044 when there is no excess electricity to produce hydrogen. If the behavior of green gas production is carefully probed, it can be said that the reason for the negligibly low production rate before 2015 is the unprofitability of upgrading despite the availability of biogas for upgrading. As both biogas and upgrading costs decline due to experience and the green gas starts to be subsidized after 2012, biogas and green gas production are stimulated till they peak in 2020 as Figure 19 demonstrates. Green gas injection to the grid is not equal to the production till 2032, since the capacity installation limits the injectable amount, as it is seen in Figure 19. However, as biomass supply stops increasing in 2020 and the biomass availability expectations of biogas producers decline as in Figure 20, no more biogas production capacity is commissioned. This results in decreasing production, especially for the gasification technology which stops utilizing the allocated biomass. In short, the inadequate availability of biomass and the overestimated response of biogas capacity investments to this are the reasons of declining green gas production an injection rates, which eventually result in low renewable gas ratio. The sharp decline in the Renewable Gas Ratio in 2052, which is also present in Green Gas Production and Injection Rates, is due to the end of subsidization in that year.

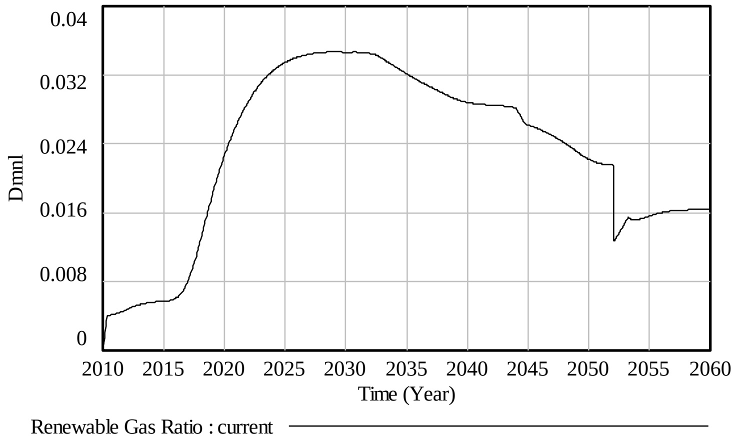

Figure 17 Renewable Gas Ratio in the Base Run

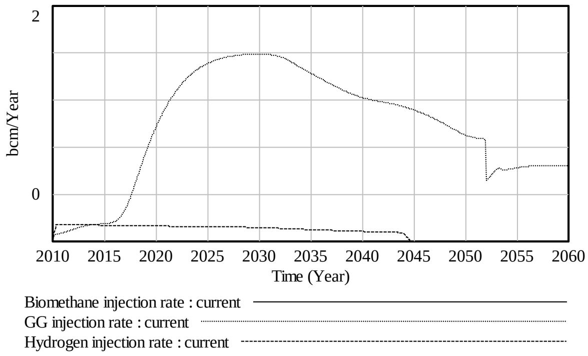

Figure 18 Production Rates of Renewable Gases in the Base Run

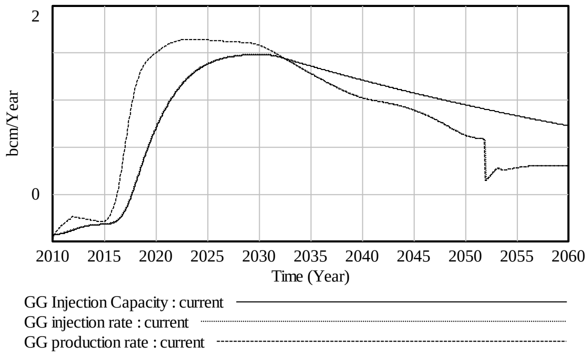

Figure 19 Green Gas Production, Capacity and Injection in the Base Run

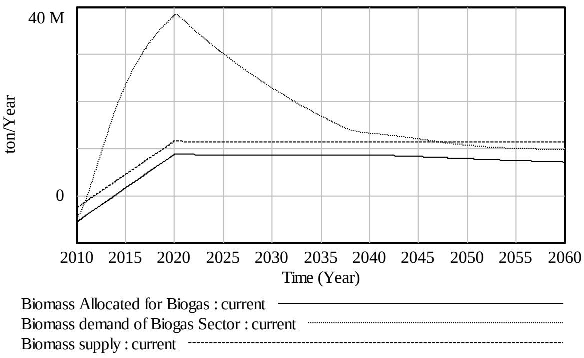

Figure 20 Biomass Supply, Allocation for Biogas and Estimation in the Base Run

4. Exploratory Uncertainty Analysis

In order to explore the impact of uncertainties on import dependency and the renewable gas ratio, 10000 scenarios are generated by simulating the model for 10000 times, each with a different combination of the possible values of uncertain elements. This analysis aims at investigating the effects of uncertainties related only to the parameter values and graphical functions, hence uncertainties related to the conceptualization and model structure are not taken into consideration. The value of uncertain parameters in each experiment (simulation) is determined by Latin Hypercube sampling from the uncertainty ranges given in Appendix VI. Graphical functions are varied by using a perturbation function, as explained in Eker et al. (2011) and the parameters of this perturbation function are included in the analysis, with the ranges given in Appendix VI, too. A shell written in Python is used to communicate with Vensim, to make the experimental designs, based on Latin Hypercube sampling in this case, and to visualize the outputs.

4.1. Import Dependency

In Figure 21, the gray shaded area shows the range between minimum and maximum values that Import Dependency takes over 50 years in these 10000 experiments. The results of a few arbitrarily selected experiments are shown within the shaded area, as well. The graph at the right depicts the Kernel Density Estimations (KDE) of the final state of Import Dependency in 2060. According to these, Import Dependency may take almost any value between 0-100% after 2020. KDE implies that there is an almost even distribution of the final values, still they are mostly around 50% or below 10%.

Moreover, the behavior pattern of Import Dependency can significantly differ from the base run result, as the few examples in Figure 21 show. The initial increase may be more rapid, or a decline can occur after this initial increase, which is certainly favorable and promising for decision making.

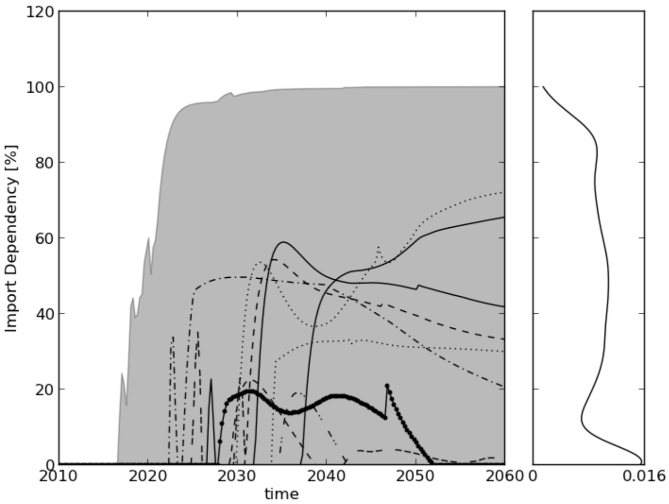

Figure 21 Import Dependency in 10000 experiments

As mentioned before, the desirable outcome is a low Import Dependency and a late occurrence of this. In order to discover the cases in which these favorable outcomes are observed among these 10000 scenarios, the Patient Rule Induction Method (PRIM) (Bryant and Lempert, 2010) is implemented on the output data. PRIM searches over the output data and finds groups of cases, for which a certain percentage of the cases result in the desired values of the selected outcome of interest. In this analysis, the group size is determined as 200, which means that the output data is divided into 50 groups. The threshold percentage is selected as 70%, which means that for a group to be selected, more than 70% of the cases in this group must result in the desired values of the selected outcome of interest. Regarding Import Dependency, two objective functions are selected, as the Import Dependency being less than 50% in 2060 and the first year the Netherlands is a net importer being later than 2035. Table 2 shows the uncertainties that are discovered to have values only in a particular subspace of their possible ranges when the first objective is met. In other words, the final Import Dependency tends to be low, if these uncertainties take values in the given ranges. It must be noted that these ranges denote subspaces of the normalized bandwidth of uncertainty ranges given in Appendix VI.

Table 2 PRIM Results for the Import Dependency Objective

Uncertainty	Group 1	Group 2	Group 3
m-Domestic Biomass Supply	0.33-1 (upper 67%)	0.36-1 (upper 64%)	0.17-1 (upper 83%)
p-Domestic Biomass Supply	0-1 (100%)	0.5-1 (upper 50%)	0.05-1 (upper 95%)
Initial well productivity [unconventional]	0.3-1 (upper 70%)	0.28-1 (upper 72%)	0.04-1 (upper 96%)
Average well lifetime [unconventional]	0.18-1 (upper 82%)	0.09-1 (upper 91%)	0.33-1 (upper 67%)
Exploration well cost [unconventional]	0-0.9 (lower 90%)	0-1 (100%)	0-0.81 (lower 81%)
m- Effect of Price on Investments	0.19-1 (upper 81%)	0.09-1 (upper 91%)	0-1(100%)
p-Effect of Price on Investments	0-0.95 (lower 95%)	0.03-0.89	0-1 (100%)
l-Effect of Demand on Investments	0.18-1 (upper 82%)	0-1 (100%)	0.05-1 (upper 95%)
m-Effect of Prospects on Exploration Investments	0.09-1 (upper 91%)	0-0.96 (lower 96%)	0.3-0.95
Annual Change Fraction of Household Demand between 2010-2030	0-0.9 (lower 90%)	0-0.75 (lower 75%)	0-1 (100%)
Investment Capital [wind]	0.04-1 (upper 96%)	0-0.89 (upper 89%)	0-1 (100%)
m- Effect of Cumulative Production on SA	0-1 (100%)	0-1 (100%)	0-0.86 (lower 86%)
Average lifetime biogas plant[gasification]	0-1 (100%)	0.05-1 (upper 95%)	0.11-1 (upper 89)

Table 2 presents the results of this analysis for the Import Dependency objective, whereas Figure 22 visualizes such subspaces of the uncertainty ranges of significant uncertainties for the second objective. According to these results, the higher amounts of available biomass especially after the first few years of time horizon, result in lower and later import dependency. (In Section 4.2, it argued that the biomass availability is an important limitation for green gas production.) Related to the natural gas production, more expensive but more productive exploration of conventional gas postpones the occurrence of import dependency; whereas the cheaper exploration and more productive production wells of unconventional gas is important in lowering import dependency in 2060. Shorter lifetime of conventional gas wells are shown to postpone the import dependency as well, and this points out the importance of low production capacity that keeps the reserves longer. In the scenarios where investors in natural gas activities give higher responses to the price change, and higher responses to the ratio of supply to demand especially when supply is low, the final import dependency is expected to be lower. Having better characteristics of gasification technology for biogas production, such as longer lifetime of plants and higher yield of the process, may help lowering and postponing import dependency. Lastly, on the demand side, a lower demand change of households in the period between 2010 and 2030 creates lower import dependency in 2060. It is worthwhile to address that the uncertainties whose ranges identified to be almost as wide as the entire uncertainty range of them in this analysis cannot be claimed to have a significant impact on the objective. For example, the lifetime of gasification plant is in the upper 90% of its uncertainty ranges in the scenarios that meet the Import Dependency objective. However, since this still a quite wide range, one must be careful to derive the conclusion about a significant positive impact of gasification plant lifetime on import dependency.

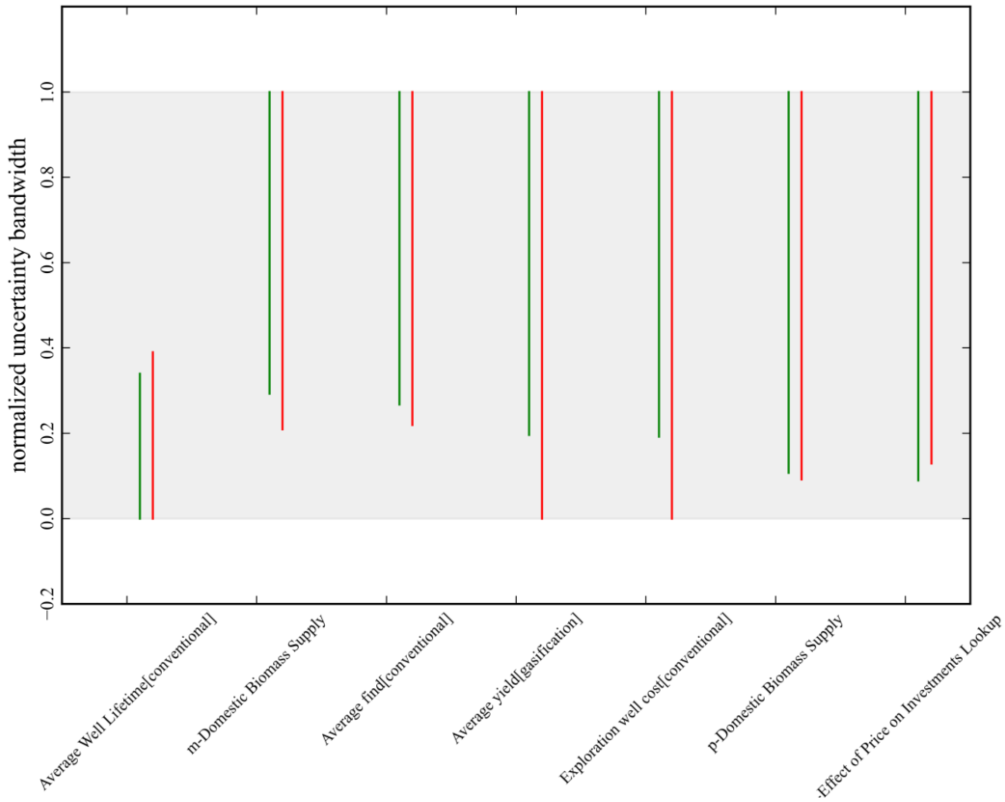

Figure 22 PRIM results for the Importing Time Objective

4.2. Renewable Gas Ratio

In Figure 23, the range of minimum and maximum values Renewable Gas Ratio takes over time in these 10000 experiments is depicted by the GRAY shaded area, and some individual trajectories are exemplified. At right, the distributions of 2020, 2050 and 2060 states are shown. According to the results, 10% natural gas replacement goal by 2020 is hardly achievable, because in the majority of scenarios the ratio of renewable gas supply to the total gas consumption is around 0% despite a few cases in which it exceeds 10% and reaches even 25%. In 2060, Renewable Gas Ratio can take values in a wider range, but still it is more likely to be below 10%. The noise in the upper edge of the shaded area indicates that in several scenarios an overshoot and decline is observed at various times and with various amplitudes.

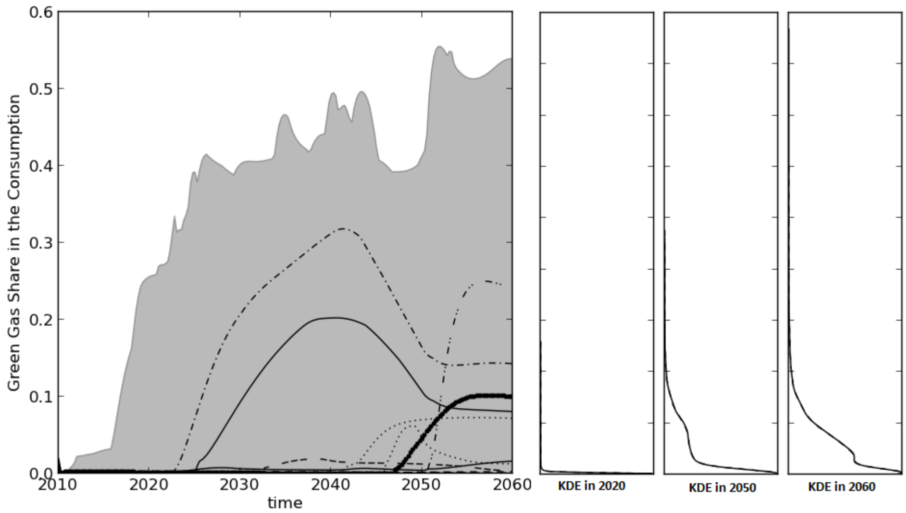

Figure 23 Renewable Gas Ratio in 10000 experiments

Similar to Section 4.1, the uncertainties which have a significantly positive impact on the Renewable Gas Ratio are sought for by PRIM analysis. The objective function is set to be the Renewable Gas Ratio being higher than 15% in 2060. Figure 24 is a visual representation of the results, where Domestic Biomass Supply appears to be the most influential factor. In the scenarios where it is more than 30% higher especially in the last 25 years of the time horizon, the Renewable Gas Ratio is higher. Similar to their effect on Import Dependency, better characteristics of gasification technology generate a higher green gas share in the gas supply. Interestingly, subsidy duration for injecting renewable gas to the grid is shown to positively affect the RGR when it is low. This means that the market price becomes even higher than the feed-in tariff, which is assumed to be constant in this study, and the renewable gas production is stimulated better when it joins the free market. Initial Societal Acceptance of wind energy is shown to have a positive impact on RGR when it is high, but since its range does not significantly differ from the entire range in many of the groups, this impact cannot be argued as significant.

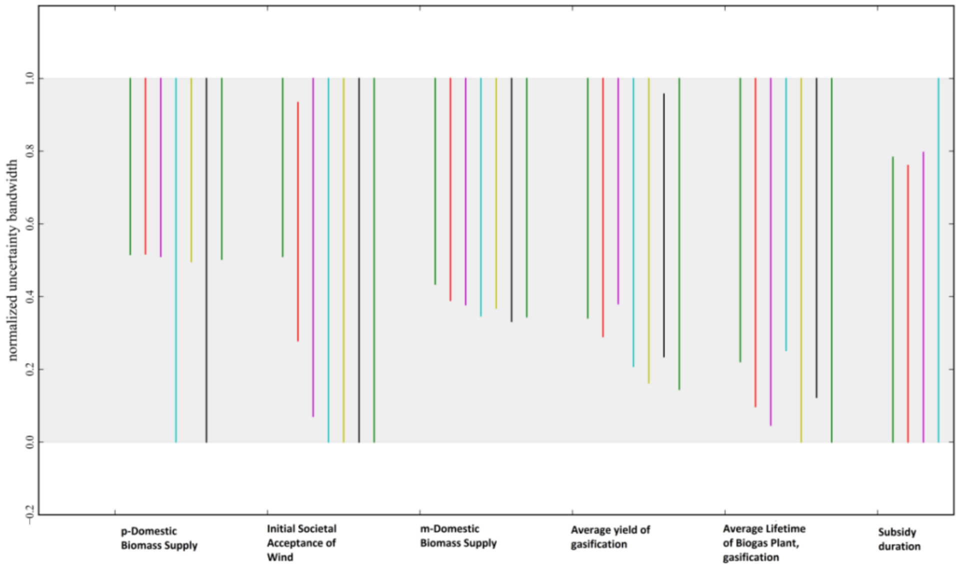

Figure 24 PRIM Results for Renewable Gas Ratio Objective

5. Conclusion

In this study, two issues that concern the future of the Dutch gas sector, import dependency and the ratio of renewable gas to the total consumption, are investigated by using a system dynamics model and exploratory uncertainty analysis. In the majority of 10000 scenarios, the future import dependency is shown to be higher and the renewable gas ratio is shown to be lower than desired. The end state of import dependency (the value in 2060) accumulate around 50%. The Renewable Gas Ratio is lower than 1% in 2020 and 10% in 2060 in the majority of scenarios, which is much lower than the targets. Still, there are scenarios in which more desirable future states are obtained. The factors that are important in creating these more desirable cases are identified in this study, too. In general terms, it is revealed that in the favorable scenarios, biomass supply is higher, the characteristics of biogas production technology is better, and the lifetime of conventional natural gas wells is shorter. It is important to mention that the model developed here for the Dutch gas sector can be generalized for any country with a similar structure of the gas sector.

The approach adopted in this study to deal with uncertainties is the generation of numerous scenarios, so that the possible futures of outcomes of interest can be explored and decision making can be based on these multiple future dynamics. Various numerically and behaviorally different dynamics obtained in the exploration compared to the base run support the initial idea that a single trajectory or a limited number of scenarios is not reliable in the presence of uncertainties. Being based on causal relations, the system dynamics model was useful to generate plausible and quantitative scenarios in this study. Before the suitability for exploration purposes, system dynamics was useful to represent the complexity of the gas sector, as the total of individual activities, with several interconnected elements, and to create long term dynamics.

In future studies, the import mechanism of the model can be extended to include the competition between the installation of import capacity and domestic supply options, and to observe the effect of the global gas trade on the Dutch imports. In terms of the uncertainty analysis, this study is focused on end states, but the variability of behavior patterns is also intriguing not only for decision-making but also to understand the relations between the structure and behavior of the model. Therefore, different behavior patterns observed in these scenarios can be identified, and the conditions under which they are created can be investigated. The analysis can be extended to design and test policy recommendations.

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