Analyzing the Dynamics of the Bio-methane Production Chain and the Effectiveness of Subsidization Schemes under Uncertainty

Sibel Eker, Els van Daalen
s.eker@tudelft.nl, C.vanDaalen@tudelft.nl
Delft University of Technology
P.O. Box 5015, 2600 GA Delft, The Netherlands

Abstract: *Bio-methane is a renewable gas option that can be injected to the natural gas grids to increase the sustainability of the energy system and to deal with natural gas supply problems. However, being based on several factors such as resource availability, competition between bio-methane and electricity sectors for biogas and biomass supply, demand, capacity installation and profitability, the future dynamics of bio-methane production is uncertain. In this study, we investigated the dynamics of bio-methane production in the Netherlands by constructing a system dynamics model and using this model for exploration of future scenarios and policy testing purposes. The results showed that the subsidization is crucial for the development of bio-methane in the early years, but increasing supply and reduced prices can cause a loss of competitiveness against the electricity sector, which can result in inadequate biomass supply for bio-methane. Future research can focus on testing more policies, enhancing the robustness of the subsidization policy and investigating the relation of bio-methane to the natural gas sector.*

Keywords: *Bio-methane, green gas, renewable gas, biogas, system dynamics, exploratory modeling and analysis, uncertainty*

1. Introduction

Technical advancements and the urge to have a sustainable energy system have led to the development of several renewable energy technologies in recent years. Currently, electricity generation technologies such as wind, solar and biomass combustion dominate the renewable energy sector. In addition to these options in the electricity sector, the production of renewable gas that can be injected to the natural gas grids has emerged as a promising renewable energy option in the last years. Renewable gas injection to the gas grid provides several benefits. Besides reducing the CO_2 emissions and contributing to a more sustainable energy system, it is a promising local alternative to the depleting natural gas resources or import dependency, and it prolongs the use of natural gas infrastructure built by huge investments.

Bio-methane is the term used for renewable gas produced in various ways and upgraded to the natural gas grid quality. Quality standards vary between countries and network segments, but the methane content of natural gas in the grid is usually 81.3-97% (GasTerra, 2014; Persson *et al.*, 2006), whereas this percentage is 52-60% for biogas (Gebrezgabher *et al.*, 2012), which is the most well-known renewable gas type.

Therefore, biogas needs to be upgraded to reach the methane content of natural gas grid. Currently, there are two main technologies used to produce bio-methane: From biomass and from excess electricity. The latter is called ‘power-to-gas’ by which excess electricity is transformed first into hydrogen, then to methane by adding CO_2. Both hydrogen and methane can be injected into the grid, but this is not a mature technology yet (Patel, 2012). Bio-methane production from biomass is realized by enhancing the methane content of gas produced in two different ways, namely digestion and gasification. Digestion is the current dominant technology used to produce “biogas”, but gasification, of which the product is called “synthetic” or “substitute natural gas”, is promising due to its higher yield (Foreest, 2012).

Renewable gas production from biomass is dependent on the interaction of several components of a commodity market such as resource availability, demand and installed production capacity. Resource availability is an important concern not only because biomass supply is limited, but also because several sectors such as electricity, heating and biogas compete for energy generation from biomass (Panoutsou and Uslu, 2011). Regarding the allocation of biomass among several sectors, especially for the biofuel production in the United States, the reader is referred to Peterson *et al.* (2013) for their modeling and scenario analysis study. For renewable gas production, demand is an important factor not only to steer the production but also to compete for resources, and installed production capacity is the main determinant of production volumes. The interaction of these factors determines the profitability of bio-methane production, investment decisions and the eventual extent of bio-methane production. Yet, the complexity created by these interactions, as well as the uncertainties about the technology characteristics, costs or relations to the natural gas market, hinder an easy investigation of the future dynamics of bio-methane production. Due to the novelty of the technology, existing studies are focused either on the micro-level and practical issues of bio-methane production (Ryckebosch *et al.*, 2011; Angelidaki *et al.*, 2009), or on the macro-level biomass availability (Hoogwijk *et al.*, 2003; Faaij *et al.*, 1997; Hedegaard *et al.*, 2008). There are only a few studies which frame the process of bio-methane production as a chain on which technological and economic factors interact at the operational level, but they mainly investigate the profitability of bio-methane production or injection with net present value (Gebrezgabher et al., 2012; Balussou *et al.*, 2012) or static calculation models (Bekkering *et al.*, 2010; Butenko *et al.*, 2012). An analysis on how the operational level factors will affect the bio-methane production chain and how the long-term dynamics of bio-methane production may evolve is still missing. (For a more thorough review of the literature status on bio-methane production from biogas, the readers are referred to (Bekkering *et al.*, 2010).

In the Netherlands, the depletion of natural gas reserves and the goals to increase the sustainability of the energy system have raised interest in bio-methane production. Despite the uncertain future, the Dutch government expects a high contribution of bio-methane to the gas supply in the future and applies several support schemes to achieve these high bio-methane production goals. However, whether these goals can be fully achieved or not is not known due to the complexity and uncertainties in the bio-methane production chain. Therefore, in this study the future dynamics of bio-methane production in the Netherlands under uncertainty are investigated, and the effectiveness of subsidization policies implemented or that can be implemented is analyzed. For this purpose, a system dynamics model has been built to understand and analyze the dynamics of the bio-methane production. This model is then used for the generation of a large ensemble of scenarios in order to explore the effects of uncertainties on the future dynamics and to test the effectiveness of subsidization policies under uncertainty.

In the remainder of this paper, first the model will be briefly described in Section 2. In the third section, validation tests and the base run behavior generated by this model will be discussed. The next section will present the results of uncertainty analysis, and the paper will end with conclusions in Section 5.

2. Model Description

Model Boundaries

As mentioned before, there are two technologies to produce bio-methane from biomass, which are digestion and gasification. These two technologies differ in terms of the biomass types used, costs, final yield and subsidy given. However, they are similar in terms of the market and capacity construction mechanism. Therefore, in this model biogas is assumed to be produced from biomass via a single technology, which is an aggregation of these two available technologies in terms of parameters such as costs, yield and subsidy. Also, there are several biomass types used or that can be used for bio-methane production. Manure and other agricultural waste products, sewage sludge, landfill gas, industrial waste water and household waste (vegetables, fruit and garden waste) are the major types used in the Netherlands. Yet, for simplification purposes in the model, biomass supply is assumed to be homogenous, which amounts to the total of these types and has an average gas yield and heating values approximating to the average of these various types.

Bio-methane is produced in a decentralized manner, and this feature raises the question of where to inject it into the gas grid. It can be injected into the distribution or transmission grid, right after production or after being collected in a hub, or it can be stored. Depending on the selected options, the gas grid may be reshaped in future, for example in a decentralized way. However, this model focuses on production and excludes spatial dynamics of the infrastructure. In other words, in the model it is assumed that all bio-methane produced can be used for a useful final purpose.

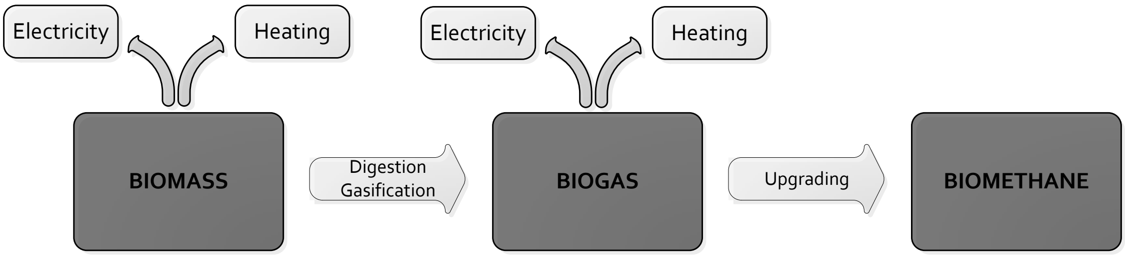


Figure 1: Production chain of bio-methane

Having the bio-methane production rate as the main concern, this model's core structure is the production chain from biomass to bio-methane. In this chain shown in Figure 1, both biomass and biogas supply is shared between heating, electricity generation and biogas production or upgrading sectors. This is how the local biomass is utilized in the Netherlands; therefore the production of biofuels for transport is excluded from the model. The production chain structure is derived from a generic commodity market model (Sterman, 2000, 798-824) where production is dependent on resource availability, installed capacity and demand, and capacity installation is dependent on expected resource availability, expected demand and price. These relations will be detailed in the next two sub-sections.

The model boundary chart below summarizes the main elements explicitly modeled (endogenous) and assumed to be an external element in the model (exogenous) as well as the factors excluded from this model.

Table 1: Summary of model boundaries

ENDOGENOUS	***EXOGENOUS***	***EXCLUDED***
Biomass allocated for power, heating and biogas	Biomass supply	Variety of biomass types
Biogas allocated for power, heating and bio-methane	Biomass price	Variety of biogas production technologies
Biogas production capacity	Change in biomass demand of heating sector	Infrastructure installation for the injection of bio-methane to the grid
Biomass and biogas demand for heating	Change in biogas demand of heating sector	Biomass use for transport biofuels
Unit costs for biogas and bio-methane production	Investment and initial production costs for biogas and bio-methane	Spatial issues of bio-methane injection
Biogas and bio-methane price	Learning effect parameter on production costs	
Natural gas demand	Gas Price Change Rate	
Renewable gas demand	Electricity Price Change Rate	
Biomass demand of the power sector	Biomass-based Power Generation Capacity Change Rate	
Biogas Demand of the power sector	Biogas-based Power Generation Capacity Change Rate	

Biogas production

The causal loop diagram in Figure 2 illustrates the relationships between the main elements of the biogas production model and the feedback loops formed by these relationships. In the model, *Biogas Production Rate*, which is the volume of gas produced each year, is dependent on two factors: *Biogas Demand* and *Biomass Allocated for Biogas*, which is the resource availability constraint on production. *Biogas Production Rate* is also restricted by the *Biogas Production Capacity*, but since *Biomass Allocated for Biogas* is not more than the capacity can accommodate, this restriction is already included in the resource availability.

The *Market Development* loop is formed by the fundamental relations between supply, demand and price. As *Biogas Production Rate* increases, high supply with respect to demand reduces the price, and lowered price increases the demand. Expected demand for biogas determines the desired production capacity, which triggers further capacity installation if it is higher than the current installed capacity. Installed *Biogas Production*

Capacity, together with *Biogas Demand*, determines *Biomass Allocated for Biogas*. Additionally, biomass is pulled into the biogas market as its availability stimulates production, which increases demand and results in higher installed capacity that demands more biomass. This positive loop formed via *Biogas Demand* is called *Pull Loop.* However, as increased supply due to biomass availability for biogas increases Biogas Production Rate and reduces price, the biogas sector becomes less attractive for biomass use compared to heating and electricity, and less biomass is allocated for biogas production. These relations form the negative feedback loop called *Shooting Yourself.* Although they are not shown in the diagram, other negative feedback loops included in the model are due to the obsolescence mechanism of the production capacity and the increased price in response to increased demand

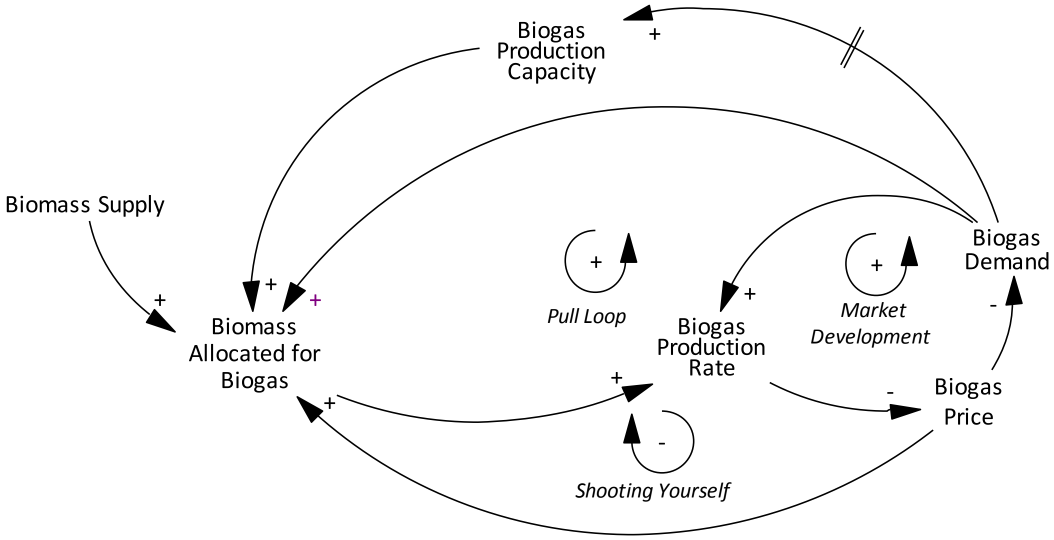


Figure 2: Causal loop diagram for biogas production

Biomass is allocated between the three sectors, namely biogas, electricity and heating, based on their demand and financial attractiveness of these sectors. The attractiveness value is determined by the price ultimately obtained in these sectors for each unit of biomass. For instance, the wholesale electricity price per energy unit is converted into price per ton of biomass, and the price value obtained by supplying biomass to the heating sector is considered equal to the natural gas market price, because that is the price of the closest heating alternative to biomass.

Biomass Demand of Heating is assumed to change fractionally for simplicity, and this fraction is assumed to be a step function in time. *Biomass Demand of Electricity* as well as that of biogas sector, is assumed to be dependent on the installed capacity. Similar to the *Biomass Demand, Biogas Demand* is the sum of demand from heating, upgrading and electricity sectors, which are modeled similarly.

Biogas Production Capacity is the accumulation of annual installation activities and loss due to obsolescence. Since installation delay is short, accumulation of capacity under construction is not taken into account in this model. The installation rate is assumed to be a percentage of the difference between desired and current capacity, where this percentage is determined by profitability. Desired capacity is determined by the demand forecasts of the producers.

Being a new technology, the production costs of biogas are expected to decline over time due to the learning effect as cumulative production increases. Therefore, unit variable cost of biogas production is calculated as the sum of production costs reduced by learning effect and fuel costs, which is the price of biomass. The unit investment costs are calculated by distributing the investment capital into equivalent annual costs (EAC) over the lifetime of a plant, and EAC is divided by the operational annual capacity to find the unit investment cost.

Biogas Price, which actually does not exist since there is no market for biogas where it is traded in this form, is a variable in the model used to represent the effect of profitability on investments and the fuel costs of technologies that use biogas. The value of biogas is determined by its producers and consumers. A profit mark-up dependent on the ratio of bio-methane price to the unit cost of biogas is added to the unit cost to represent the desired price of producers, and this is multiplied by the effect of supply-demand balance, which is formulated as a graphical function.

As mentioned before, the percentage of desired additions to the capacity to be installed is determined by profitability, which is formulated as an increasing function of unit profit percentage (ratio of unit profit to the unit cost). In the base form, this function is assumed to give very little response to negative profit, i.e. 5% installation for -10% profit, but increases as the profit percentage increases and creates 100% installation of the desired capacity if the profit percentage is 125%.

The list of equations used to formulate these relationships and detailed explanations of them can be seen in the Model Documentation in Appendix I.

Bio-methane production

Bio-methane production is modeled almost the same as biogas production, except that the resource for production, which was biomass for biogas, is replaced by biogas for bio-methane, and the demand is replaced by renewable gas demand of consumers (households, industry, agriculture, transport). Figure 3 shows how biogas supply stimulates the bio-methane market and further demand for biogas, which also illustrates how Figure 2 and Figure 4 are connected.

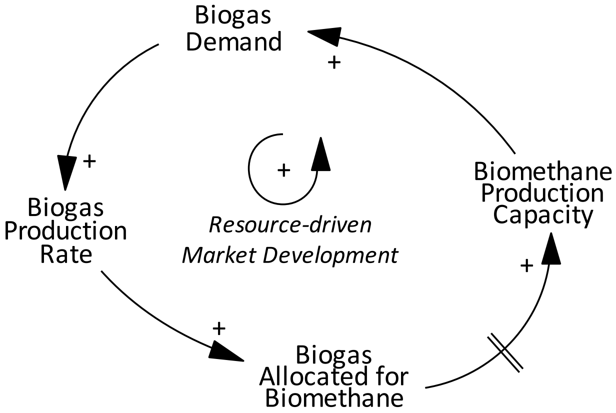


Figure 3: Resource-driven Market Development Loop for Bio-methane

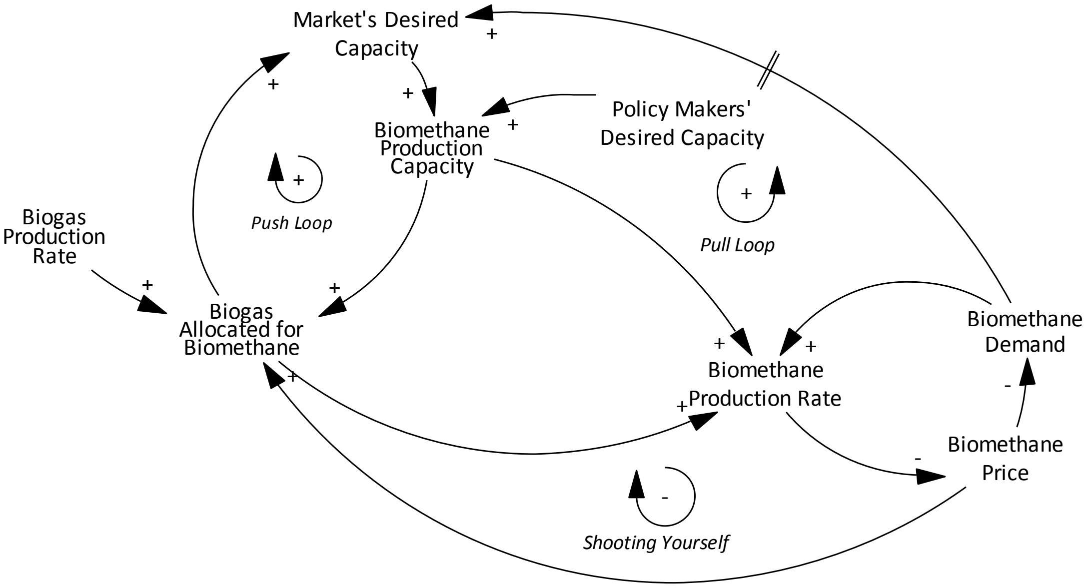


Figure 4: Causal Loop Diagram for Bio-methane Production

The causal loop diagram that summarizes the bio-methane production model and shown in Figure 4 is almost the same as that of Figure 2, because the same framework of resource, capacity, production and demand interaction have been applied. However, the major difference is the effect of policy on capacity construction. Bio-methane production is supported by subsidies given per unit produced to make it financially attractive for producers. The driver behind this subsidization is the Dutch government's ambition to inject 3 billion cubic meters (bcm) per year bio-methane into the gas grid by 2020, as shown in Figure 5. Besides subsidies, government agencies and related distribution and transmission system operators (DSO's and TSO's) are actively involved in capacity installation projects to realize this goal. Attributed to this policy-driven mechanism of bio-methane production, two types of desired capacity are defined in the model. *Market's Desired Capacity* is assumed to be the minimum of expected renewable gas demand of consumers and expected resource (biogas) availability. *Policy Makers' Desired Capacity* is assumed to be an increasing function approximated to the goals specified in Figure 5, starting from 0.24 bcm in 2009 and increasing to 3 bcm in 2020 with an annual increase fraction of 25.3%. The eventual desired capacity to be installed every year is the maximum of market's and policy makers' desired capacity levels. However, policy makers' are assumed to adjust this goal depending on the level of achievement after 2020. Therefore, a floating goal mechanism (Sterman, 2000, 532-535) is implemented as seen in Figure 6, in which the desired capacity level of policy makers is adjusted according to the discrepancy between the desired and actual *Bio-methane Upgrading Capacity*, the further capacity is installed according to this adjusted goal.

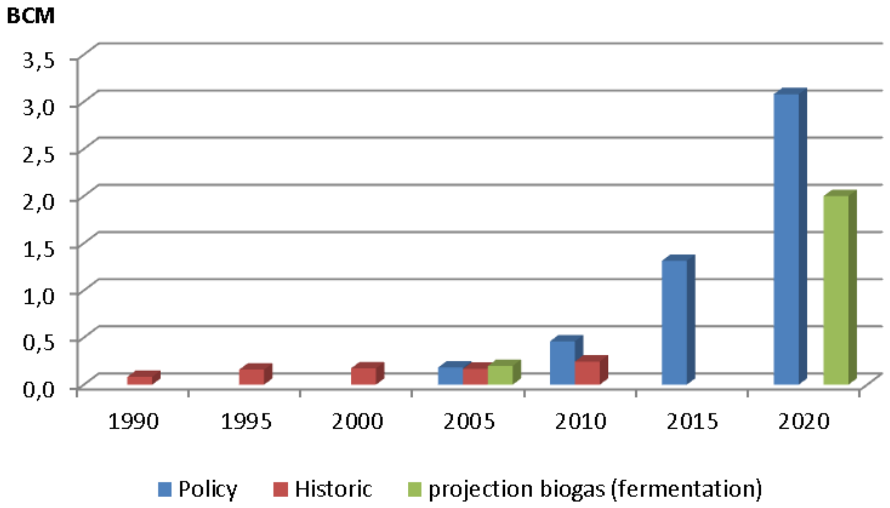


Figure 5: Green gas targets - Source: (Scheepers, 2013)

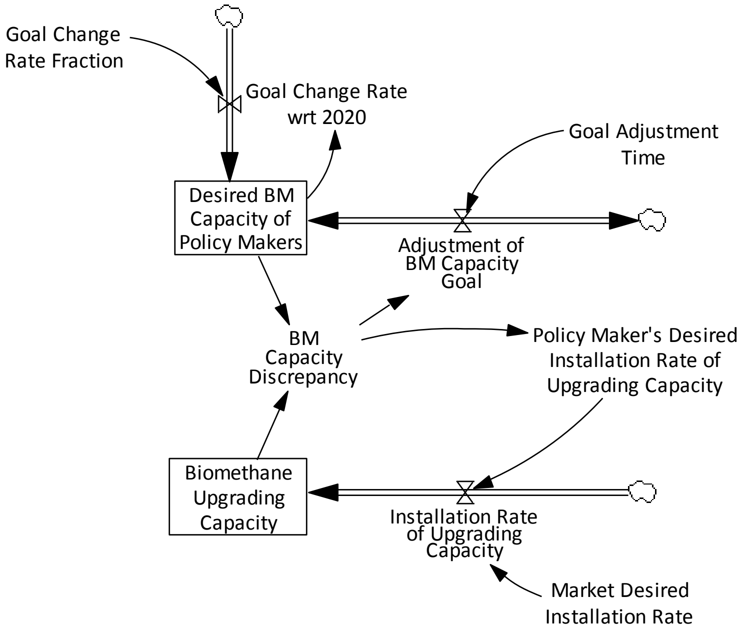


Figure 6: Floating Goal of the Policy Makers for Bio-methane Upgrading Capacity

Bio-methane is currently sold to the Dutch consumers based on a certification system. Producers are certified to be able to inject gas into the grid, and consumers who are willing to pay extra subscribe to the ‘green’ option and replace their natural gas supply with bio-methane. Following this, bio-methane demand of consumers is modeled based on the substitution of natural gas by bio-methane depending on their relative price and societal acceptance of natural gas. External factors such as income effect or energy need are aggregated as a ‘normal’ change rate of both natural gas and bio-methane demand, whereas price-dependent change rate is formulated separately. Figure 7 depicts an overview of the stock-flow structure of the demand model.

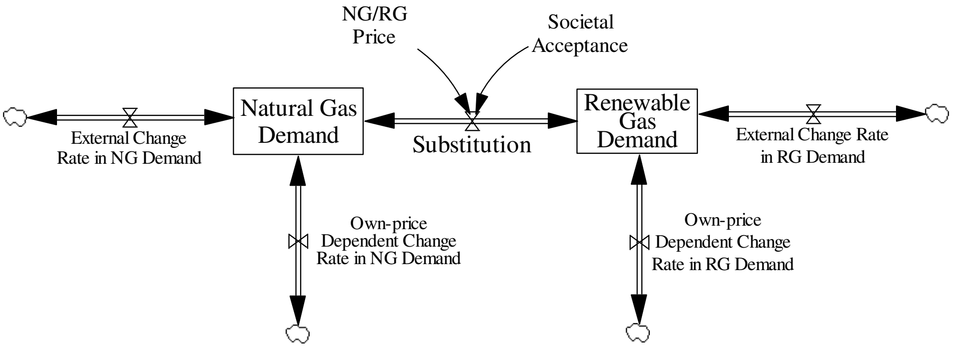


Figure 7: Stock-Flow Diagram of the Demand Segment of the Model

In the rest of the model, biogas is allocated between electricity, heating and upgrading sectors similar to the biomass allocation. Bio-methane costs and price are also formulated similar to those of biogas.

The detailed list of model equations and explanations of them are provided in the Model Documentation in Appendix I.

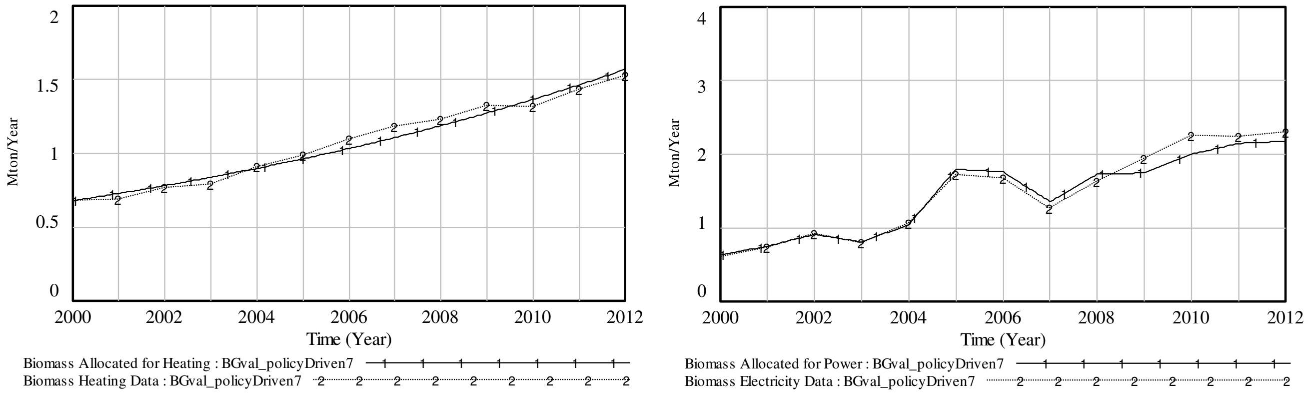
3. Base Run Results

3.1. Behavior Reproduction Tests

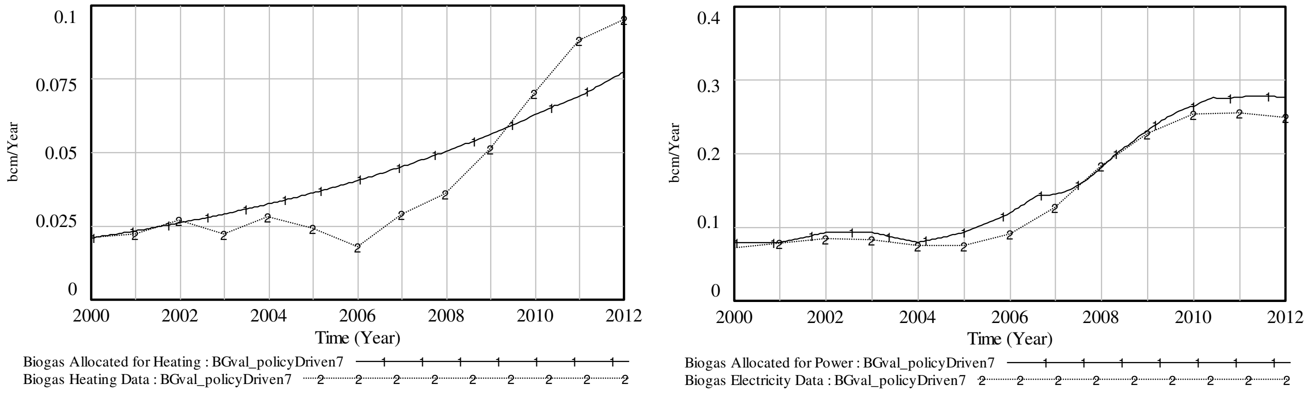
For validation, the model outcome is compared to the past values of several variables in the period 2000-2012. This time span is chosen because the technologies of concern have emerged or been significantly developed in this decade. The historical values are retrieved from the databases of the Central Statistics Bureau of the Netherlands (CBS, 2014). However, there is no data available yet about bio-methane production, which is one of the major outcomes of interest in this study.

In Figures 7a-d below, allocation of biomass and biogas to the power generation and heating sectors generate results comparable to the data both numerically and pattern-wise. *Biomass Allocated for Biogas* (Figure 7e) and *Biogas Production Rate* (Figure 7b) show similar behavior to the data, but there is a numerical difference. This difference stems from the exclusion of the use of biogas for purposes other than upgrading, heating and power generation, i.e. for local energetic purposes of producers, from the model scope. The effect of this exclusion is more evident in Figure 7g, because the data (line 2) shows the total amount of biogas used for energetic purposes other than heating and power generation, whereas *Biogas Allocated for Upgrading* (line 1) is very low compared to this, not only in the model but also in the reality since biogas upgrading in the Netherlands was negligible before 2009. Lastly, the comparison for the *Installation Rate of Upgrading Capacity* can be seen in Figure 7h. The start of subsidization in 2009 boosts the installation both in reality and in the model, and the numerical difference between the two is due to the graphical function used to represent the investment response to profitability. This function could be calibrated to obtain a better match, but this calibration based on the data of past three years is not expected to reduce the uncertainty in the representation of investment responses in the future. The implications of different alternatives of this function, as well as other uncertain elements of the models, will be investigated in the Uncertainty Analysis section where plausible future dynamics are explored. Therefore, the results are found satisfactory in terms of generating plausible futures.

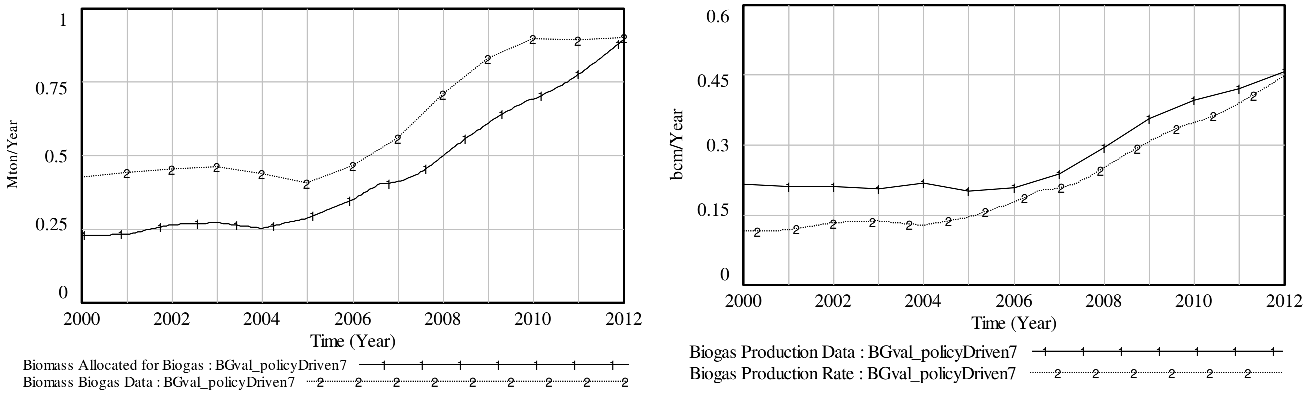
(a) Biomass allocated for heating *(b) Biomass allocated for power*



(c) Biogas allocated for heating *(d) Biogas allocated for power*



(e) Biomass allocated for biogas *(f) Biogas production rate*



(g) Biogas allocated for upgrading *(h) Installation rate of upgrading capacity*

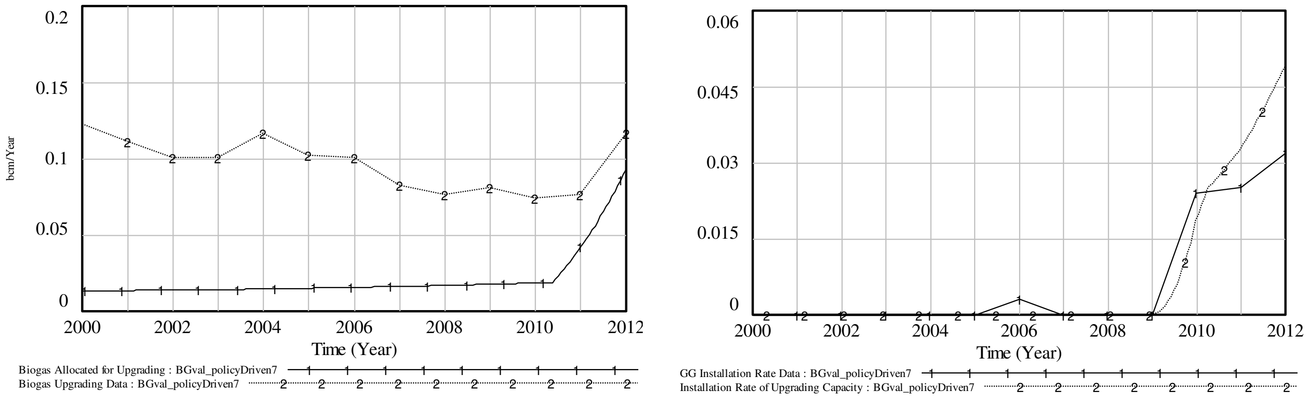


Figure 8: Comparison of Model Results to the Historical Data

As this data comparison showed, with a particular set of inputs, the model generates behaviors similar to the ones observed in the past. Therefore, the model can be said to generate plausible future scenarios, which is the main purpose of this model, with different input sets representing future uncertainty.

3.2. Model Behavior

In the base case, the model is simulated with a base set of inputs which can be seen in Appendix II, over the time period 2012-2050. With the results of this simulation, the behavior of the model is observed to obtain insights about the relations in the model. The subsidization policy is included only till 2014, since subsidies for the period 2012-2014 are already realized. The policy makers' goal to produce 3 bcm bio-methane by 2020, even though it is floating, is included in the base model since it is one of the main driving mechanisms behind production.

As seen in Figure 9, *Bio-methane Production Rate* follows the capacity till around 2028, then it is equal to the producible volume, which points out the lack of biogas for upgrading. Also, *Bio-methane Production Rate* shows an increase before 2014, ascribed to the subsidization, but the cease of subsidies result in a decreasing capacity and production. Around 2021, decreasing production costs due to learning effects and increasing gas prices make the bio-methane production profitable, as seen in Figure 10, and the boosted capacity installation results in high production rates. Yet, the capacity and production stagnates around 2 bcm after 2026, due to the adjustment in the goal of policy makers towards a lower value. The decline in the production and *Producible Bio-methane* after 2029 is traced back to the *Biogas Production Rate,* which also demonstrates a declining pattern after this point as seen in Figure 11 due to the lack of biomass allocated for biogas. The reason of this shortage in biomass supply for biogas is that the total biomass demand exceeds the total biomass supply in 2029, as Figure 12 shows, especially due to the increase in the demand of power sector. As seen in Figure 13, low prices in the biogas market makes it less competitive to pull the biomass supply compared to the power sector which is facing high electricity prices at that time.

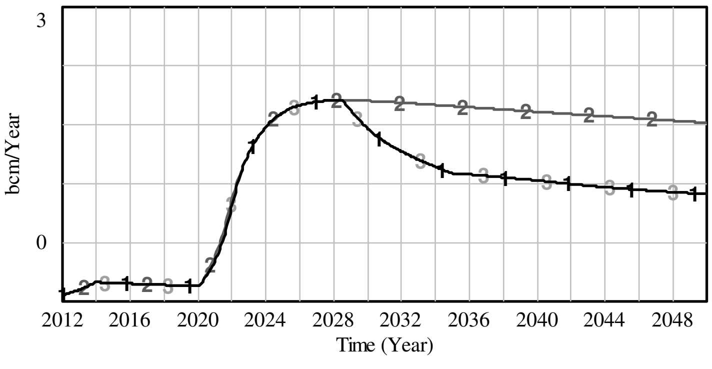


Figure 9: Base Run Behavior of Bio-methane Production Rate, Capacity, and Producible Bio-methane

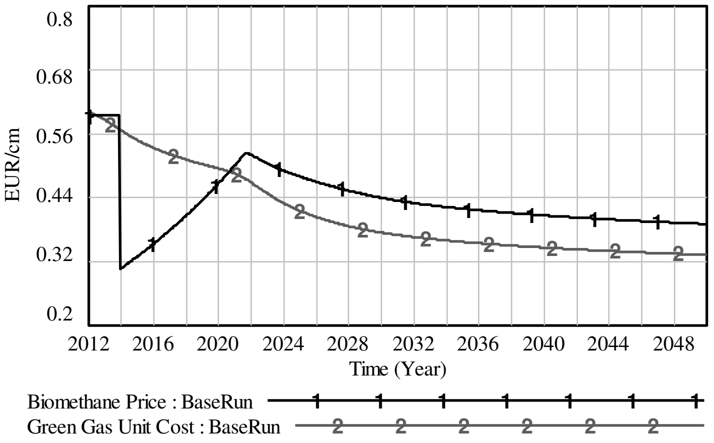


Figure 10: Base Run Behavior of Bio-methane Costs and Price

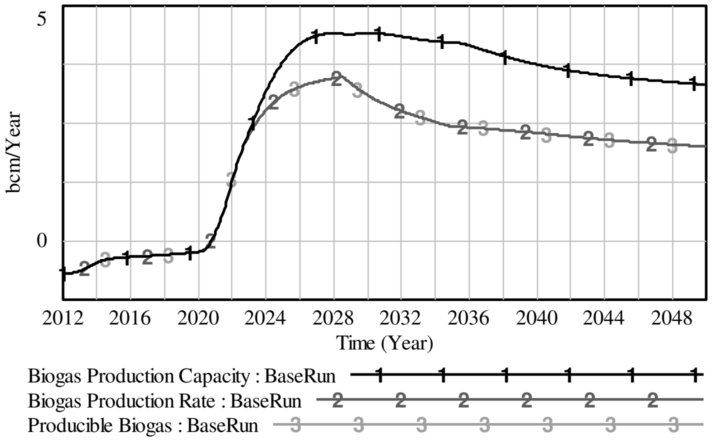


Figure 11: Base Run Behavior of Biogas Production Rate, Capacity and Producible Biogas

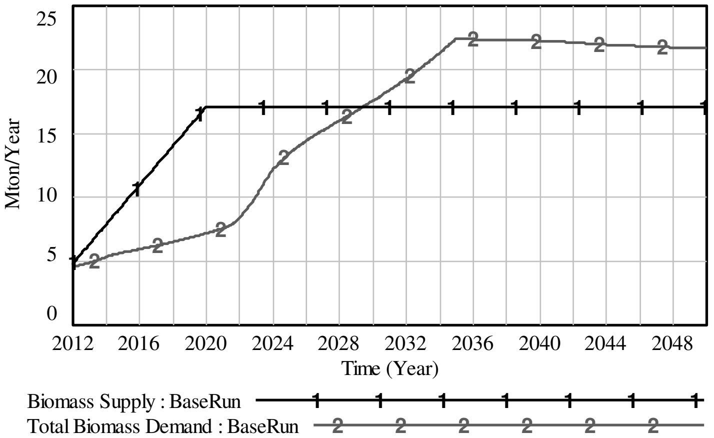


Figure 12: Base Run Behavior of Total Biomass Demand and Supply

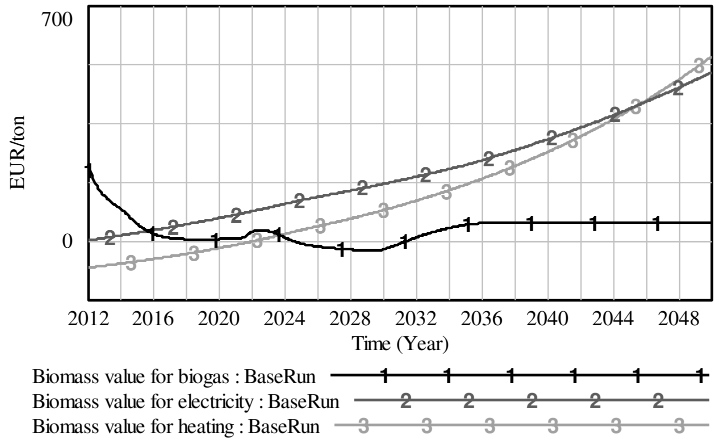


Figure 13: Base Run Behavior of Biomass Values for Electricity, Heating and Biogas Sectors

3.3. Policy Comparison

The current policy implemented to stimulate the bio-methane production in the Netherlands is the subsidization of production with a predetermined unit price (feed-in tariff) for a certain period of time. Currently, the feed-in tariff is updated each year and provided to the producers who subscribe in that year for the period of the coming 12 years. This policy is implemented in the model with a feed-in tariff set to 15% higher than the average unit costs of bio-methane production, and for 12 years.

Another option for subsidization is to directly participate in the installation of capacity, as the Dutch government currently does for natural gas fields. The participation policy is assumed to be implemented between 2014 and 2020 by covering 25% of the investment costs of producers.

In Figure 14, the dynamics of *Bio-methane Production Rate* with the intervention of these two policies and the combination of these is shown. The participation policy alone (line 2) does not create an important difference compared to the base case (line 3), because the investment costs constitute a low portion of the total costs of bio-methane production and a reduction in these does not significantly increase the profitability for producers. However, the continuation of subsidization with feed-in tariffs prevents the reduction in capacity installation after 2014, hence the increase in production is maintained and 1.8 bcm is achieved in 2020, which goes up to 2.4 bcm later. Yet, the higher production rates result in lower bio-methane prices but higher biomass demand, and the decline in production due to the shortage of biomass allocated to biogas production is observed earlier in time. Due to the minor effect of the participation policy, implementing these policies together do not improve the results compared to the subsidization policy.

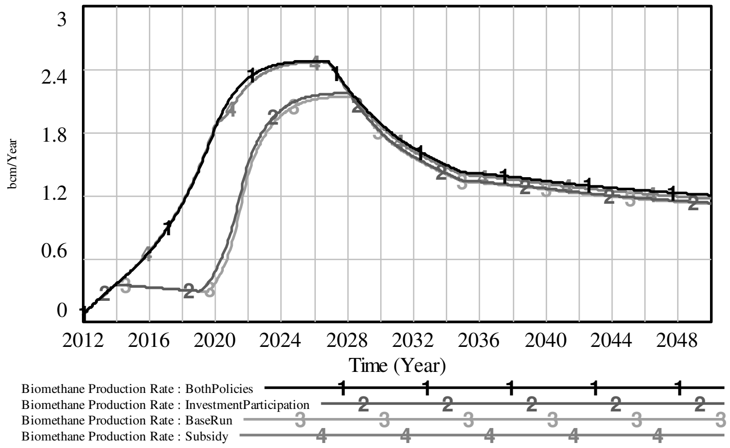


Figure 14: The effects of subsidization schemes on Bio-methane Production Rate

As for the costs of these support schemes to the government, the costs of the participation scheme is negligible since it does not steer installation and does not result in expenditure. However, the costs of subsidization until 2020 sums up to 13.67 billion euros as seen in Figure 15, whereas this is 13.28 billion EUR if the combination of participation and subsidization is implemented. This reduction in the total policy costs is due to the production increased by the participation policy, which reduces the production costs due to learning and necessitates less subsidization.

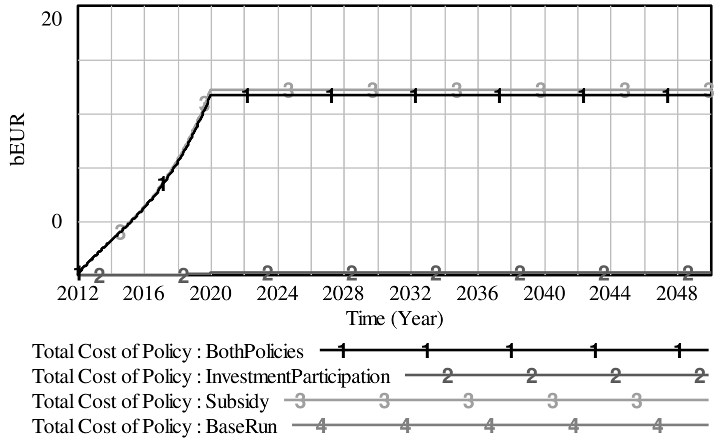


Figure 15: The total costs of policies to the government

4. Uncertainty Analysis

Our analysis in this section to deal with uncertainty is based on Bankes (1993) who sates that a ‘best estimate’ future can be reached neither with an extensive modeling study nor with stochastic methods under deep uncertainty. Therefore, the future should be explored rather than estimated by comprehensively taking uncertainties into account. This approach, named Exploratory Modeling and Analysis (Bankes, 1993; Bankes *et al.*, 2013; Agusdinata, 2008) has gained attention in the system dynamics field in recent years, since being based on causal relations, system dynamics models enable exploring the future by generating plausible future dynamics. Kwakkel and Pruyt (2013a, 2013b) discussed the benefits of this approach and presented several cases to demonstrate these benefits. More studies in which this approach is used can be found in the system dynamics literature of the recent years (Auping *et al.*, 2012; Eker and Daalen, 2013; Pruyt and Hamarat, 2010).

Following this Exploratory Modeling and Analysis approach, in order to explore possible future dynamics, we run 10000 simulations each with a different combination of the possible input values selected from their uncertainty ranges with Latin Hypercube Sampling. Each combination of the uncertain inputs, parameter or model structure, can be considered as a scenario as well. For this purpose, we use an interface coded in the Python programming language that controls Vensim DSS. The uncertainty ranges assigned to the parameters of the model can be seen in Appendix II, and the results of exploration which indicate the uncertainty around the base case can be seen in Figure 16. *Bio-methane Production Rate* show a decline in almost all cases since there is no subsidization after 2014. Following this, the maximum achievable production rate is around 0.5 bcm in 2020, instead of the 3 bcm goal. The two graphs below the time series plot show the Kernel Density Estimation (KDE) of the values of the *Bio-methane Production Rate* in these 10000 simulations. In other words, they show the density distribution of *Bio-methane Production Rate* values in the range covered by these simulations (y-axis). According to the density graph of 2020, in most of the cases the production rate is below 0.1 bcm, or they tend to accumulate around 0.25 bcm. Still, some simulations result in an increase afterwards, which may be attributed to the decline in costs due to learning effects as explained in the previous section. However, even in these cases the production volumes do not reach the desired level of 2020, and density graph of 2050 shows that a big majority of the scenarios still result in production volumes less than 0.2 bcm.

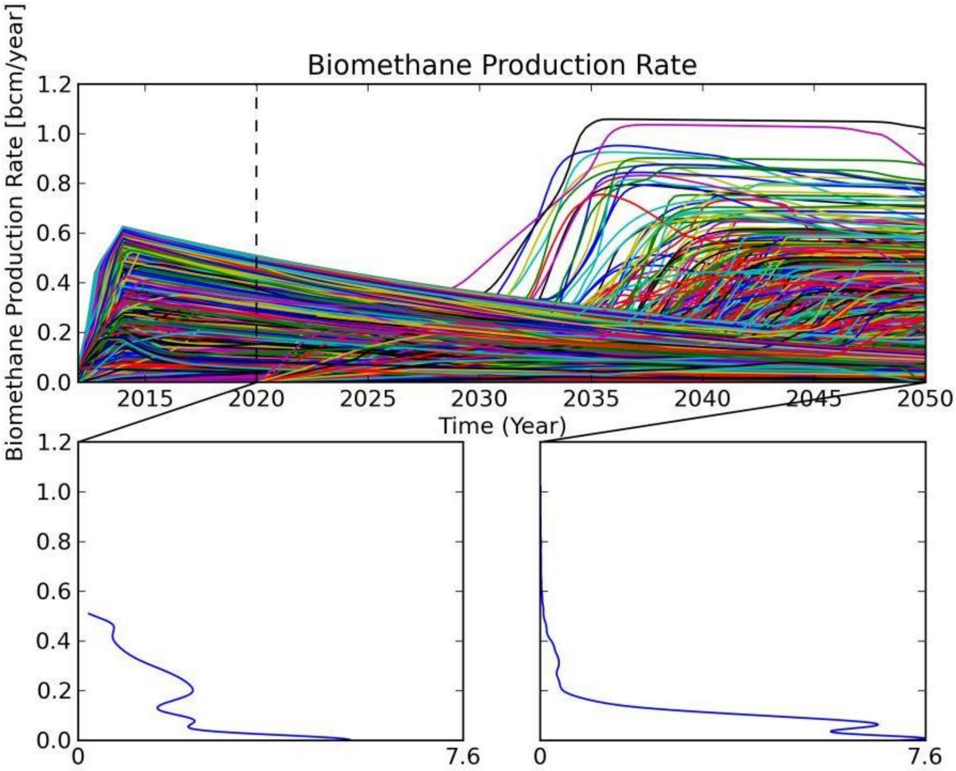


Figure 16: Possible Future Dynamics of Bio-methane Production Rate in 10000 simulations and distribution of states in 2020 and 2050

Hence, the main conclusion from this exploration is that without any intervention, it is not possible to obtain a considerable contribution of bio-methane to the gas supply. Therefore, we investigate how the two policies introduced in the previous section, namely the subsidization and participation policies, perform under uncertainty. In Figure 17, the shaded areas show the envelopes that encompasses the set of simulations with each policy, no policy and the combinations of these policies. In particular, these envelopes depict the range between minimum and maximum values that *Bio-methane Production Rate* take over 48 years in 2500 experiments. The significant effect of the subsidization policy (green line) compared to the no policy option (dark blue overlapped by red) can be seen in the envelopes and density graphs below. Subsidization policies enable obtaining up to 2.5 bcm/year production by 2020 and the density curve is shifted upwards which means that the majority of the scenarios result in higher production volumes. Yet, the decline after the cease of subsidization in 2020 in the maximum possible values and in the mean value of the simulations is inevitable. As for the participation policy (red line), as in the base case it is not considerably more effective compared to the no policy option.

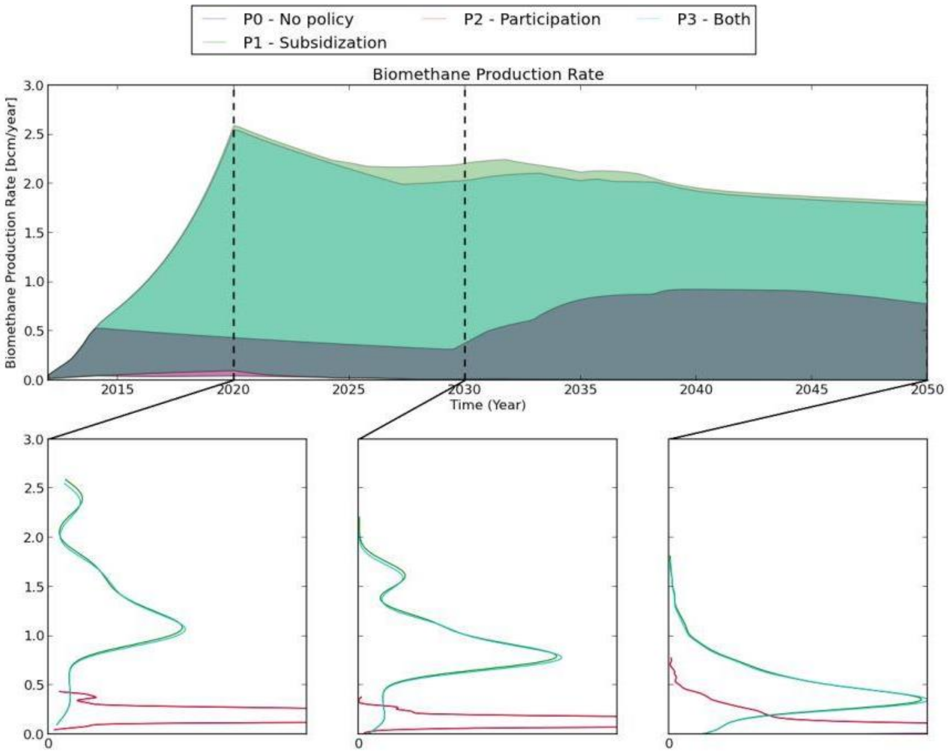


Figure 17: Comparison of policies in terms of the uncertainty ranges of Bio-methane Production Rate

In the above analysis, the subsidization policy is implemented with a certain percentage of costs (15%) and with a certain period of time (until 2020) to do that. In order to investigate the effects of these two policy variables, we ran the model 10000 again with all other uncertainties and the cost percentage between 0 and 50%, which makes the 'subsidy to cost ratio' between 1 and 1.5, and the subsidy duration with 6 to 42 years implemented after 2008. The scatter plots in Figure 18 show the correlations between these two policy variables and two outcomes of interest, which are the 'total (cumulative) bio-methane production by 2050' and 'total costs of the policy'. In Figure

18a, the ‘maximum’ values of total bio-methane production are shown to increase with increasing subsidization ratio. However, there is no such an obvious trend after 10%. Subsidy duration is shown to significantly affect the total production, but the increasing trend is smoothened after 15 years, which means that prolonging the subsidization more than 15 years can still increase the total production, but not at a high rate as before. Expectedly, there is a positive correlation between the two policy variables and the total costs despite a high range of variety in the values. Yet, the maximum values do not significantly increase even if subsidy percentage and duration increase.

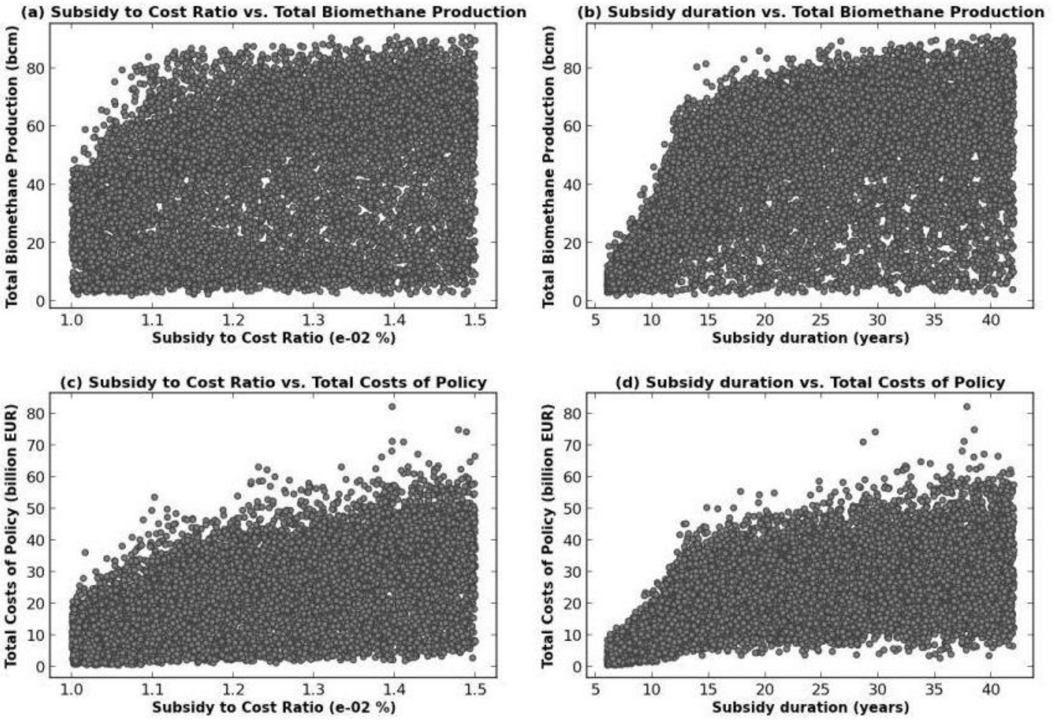


Figure 18: Scatter Plots of Subsidization Policy Variables vs. Total Bio-methane Production and Total Costs of the Policy

This analysis of the effect of subsidization policy variables with scatter plots is not adequate to generate useful insights due to the lack of an evident correlation. Still, identifying the factors that lead to more desirable states can help observing the effects of these policy variables and forming further policies. Therefore, the uncertainties that lead to more than 2 bcm production in 2020, and more than 1 bcm production in 2050 with the subsidization policy are determined with the implementation of the Patient Rule Induction Method (PRIM) (Bryant and Lempert, 2010) on the output data of experiments. This method searches over the uncertainty space to find the subspaces of uncertainty which yield a predetermined condition in the output set. The findings below in Table 2 indicate that in addition to the more than 15% subsidy percentages and more than 12.5 years of subsidization, not only short installation times of plants and higher yields of biomass, but also a high decrease in the societal acceptance of natural gas, which increases the renewable gas demand, yield more desirable states in 2020. Looking at the factors that are important in generating more than 1 bcm in 2050, we see that the desired range policy variable ‘Subsidy to cost ratio’ does not change, whereas much longer subsidy durations, i.e. more than 26 years, are required. It can also be seen in these results that the installation delay and societal acceptance are no longer influential in obtain desired states in the long-term, but the change rate of electricity price and biogas-based power generation capacity between 2035 and 2050 take low values in the scenarios leading to desired states in 2050. This finding can be interpreted as high production rates in the long-term are obtained if the competitiveness of electricity sector for biomass and biogas sharing is not high. Based on this finding, more policy options can be formulated in order to shorten the installation period of upgrading and biogas plants, to use biomass types with higher biogas yields or to increase the efficiency of biogas production process, and to maintain the competitiveness of bio-methane sector for biomass and biogas sharing.

Table 2: PRIM results showing uncertainty subspaces effective in creating desired states in 2020 and 2050

Uncertainty	*Desired Uncertainty Subspace 2020*	*Desired Uncertainty Subspace 2050*	*Entire Uncertainty Space*
Small Plant Installation Delay	1 – 1.98		1 - 3
Subsidy to cost ratio	1.14 – 1.5	1.1 – 1.5	1 - 1.5
Average Biomass Yield	0.25 – 0.8	0.21 – 0.8	0.02 - 0.8
Societal Acceptance Decrease Fraction in 2012-2025	0.02 – 0.1		0 - 0.1
Subsidy Duration	12.5 - 42	26 - 42	6 - 42
Electricity Price 2035 2050		-0.1 – 0.08	-0.10 - 0.15
PGC Biogas 2035 2050		-0.20 - 0.10	-0.20 - 0.20

5. Conclusion

In this paper, the future dynamics of bio-methane production in the Netherlands under uncertainty are investigated by using a system dynamics model and an exploratory approach to deal with uncertainty. In contrast to the existing studies which mainly deal with short-term or static problems of bio-methane production such as profitability, a broader and long-term view is adopted in this study. With this view, bio-methane production is framed as a result of a chain of interacting factors such as resources, demand and capacity installation, from biomass to bio-methane. Due to the novelty of the technology, even technical and financial factors are uncertain, in addition to the effects of related sectors such as electricity and heating, or the behavior of producers and consumers. To deal with these uncertainties, possible future dynamics are explored by generating a large number of scenarios and implications about the subsidization policy are analyzed by using this ensemble of scenarios.

Our findings showed that the development of bio-methane production is highly dependent on subsidization, especially in the early years. However, the limited supply of biomass and reduced competitiveness against the electricity sector does not allow the production volumes to grow or to remain stable. Also, the lack of demand switch from natural gas to bio-methane hinders the development of a market-driven production system. In addition to the subsidization amount and period, installation delay of plants, biogas yield of biomass, and the decrease in the societal acceptance of natural gas are found to be influential uncertainties in achieving favorable production rates in 2020. As for obtaining favorable production rates in the long-term, for instance in 2050, electricity price and production capacity of biogas-based electricity play an important role in addition to the subsidy duration. More policy options can be formulated in order to affect these uncertain factors.

In addition to formulating and testing more policy options, in future analyses, the suggestions for the subsidization policy can be enriched by finding the robust values of policy variables, namely the values which maximize the robustness of the policy against the uncertainties. Additionally, future research can focus on extending the model to better investigate the relation of bio-methane production to the other supply sources in the gas sector, such as natural gas and imports.

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7. APPENDIX I : Model Documentation

i. Biomethane Production

Formulations and Comments	**Units**
In all of the equations in this table, t = time All parameter values and lookup functions can be seen in Appendix II: Data Set.	
$BM_p(t) = MIN\left(BM_R\left(t\right), BM_C\left(t\right), D_{RG}\left(t\right)\right)$	bcm/year
Biomethane Production Rate (BM_p) is the minimum of Producible Biomethane (BM_R), Biomethane Production Capacity (BM_C) and Renewable Gas Demand (D_{RG}).	

Biomethane Capacity Construction

$$BM_C(t) = BM_C(0) + \int_0^t \left(IBM_C(\tau) - OBM_C(\tau)\right)d\tau$$

bcm/year

Biomethane Production Capacity (BM_C) is the variable that represents the total capacity of upgrading facilities installed, in terms of biomethane (upgraded biogas) yield per year. Hence, it is formulated as a stock variable that increases with Installation Rate of Biomethane Production Capacity (IBM_C), and decreases with Obsolescence Rate of Biomethane Production Capacity (OBM_C).

$$IBM_C(t) = IBM_C^*\left(t\right) IRP_{BM}\left(t\right)$$

bcm/year^2

Installation of upgrading capacity is the result of investment decisions of individual producers, which are mostly farmers who produce biogas, but it is highly supported by the transmission network owner (GasUnie) and the distribution system operators (DSO's), and the government agencies (Agentschap). It is assumed that these investors have a Desired Installation Rate of Biomethane Production Capacity (IBM_C^*) and they actually invest in installation of only a percentage of this desired value. This percentage is represented by Investment Response to Profitability for Biomethane Capacity (IRP_{BM}).

$$IRP_{BM}(t) = f_{BM}^I\left(PP_{BM}\right)$$

Dimensionless

Investment Response to Profitability for Biomethane Capacity (IRP_{BM}) is formulated by using a lookup function (f_{BM}^I) which takes Profit Percentage of Biomethane (PP_{BM}) as input. f_{BM}^I is an increasing function which takes values between 0 and 1, and the form of this function for the base simulation is calibrated by minimizing the difference between the data and model results for the Installation Rate of Upgrading Capacity.

$$OBM_C(t) = \frac{BM_C(t)}{d_T}$$

bcm/year^2

Obsolescence Rate of Biomethane Production Capacity (OBM_c)is determined by a single negative feedback loop mechanism, and its formula is Biomethane Production Capacity (BM_C) divided by the Average Lifetime of Upgrading Plants (d_T).

$$IBM_C^*\left(t\right) = PIBM_C^*\left(t\right) f_{\max}\left(\frac{MIBM_C^*\left(t\right)}{PIBM_C^*\left(t\right)}\right)$$

bcm/year^2

To formulate the Desired Installation Rate of Biomethane Production Capacity (IBM_C^*), two perspectives are taken into account: Market's and policy makers'. Given the goals to reduce CO_2 emissions and have a more sustainable energy system, what policy makers require to install differs from what the market independently would install. As mentioned before, system operators and government agencies highly support installation in the Netherlands, therefore it is possible to commission more capacity than the market is actually willing to. Hence, Desired Installation Rate of Biomethane Production Capacity (IBM_C^*) is formulated as the maximum OF Market's Desired Installation Rate of Biomethane Production

Capacity ($MIBM_C^*$) and Policy Makers' Desired Installation Rate of Biomethane Production Capacity ($PIBM_C^*$). A 'fuzzy max' function which is defined as lookup function representing a percentage of the policy makers' desired value and provides a smooth transition from one element to the other, is used for this maximum formulation.

$$PIBM_C^*(t) = \frac{MAX\left(DPBM_C(t), 0\right)}{d_I} \qquad \text{bcm/year^2}$$

Policy Makers' Desired Installation Rate of Biomethane Production Capacity ($PIBM_C^*$) is formulated as the maximum of zero and Discrepancy between the Policy Makers' Desired and Current BM Capacity ($DPBM_C$) divided by the Small Plant Installation Delay, which is the delay time between the decision for commissioning and realization of it. MAX function is used to exclude negative discrepancies between the desired and current capacity since installation occurs only if this discrepancy is positive.

$$DPBM_C(t) = PBM_C^*(t) - BM_C(t) \qquad \text{bcm/year}$$

Discrepancy between the Policy Makers' Desired and Current BM Capacity ($DPBM_C$) is the difference between the Policy Makers' Desired Capacity (PBM_C^*) and the current level of Biomethane Production Capacity (BM_c).

$$PBM_C^*(t) = PBM_C^*(0) + \int_0^t \left(GCR_{BM}^{2020}(\tau) - AR_{BM}(\tau)\right) d\tau \qquad \text{bcm/year}$$

To represent the floating goal of the policy makers, Policy Makers' Desired Capacity (PBM_C^*) is formulated as a stock variable which has two flows: 2020 Goal Change Rate (GCR_{BM}^{2020}) and Adjustment Rate of Bio-methane Capacity Goal (AR_{BM}). Whereas the former is and inflow, the latter is a bidirectional flow which decreases the goal if its positive and increases if it is negative.

$$GCR_{BM}^{2020}(t) = PBM_C^*(t) * r_{BM}(t) \qquad \text{bcm/year^2}$$

2020 Goal Change Rate (GCR_{BM}^{2020}) is a fraction of Policy Makers' Desired Capacity (PBM_C^*) so that an exponential increase until 2020 can be obtained.

$$r_{BM}(t) = 0.25 - STEP(0.25, 2020) \qquad \text{1/year}$$

Fraction of 2020 Goal Change Rate (r_{BM}) is determined to be 0.25 to have 3 bcm capacity in 2020 with exponential increase from 0.4 in 2012. This fraction is set to 0 after 2020, since the goal for the period after 2020 is not specified for the policy makers.

$$AR_{BM}(t) = \frac{DPBM_C(t)}{d_{AR}} \qquad \text{bcm/year^2}$$

As in the generic floating goal mechanism, Adjustment Rate of Bio-methane Capacity Goal (AR_{BM}) is division of Discrepancy between the Policy Makers' Desired and Current BM Capacity ($DPBM_C$) by the Goal Adjustment Time (d_{AR}). This formulation enables increasing the goal when the discrepancy is negative, which means that the installed capacity is higher than the goal, and vice versa.

$$MIBM_C^*(t) = \frac{DMBM_C(t)}{d_I} \qquad \text{bcm/year^2}$$

Market's Desired Installation Rate of Biomethane Production Capacity ($MIBM_C^*$) is formulated as the Discrepancy between the Market's Desired and Current BM Capacity ($DPBM_C$) divided by the Small Plant Installation Delay.

$$DMBM_C(t) = MAX\left(MBM_C^*(t) - BM_C(t), 0\right) \qquad \text{bcm/year}$$

Discrepancy between the Market's Desired and Current BM Capacity ($DMBM_C$) is the nonnegative difference between the Market's Desired Capacity (MBM_C^*) and the current level of Biomethane Production Capacity (BM_c).

$$MBM_C^*(t) = MIN\left(EBM_R(t), ED_{RG}(t)\right) \qquad \text{bcm/year}$$

To decide on the desired capacity level, the market producers are assumed to take two factors into account: Expected resource availability and demand. Therefore, Market's Desired Capacity (MBM_C^*) is formulated as the minimum of Expected Producible Biomethane (EBM_R) and Expected Total Renewable Gas Demand (ED_{RG}).

$$ED_{RG}(t) = FORECAST\left(D_{RG}(t), \mu_p, \mu_h\right) \qquad \text{bcm/year}$$

Expected Total Renewable Gas Demand (ED_{RG}) is the demand estimated in 'Estimation Horizon (μ_h)' ahead of the current time, by looking at the past data of last 'Estimation Period (μ_p)' many years. In other words, $ED_{RG}(t)$ is the demand estimate for the year $(t+\mu_h)$, formed by considering the data of the period from $(t-\mu_p)$ to t. FORECAST is a simple trend extrapolation function. Total Renewable Gas Demand (D_{RG}) is the sum of renewable gas demand of households, agriculture, transport and industry; but since it is determined in another segment of the model, its documentation is not detailed here.

$$EBM_R(t) = FORECAST\left(BM_R(t), \mu_p, \mu_h\right) \qquad \text{bcm/year}$$

Expected Producible Biomethane (EBM_R) is the volume of biomethane that can be produced based on estimated resource (biogas) availability. It is forecasted similarly to the demand, from the variable Producible Biomethane (BM_R).

$$BM_R(t) = BG_U(t)\upsilon \qquad \text{bcm/year}$$

Producible Biomethane (BM_R) is the volume of Biogas Allocated for Upgrading (BG_U) multiplied by the Upgrading Efficiency (υ). Biogas has a 40 - 60% methane content, whereas this is 89.4% for the natural gas in the grid. Upgrading process includes clearing other materials like chlorine or sulphur, or adding CO2, and eventually, the volume of biomethane produced is around 60% of the volume of the biogas used. Therefore, the parameter Upgrading Efficiency (υ) represents this volume change in the process of upgrading biogas to biomethane.

Biogas Allocation

$$BG_U(t) = MIN\left(ABG_U(t) + IBG_U(t), BGD_U\right) \qquad \text{bcm/year}$$

Biogas Allocated for Upgrading (BG_U) is the minimum of Biogas Demand of Upgrading Sector (BGD_U), and the sum of Additional Biogas Allocated for Upgrading (ABG_U) and Initial Biogas Allocated for Upgrading (IBG_U). This formulation is the same for Biogas Allocated for Electricity (BG_E) and Biogas Allocated for Heating (BG_H), with corresponding variables. Minimum function ensures that no sector gets more than demanded.

$$IBG_U(t) = MIN\left(BGD_U(t), BG_p(t)\delta_U(t)\right) \qquad \text{bcm/year}$$

Initial Biogas Allocated for Upgrading (IBG_U) is the minimum of Biogas Demand of Upgrading (BGD_U) and a fraction of Biogas Production Rate (BG_p) where this fraction is called Biogas Fraction of Upgrading (δ_U). In other words, IBG_U is equal either to a percentage of Biogas Production Rate, or to Biogas Demand of Upgrading. This formulation is the same for Initial Biogas Allocated for Electricity (IBG_E) and Initial Biogas Allocated for Heating (IBG_H), with the corresponding demand and fraction variables.

$$\delta_U(t) = \frac{p_U^{bg}(t)}{p_U^{bg}(t) + p_E^{bg}(t) + p_H^{bg}(t)} \qquad \text{Dimensionless}$$

Biogas Fraction of Upgrading (δ_U) is assumed to be dependent only on economic value, therefore it is formulated as the percentage of Biogas Value for Upgrading (p_U^{bg}) to the sum of such values for all three sectors. Biogas Fraction of Electricity (δ_E) and Biogas Fraction of Heating (δ_H) are formulated similarly, with the corresponding biogas values in the numerator.

$$p_U^{bg}(t) = p_{bm}^*(t)\upsilon \qquad \text{EUR/cm}$$

Biogas Value for Upgrading (p_U^{bg}) represents the revenue gained from a unit biogas in the case of using for upgrading. It is the multiplication of Perceived Biomethane Price (p_{bm}^{*}) and Upgrading Efficiency (υ). Since 1 m^3 biogas yields a smaller volume of biomethane, the price of biogas needed to be multiplied by this volume reduction.

$$p_E^{bg}(t) = p_{e,bg}(t)\, HV_{bg}\, eff_{bg}$$
EUR/cm

Similarly, Biogas Value for Electricity (p_E^{bg}) represents the revenue gained from a unit biogas in the case of using for electricity production. Therefore, it is the multiplication of Wholesale Electricity Price for Biogas ($p_{e,bg}$) including subsidies, the Heating Value of Biogas (HV_{bg}) and Fuel Efficiency of biogas (eff_{bg}) in power generation. With this formulation, simply the final gain of using 1 unit of biogas for electricity production is calculated. (The actual formulation includes conversion factors for different scales of the same unit, e.g. TWh to GWh.)

$$p_H^{bg}(t) = p_{ng}^{*}(t)\, \rho_{bg,ng}$$
EUR/cm

Biogas Value for Heating (p_H^{bg}) is formulated as the multiplication of Expected Natural Gas Market Price (p_{ng}^{*}) and the Ratio of Biogas Methane Content to Natural Gas ($\rho_{bg,ng}$). As explained in the Model Description section, direct price value of biogas used for heating is not known, and the natural gas price is used instead since it is the cost saved by using biogas. Methane contents of biogas and natural gas are not the same, which results in different volumes required to obtain the same heating value. This is why the expected natural gas price is multiplied by the ratio of methane contents.

$$ABG_U(t) = SBG(t) * \frac{FN_U(t)}{FNBG(t)}$$
bcm/year
$$ABG_U(t) = SBG(t) * \mathrm{XIDZ}\big(FN_U(t), FNBG(t), 0\big)$$

Additional Biogas Allocated for Upgrading (ABG_U) is the volume of biogas allocated for upgrading if upgrading sector took less than its demand, and if there is surplus of biogas supply which is not allocated to any sector after the initial allocation based on prices. Therefore, Additional Biogas Allocated for Upgrading (ABG_U) is assumed to be a fraction Total Surplus of Biogas Supply (SBG) where this fraction is the ratio of Further Biogas Need of Upgrading (FN_U) to the Total Further Biogas Need ($FNBG$). However, when Total Further Biogas Need ($FNBG$) is zero, which means that all the sectors could get what they demand in the first allocation round, Additional Biogas Allocated for Upgrading (ABG_U) is zero, too. To ensure that formulation works in this condition, too, the XIDZ function which sets a fraction to zero if the denominator is zero is used. Additional Biogas Allocated for Electricity (ABG_E) and Additional Biogas Allocated for Heating (ABG_H) are formulated similarly, with the corresponding Further Need variables.

$$SBG(t) = BG_p(t) - IBG_U(t) - IBG_E(t) - IBG_H(t)$$
bcm/year

Total Surplus of Biogas Supply (SBG) is the difference between Biogas Production Rate (BG_p), which is the annual total biogas supply, and the sum of Initial Biogas Allocated for Upgrading, Electricity and Heating (IBG_U, IBG_E, IBG_H) based on price values.

$$FN_U(t) = BGD_U(t) - IBG_U(t)$$
bcm/year

Further Biogas Need of Upgrading (FN_U) is the difference between the Biogas Demand of Upgrading (BGD_U) and Initial Biogas Allocated for Upgrading (IBG_U). This variable is nonnegative by definition, since Initial Biogas Allocated is not allowed to be more than the demand. Further Biogas Need of Electricity (FN_E) and Further Biogas Need of Heating (FN_H) are calculated similarly.

$$FNBG(t) = FN_U(t) + FN_E(t) + FN_H(t)$$
bcm/year

Total Further Biogas Need ($FNBG$) is the sum of Further Biogas Need of all three sectors.

$$BGD_U(t) = \frac{BM_C(t)}{\upsilon}$$
bcm/year

Biogas Demand of Upgrading (BGD_U) is formulated as the division of Biomethane Production Capacity (BM_C), which can be interpreted as the intended production rate, by the Upgrading Efficiency (υ) since the biogas volume required to produce one unit of biomethane is higher. The reason for having the installed capacity as the only factor determining the biogas demand of the upgrading sector, excluding the renewable gas demand (D_{RG}) for instance, is the current policy-driven mechanism focused on producing as much as possible rather than meeting the demand.

$$BGD_E(t) = \frac{PGC_{bg}(t)\, ACU_{bg}(t)\, a_{bg}\, H}{HV_{bg}\, eff_{bg}}$$

bcm/year

Biogas Demand of Electricity (BGD_E) is calculated based on the installed Power Generation Capacity of Biogas plants (PGC_{bg}). The numerator shows the average electricity production, where the capacity is multiplied by Average Capacity Utilization (ACU_{bg}), Availability Factor (a_{bg}) and Hours per Year (H). The denominator is the average electricity energy obtained from one unit of biogas, hence the division yields the biogas volume demanded for an average utilization of the capacity.

$$BGD_H(t) = BGD_H(0) + \int_0^t \left(BGD_H(\tau)\, r_{bg}^{h}(\tau) \right) d\tau$$

bcm/year

Biogas Demand of Heating (BGD_H) is formulated as a stock variable of which the annual change rate is a fraction of itself. This fraction, Net Change Fraction of Biogas Demand of Heating (r_{bg}^{h}) is a step function which is constant in a certain period of time and then jumps to another value for another period of time, as mentioned in the Model Description section.

Costs and Price of Biomethane

$$p_{bm}^{*}(t) = SMOOTHI\left(p_{bm}(t), \mu_{mp}, p_{bm}^{*}(0) \right)$$

EUR/cm

Perceived Biomethane Price (p_{bm}^{*}) is the delayed value of the actual Biomethane Price (p_{bm}), because producers and suppliers do not perceive the changes in the price level immediately.

$$p_{bm}(t) = MAX\left(p_{bm}^{f}(t), p_{bm}^{m}(t) \right)$$

EUR/cm

Biomethane Price (p_{bm}) is equal to the maximum of Biomethane Feed-in Tariff (p_{bm}^{f}) and Biomethane Market Price (p_{bm}^{m}). Biomethane Feed-in Tariff (p_{bm}^{f}) is the basis average subsidy amount set by the government for biomethane injected to the gas grid, for the duration of subsidy. In the base case, it is provided till 2015 as 115% of the Total Unit cost of Biomethane (TUC_{bm}).

$$p_{bm}^{m}(t) = MIN\left(DP_{bm}^{p}(t), DP_{bm}^{m}(t) \right)$$

EUR/cm

Biomethane Market Price (p_{bm}^{m}) is the minimum of Producers' Desired Biomethane Price (DP_{bm}^{p}) and Market's Desired Biomethane Price (DP_{bm}^{m}). The reasoning behind this formulation is that producers cannot sell their product at the price value they desire, it is limited by the market price, because the market price is adjusted according to the natural gas price, which is the closest alternative consumers can switch to.

$$DP_{bm}^{m}(t) = p_{ng}^{*}(t)\, m_{bm,ng}$$

EUR/cm

Market's Desired Biomethane Price (DP_{bm}^{m}) is assumed to be a multiplier of Expected Natural Gas Market Price (p_{ng}^{*}). This multiplier is a constant named the Ratio of Biomethane to Natural Gas Price ($m_{bm,ng}$).

$$DP_{bm}^{p}(t) = TUC_{bm}(t)\left(1 + PM_{bm}(t) \right)$$

EUR/cm

Producers' Desired Biomethane Price (DP_{bm}^{p}) is calculated by the addition of Biomethane Profit Markup Percentage (PM_{bm}) to the Total Unit Cost of Biomethane (TUC_{bm}).

$$PM_{bm}(t) = PM_{bm}^{*}\, f_{bm}^{PM}\left(\frac{p_{ng}^{*}(t)}{TUC_{bm}(t)} \right)$$

Dimensionless

Biomethane Profit Markup Percentage (PM_{bm}) is assumed to be a variable adjusted by the biomethane producers according to their production costs and natural gas market price. Therefore, it is formulated as the multiplication of the Desired Profit Markup of Biomethane (PM_{bm}^{*}) and the Effect of Market Price on BM Profit Markup (f_{bm}^{PM}). The latter is an increasing function of the ratio of Expected Natural Gas Market Price (p_{ng}^{*}) to Total Unit Cost of Biomethane (TUC_{bm}).

$$TUC_{bm}(t) = IUC_{bm} + VUC_{bm}(t) \qquad \text{EUR/cm}$$

Total Unit Cost of Biomethane (TUC_{bm}) is the sum of Unit Investment Cost of Biomethane (IUC_{bm}) and Variable Unit Cost of Biomethane (VUC_{bm}).

$$IUC_{bm} = \frac{IC_{bm}\, r\, (1+r)^{d_T}}{\left((1+r)^{d_T} - 1\right)} \qquad \text{EUR/cm}$$

Unit Investment Cost of Biomethane (IUC_{bm}) is a constant calculated by spreading the Investment Cost of a capacity unit (IC_{bm}) to the potential production throughout the Average Lifetime of of Upgrading Plants (d_T). With Interest Rate r, the formula given above is the formula of Equivalent Annual Cost, which distributes a capital cost to equal annuities. Since full utilization is assumed, i.e. the annual production from a capacity unit (1 bcm) is assumed to be 1 bcm, no element for the annual production is added to this formula.

$$VUC_{bm}(t) = FC_{bm}(t) + PC_{bm} L_{bm}(t) \qquad \text{EUR/cm}$$

Variable Unit Cost of Biomethane (VUC_{bm}) is the sum of Fuel Cost of Biomethane (FC_{bm}) and the multiplication of the Normal Production Cost of Biomethane (PC_{bm}) by the Learning Effect on Biomethane Production Costs (L_{bm}).

$$FC_{bm}(t) = \frac{TUC_{bg}(t)}{\upsilon} \qquad \text{EUR/cm}$$

Fuel Cost of Biomethane (FC_{bm}) is derived from the Total Unit Cost of Biogas (TUC_{bg}) since biogas is the fuel for biomethane production. Hence, sincw $1/\upsilon$ is the volume of biogas needed to produce 1 unit of biomethane, the fuel cost of one unit of biomethane is the division of Total Unit Cost of Biogas (TUC_{bg}) by Upgrading Efficiency (υ).

$$L_{bm}(t) = \left(\frac{C_{bm}(t)}{C_{bm}(0)}\right)^{-l_{bm}} \qquad \text{Dimensionless}$$

Learning Effect on Biomethane Production Costs (L_{bm}) is assumed to be a monotonically decreasing function of the Ratio of Cumulative Biomethane Production (C_{bm}) to its initial value. This monotonic decrease is presented by a negative exponent, which is named the Learning Curve Parameter of Biomethane (l_{bm}).

$$C_{bm}(t) = C_{bm}(0) + \int_0^t BM_p(\tau)\, d\tau \qquad \text{bcm}$$

Cumulative Biomethane Production is a stock variable which cumulates the Biomethane Production Rate (BM_p) over time.

$$PP_{BM}(t) = \frac{p_{bm}(t) - TUC_{bm}(t)}{TUC_{bm}(t)} \qquad \text{Dimensionless}$$

Profit Percentage of Biomethane (PP_{BM}) which is the input to the Investment Response to Profitability for Biomethane Capacity (IRP_{BM}) is the ratio of unit profit to the Total Unit Cost of Biomethane (TUC_{bm}). Unit profit is certainly the difference between the Biomethane Price (p_{bm}) and the Total Unit Cost of Biomethane (TUC_{bm}).

ii. Biogas Production

Formulations and Comments	**Units**
In all of the equations in this table, t = time All parameter values and lookup functions can be seen in Appendix II: Data Set.	
$BG_p(t) = MIN\left(BG_R\left(t\right), D_{BG}\left(t\right)\right)$	bcm/year
Biogas Production Rate (BG_p) is the minimum of Producible Biogas (BG_R) and Biogas Production Capacity (BG_C).	
Biogas Capacity Construction	
$BG_C(t) = BG_C(0) + \int_0^t \left(IBG_C(\tau) - OBG_C(\tau)\right)d\tau$	bcm/year
Biogas Production Capacity (BG_C) is the variable that represents the total capacity of biogas production facilities (digestion or gasification) installed, in terms of biogas yield per year. Hence, it is formulated as a stock variable that increases with Installation Rate of Biogas Production Capacity (IBG_C), and decreases with Obsolescence Rate of Biogas Production Capacity (OBG_C).	
$IBG_C(t) = IBG_C^*\left(t\right)IRP_{BG}\left(t\right)$	bcm/year^2
Similar to the biomethane capacity installation, Installation Rate of Biogas Production Capacity (IBG_C) is formulated as a percentage Desired Installation Rate of Biogas Production Capacity (IBG_C^*), where this percentage is denoted by Investment Response to Profitability for Biogas Capacity (IRP_{BG}).	
$IRP_{BG}(t) = f_{BG}^I\left(PP_{BG}\right)$	Dimensionless
Investment Response to Profitability for Biogas Capacity (IRP_{BG}) is formulated by using a lookup function (f_{BG}^I) which takes Profit Percentage of Biogas (PP_{BG}) as input. f_{BG}^I is an increasing function which takes values between 0 and 1, and it is formed partially based on educated guesses and partially on calibration to the available data.	
$OBG_C(t) = \dfrac{BG_C(t)}{d_T^{BG}}$	bcm/year^2
Obsolescence Rate of Biogas Production Capacity (OBG_c)is determined by a single negative feedback loop mechanism, and its formula is Biogas Production Capacity (BG_C) divided by the Average Lifetime of Biogas Plants (d_T^{BG}).	
$IBG_C^*\left(t\right) = \dfrac{MAX\left(0, BG_C^*\left(t\right) - BG_C\left(t\right)\right)}{d_I}$	bcm/year^2
Desired Installation Rate of Biogas Production Capacity (IBG_C^*) is formulated as the nonnegative discrepancy between the Desired Biogas Capacity (BG_C*) and current Biogas Production Capacity (BG_C) divided by the Small Plant Installation Delay (d_I).	
$BG_C^*\left(t\right) = ED_{BG}\left(t\right)$	bcm/year
Desired Biogas Capacity (BG_C*) is assumed to be equal to the Expected Total Biogas Demand (ED_{BG}). The reason behind this demand-driven capacity formulation which does not take resource availability into account was the confidence of biogas producers in renewable biomass supply.	
$ED_{BG}\left(t\right) = FORECAST\left(D_{BG}\left(t\right), \mu_p, \mu_h\right)$	bcm/year
Expected Total Biogas Demand (ED_{BG}) is the Total Biogas Demand (D_{BG}) forecasted in 'Estimation Horizon (μ_h)' ahead of the current time, by looking at the past data of last 'Estimation Period (μ_p)' many	

years.

$$D_{BG}(t) = BGD_U(t) + BGD_E(t) + BGD_H^*(t) \qquad \text{bcm/year}$$

Total Biogas Demand (D_{BG}) is the sum of Biogas Demand of Upgrading (BGD_U), Biogas Demand of Electricity (BGD_E) and Adjusted Biogas Demand of Heating (BGD_H^*).

$$BGD_H^*(t) = BGD_H(t)\left(1 + PD_H(t)\right) \qquad \text{bcm/year}$$

Adjusted Biogas Demand of Heating (BGD_H^*) shows the demand value adjusted according to the price change. It is the result fractional effect of Percentage Change in Biogas Demand of Heating (PD_H) on Biogas Demand of Heating (BGD_H).

$$PD_H(t) = SMOOTHI\left(e_H PC(t),\, d_P,\, PD_H(0)\right) \qquad \text{Dimensionless}$$

Percentage Change in Biogas Demand of Heating (PD_H) is the delayed value of the multiplication of Percentage Biogas Price Change (PC) and the Price Elasticity of Biogas Demand of Heating (e_H). This multiplication shows the percentage response of demand to the percentage change in price, but consumers are assumed to adjust their demand after a time delay. This delay time is named the Price Adjustment Delay (d_P), and the Percentage Change is assumed to be 0 initially.

$$PC(t) = \frac{p_{bg}(t) - p_{bg}(t-1)}{p_{bg}(t-1)} \qquad \text{Dimensionless}$$

Percentage Biogas Price Change (PC) is the ratio of the difference between the current Biogas Price (p_{bg}) and the previous year's Biogas Price to the previous year's price.

$$BG_R(t) = BMS_{BG}(t)\, y \qquad \text{bcm/year}$$

Producible Biogas (BG_R) is the volume of Biomass Allocated for Biogas (BMS_{BG}) multiplied by the Average Biogas Yield of Biomass (y).

Biomass Allocation

$$BMS_{BG}(t) = MIN\left(ABMS_{BG}(t) + IBMS_{BG}(t),\, BMSD_{BG}\right) \qquad \text{Mton/year}$$

Biomass Allocated for Biogas (BMS_{BG}) is the minimum of Biomass Demand of Biogas Sector ($BMSD_{BG}$) and the sum of Additional Biomass Allocated for Biogas ($ABMS_{BG}$) and Initial Biomass Allocated for Biogas ($IBMS_{BG}$). This formulation is the same for Biomass Allocated for Electricity (BMS_E) and Biomass Allocated for Heating (BMS_H), with corresponding variables. Minimum function ensures that no sector gets more than demanded.

$$IBMS_{BG}(t) = MIN\left(BMSD_{BG}(t),\, BMS(t)\theta_{BG}(t)\right) \qquad \text{Mton/year}$$

Initial Biomass Allocated for Biogas ($IBMS_{BG}$) is the minimum of Biomass Demand of Biogas Sector ($BMSD_{BG}$) and a fraction of Biomass Supply (BMS) where this fraction is called Biomass Fraction of Biogas (θ_{BG}). This formulation is the same for Initial Biomass Allocated for Electricity ($IBMS_E$) and Initial Biomass Allocated for Heating ($IBMS_H$), with the corresponding demand and fraction variables.

$$\theta_{BG}(t) = \frac{p_{BG}^{bms}(t)}{p_{BG}^{bms}(t) + p_E^{bms}(t) + p_H^{bms}(t)} \qquad \text{Dimensionless}$$

Biomass Fraction of Biogas (θ_{BG}) is assumed to be dependent only on economic value, as in the biogas allocation mechanism. Therefore, it is formulated as the percentage of Biomass Value for Biogas (p_{BG}^{bms}) to the sum of such values for all three sectors. Biomass Fraction of Electricity (θ_E) and Biomass Fraction of Heating (θ_H) are formulated similarly, with the corresponding biomass values in the numerator.

$$p_{BG}^{bms}(t) = p_{bg}^*(t)\, y \qquad \text{EUR/ton}$$

Biomass Value for Biogas (p_{BG}^{bms}) is the multiplication of Perceived Biogas Price (p_{bg}^*) and Average Biogas Yield of Biomass (y). Actual formulation includes a scale factor to convert Mton to ton.

$$p_E^{bms}(t) = p_{e,bms}(t) HV_{bms}\, eff_{bms} \qquad \text{EUR/ton}$$

Biomass Value for Electricity (p_E^{bms}) is the multiplication of Wholesale Electricity Price for Biomass ($p_{e,bms}$) including subsidies, the Heating Value of Biomass (HV_{bms}) and Fuel Efficiency of biomass (eff_{bms}) in power generation. With this formulation, simply the final gain of using 1 unit of biomass for electricity production is calculated.

$$p_H^{bms}(t) = p_{ng}^{*}(t)\, y \rho_{bg,ng} \qquad \text{EUR/ton}$$

Biomass Value for Heating (p_H^{bms}) is formulated as the multiplication of Expected Natural Gas Market Price (p_{ng}^{*}), Average biogas yield of Biomass (y) and the Ratio of Biogas Methane Content to Natural Gas ($\rho_{bg,ng}$). In that way, biomass value is related to natural gas, which is the closes alternative, via biogas since these two parameters are already included in the model.

$$ABMS_{BG}(t) = SBMS(t) * \frac{FN_{BG}^{bms}(t)}{FNBMS(t)}$$

$$ABMS_{BG}(t) = SBMS(t) * \text{XIDZ}\left(FN_{BG}^{bms}(t),\, FNBMS(t),\, 0\right) \qquad \text{Mton/year}$$

Additional Biomass Allocated for Biogas ($ABMS_{BG}$) is assumed to be a fraction Total Surplus of Biomass Supply ($SBMS$) where this fraction is the ratio of Further Biomass Need of Biogas (FN_{BG}^{bms}) to the Total Further Biomass Need ($FNBMS$). For the condition of Total Further Biomass Need ($FNBMS$) being zero, which means that all the sectors could get what they demand in the first allocation round, the XIDZ function which sets a fraction to zero if the denominator is zero is used. Additional Biomass Allocated for Electricity ($ABMS_E$) and Additional Biomass Allocated for Heating ($ABMS_H$) are formulated similarly, with the corresponding Further Need variables.

$$SBMS(t) = BMS(t) - IBMS_{BG}(t) - IBMS_E(t) - IBMS_H(t) \qquad \text{Mton/year}$$

Total Surplus of Biomass Supply ($SBMS$) is the difference between Biomass Supply (BMS), which is the annual total biomass supply defined as a time dependent function, and the sum of Initial Biomass Allocated for Biogas, Electricity and Heating ($IBMS_{BG}$, $IBMS_E$, $IBMS_H$) based on price values.

$$FN_{BG}^{bms}(t) = BMSD_{BG}(t) - IBMS_{BG}(t) \qquad \text{Mton/year}$$

Further Biomass Need of Biogas (FN_{BG}^{bms}) is the difference between the Biomass Demand of Biogas sector ($BMSD_{BG}$) and Initial Biomass Allocated for Biogas ($IBMS_{BG}$). This variable is nonnegative by definition, since Initial Biomass Allocated is not allowed to be more than the demand. Further Biomass Need of Electricity (FN_E^{bms}) and Further Biomass Need of Heating (FN_H^{bms}) are calculated similarly.

$$FNBMS(t) = FN_{BG}^{bms}(t) + FN_E^{bms}(t) + FN_H^{bms}(t) \qquad \text{Mton/year}$$

Total Further Biomass Need ($FNBMS$) is the sum of Further Biomass Need of all three sectors.

$$BMSD_{BG}(t) = \frac{MIN\left(D_{BG}(t),\, BG_C(t)\right)}{y} \qquad \text{Mton/year}$$

Biomass Demand of Biogas ($BMSD_{BG}$) is formulated as the minimum of Total Biogas Demand (D_{BG}) and Biogas Production Capacity (BG_C) which can be interpreted as the intended production rate, divided by the Average Biogas Yield of Biomass (y). The use of minimum function here is to ensure that no biomass is demanded more than what the installed capacity can process or what the biogas market eventually needs.

$$BMSD_E(t) = \frac{PGC_{bms}(t) ACU_{bms}(t) a_{bms} H}{HV_{bms}\, eff_{bms}} \qquad \text{Mton/year}$$

Biomass Demand of Electricity ($BMSD_E$) is calculated the same as Biogas Demand of Electricity is calculated, based on the installed Power Generation Capacity of Biomass plants (PGC_{bms}). The numerator shows the average electricity production, where the capacity is multiplied by Average Capacity

Utilization (ACU_{bms}), Availability Factor ($abms$) and Hours per Year (H). The denominator is the average electricity energy obtained from one unit of biomass, hence the division yields the biomass amount demanded for an average utilization of the capacity.

$$BMSD_H(t) = BMSD_H(0) + \int_0^t \left(BMSD_H(\tau)\, r_{bms}^h(\tau) \right) d\tau \qquad \text{Mton/year}$$

Similar to the Biogas Demand of Heating, Biomass Demand of Heating ($BMSD_H$) is formulated as a stock variable of which the annual change rate is a fraction of itself. This fraction, Net Change Fraction of Biomass Demand of Heating (r_{bms}^{h}) is a step function which is constant in a certain period of time and then jumps to another value for another period of time.

Costs and Price of Biogas

$$p_{bg}^*(t) = SMOOTHI\left(p_{bg}(t), \mu_{mp}, p_{bg}^*(0) \right) \qquad \text{EUR/cm}$$

Perceived Biogas Price (p_{bg}^{*}) is the delayed value of the actual Biogas Price (p_{bg}), because producers and suppliers do not perceive the changes in the price level immediately. The perception delay is equal to the Market Price Estimation Time (μ_{mp}) and the initial value is $p_{bg}^{*}(0)$.

$$p_{bg}(t) = DP_{bg}(t)\, f_{bg}^D(t) \qquad \text{EUR/cm}$$

Biogas Price (p_{bg}) is the multiplication of Desired Biogas Price (DP_b) by the Effect of Demand Coverage on Biogas Price (f_{bg}^{D}).

$$f_{bg}^D(t) = f_{bg}^D\left(\frac{BG_p(t)}{D_{BG}(t)} \right) \qquad \text{Dimensionless}$$

Effect of Demand Coverage on Biogas Price (f_{bg}^{D}) is a decreasing function of the ratio of Biogas Production Rate (BG_p) to Total Biogas Demand (D_{BG}). A lookup function (f_{bg}^{D}) is used to represent this.

$$DP_{bg}(t) = TUC_{bg}(t)\left(1 + PM_{bg}(t)\right) \qquad \text{EUR/cm}$$

Desired Biogas Price (DP_{bg}) is calculated by the addition of Biogas Profit Mark-up Percentage (PM_{bg}) to the Total Unit Cost of Biogas (TUC_{bg}).

$$PM_{bg}(t) = PM_{bg}^*\, f_{bg}^{PM}\left(\frac{p_{bm}^*(t)}{TUC_{bg}(t)} \right) \qquad \text{Dimensionless}$$

Biogas Profit Markup Percentage (PM_{bg}) is assumed to be a variable adjusted by producers according to the ratio of Perceived Biomethane Price ($p_{bm}*$) to Total Unit Cost of Biogas (TUC_{bg}). It is formulated as the multiplication of the Desired Profit Mark-up of Biogas (PM_{bg}^{*}) and the Effect of Market Price on BG Profit Mark-up (f_{bg}^{PM}). The latter is the same function used for adjusting the profit mark-up of biomethane.

$$TUC_{bg}(t) = IUC_{bg} + VUC_{bg}(t) \qquad \text{EUR/cm}$$

Total Unit Cost of Biogas (TUC_{bg}) is the sum of Unit Investment Cost of Biogas (IUC_{bg}) and Variable Unit Cost of Biogas (VUC_{bg}).

$$IUC_{bg} = \frac{IC_{bg}\, r\, (1+r)^{d_T^{BG}}}{\left((1+r)^{d_T^{BG}} - 1 \right)} \qquad \text{EUR/cm}$$

Unit Investment Cost of Biogas (IUC_{bg}) is calculated similar to that of Biomethane by spreading the Investment Cost of a capacity unit (IC_{bg}) to the potential production throughout the Average Lifetime of of Biogas Plants (d_T^{BG}).

$$VUC_{bg}(t) = FC_{bg}(t) + PC_{bg}L_{bg}(t) \qquad \text{EUR/cm}$$

Variable Unit Cost of Biogas (VUC_{bg}) is the sum of Fuel Cost of Biogas (FC_{bg}) and the multiplication of the Normal Production Cost of Biogas (PC_{bg}) by the Learning Effect on Biogas Production Costs (L_{bg}).

$$FC_{bg}(t) = \frac{p_{bms}}{y} \qquad \text{EUR/cm}$$

Fuel Cost of Biogas (FC_{bg}) is the division of Biomass Price (p_{bms}), which is assumed to be a constant in the model, by Average Biogas Yield of Biomass (y). This formulation yields the costs of biomass used for producing one unit of biogas.

$$L_{bg}(t) = \left(\frac{C_{bg}(t)}{C_{bg}(0)}\right)^{-l_{bg}} \qquad \text{Dimensionless}$$

Learning Effect on Biogas Production Costs (L_{bg}) is assumed to be a monotonically decreasing function of the Ratio of Cumulative Biogas Production (C_{bg}) to its initial value. This monotonic decrease is presented by a negative exponent, which is named the Learning Curve Parameter of Biogas (l_{bg}).

$$C_{bg}(t) = C_{bg}(0) + \int_0^t BG_p(\tau)\,d\tau \qquad \text{bcm}$$

Cumulative Biogas Production is a stock variable which cumulates the Biogas Production Rate (BG_p) over time.

$$PP_{BG}(t) = \frac{p_{bg}(t) - TUC_{bg}(t)}{TUC_{bg}(t)} \qquad \text{Dimensionless}$$

Profit Percentage of Biogas (PP_{BG}) which is the input to the Investment Response to Profitability for Biogas Capacity (IRP_{BG}) is the ratio of unit profit to the Total Unit Cost of Biogas (TUC_{bg}). Unit profit is certainly the difference between the Biogas Price (p_{bg}) and the Total Unit Cost of Biogas (TUC_{bg}).

8. APPENDIX II : Data Set

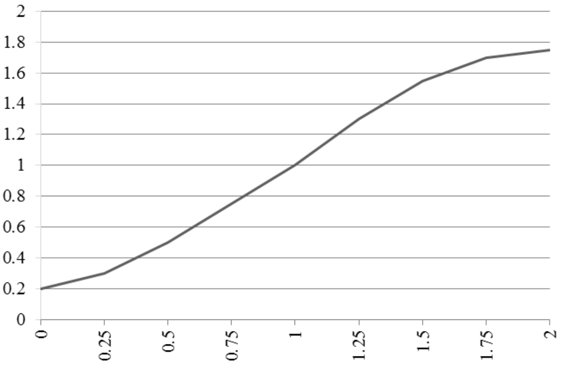
iii. Biomethane Production

Parameter	***Symbol***	***Unit***	***Base Value***	***Resource or Explanation***	***Uncertainty Range***
Average Lifetime of Upgrading Plants	d_T	year	25	Assumption	20 -30
Initial Biomethane Production Capacity	$BM_C(0)$	bcm/year	1.00E-07	Assumed to be nearly 0 in 2000, since there was no biomethane production at that time.	-
Upgrading Efficiency	υ	Dmnl	0.74	The methane content of biogas is 55-65% (Wempe and Dumont, 2008), whereas the methane content of G-gas is 81%, and it must be higher than 80% for the grid (GasTerra, 2014). Therefore, the volume-wise efficiency of upgrading biogas with 60%	0.68 - 8

				methane content to 81% methane content is 74%. The efficiency range for 55-65% methane content is 68-80%.	
Investment Cost of Biomethane Capacity	IC_{bm}	bEUR/(bcm/Year)	0.45	Investment costs for upgrading plants are 3880 EUR/(m^3/h) per unit of biogas handled (Bekkering et al., 2010). With 74% efficiency, it is 5243 EUR/(m^3/hr) per unit of biomethane, and with 8000 hours/year, it is 0.655 EUR/(m^3/year). However, calibration of this parameter by minimizing the difference between model output and data for the installation of upgrading plants results in 0.45 EUR/(m^3/year)	0.35 - 0.7
Normal Production Cost of Biomethane	PC_{bm}	EUR/m^3	0.17	Total unit cost of biomethane is given as 8.13 EUR/kWh (Foreest, 2012), which is equal to 0.797 EUR/m^3 or as 0.872 EUR/m^3 (Bekkering et al., 2010), and upgrading related costs (other than biogas production) is estimated to be between 21.7% and 28.2% of the total cost (Bekkering et al., 2010). According to these, the range for biomethane production costs is 0.173-0.246, and the base case value is chosen as 0.17.	0.12 - 0.25
Learning Curve Parameter of Biomethane	l_{bm}	Dmnl	0.5	Assumed to be between 0 and 0.5, following the value given as 0.4551 in Bekkering et al. (2010).	0 - 0.5
Desired Profit Markup of Biomethane	PM_{bm}^*	Dmnl	0.1	Assumption	0 - 0.25
Sensitivity of Biomethane Price to Demand Coverage	β_{bm}	Dmnl	-0.2	Assumption. (Biomethane shortage would be easily covered by natural gas, so not high price changes are expected.)	-1 - 0
Reference Biomethane Price	$p_{bm}^*(0)$	EUR/m^3	0.59	Feed-in tariff in 2012.	-

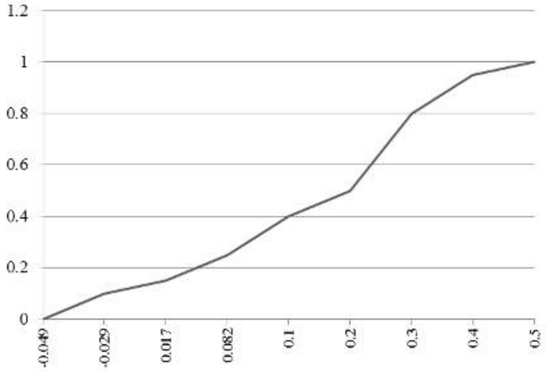
Lookup Functions

Effect of Market Price on BM Profit Markup (f_{bm}^{PM})



Biomethane producers are assumed to increase their desired profit mark-up as the market price increases. The monotonically increasing function formulated for this purpose makes the profit mark-up equal to the normal value when the ratio of market price to the cost of biomethane is 1 and saturates at 175% of the normal mark-up when this ratio is 2.

Investment Response to Profitability for Biomethane Capacity (f_{BM}^{I})



Investment response increases as the profit percentage increases. Therefore, a function that gives little response even to negative profit percentage and full response to higher than 50% profit is used. The values of this function between -0.03 and 0.1 are calibrated based on the data for the installation rate of upgrading plants.

iv. Biogas Production

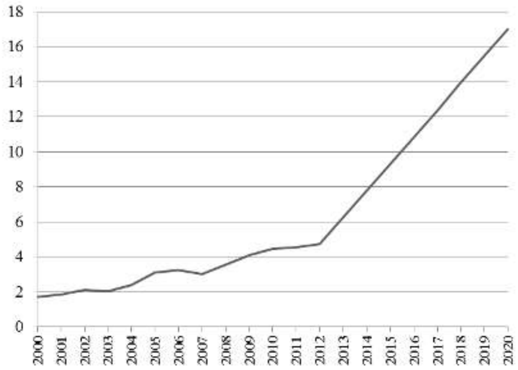
Parameter	***Symbol***	***Unit***	***Base Value***	***Resource or Explanation***	***Uncertainty Range***
Average Lifetime of Biogas Plants	d_T^{BG}	Year	25	Assumption	20-30
Small Plant Installation Delay	d_I	Year	1	groengas.nl	1-3
Initial Value of Biogas Production Capacity	$BG_C(0)$	bcm/Year	0.255	Production volume in 2000, which is 0.255 bcm (CBS, 2014), is assumed to be the capacity in that year.	-
Average Biomass Yield	y	bcm/Mton	0.5	Average biogas yield is 25m^3/ton for cow manure, 175 m^3/ton silage maize (Bekkering et al., 2010). In Foreest (2012) it is given in the range 20 - 800 m^3/ton (Fig 23). 0.5 bcm/Mton is assumed to be the base case value in this range.	0.02-0.8
Initial Biogas Demand of Heating	$BGD_H(0)$	bcm/year	0.021	Use of biogas for heating in 2000 was 284 TJ (CBS, 2014). This is converted to cubic meters by assuming 74% efficiency and 5 kWh/m^3 heating value.	-
Net Change Fraction of Biogas Demand of Heating	r_{bg}^{h}	1/Year	(i) 0.11, (ii) -0.04, (iii) -0.08	The first value is the fraction between 2000 and 2012, the second between 2012 and 2025 and the last for 2025 onwards. For the period 2000-2012, it is calibrated based on the data, but the other parameters are estimations.	(i) - (ii) -0.05 - 0.05 (iii) -0.1 - 0.1
Initial Biomass Demand of Heating ($BMSD_H$)	$BMSD_H$ (0)	Mton/year	0.679	Use of biomass for heating in 2000 was 9771 TJ (CBS, 2014). This is converted to million tonnes by assuming 0.004 GWh/ton heating value.	-

Net Change Fraction of Biomass Demand of Heating	r_{bms}^{h}	1/year	(i) 0.07, (ii) -0.01, (iii) -0.02	The first value is the fraction between 2000 and 2012, the second between 2012 and 2025 and the last for 2025 onwards. For the period 2000-2012, it is calibrated based on the data, but the other parameters are estimations.	(i) - (ii) -0.05 - 0.05 (iii) -0.05 - 0.05
Price Elasticity of Biogas Demand	e_H	Dmnl	-0.1	Assumption	-1 - 0
Price Adjustment Delay	d_P	Year	2	Assumption	0-3
Heating Value of Biogas	HV_{bg}	TWh/bcm	5	Heating value of biogas is highly dependent on the feedstock composition, and the data is not directly available. An example value is derived as follows: 56% methane content of biogas (Bekkering et al., 2010) makes the heating value 56/81=69% of the G-gas heating value. Hence, 69%*9.8kWh/m^3=6.7 kWh/m3=TWh/bcm. Yet, we chose 5 TWh/bcm for the base case, which results from the calibration of model according to the data.	4.7 - 6.7
Investment Cost of Biogas Capacity	IC_{bg}	bEUR/(bcm/Year)	0.53	The costs per unit of capacity depends on the plant size (economies of scale), plant type and the feedstock mix used in the plant. Foreest (2012) shows the investment costs of 4 plants from various countries with different sizes and feedstock mixes between 3700 and 4900 EUR/(m3/hr). Assuming 8000 operating hous per year, this makes 0.46-0.61 bEUR/(bcm/year), with 0.53 on average.	0.46 - 0.61
Interest rate	r	1/Year	0.15	Assumption	0.05- 0.15
Normal Production Cost of Biogas	PC_{bg}	EUR/m^3	0.2	For bio SNG, production costs are in 10-18 EUR/GJ (Scheepers, 2013), which is equal to 0.225-0.405 EUR/m^3. In GasTerra (2009) it is given as 0.15-0.17 EUR/m3. Therefore, the base value is assumed to be 0.2 within the range 0.15 – 0.4.	0.15 - 0.4
Learning Curve Parameter of Biogas	l_{bg}	Dmnl	0.35	Assumption	0 - 0.5
Initial Total Biogas Production	$C_{bg}(0)$	bcm	2.76	According to the CBS data (CBS, 2014), total biogas production from 1990 to 2000 accounts to 49714 TJ, which is equal to 2.76 bcm assuming 5 TWh/bcm calorific value and 0.27778 conversion factor btw TJ and GWh.	-
Biomass Price	p_{bms}	EUR/ton	15	The price of biomass is certainly dependent on the type. Maize price is between 28 EUR/ton (Bekkering et al., 2010) and 35 EUR/ton (Foreest, 2012). When manure is used, it is -15 eur/ton	-15 - 35

				(Bekkering et al., 2010). Roughly, 15 EUR/ton is assumed to be the base value in the range of -15 - 35.	
Reference Biogas Price	$p_{bg}^{*}(0)$	EUR/cm	0.6465	According to Bekkering et al. (2010) the process of biogas production constitutes 72-79% of green gas production costs. Since 0.872EUR/m^3 is the given green gas cost-price, 75% of this, 0.6465 is assumed to be the reference price.	0.4 - 0.65
Biogas Desired Profit Markup	PM_{bg}^{*}	Dmnl	0.05	Assumption	0 - 0.25

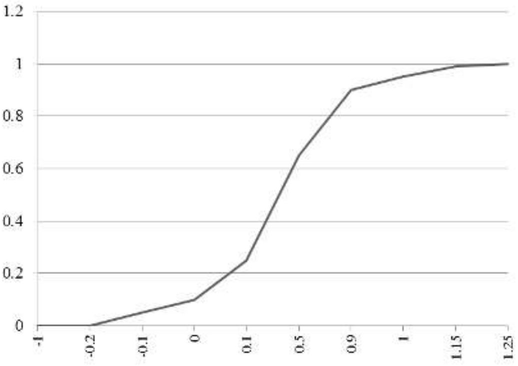
Lookup Functions

Biomass supply (BMS)



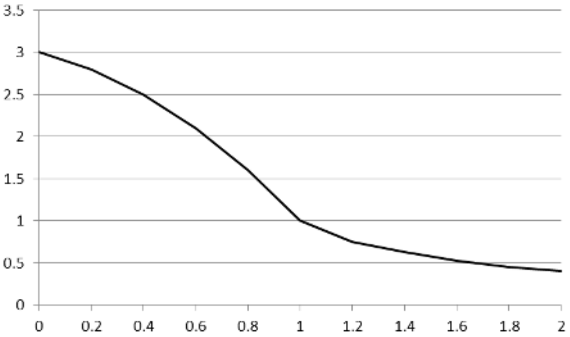
For the period 2000-2012, biomass supply is assumed to be the total amount used for biogas and electricity production, and heating. The rest of the function is formed based on the projections by Panoutsou and Uslu (2011).

Investment Response to Profitability for Biogas Capacity (f_{BG}^{I})



Investment response increases as the profit percentage increases. Therefore, a function that gives little response even to negative profit percentage and full response to higher than 125% profit is used. The function is assumed to be steeper for the profit percentages between 10 and 90%.

Effect of Demand Coverage on Price Lookup (f_{BG}^{D})



Price decreases as the demand coverage, namely the ratio of biogas production to the total biogas demand, increases.