APPENDIX I : Equation List of the Power Generation Sub-model

Formulations and Comments	**Units**
In all of the equations in this table, *i = biogas, biomass, coal, coalCCS, gas, gasDecentral, gasCCS, nuclear, solar, wind* *t = time*	

$$DAC_i(t) = \frac{\max(\text{Discrepancy}_L(\text{t}),\ 0)\, d_i(\text{t})}{a_i H}$$ GW

For the Desired Additional Capacity of each technology (DAC_i), the expected supply discrepancy in long-term (e.g 10 years), only if it is non-negative, is distributed among the options by multiplying with the distribution fraction (d_i) which is determined according to their ‘scores’. To obtain the additional capacity, the share of each technology in the discrepancy is divided by the total annual expected operating hours of this technology, which is the multiplication of availability factor (a_i) and the hours in a year (H).

$$d_i(\text{t}) = \frac{ST_i(\text{t})}{\sum_i ST_i(\text{t})}$$ Dimensionless

The distribution fraction (d_i) of each technology is assumed to be the normalized value of its score (ST_i).

$$Discrepancy_L(t) = (\text{DF}_L(\text{t})\text{-TAE}^*(\text{t}))$$ TWh/year

The expected long-term electricity supply discrepancy, Discrepancy_L, is the difference between the long-term demand forecast years and the current total actual supply, assuming that the capacity utilization and the installed capacity will not change.

$$\text{TAE}^*(\text{t}) = \text{TAE(t)}(1-\text{nw})$$ TWh/year

The actual Total Annual Electricity (*TAE**) is the fraction of Total Annual Electricity Generated (*TAE*) which remains after the network loss, where *nw* is the network loss fraction.

$$\text{TAE(t)} = \sum_i AE_i(t)$$ TWh/year

Total Annual Electricity Generated (*TAE*) is the sum of Annual Electricity Generated (AE_i) by each technology.

$$DF_L(\text{t}) = \text{FORECAST(ED(t)},\ \mu_e,\ h_L)$$ TWh/year

The long-term demand forecast, DF_L, is calculated by using the FORECAST function, which takes the values of Electricity Demand (*ED*) in the last μ_e years and projects this to h_L years ahead.

$$AE_i(t) = \begin{cases} \min(\text{AEtb}_i(\text{t}), \text{FA}_i(\text{t}))\ ; i = biogas, biomass \\ AEtb_i(t) \qquad ; otherwise \end{cases}$$ TWh/year

There are two main factors that affect the Annual Electricity Generated (AP_i): Annual Electricity to be Generated for each technology ($AEtb_i$) and the Fuel Availability (FA_i). The amount that can be generated by the installed capacity is calculated in Annual Electricity to be Generated ($AEtb_i$) for each technology. Fuel availability is not a constraint for solar and wind technologies. For coal and nuclear, fuel is assumed to be always available for electricity generation. Since the primary purpose of this sub-model is to create the dynamics of gas demand of the power sector, gas is assumed also not to be a constraint. Therefore, the availability of only biogas and biomass, which is internally calculated in this model, is a constraint for the electricity generation.

$$AEtb_i(t) = EGC_i(t) c_i(t)$$ TWh/year

Annual Electricity to be Generated for each technology ($AEtb_i$) is a fraction of the producible energy from the installed capacity, which is Electricity Generation Capacity (EGC_i), and this fraction is equal to the Capacity Utilization Factor (c_i).

$$EGC_i(t) = PGC_i(t)\, a_i\, H$$ TWh/year

Electrical energy is measured with the simple equation *Power x Time*. Following this, Electricity Generation Capacity of each technology (EGC_i) is formulated as the multiplication of installed Power Generation Capacity (PGC_i), and the total annual expected operating hours (a_iH).

$$c_i(t) = \begin{cases} if\ \ EGC_i(t) > 0;\ f_{capacity}\left(\frac{DAE_i(t)}{EGC_i(t)}\right) \\ else; \qquad 0 \end{cases}$$ Dimensionless

Capacity Utilization Factor (c_i) is a function of the ratio of Desired Annual Electricity Production by each technology (DAE_i) to the Electricity Generation Capacity (EGC_i), as in the generic commodity market model. This relation is formulated as a graphical function ($f_{capacity}$) which can be seen in Appendix VI, Table 2.

$$DAE_i(t) = DF_1(\mathrm{t})\, es_i(t)(1+nw) \qquad \text{TWh/year}$$

Desired Annual Electricity Production (DAE_i) is the estimated share of each technology (es_i) to satisfy the Demand Forecast in one year (DF_1), by considering the network loss.

$$DF_1(t) = FORECAST(\mathrm{ED(t)}, \mu_e, 1) \qquad \text{TWh/year}$$

Demand Forecast in one year (DF_1) is calculated by considering the last μ_e years Electricity Demand (ED) and projecting this to one year ahead by using the FORECAST function.

$$es_i(t) = SMOOTHI(s_i(t), \gamma_s, \mathrm{s}_i(0)) \qquad \text{Dimensionless}$$

Estimated Share of technology i (es_i) in power mix is an expectation of the actual Share of technology i in power mix (s_i), and formulated as a first order information delay with a delay time of γ_s years by using the SMOOTHI function.

$$s_i(t) = \frac{AE_i(t)}{TAE(t)} \qquad \text{Dimensionless}$$

The share of each technology in power mix is simply the ratio of Annual Electricity produced (AE_i) by this technology to the Total Annual Electricity produced (TAE).

$$s_i(0) = \frac{CP_i(0)}{\sum_i CP_i(0)} \qquad \text{Dimensionless}$$

The initial value of the actual Share of technology i in power mix (s_i) is calculated by the ratio of Initial Cumulative Production of each technology (CP_i) to the sum of initial cumulative productions.

$$FA_{biogas}(t) = BGaE(t)\, cal_{biogas}\, eff_{biogas}$$
$$FA_{biomass}(t) = BM_e(t) cal_{biomass} eff_{biomass} \qquad \text{GWh/year}$$

Annual electricity that can be generated depending on the Fuel Availability (FA) of biogas and biomass is calculated as the multiplication of volume and mass of biogas and biomass, respectively, allocated for electricity generation ($BGaE$, BM_e), the calorific value of each (i.e. the energy yield of unit volume or mass), and the fuel efficiency of this generation process.

$$\mathrm{ED}(t) = ED(0) + \int_0^t f_e ED(\tau)\, d\tau \qquad \text{TWh/year}$$

Electricity Demand (ED) is formulated in a manner similar to the formulation of gas demand, as described in Section 2.2.

$$ST_i(\mathrm{t}) = \frac{w_{RoI}\, RoIr_i(\mathrm{t}) + w_{SA} SA_i(\mathrm{t})}{w_{RoI} + w_{SA}} \qquad \text{Dimensionless}$$

The score of each technology (ST_i) is defined as the weighted average of the value of its Return on Investment Response ($RoIr_i$) and its Societal Acceptance (SA_i). The weights of these two score components, w_{RoI} and w_{SA} are parameters depending on the decision maker preferences.

$$SA_i(t) = SA_i(0) + \int_0^t \left(fi_i(\tau)(1 - SA(\tau)) - fd_i(\tau) SA(\tau) \right) d\tau \qquad \text{Dimensionless}$$

The Societal Acceptance (SA_i(t)) of each power technology is formulated as a stock variable between 0 and 1, since acceptance accumulates over time. The increase in SA is assumed to be formulated as a fractional goal seeking mechanism, to reach the maximum SA level, 1. However, this Increase Fraction (fi_i(t)) changes over time as described below. Similarly, the decrease in SA is also assumed to be a fractional goal seeking mechanism, where the goal is minimum SA level, 0, and the Decrease Fraction (fd_i(t)) is a variable.

$$fi_i(t) = \begin{cases} fi_i(0)\, f_{scarcity}(sDSR_e(t)) & ; i = coal \\ fi_i(0)\, f_{scarcity}\left(sDSR_e(t)\right) f_{CO_2}\left(\dfrac{TCO_2(t)}{CO_2^*(t)}\right) & ; i = coalCCS, gasCCS, nuclear \\ fi_i(0) & ; otherwise \end{cases} \qquad \text{1/year}$$

Increase Fraction (fi_i(t)) of Societal Acceptance is variable only for coal, CCS and nuclear technologies, since the SA of other technologies is assumed to be constant. For the others, the increase fraction is formulated based on its initial value, where multiplicative effects of Scarcity and/or CO_2 are present. For coal, only Scarcity influences the SA, whereas CO_2 is also effective for CSS and nuclear. The graphical functions used to formulate these effects can be seen in Appendix VI, Table 2.

The Scarcity is assumed to be represented by the Smoothed Demand to Supply Ratio of electricity (*sDSR*), whereas the level of CO_2 urgency is indicated by the ratio of Total CO_2 emissions of the electricity generation (TCO_2) to the target CO_2 emission level for this sector (CO_2*).

$$fd_i(t) = \begin{cases} fd_i(0)\, f_{CO_2}\left(\dfrac{TCO_2(t)}{CO_2^*(t)}\right) & ; i = coal \\ fd_i(0)\, f_{safety}\left(\dfrac{CP_i(t)}{CP_i(0)}\right) & ; i = coalCCS, gasCCS, nuclear \\ fd_i(0) & ; otherwise \end{cases} \qquad \text{1/year}$$

Similar to the Increase Fraction (fi_i), the Decrease Fraction (fd_i) of SA is formulated as a multiple of its initial value, where this multiplier is determined by the CO_2 urgency in the case of coal, and by the safety issues linked to the relative Cumulative Production (*CP*). The graphical function of safety effect can be seen in Appendix V, Table 2. It must be noted that initial values of increase and decrease fractions are set to the values that keep them at the equilibrium.

$$sDSR_e(t) = SMOOTHI(DSR_e(t), \gamma_{DSR}, 1)$$

$$DSR_e(t) = \frac{ED(t)}{TAE^*(t)} \qquad \text{Dimensionless}$$

It is assumed that there is an information delay between the occurrence of scarcity and people's perception of this scarcity. Therefore, Demand to Supply Ratio of electricity (DSR_e), which is the ratio of Electricity Demand (*ED*) to the Total Actual Annual Electricity generated (*TAE**), is smoothed with a delay of γ_{DSR} years and the initial value assumed to be 1.

$$p_{e,i}(t) = p_e(0)\, m_i\, f_{price}(sDSR(t)) \qquad \text{EUR/GWh}$$

The price of electricity generated by each technology ($p_{e,i}$) is assumed to be a variable that depends on the scarcity of electricity, indicated by sDSR with the assumption that price change does also not respond immediately to scarcity, and on the feed-in tariffs applied to some of the technologies. These are formulated as multiplicative effects on the initial value of price, where m_i is the feed-in tariff multiplier that adjusts the individual price to the market price, and f_{price} is a graphical function shown in Appendix VI, Table 2.

$$C_{v,i}(t) = C_{fuel,i}(t) + C_{CO_2,i} + C_{o,i}(t) \qquad \text{EUR/GWh}$$

The total variable cost of technology i ($C_{v,i}$) is the sum of the fuel cost ($C_{fuel,i}$), CO_2 cost ($C_{CO2,\, i}$) and the operating cost ($C_{o,i}$) which varies over time due to the learning effect.

$$C_{fuel,i} = \frac{p_{fuel,i}(t)}{eff_i} \qquad \text{EUR/GWh}$$

Fuel cost is the price of fuel for each technology (except solar and wind) per unit energy divided by the fuel efficiency of this technology (eff_i).

$$p_{fuel,biogas}(t) = \frac{p_{biogas}(t)}{cal_{biogas}}$$

$$p_{fuel,biomass}(t) = \frac{p_{biomass}(t)}{cal_{biomass}} \qquad \text{EUR/GWh}$$

$$p_{fuel,gas}(t) = \frac{p^*_{gas}(t)\, p_{markup}}{cal_{ngas}}$$

The price of coal as a power fuel is assumed to be constant in this model, however the price (*p*) of biogas and natural gas are internal variables of this model. Since these price values are concluded per unit volume of gas in the other sectors of the model, they are converted into price per energy unit, by using their calorific values (*cal*). For natural gas, a profit markup (p_{markup}) is added since the market price indicates the wholesale price that it is brought to the market, and the traders obtain a little profit from the electricity sector. Biomass price is converted to the price per unit energy in the same manner as biogas.

$$C_{CO_2,\mathrm{i}} = p_{CO_2} e_i \qquad \text{EUR/GWh}$$

CO_2 cost per unit electricity produced by each technology is the multiplication of CO_2 price (p_{CO2}) and the average CO_2 emitted for the unit production of electricity by that technology (e_i).

$$I = \frac{TCO_2(\mathrm{t})}{TAE(\mathrm{t})} \qquad \text{Mton/TWh}$$

I stands for the CO_2 intensity of the electricity generation, which is the amount of CO_2 emitted per unit of electricity, and calculated as the total CO_2 emission of electricity production (TCO_2) divided by the total electricity produced.

$$TCO_2(t) = \sum_i ACO_{2,i}(\mathrm{t}) - \mathrm{RCO}_2(t) \qquad \text{Mton/year}$$

$$ACO_{2,\mathrm{i}}(t) = AE_i(t)\, e_i$$

The total CO_2 emission of electricity production (TCO_2) is the sum of CO_2 emission of each technology ($ACO_{2,i}$) minus the Recycled CO_2 (RCO_2) which is the amount of CO_2 used in Power-to-Gas technologies. Annual CO_2 emission of each technology ($ACO_{2,i}$) is calculated by the multiplication of the average CO_2 emitted for the unit production of electricity by that technology (e_i) and Annual Electricity produced (AE_i).

$$D_p(t) = \left(\frac{AE_{gas}(t)}{eff_{gas}} + \frac{AE_{gasDecentral}(t)}{eff_{gasDecentral}} + \frac{AE_{gasCCS}(t)}{eff_{gasCCS}} \right) \frac{1}{cal_{ngas}} \qquad \text{bcm/year}$$

Eventually, the gas consumption of the power sector (D_p) is formulated as the sum of ‘gas energy’ usages of all technologies that combust natural gas, which is calculated by dividing the Annual Electricity produced (AE_i) by the fuel efficiency (eff_i), divided by the calorific value of natural gas (cal_{ngas}). The unit ‘bcm’ stands for billion cubic meters.

$$P_h(t) = \frac{\left(AE_{gasDecentral}(t) + AE_{biogas}(t) \right) heat_e}{heat_{ngas}} \qquad \text{bcm/year}$$

During thermal electricity production by natural gas, coal, biogas or biomass, some amount of heat is generated as by-product. At central generation units, the heat generated is either negligible, or unusable. However, at the decentral units that use natural gas or biogas with Combined Heat and Power technology, heat generation is substantial, and reduces the natural gas demand. This reduction amount, natural gas equivalent of the heat generated by the power sector (P_h) is determined by the multiplication of heat generated by unit electricity at these units ($heat_e$) and the Annual Electricity produced by decentral gas and biogas, which is then divided by the heat value of natural gas ($heat_{ngas}$) to obtain the volume equivalent.

APPENDIX II : Equation List of the Natural Gas Production Sub-model

Formulations and Comments	**Units**
In all of the equations in this table, *i = conventional, unconventional* *t = time*	
$$PR_i(t)=\begin{cases} if\ \ DRv_i(t)>0;\ \ DRv_i(t)\ f_{RMin}\left(\dfrac{GPC_i(t)}{DRv_i(t)}\right) \\ else; \qquad\qquad 0 \end{cases}$$	bcm/year
The Production Rate (*PR*) of each type of natural gas is formulated as a fraction of the Developed Reserves (*DRv*), which is based on the general fuzzy-min formulation (Sterman, 2000). The fraction is determined by the function f_{RMin}, of which the input is the ratio of Gas Production Capacity (*GPC*) to the Developed Reserves. In the case of Developed Reserves being zero (for instance, unconventional initial value), the Production Rate is set to zero due to the calculation error encountered otherwise.	
$$GPC_i(t)=GPC_i(0)+\int_0^t (Cinc_i(\tau)-Cdec_i(\tau))\,d\tau$$ $$Cinc_i(t)=NPW_i(t)\,\alpha_i$$ $$Cdec_i(t)=GPC_i(t)\,CDM_i$$	bcm/year bcm/year^2 bcm/year^2
Gas Production Capacity (*GPC*) is a stock variable increased by Capacity Increase (C_{inc}) and decreased by Capacity Decay (C_{dec}). Capacity Increase is the multiplication of Total New Production Wells (*NPW*) and Initial Well Productivity (α_i), assuming that each well increases the capacity as much as its initial productivity. Capacity Decrease is a fraction of the total capacity, where this fraction is called Capacity Decay Multiplier (CDM).	
$$CDM_i=\frac{2\ln(2)}{T_i}$$	1/year
The productivity of natural gas wells is assumed to decay logarithmically. Since exponential growth (that single linear loop structure creates) has a constant doubling time, the half-life is *ln2* divided by the decay multiplier. The lifetime is assumed to be simply the double of that.	
$$DRv_i(t)=DRv(0)+\int_0^t \left(DeR_i(\tau)-PR_i(\tau)\right)d\tau$$	bcm
Developed Reserves (DRv), Development Rate (DeR), Production Rate (PR)	
$$DeR_i(t)=DeR_i^*(t)\ f_{RMin}\left(\frac{URv_i(t)}{DeR_i^*(t)}\right)$$	bcm/year
Desired Development Rate (DeR^*), Undeveloped Reserves (URv)	
$$DeR_i^*(t)=NPW_i(t)EUR_i$$	bcm/year
Total New Production Wells (NPW), Estimated Ultimate Recoverability (EUR)	
$$EUR_i=\frac{\alpha_i\left(1-e^{-CDM_iT_i}\right)}{CDM_i}$$	bcm/well
$$URv_i(t)=URv_i(0)+\int_0^t \left(ER_i(\tau)-DeR_i(\tau)\right)d\tau$$	bcm
Economic Recoverability Rate (ER_i)	
$$ER_i(t)=CRs_i(t)\,f_{ER}\left(UDC_i^*\right)$$	bcm/year
Contingent Resources (CRs), Breakeven Unit Development Cost (UDC^*), Fraction Distribution over Cost (f_{ER})	
$$UDC_i^*(t)=\frac{\left(p_i(t)-UOC_i(t)\right)CDM_i\left(1-e^{-CDM_iT_i}\left(1+r\right)^{-T_i}\right)}{\left(1-e^{-CDM_iT_i}\right)\left(CDM_i+\log\left(1+r\right)\right)}$$	mil EUR/bcm
Wellhead Gas Price (p), Unit Operating Cost (UOC)	
$$CRs_i(t)=CRs_i(0)+\int_0^t \left(DR_i(\tau)-ER_i(\tau)\right)d\tau$$	bcm
Discovery Rate (DR)	

$$DR_i(t) = SEW_i(t)\, ADW_i(t)$$ bcm/year

Successful Exploration Wells (SEW), Actual Discoveries per Well (ADW)

$$ADW_i(t) = FW_i \frac{PRs_i(t)}{PRs_i(0)}$$ bcm/well

Average Find per Well (FW), Prospective Resources (PRs)

$$PRs_i(t) = PRs_i(0) + \int_0^t \left(NRs_i(\tau) - DR_i(\tau) \right) d\tau$$ bcm

New Estimated Resources (NRs)

$$EW_i(t) = EW_i(0) + \int_0^t \left(DEW_i(\tau) - SEW_i(\tau) - FEW_i(\tau) \right) d\tau$$ well

Exploration Wells (EW), Drilling Rate of Exploration Wells (DEW), Successful Exploration Wells (SEW), Dry Exploration Wells (FEW)

$$DEW_i(t) = \frac{CAPEX^*_{e,i}(t)}{EWC_i}$$ well/year

Effective Capital Expenditure in Exploration ($CAPEX_e^*$), Exploration Well Cost (EWC)

$$SEW_i(t) = \frac{EW_i(t)\, SR_i}{DD_i}$$ well/year

Success Rate (SR), Discovery Delay (DD)

$$FEW_i(t) = \frac{EW_i(t)\left(1 - SR_i\right)}{DD_i}$$ well/year

$$PW_i(t) = PW_i(0) + \int_0^t \left(SEW_i(\tau) + DPW_i(\tau) - OPW_i(s) \right) d\tau$$ well

Production Wells (PW), Drilling Rate of Production Wells (DPW), Obsolescence Rate of Production Wells (OPW)

$$DPW_i(t) = \frac{CAPEX^*_{p,i}(t)}{PWC_i}$$ well/year

Effective Capital Expenditure in Production ($CAPEX_p^*$), Production Well Cost (EWC)

$$OPW_i(t) = \frac{PW_i(t)}{T_i}$$ well/year

$$CAPEX^*_{e,i}(t) = CAPEX_{e,i}\ f_{PRs}\left(\frac{PRs_i(t)}{PRs_i(0)}\right) f_p\left(\frac{p_i(t)}{pF_i(t)}\right) f_D\left(\frac{TPR(t)}{TD(t)}\right) SA_i(t)$$ mil EUR/year

Normal CAPEX in exploration ($CAPEX_e$), Effect of Prospects on Exploration Investments (f_{PRs}), Effect of Price on Investments (f_P), Effect of Demand on Investments (f_D), Societal Acceptance (SA), Price Forecast (pF), Total Natural Gas Production (TPR), Total Gas Demand (TD)

$$TPR(t) = \sum_i PR_i(t)$$ bcm/year

Total Natural Gas Production (TPR)

$$CAPEX^*_{p,i}(t) = CAPEX_{p,i}\ f_{URv}\left(R_{URv,i}(t)\right) f_p\left(\frac{p_i(t)}{pF_i(t)}\right) f_D\left(\frac{TPR(t)}{TD(t)}\right) SA_i(t)$$ mil EUR/year

Normal CAPEX in production ($CAPEX_p$), Effect of Availability on Development Investments (f_{URv}), Ratio of Undeveloped Reserves to the Production Rate (R_{URv})

$$R_{URv,i}(t) = \begin{cases} if\ \ PR_i(t) > 0; & \dfrac{URv_i(t)}{PR_i(t)} \\ else; & 0 \end{cases}$$ year

$$pF_i(t) = FORECAST(p_i(t), \lambda, \lambda)$$ mil EUR/bcm

Price forecast (pF), Price Estimation Period (λ)

$$p_i(t) = TUC_i^*(t)\left(1 + GPM_i(t)\right)$$ mil EUR/bcm

Wellhead Gas Price (p), Perceived Total Unit Cost (TUC^*), Gas Profit Markup (GPM)

$$p_i^*(t) = p_i(t)\left[\frac{10^6 \; milEUR/EUR}{10^9 \; bcm/cm}\right]$$ EUR/cm (cm=m^3)

Wellhead Gas Price Converted (p^*): Wellhead price per m^3, instead of billion m^3

$$GPM_i(t) = GPM_i^* \; f_{market}\left(\frac{EMP(t)}{TUC_i^{**}(t)}\right)$$ Dimensionless

Desired Gas Profit Markup (GPM^*), Expected Market Price (EMP), Perceived Total Unit Cost Converted (TUC^{**})

$$TUC_i^{**}(t) = TUC_i^*(t)\left[\frac{10^6 \; milEUR/EUR}{10^9 \; bcm/cm}\right]$$ EUR/cm

Total Perceived unit cost per m^3

$$TUC_i^*(t) = SMOOTHI\left(\mathrm{TUC}_i(\mathrm{t}),\; \gamma_p,\; TUC_i(0)\right)$$ mil EUR/bcm

Total Unit Cost (TUC), Market Price Estimation Time (γ_p)

$$TUC_i(t) = UDC_i(t) + UOC_i(t) + UEC_i(t)$$ mil EUR/bcm

Unit Development Cost (UDC), Unit Operating Cost (UOC), Unit Exploration Cost (UEC)

$$UDC_i(t) = \frac{CAPEX^*_{p,i}(t)}{DeR_i(t)}$$ mil EUR/bcm

$$UOC_i(t) = \mathrm{C}_{O,i} + \mathrm{C}_{M,i} + \mathrm{C}_{P,i}(t)$$ mil EUR/bcm

Unit Overhead Cost (C_O), Unit Maintenance Cost (C_M), Unit Production Cost (C_P)

$$C_{P,i}(t) = C^*_{P,i} \; f_{Depletion}(t)$$ mil EUR/bcm

$$f_{Depletion}(t) = \begin{cases} if \;\; PR_i(t) > 0; & \dfrac{DRv_i(t)}{DRv_i(t) - PR_i(t)\,TIMESTEP} \\ else\,; & 1 \end{cases}$$ Dimensionless

Normal Unit Production Cost (C_P^*)

$$UEC_i(t) = \frac{CAPEX^*_{e,i}(t)}{DR_i(t)}$$ mil EUR/bcm

$$SA_i(t) = SA_i(0) + \int_0^t \Big(\big(fi_i(\tau)\left(1 - SA_i(\tau)\right)\big) - \big(fd_i(\tau)\,SA_i(\tau)\big)\Big)\, d\tau$$ Dimensionless

$$fi_i(t) = fi_i(0) \; f_{scarcity}(DSR_g(t))$$ 1/year

Increase fraction of Societal Acceptance (fi)

$$fd_i(t) = fd_i(0) \; f_{safety}\left(\frac{CP_i(t)}{CP_i(0)}\right)$$ 1/year

Decrease fraction of Societal Acceptance (fd)

$$CP_i(t) = CP_i(0) + \int_0^t PR_i(\tau)\, d\tau$$ bcm

APPENDIX III: Equation List of the Biogas and Green Gas Production Sub-model

Formulations and Comments	Units
In all of the equations in this table, *j = digestion, gasification* *t = time*	
$GG_i(t) = MIN\left(GG(t)/TIMESTEP, GG_iC(t)\right)\rho$	bcm/year
Green Gas Injection Rate (GG_i), Green Gas Produced (GG); Green Gas Injection Capacity (GGiC)	
$GG(t) = GG(0) + \int_0^t \left(GG_p(\tau) - GG_i(\tau) - GG_m(\tau s)\right) d\tau$	bcm
Green Gas Production Rate (GG_p); Green Gas Used for Mobility and Industry (GG_m)	
$GG_m(t) = \left(GG(t)/TIMESTEP\right) - GG_i(t)$	bcm/year
$GG_p(t) = BG_g(t)\upsilon$	bcm/year
Biogas Upgraded to Green Gas (BG_g); Upgraded Volume Fraction (υ)	
$GG_iC(t) = GG_iC(0) + \int_0^t \left(GG_{com}(\tau) - GG_{dec}(\tau)\right) d\tau$	bcm/year
Injection Capacity Commissioning Rate (GG_{com}), Injection Capacity Decommissioning Rate (GG_{dec}),	
$GG_{com}(t) = \dfrac{GG_p(t) - GG_iC(t)}{d_{NW}}$	bcm/year^2
Pipeline installation delay (d_{NW})	
$GG_{dec}(t) = \dfrac{GG_iC(t)}{T_{NW}}$	bcm/year^2
Average lifetime of network (T_{NW})	
$BG_g(t) = MIN\left(BGaG(t), BGuC(t)\right)$	bcm/year
Biogas Allocated for Upgrading (BGaG), Biogas Upgrading Capacity (BGuC)	
$BGuC(t) = BGuC(0) + \int_0^t \left(BGuC_{com}(\tau) - BGuC_{dec}(\tau)\right) d\tau$	bcm/year
Commissioning of Biogas Upgrading Capacity ($BGuC_{com}$), Decommissioning of Biogas Upgrading Capacity ($BGuC_{dec}$)	
$BGuC_{com}(t) = \left(BGaG(t) - BGuC(t)\right) f^*_{RoI}\left(RoI_u\right)$	bcm/year^2
$C_{v,u}(t) = \dfrac{UBC(t)}{\nu}$	EUR/cm
Upgrading Variable Cost ($C_{v,u}$), Unit Biogas Cost (UBC)	
$BGuC_{dec}(t) = \dfrac{BGuC(t)}{T_u}$	bcm/year^2
Average lifetime of Upgrading plant (T_u)	
$BGaG(t) = BG(t)\delta_u(t)$	bcm/year
Fraction of Biogas for Upgrading (δ_u)	
$BG(t) = BG(0) + \int_0^t \left(BG_p(\tau) - BG_e(\tau) - BG_h(\tau) - BG_g(\tau)\right) d\tau$	bcm
Total Biogas Production Rate (BG_p), Biogas Used for Electricity Generation (BG_e), Biogas Used for Heating (BG_h)	
$BG_h(t) = BG(t)\delta_h(t)$	bcm/year
Fraction of Biogas for Heating (δ_h)	
$BG_e(t) = \dfrac{AE_{biogas}(t)}{cal_{biogas}\, eff_{biogas}}$	bcm/year
Annual Electricity Generated by Biogas (AE_{biogas}), calorific value of biogas (cal_{biogas}), fuel efficiency of biogas (eff_{biogas})	

$$BGaE(t) = BG(t)\,\delta_e(t)$$ bcm/year

Biogas Allocated for Electricity (BGaE), Fraction of Biogas for Electricity (δ_e)

$$\delta_k(t) = \frac{p_k(t)}{\sum_k p_k(t)} \;\; ; \quad k = bg, h, gg$$ 1/year

Fraction of Biogas for option k (δ_k), price of biogas when used as k (p_k) What to do with p_h?

$$BG_p(t) = \sum_j PR_j\left(t\right)$$ bcm/year

Biogas Production Rate by technology j (PR_j)

$$PR_j(t) = MIN\left(BGC_j(t), PBG_j(t)\right)$$ bcm/year

Biogas Production Capacity by technology j (BGC_j), Producible Biogas by technology j (PBG_j)

$$PBG_j(t) = BMA_j(t)\,y_j\left[\frac{bcm}{cm}\right]$$ bcm/year

Biomass Allocated for technology j (BMA_j), Average yield of technology j (y_j)

$$BMA_j(t) = BM_b(t)\frac{BGC_j(t)}{\sum_j BGC_j(t)}$$ ton/year

Biomass Allocated for Biogas Production (BM_b)

$$BGC_j(t) = BGC_j(0) + \int_0^t \left(BGC_{com,j}(\tau) - BGC_{dec,j}(\tau)\right)d\tau$$ bcm/year

Commissioning of Biogas Production Capacity ($BGC_{com,j}$), Decommissioning of Biogas Production Capacity ($BGC_{dec,j}$)

$$BGC_{dec,j}(t) = \frac{BGC_j(t)}{T_j}$$ bcm/year^2

Average lifetime of Biogas Production Plant (T_j)

$$BGC_{com,j}(t) = \left(EPB(t) - TBC(t)\right)d_j(t)$$ bcm/year^2

Expected Producible Biogas (EPB), Total Biogas Production Capacity (TBC), Distribution Fraction for Biogas Commissioning (d_j)

$$TBC(t) = \sum_j BGC_j(t)$$ bcm/year

$$d_j(t) = \begin{cases} if \;\; \sum_j RoIr_j(t) > 0; & \dfrac{RoIr_j(t)}{\sum_j RoIr_j(t)} \\ else; & 0 \end{cases}$$ 1/year

$$C_{v,j}(t) = C^*_{v,j}L_j(t) + \frac{p_{bm}}{y_j}$$ EUR/cm

Variable cost of biogas production ($C_{v,j}$), Biomass Price (p_{bm})

$$EPB(t) = EBMb(t)\frac{1}{2}\sum_j y_j\left[\frac{bcm}{cm}\right]$$ bcm/year

EPB expected producible biogas, Expected Biomass Allocated for Biogas (EBMb)

$$EBMb(t) = FORECAST\left(BM_b(t), \mu_{bm}, h_{bm}\right)$$ ton/year

EBMb estimated biomass allocated for biogas
BMb biomass allocated for biogas

$$BM_b(t) = MIN\left(DBM_b(t), MAX\left(BMS(t)\beta_b, BMS(t) - \mathrm{DBM}_h(t) - \mathrm{DBM}_e(t)\right)\right)$$ ton/year

Biomass Allocated for Biogas (BM_b) is the minimum of Biomass Demand of Biogas sector and the share fo biogas in the total biomass supply. This share is usually a certain fraction determined according to the score of each sector (BMS(t)β_b), but if the demand of the other two sectors is less than their fractional share, the remaining amount (BMS(t)-DBM_h(t)-DBM_e(t)) is all available to the biogas sector.

$$BM_e(t) = \mathrm{MIN}\left(DBM_e(t), \mathrm{MAX}\left(BMS(t)\beta_e, BMS(t) - \mathrm{DBM}_b(t) - \mathrm{DBM}_h(t)\right)\right)$$ ton/year

$$BM_h(t) = MIN\left(DBM_h(\mathrm{t}), \mathrm{MAX}\left(BMS(\mathrm{t})\beta_h, BMS(t) - DBM_e(\mathrm{t}) - \mathrm{DBM}_b(\mathrm{t})\right)\right) \quad \text{ton/year}$$

$$\beta_h = 1 - \beta_e - \beta_b \quad \text{Dmnl}$$

$$BMS(\mathrm{t}) = \mathrm{BMS}_{dom}(\mathrm{t}) + \mathrm{BMS}_{im}(\mathrm{t}) \quad \text{ton/year}$$

$$DBM_b(t) = \sum_j \frac{BGC_j(t)}{y_j}\left[\frac{cm}{bcm}\right] \quad \text{ton/year}$$

Biomass Demand of Biogas Sector

$$DBM_e(\mathrm{t}) = \frac{PGC_{biomass}(t)\,\mathrm{a}_{biomass}\,H\,eff_{biomass}}{cal_{biomass}} \quad \text{ton/year}$$

$$p_{gg}(\mathrm{t}) = \mathrm{p}_{gg,c}(\mathrm{t}) + \mathrm{step}\left(\mathrm{trf}_{gg} - \mathrm{p}_{gg,c}, 2012\right) - \mathrm{step}\left(\mathrm{trf}_{gg} - \mathrm{p}_{gg,c}(\mathrm{t}), 2012 + \mathrm{d}_{trf}\right) \quad \text{EUR/cm}$$

Green Gas Price (p_{gg}), Feed-in Tariff of Green Gas (trf_{gg}), Green Gas Cost-Dependent Price ($p_{gg,c}$), subsidy duration (d_{trf})

$$p_{gg,m}(\mathrm{t}) = UC^*_{gg}(\mathrm{t})\left(1 + PM_{gg}\,f_{market}\left(\frac{EMP(\mathrm{t})}{UC^*_{gg}(\mathrm{t})}\right)\right) \quad \text{EUR/cm}$$

Desired Profit Markup for Green Gas (PM_{gg}), Expected Market Price (EMP)

$$UC^*_{gg}(\mathrm{t}) = \mathrm{SMOOTHI}\left(UC_{gg}(\mathrm{t}), \gamma_p, \mathrm{UC}_{gg}(0)\right) \quad \text{EUR/cm}$$

Perceived Unit Green Gas Cost (UC_{gg}^*)

$$UC_{gg}(\mathrm{t}) = \mathrm{C}_{v,u}(\mathrm{t}) + \mathrm{UCC}_u(\mathrm{t}) \quad \text{EUR/cm}$$

Unit Green Gas Cost (UC_{gg}), Unit Capacity Cost of Upgrading (UCC_u)

$$UCC_u(\mathrm{t}) = \frac{CC_u(\mathrm{t})}{BG_g(\mathrm{t})\left[\frac{cm}{bcm}\right]} \quad \text{EUR/cm}$$

Unit Capacity Cost of Upgrading (UCC_u), Capacity Cost of Upgrading (CC_u)

$$CC_u(\mathrm{t}) = \frac{\left(C_{f,u}(\mathrm{t}) + \mathrm{EAC}_u(\mathrm{t})\right)BGuC(\mathrm{t})}{\left[\frac{bcm}{cm}\right]H_{bg}} \quad \text{EUR/year}$$

Capacity Cost of Upgrading (CC_u), Operating Hours (H_{bg})

$$UC^*_{bg}(\mathrm{t}) = \frac{\sum_j\left(PR_j(\mathrm{t})\,\mathrm{UC}_{bg,j}(\mathrm{t})\right)}{BG_p(\mathrm{t})} \quad \text{EUR/cm}$$

Average Unit Biogas Cost (UC_{bg}^*), Unit Biogas Cost ($UC_{bg,j}$)

$$UC_{bg,j}(\mathrm{t}) = \mathrm{C}_{v,j}(\mathrm{t}) + UCC_{bg,j}(\mathrm{t}) \quad \text{EUR/cm}$$

Unit Biogas Cost ($UC_{bg,j}$), Unit Capacity Cost of Biogas ($UCC_{bg,j}$)

$$UCC_{bg,j}(\mathrm{t}) = \frac{CC_{bg,j}(\mathrm{t})}{PR_j(\mathrm{t})\left[\frac{cm}{bcm}\right]} \quad \text{EUR/cm}$$

Unit Capacity Cost of Biogas ($UCC_{bg,j}$), Capacity Cost of Biogas ($CC_{bg,j}$)

$$CC_{bg,j}(\mathrm{t}) = \frac{\left(C_{f,j}(\mathrm{t}) + \mathrm{EAC}_j(\mathrm{t})\right)BGC_j(\mathrm{t})}{\left[\frac{bcm}{cm}\right]H_{bg}} \quad \text{EUR/year}$$

APPENDIX IV: Equation List of the Import Sub-model

Formulations and Comments	**Units**
In all of the equations in this table, *j = pipeline, LNG* *t = time*	

$$TI(t) = \sum_j I_j(t)$$ bcm/year

Total Import (TI) is the sum of Imports (I_j) by pipeline and LNG.

$$I_j(t) = MIN\left(DI_j(t), PI_j(t)\right) + MIN\left(FIN_j(t), EC_{j^-}(t)\right)$$ bcm/year

Imports by each transportation mean (I_j) is the minimum of Desired Imports (DI_j) and Possible Imports (PI_j). However, in the case of Desired Imports being greater than Possible Imports, which means that there is a Further Import Need (FIN_j), this further need is tried to be met by the other import mean if it has an Excess Capacity (EC_{j-}). Therefore, a second term, the minimum of Further Import Need and Excess Capacity of the other mean is added to the formulation.

$$DI_j(t) = DSS(t)\ f_j(t)$$ bcm/year

Domestic Supply Shortage (DSS), Fraction Import Mean (f_j)

$$PI_j(t) = MIN\left(AI_j(t), IC_j(t)\right)$$ bcm/year

Possible Imports (PI_j), Available Imports (AI_j), Import Capacity (IC_j)

$$FIN_j(t) = MAX\left(DI_j(t) - PI_j(t), 0\right)$$ bcm/year

Further Import Need (FIN_j), Desired Imports (DI_j), Possible Imports (PI_j)

$$EC_j(t) = MAX\left(PI_j(t) - DI_j(t), 0\right)$$ bcm/year

Excess Capacity (EC_j)

$$DSS(t) = MAX\left(TD(t) - G_s(t), 0\right)$$ bcm/year

Domestic Supply Shortage (DSS), Total Domestic Gas Demand (TD), Gas Supply (G_s).

$$f_j(t) = SMOOTHI\left(\frac{p_{imp,j}(t)}{\sum_j p_{imp,j}(t)}, \gamma_p, \frac{p_{imp,j}(0)}{\sum_j p_{imp,j}(0)}\right)$$ Dimensionless

Fraction Import Mean (f_j), Import Price ($p_{imp,j}$), Market Price Estimation Time (γ_p)

$$AI_j(t) = IP_j R_{pol,j} R_{NL,j}(t)$$

Available Imports (AI_j), Import Potential (IP_j), Political Restriction Fraction ($R_{pol,j}$), Fraction of Potential Imports for the Netherlands ($R_{NL,j}$)

$$R_{NL,j}(t) = 1 - e^{-\phi_j RMP(t)}$$ Dimensionless

Fraction of Potential Imports for the Netherlands ($R_{NL,j}$), ϕ_j being the sensitivity of Fraction of Potential Imports for the Netherlands ($R_{NL,j}$) to the Relative Market Price (RMP).

$$RMP(t) = \frac{EMP(t)}{IMP}$$ Dimensionless

International Market Price (IMP), Expected Market Price (EMP) in the Netherlands, Relative Market Price (RMP)

$$IC_j(t) = IC_j(0) + \int_0^t \left(ICIR_j(\tau) - ICOR_j(\tau)\right) d\tau$$ bcm/year

Import Capacity (IC_j), Import Capacity Installation Rate ($ICIR_j$), Import Capacity Obsolescence Rate ($ICOR_j$)

$$p_{imp,j}(t) = \frac{p_{imp,j}(0)}{\delta_j}\left(CID_j(t)\frac{\delta_j - p_{imp,j}(0)}{II_j} + \delta_j\right)$$ EUR/cm

Import Price ($p_{imp,j}$), Change in Demand (CID), Initial Imports (II_j), Import Demand Curve Constant (δ_j)

$$CID_j(t) = MAX\left(DI_j(t) - II_j, MnDS_j\right)$$ bcm/year

Change in Demand (CID_j), Desired Imports (DI_j), Initial Imports (II_j), Maximum Negative Demand Shift ($MnDS_j$)

$$MnDS_j = \frac{-\delta_j II_j}{\delta_j - p_{imp,j}(0)}$$ bcm/year

Maximum Negative Demand Shift ($MnDS_j$)

$$ICOR_j(t) = \frac{IC_j(t)}{T_j}$$ bcm/year^2

Import Capacity Obsolescence Rate ($ICOR_j$), Import Capacity (IC_j) Average Lifetime of the Import Capacity (T_j)

$$ICIR_j(t) = \frac{DAIC(t)\, AICs_j(t)}{ICd_j}$$ bcm/year^2

Import Capacity Installation Rate ($ICIR_j$) Desired Additional Import Capacity ($DAIC$), Additional Import Capacity Share ($AICs_j$), Import Commissioning Delay (ICd_j)

$$DAIC(t) = MAX\left(EDSS(t) - \sum_j IC_j(t),\ 0\right)$$ bcm/year

Desired Additional Import Capacity ($DAIC$), Expected Domestic Supply Shortage ($EDSS$), Import Capacity (IC)

$$EDSS(t) = MAX\left(ETD(t) - EG_s(t),\ 0\right)$$
$$or$$
$$EDSS(t) = FORECAST\left(DSS(t),\ \mu_{imp},\ h_{imp}\right)$$ bcm/year

Expected Domestic Supply Shortage ($EDSS$), Expected Total Demand (ETD), Expected Gas Supply (EG_s), Domestic Supply Shortage (DSS), Import Potential Estimation Period (μ_{imp}), Import Potential Estimation Horizon (h_{imp})

$$ETD(t) = SMOOTHI\left(TD(t),\ \mu_{imp},\ TD(0)\right)$$ bcm/year

Expected Total Demand (ETD), Total Demand (TD), Import Potential Estimation Period (μ_{imp})

$$EG_s(t) = SMOOTHI\left(G_s(t),\ \mu_{imp},\ G_s(0)\right)$$ bcm/year

Expected Gas Supply (EG_s), Gas Supply (G_s), Import Potential Estimation Period (μ_{imp})

$$AICs_j(t) = \frac{TEI_j(t)}{\sum_j TEI_j(t)}$$ Dimensionless

Additional Import Capacity Share ($AICs_j$), Total Effect on Installation (TEI_j)

$$TEI_j(t) = EI_{cost,j}(t)\, EI_{availability,j}(t)$$ Dimensionless

Total Effect on Installation (TEI_j), Cost Effect on Installation ($EI_{cost,j}$), Availability Effect on Installation ($EI_{availability,j}$)

$$EI_{availability,j}(t) = 1 - e^{-\frac{EAG_j(t)}{EAG_j^*(t)}}$$ Dimensionless

Availability Effect on Installation ($EI_{availability,j}$), Estimated Available Gas (EAG_j), Reference Estimated Available Gas (EAG_i^*)

$$EAG_j(t) = FORECAST\left(AI_j(t),\ \mu_{imp},\ h_{imp}\right)$$
$$or$$
$$EAG_j(t) = FORECAST\left(IP_j(t),\ \mu_{imp},\ h_{imp}\right)$$ bcm/year

Available Imports (AI), Import Potential (IP), Estimated Available Gas (EAG_j), Import Potential Estimation Period (μ_{imp}) Import Potential Estimation Horizon (h_{imp})

$$EI_{cost,j}(t) = e^{-\frac{EITC_j(t)}{ITC_j^*(t)}}$$ Dimensionless

Cost Effect on Installation ($EI_{cost,j}$), Cost Effect on Installation ($EI_{cost,j}$), Expected Import Total Cost ($EITC_j$), Reference Import Total Cost (ITC_i^*)

$$EITC_j(t) = SMOOTHI\left(ITC_j(t),\ \mu_{imp},\ ITC_j(0)\right)$$ EUR/cm

Expected Import Total Cost ($EITC_j$), Import Total Cost (ITC_j), Import Potential Estimation Period (μ_{imp})

$$ITC_j = IIC_j + IOC_j + p_{imp,j}(t)$$ EUR/cm

Import Total Cost (ITC_j), Import Investment Cost (IIC_j), (unit) Import Operating Cost (IOC_j), Import Price as the variable cost ($p_{imp..j}$)

APPENDIX V: Equation List of the Market Segment

Formulations and Comments	Units
$EMP(t) = SMOOTHI\left(p_{market}(t), \gamma_p, EMP(0)\right)$	EUR/cm
Expected Market Price (*EMP*), Market Price (p_{market}), Market Price Estimation Period (γ_p)	
$p_{market}(t) = TEP(t)\ EDC(t)\ EC(t)$	EUR/cm
Market Price (p_{market}), Traders' Expected Price (*TEP*), Effect of Demand Coverage on Price (*EDC*) and Effect of Costs on Price (*EC*)	
$TEP(t) = TEP(0) + \int_0^t CTEP(\tau) d\tau$	EUR/cm
Traders' Expected Price (*TEP*), Change in Traders' Expected Price (*CTEP*)	
$CTEP(t) = \dfrac{InP(t) - TEP(t)}{d_{TEP}}$	(EUR/cm)/year
Indicated Price (*InP*), Time to Adjust Traders' Expected Price (d_{TEP})	
$InP(t) = MAX\left(p_{market}(t),\ p_{min}(t)\right)$	EUR/cm
Indicated Price (*InP*), Market Price (p_{market}), Minimum Price (p_{min})	
$p_{min}(t) = \dfrac{PR_{con}(t) UOC^*_{con}(t) + PR_{unc}(t) UOC^*_{unc}(t) + GG_i(t) C_{v,u}(t) + I_{pipe}(t)\ p_{imp,pipe}(t) + I_{LNG}(t)\ p_{imp,LNG}(t)}{PR_{con}(t) + PR_{unc}(t) + GG_i(t) + I_{pipe}(t) + I_{LNG}(t)}$	EUR/cm
Minimum Price (p_{min}), Production Rates (*PR*), Unit Operating Cost (UOC^*), Green Gas Injection Rate (GG_i), Upgrading Variable Cost ($C_{v,u}$), Imports (*I*), Import Prices (p_{imp})	
$EDC(t) = \left(\dfrac{PDC(t)}{RDC}\right)^{-k_{DC}}$	Dimensionless
Effect of Demand Coverage on Price (*EDC*), Perceived Demand Coverage (*PDC*), Reference Demand Coverage (*RDC*), Sensitivity of Price to Demand Coverage (k_{DC})	
$PDC(t) = PDC(0) + \int_0^t CPDC(\tau) d\tau$	Dimensionless
Perceived Demand Coverage (*PDC*), Change in Perceived Demand Coverage (*CPDC*)	
$CPDC(t) = \dfrac{DC(t) - PDC(t)}{d_{DC}}$	Dimensionless/ year
Change in Perceived Demand Coverage (*CPDC*), Demand Coverage (*DC*), Perceived Demand Coverage (*PDC*), Coverage Perception Time (d_{DC})	
$DC(t) = \dfrac{G_s(t) + TI(t)}{TD(t)}$	Dimensionless
Demand Coverage (*DC*), Domestic Gas Supply (G_s), Total Imports (*TI*), Total Demand (*TD*)	
$EC(t) = 1 + k_C\left(\dfrac{EPC(t)}{TEP(t)} - 1\right)$	Dimensionless
Effect of Costs on Price (*EC*), Expected Production Costs (*EPC*), Traders' Expected Price (*TEP*), Sensitivity of Price to Costs (k_C)	
$EPC(t) = \dfrac{PR_{con}(t) DWP^*_{con}(t) + PR_{unc}(t) DWP^*_{unc}(t) + GG_i(t)\ p_{gg,c}(t) + I_{pipe}(t) ITC_{pipe}(t) + I_{LNG}(t) ITC_{LNG}(t)}{PR_{con}(t) + PR_{unc}(t) + GG_i(t) + I_{pipe}(t) + I_{LNG}(t)}$	EUR/cm
Expected Production Costs (*EPC*), Desired Wellhead Price (*DWP*), Green Gas Cost-Dependent Price ($p_{gg,c}$), Import Total Cost (*ITC*)	
$G_s(t) = TPR(t) + GG_i(t) + BMetI(t) + H_2I(t)$	bcm/year
Domestic Gas Supply (G_s), Total Natural Gas Production Rate (*TPR*), Green Gas Injection Rate (GG_i), Biomethane Injection Rate (*BMetI*) and Hydrogen Injection Rate (*H2I*)	
$G_c(t) = MIN\left(G_s(t) + TI(t), TD(t)\right)$	bcm/year

Gas Consumption (G_c), Domestic Gas Supply (G_s), Total Imports (TI), Total Demand (TD)

$$ID(t) = \frac{TI(t)}{G_c(t)}$$ Dimensionless

Import Dependency (ID), Total Imports (TI), Gas Consumption (G_c)

$$t_{import} = SAMPLE\ IF\ TRUE\left(IST(t) > \text{INITIALTIME}, IST(t), \text{INITIALTIME}\right)$$ year

The year in which the Netherlands becomes a net importer (t_{import}), Import Switch Time (IST)

$$IST(t) = \begin{cases} if\ \ TI(t-1) = 0 \text{ AND } TI(t) > 0;\ \ t * PULSE\left(t, 1\right) \\ \text{INITIALTIME} \end{cases}$$ year

Total Imports (TI)

APPENDIX VI: Parameter and Graphical Function Values in the Base Run and in the Uncertainty Analysis

The parameters whose ‘Uncertainty Range’ is ‘-’ are not included in the uncertainty analysis, due to the relatively high reliability of data and information. The data is collected from the literature, company reports and publicly available databases. For the parameters which no data is available for, approximate estimated values are used.

TABLE 1 Base Run Values and Uncertainty Ranges of Model Parameters

		DEMAND		
Notation	**Name**	**Unit**	**Base Run Value**	**Uncertainty Range**
$D_i(0)$	Initial Household Gas Demand	bcm/year	14	-
$D_i(0)$	Initial Agriculture Gas Demand	bcm/year	4	-
$D_i(0)$	Initial Industry Gas Demand	bcm/year	19	-
$D_i(0)$	Initial Transport Gas Demand	bcm/year	1	-
$f_{i,2010}$	Annual Change Fraction of Household Demand between 2010-2030	1/year	-0.01	(0.02, 0.01)
$f_{i,2030}$	Annual Change Fraction of Household Demand between 2030-2050	1/year	-0.025	(-0.03, 0.01)
$f_{i,2050}$	Annual Change Fraction of Household Demand between 2050-2060	1/year	0.035	(-0.02, 0.01)
$f_{i,2010}$	Annual Change Fraction of Agriculture Demand between 2010-2030	1/year	0.01	(-0.001, 0.011)
$f_{i,2030}$	Annual Change Fraction of Agriculture Demand between 2030-2050	1/year	-0.002	(-0.003, 0.001)
$f_{i,2050}$	Annual Change Fraction of Agriculture Demand between 2050-2060	1/year	0	(-0.004, 0.014)
$f_{i,2010}$	Annual Change Fraction of Industry Demand between 2010-2030	1/year	0.005	(0, 0.01)
$f_{i,2030}$	Annual Change Fraction of Industry Demand between 2030-2050	1/year	-0.005	(-0.01, 0.01)
$f_{i,2050}$	Annual Change Fraction of Industry Demand between 2050-2060	1/year	0	(-0.005, 0.005)
$f_{i,2010}$	Annual Change Fraction of Transport Demand between 2010-2030	1/year	0.001	(0, 0.005)
$f_{i,2030}$	Annual Change Fraction of Transport Demand between 2030-2050	1/year	-0.001	(-0.005, 0.003)
$f_{i,2050}$	Annual Change Fraction of Transport Demand between 2050-2060	1/year	0	(-0.008, 0.005)
m	Biogas methane ratio to natural gas	Dmnl	0.6	-
		ELECTRICITY GENERATION		
Notation	**Name**	**Unit**	**Base Run Value**	**Uncertainty Range**
a_i	Availability factor[biogas]	Dmnl	0.9	(0.6, 1)
	Availability factor[biomass]	Dmnl	0.6	(0.5, 0.9)
	Availability factor[coal]	Dmnl	0.86	(0.8, 0.9)
	Availability factor[coalCCS]	Dmnl	0.86	(0.8, 0.9)
	Availability factor[gas]	Dmnl	0.9	(0.7, 0.95)
	Availability factor[gasDecentral]	Dmnl	0.95	(0.8, 1)
	Availability factor[gasCCS]	Dmnl	0.9	(0.7, 0.95)
	Availability factor[nuclear]	Dmnl	0.9	(0.85, 0.95)
	Availability factor[solar]	Dmnl	0.1	(0.05, 0.25)
	Availability factor[wind]	Dmnl	0.4	(0.35, 0.55)
T_i	Average Lifetime of Power Plant[biogas, biomass, coal, coalCCS, gas, gasDecentral, gasCCS, nuclear, solar, wind]	year	30, 40, 40, 40, 30, 25, 30, 45, 25, 25	-
H	Hours per year	GWh/(gw* Year)	8760	-
nw	Network loss fraction	Dmnl	0.06	-
μ_e	Average time	year	5	-
h_L	Forecast Horizon	year	10	(5, 25)
γ_s	Power Mix Smooth Delay	year	1	-

$CP_i(0)$	Initial Cumulative Electricity Production[biogas]	TWh	1	-
	Initial Cum Electricity Production [biomass]	Dmnl	6	-
	Initial Cum Electricity Production [coal]	Dmnl	21	-
	Initial Cum Electricity Production [coalCCS]	Dmnl	0.001	-
	Initial Cum Electricity Production [gas]	Dmnl	43	-
	Initial Cum Electricity Production [gasDecentral]	Dmnl	30	-
	Initial Cum Electricity Production [gasCCS]	Dmnl	0.001	-
	Initial Cum Electricity Production [nuclear]	Dmnl	3.9	-
	Initial Cum Electricity Production [solar]	Dmnl	0.059	-
	Initial Cum Electricity Production [wind]	Dmnl	4	-
cal_{biogas}	Biogas calorific value	TWh/bcm	5	-
$cal_{biomass}$	Biomass Avg calorific value	GWh/ton	0.004	-
eff_i	Fuel Efficiency[biogas]	Dmnl	0.5	(0.4, 0.6)
	Fuel Efficiency [biomass]	Dmnl	0.35	(0.3, 0.55)
	Fuel Efficiency[coal]	Dmnl	0.45	(0.4, 0.6)
	Fuel Efficiency[coalCCS]	Dmnl	0.34	(0.3, 0.5)
	Fuel Efficiency[gas]	Dmnl	0.57	(0.5, 0.6)
	Fuel Efficiency[gasDecentral]	Dmnl	0.4	(0.35, 0.55)
	Fuel Efficiency[gasCCS]	Dmnl	0.47	(0.45, 0.55)
	Fuel Efficiency[nuclear]	Dmnl	1	-
	Fuel Efficiency[solar]	Dmnl	1	-
	Fuel Efficiency[wind]	Dmnl	1	-
f_e	Power demand change fraction	1/year	0.0053-step (0.0067, 2030)	-
w_{RoI}	Weight RoI	Dmnl	0.5	(0.2, 1)
$SA_i(0)$	Initial Societal Acceptance [biogas]	Dmnl	1	(0.9, 1)
	Initial Societal Acceptance [biomass]	Dmnl	1	(0.9, 1)
	Initial Societal Acceptance [coal]	Dmnl	0.5	(0.3, 0.7)
	Initial Societal Acceptance [coalCCS]	Dmnl	0.2	(0.1, 0.5)
	Initial Societal Acceptance [gas]	Dmnl	0.9	(0.8, 0.9)
	Initial Societal Acceptance [gasDecentral]	Dmnl	0.9	(0.8, 0.9)
	Initial Societal Acceptance[gasCCS]	Dmnl	0.5	(0.4, 0.6)
	Initial Societal Acceptance[nuclear]	Dmnl	0.2	(0.1, 0.3)
	Initial Societal Acceptance[solar]	Dmnl	1	(0.9, 1)
	Initial Societal Acceptance[wind]	Dmnl	0.98	(0.9, 1)
$fi_i(0)$	Initial SA Increase Fraction [biogas]	1/year	1	-
	Initial SA Increase Fraction [biomass]	1/year	1	-
	Initial SA Increase Fraction [coal]	1/year	0.03	-
	Initial SA Increase Fraction [coalCCS]	1/year	0.05	-
	Initial SA Increase Fraction [gas]	1/year	1	-
	Initial SA Increase Fraction [gasDecentral]	1/year	1	-
	Initial SA Increase Fraction [gasCCS]	1/year	0.06	-
	Initial SA Increase Fraction [nuclear]	1/year	0.03	-
	Initial SA Increase Fraction [solar]	1/year	1	-
	Initial SA Increase Fraction [wind]	1/year	1	-
$fd_i(0)$	Initial SA Decrease Fraction [biogas]	1/year	0	-
	Initial SA Decrease Fraction [biomass]	1/year	0	-
	Initial SA Decrease Fraction [coal]	1/year	0.03	-
	Initial SA Decrease Fraction [coalCCS]	1/year	0.2	-
	Initial SA Decrease Fraction [gas]	1/year	0.111	-
	Initial SA Decrease Fraction [gasDecentral]	1/year	0.111	-
	Initial SA Decrease Fraction [gasCCS]	1/year	0.06	-
	Initial SA Decrease Fraction [nuclear]	1/year	0.12	-
	Initial SA Decrease Fraction [solar]	1/year	0	-
	Initial SA Decrease Fraction [wind]	1/year	0.0204	-
γ_{DSR}	Electricity Smooth Time	year	3	(1, 5)
m_i	Feedin Tariff Multiplier[biogas]	Dmnl	1	(1, 1.1)
	Feedin Tariff Multiplier[biomass]	Dmnl	3	(2.8, 3.2)
	Feedin Tariff Multiplier[coal]	Dmnl	1	-
	Feedin Tariff Multiplier[coalCCS]	Dmnl	1	-
	Feedin Tariff Multiplier[gas]	Dmnl	1	-

	Feedin Tariff Multiplier[gasDecentral]	Dmnl	1	-
	Feedin Tariff Multiplier[gasCCS]	Dmnl	1	-
	Feedin Tariff Multiplier[nuclear]	Dmnl	1	-
	Feedin Tariff Multiplier[solar]	Dmnl	10	(5, 10)
	Feedin Tariff Multiplier[wind]	Dmnl	3.6	(3.5, 4)
$p_e(0)$	Initial Wholesale Electricity Price	EUR/GWh	50000	-
	Fuel Price[coal]	EUR/GWh	12238	(10000, 15000)
	Fuel Price[coalCCS]	EUR/GWh	12238	(10000, 15000)
$P_{fuel,i}$	Fuel Price[coal]	EUR/GWh	9.08e-007	-
	Fuel Price[coal]	EUR/GWh	0	-
	Fuel Price[coal]	EUR/GWh	0	-
p_{CO2}	CO2 price	EUR/ton	22	(20, 45)
	Avg CO2 emission[biogas]	ton/TWh	0	(0, 1000)
	Avg CO2 emission[biomass]	ton/TWh	0	(0, 2000)
	Avg CO2 emission[coal]	ton/TWh	750000	(700000, 800000)
	Avg CO2 emission[coalCCS]	ton/TWh	130000	(50000, 250000)
e_i	Avg CO2 emission[gas]	ton/TWh	350000	(300000, 400000)
	Avg CO2 emission[gasDecentral]	ton/TWh	380000	(320000, 420000)
	Avg CO2 emission[gasCCS]	ton/TWh	60000	(50000, 150000)
	Avg CO2 emission[nuclear]	ton/TWh	0	-
	Avg CO2 emission[solar]	ton/TWh	0	-
	Avg CO2 emission[wind]	ton/TWh	0	-
	Investment Capital[biogas]	EUR/GW	5^{e}+009	(3e+009, 7e+009)
	Investment Capital[biomass]	EUR/GW	2.45^{e}+009	(2e+009, 4e+009)
	Investment Capital[coal]	EUR/GW	1.5^{e}+009	(1e+009, 2e+009)
	Investment Capital[coalCCS]	EUR/GW	2.8^{e}+009	(2e+009, 4e+009)
$C_{k,i}$	Investment Capital[gas]	EUR/GW	0.75^{e}+009	(7e+008, 8e+008)
	Investment Capital[gasDecentral]	EUR/GW	0.9^{e}+009	(8.5e+008, 10.5e+009)
	Investment Capital[gasCCS]	EUR/GW	1.55^{e}+009	(1.5e+009, 2.5e+009)
	Investment Capital[nuclear]	EUR/GW	3^{e}+009	(3e+009, 5e+009)
	Investment Capital[solar]	EUR/GW	5^{e}+009	(5e+009, 7e+009)
	Investment Capital[wind]	EUR/GW	3.3^{e}+009	(2.5e+009, 3.5e+009)
	Normal Fixed Cost of Production[biogas]	EUR/GWh	3.2e+007	(3e+007, 4e+007)
	Normal Fixed Cost of Production[biomass]	EUR/GWh	6e+007	(5e+007, 7e+007)
	Normal Fixed Cost of Production[coal]	EUR/GWh	6e+007	(5.5e+007, 6.5e+007)
	Normal Fixed Cost of Production[coalCCS]	EUR/GWh	7.5e+007	(7e+007, 9e+007)
	Normal Fixed Cost of Production[gas]	EUR/GWh	1.5e+007	(1e+007, 2e+007)
$C_{f,i}(0)$	Normal Fixed Cost of Production [gasDecentral]	EUR/GWh	3.375e+007	(3e+007, 4e+007)
	Normal Fixed Cost of Production[gasCCS]	EUR/GWh	2.6e+007	(1.5e+007, 3.5e+007)
	Normal Fixed Cost of Production[nuclear]	EUR/GWh	5.2e+007	(5e+007, 8e+007)
	Normal Fixed Cost of Production[solar]	EUR/GWh	1.4e+007	(1e+007, 2e+007)
	Normal Fixed Cost of Production[wind]	EUR/GWh	7.5e+007	(5e+007, 9e+007)
	Normal Operating Cost[biogas]	EUR/GWh	36	(30, 40)
	Normal Operating Cost[biomass]	EUR/GWh	936	(850, 1000)
	Normal Operating Cost[coal]	EUR/GWh	936	(850, 950)
	Normal Operating Cost[coalCCS]	EUR/GWh	3456	(3000, 5000)
$C_{v,i}(0)$	Normal Operating Cost[gas]	EUR/GWh	36	(30, 40)
	Normal Operating Cost [gasDecentral]	EUR/GWh	1980	(1800, 2100)
	Normal Operating Cost[gasCCS]	EUR/GWh	1080	(1000, 1200)
	Normal Operating Cost[nuclear]	EUR/GWh	1800	(1700, 2100)
	Normal Operating Cost[solar]	EUR/GWh	5000	(4000, 6000)
	Normal Operating Cost[wind]	EUR/GWh	1000	(900, 1200)
	Learning Curve Parameter[biogas]	Dmnl	0.1	(0.05, 0.15)
	Learning Curve Parameter[biomass]	Dmnl	0.1	(0.05, 0.15)
	Learning Curve Parameter[coal]	Dmnl	0	(0, 0.05)
	Learning Curve Parameter[coalCCS]	Dmnl	0.05	(0.01, 0.11)
n_i	Learning Curve Parameter[gas]	Dmnl	0	(0, 0.05)
	Learning Curve Parameter [gasDecentral]	Dmnl	0.05	(0, 0.05)
	Learning Curve Parameter[gasCCS]	Dmnl	0.05	(0.01, 0.11)
	Learning Curve Parameter[nuclear]	Dmnl	0	(0, 0.05)
	Learning Curve Parameter[solar]	Dmnl	0.05	(0.05, 0.15)
	Learning Curve Parameter[wind]	Dmnl	0.1	(0.05, 0.25)

$CP_i(0)$	Threshold Electricity Generated	TWh	5	(2.5, 7.5)
cal_{ngas}	Avg Energy Value of Gas	TWh/bcm	9.8	-
$heat_e$	Heat generated per unit electricity	TJ/TWh	5400	-
$heat_{ngas}$	Heat value of gas	TJ/bcm	35170	-

NATURAL GAS PRODUCTION

Notation	Name	Unit	Base Run Value	Uncertainty Range
$GPC_i(0)$	Initial Production Capacity[conventional]	bcm/year	83	-
	Initial Production Capacity[unconventional]		0	-
α_i	Initial well productivity[conventional]	bcm/(well* Year)	0.15	(0.1, 0.2)
	Initial well productivity[unconventional]		0.009	(0.0075, 0.025)
T_i	Average Well Lifetime[conventional]	year	30	(20, 35)
	Average Well Lifetime[unconventional]		20	(10, 30)
$DRv_i(0)$	Initial Developed Reserves[conventional]	bcm	933	-
	Initial Developed Reserves[unconventional]		0	-
$URv_i(0)$	Initial Undeveloped Reserves[conventional]	bcm	254	-
	Initial Undeveloped Reserves[unconventional]		0.5	-
$CRs_i(0)$	Initial Contingent Resources[conventional]	bcm	203	-
	Initial Contingent Resources[unconventional]		0	-
FW_i	Average find[conventional]	bcm/well	4	(0.5, 4.5)
	Average find[unconventional]		1	(0.5, 2)
$PRs_i(0)$	Initial Prospective Resources[conventional]	bcm	500	(400, 800)
	Initial Prospective Resources[unconventional]		110000	(48000, 230000)
$EW_i(0)$	Initial Exploration Wells[conventional]	well	12	-
	Initial Exploration Wells[unconventional]		1	-
EWC_i	Exploration well cost[conventional]	mil Euros/well	18.5	(5, 28)
	Exploration well cost[unconventional]		18.5	(13, 28)
SR_i	Success ratio[conventional]	Dmnl	0.6	-
	Success ratio[unconventional]		0.55	-
DD_i	Discovery delay[conventional]	year	3	-
	Discovery delay[unconventional]		4	-
$PW_i(0)$	Inital Production Wells[conventional]	well	1100	-
	Inital Production Wells[unconventional]		1	-
PWC_i	Production well cost[conventional]	mil Euros/well	28	(11, 35)
	Production well cost[unconventional]		40	(20, 60)
$CAPEX_{e,i}$	Normal CAPEX in Exploration[conventional]	mil Euros/Year	375	(300, 600)
	Normal CAPEX in Exploration[unconventional]		300	(200, 500)
$CAPEX_{p,i}$	Normal CAPEX in Production[conventional]	mil Euros/Year	350	(300, 600)
	Normal CAPEX in Production[unconventional]		250	(200, 500)
λ	Price Estimation period	year	5	(1, 11)
GPM_i^*	Desired Gas Profit Markup[conventional]	Dmnl	1	(0.1, 2.1)
	Desired Gas Profit Markup[unconventional]		0.2	(0.1, 1.1)
γ_p	Market Price Estimation Time	year	1	-
$TUC_i(0)$	Initial Perceived Total Unit Cost	mil Euros/bcm	104.8	-
$C_{O,i}$	Unit overhead cost[conventional]	mil Euros/bcm	7.23	(5, 10)
	Unit overhead cost[unconventional]		8	(5, 15)
$C_{M,i}$	Unit maintenance cost[conventional]	mil Euros/bcm	3.12	(1,5)
	Unit maintenance cost[unconventional]		5	(2, 8)
$C_{P,i}^*$	Normal unit production cost[conventional]	mil Euros/bcm	45	(35, 55)
	Normal unit production cost[unconventional]		70	(50, 90)
$SA_i(0)$	Initial Societal Acceptance[conventional]	Dmnl	0.95,	(0.6, 1)
	Initial Societal Acceptance[unconventional]		0.5	(0.1, 0.6)
$fi_i(0)$	Initial SA Increase Fraction[conventional]	1/year	0.01,	(0.005, 0.025)
	Initial SA Increase Fraction[unconventional]		0.05	(0.005, 0.015)
$fd_i(0)$	Initial SA Decrease Fraction[conventional]	1/year	0.01	(0.005, 0.025)
	Initial SA Decrease Fraction[unconventional]		0.05	(0.005, 0.025)

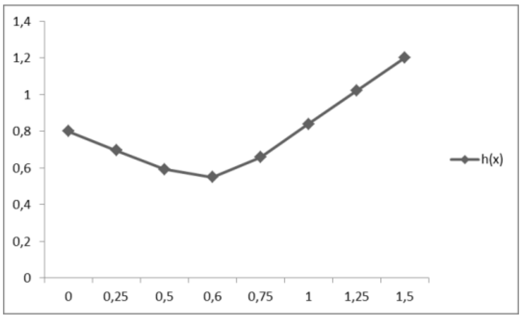
Notation	Name	Unit	Base Run Value	Uncertainty Range
$CP_i(0)$	Initial Cumulative Gas Production[gas type]	bcm	3000	-
	Initial Cumulative Gas Production[unconventional]		10	(1, 21)
BIOGAS AND GREEN GAS PRODUCTION				
Notation	**Name**	**Unit**	**Base Run Value**	**Uncertainty Range**
ρ	Pressure correction for green gas injection	Dmnl	1	(0.6, 1)
GG(0)	Initial Green Gas Produced	bcm	0.5	(0.2, 0.8)
υ	Upgraded volume fraction	Dmnl	0.614	-
GGiC(0)	Initial Green Gas Injection Capacity	bcm/year	0.06	(0.05, 1.05)
d_{NW}	Pipeline installation delay	year	3	-
T_{NW}	Average lifetime of gas pipelines	year	60	-
BGuC(0)	Initial Biogas Upgrading Capacity	bcm/year	0.026	(0.02, 0.1)
T_u	Average lifetime upgrade plant	year	12	-
BG(0)	Initial Biogas Produced	bcm	0.715	-
y_j	Average yield[digestion]	cm/ton	175,	(150, 250)
	Average yield[gasification]		500	(200, 500)
$BGC_j(0)$	Initial Biogas Production Capacity[digestion]	bcm/year	0.715	-
	Initial Biogas Production Capacity[gasification]		0	-
T_j	Average lifetime biogas plant[digestion]	year	25	(12, 32)
	Average lifetime biogas plant[gasification]		25	(12, 42)
$C_{k,j}$	Biogas Investment Cost [digestion]	EUR / (cm/hour)	4490	(4000, 5000)
	Biogas Investment Cost [gasification]		4500	(4000, 5000)
$C_{f,j}^*$	Normal Biogas Fixed Operating and Maintenance Cost [digestion]	EUR / (cm/hour) * year	295	(280, 300)
	Normal Biogas Fixed OM Cost [gasification]		350	(300, 400)
$C_{v,j}^*$	Normal biogas production cost[digestion]	EUR/cm	0.25	(0.2, 0.3)
	Normal biogas production cost[gasification]		0.35	(0.3, 0.5)
$CP_j(0)$	Initial Total Biogas Production [digestion]	bcm	10	(8, 15)
	Initial Total Biogas Production [gasification]		1	(0.5, 1)
n_i	Biogas learning curve parameter	Dmnl	0.2	(0.05, 0.25)
$C_{k,u}$	Upgrading investment cost	EUR/(cm/hour)	3880	(3500, 4000)
$C_{f,u}^*$	Initial Upgrading Fixed OM Cost	EUR/(cm/hour) * year	385	-
n_i	Green Gas learning curve parameter	Dmnl	0.2	(0.05, 0.25)
p_{bm}	Biomass Price	EUR/ton	15	(10, 20)
μ_{bm}	Averaging time for forecasting biomass	year	5	(3, 8)
h_{bm}	Forecast horizon biomass	year	12	(5, 25)
β_e	Biomass Score Electricity	Dmnl	0.285	(0.2, 0.4)
β_b	Biomass Score Biogas	Dmnl	0.3575	(0.3, 0.5)
DBM_h	Biomass demand of Heating sector	ton/Year	1.67E+06	(1500000, 2000000)
BMS_{im}	Biomass Import	ton/year	0	(0, 10000000)
$UC_{gg}(0)$	Initial Perceived Green Gas Cost	EUR/cm	0.65	-
PM_{gg}	GG Desired Profit Markup	Dmnl	0.8	(0.2, 1.2)
d_{trf}	Subsidy duration	year	40	(10, 50)
trf_{gg}	Green Gas Feedin Tariff	EUR/cm	0.75	(0.65, 0.85)
H_{bg}	Operating Hours	hour/year	8000	-
POWER TO GAS				
Notation	**Name**	**Unit**	**Base Run Value**	**Uncertainty Range**
	Maximum hydrogen injection fraction	Dmnl	0.01	(0.01, 0.21)
	Electrolysis commissioning delay	year	3	-
	Methanation commissioning delay	year	3	-
$CP_i(0)$	Initial PtoG Experience	bcm	0.5	(0.1, 0.6)
n_i	PtoG learning curve parameter	Dmnl	0.1	(0.05, 0.25)
T_i	PtoG Average Lifetime	year	30	-
$C_{k,i}$	PtoG Electrolysis Investment Cost	EUR/TW	3.00E+11	(1.00e+11, 3.00e+11)
$C_{f,i}(0)$	Initial PtoG Electrolysis OM Cost	(EUR/TW)/ Year	6.00E+09	(5.00e+09, 7.00e+09)
$C_{v,i}(0)$	Initial PtoG Electrolysis Variable Cost	EUR/TWh	1.00E+06	(0.50e+06, 1.50e+06)
$C_{k,i}$	PtoG Methanation Investment Cost	EUR/(cm/hour)	2054	(1800, 2200)
$C_{f,i}(0)$	Initial PtoG Methanation Variable Cost	EUR/cm	0.005	(0.003, 0.007)

$C_{v,j}(0)$	Initial PtoG Methanation OM Cost	EUR/(cm/hour) * year	41	(35, 45)
THE MARKET				
Notation	**Name**	**Unit**	**Base Run Value**	**Uncertainty Range**
$p_{im}(0)$	Initial Import Price	EUR/cm	0.3	(0.2, 0.4)
EMP(0)	Initial Expected Market Price	EUR/cm	0.26	-
r	Interest rate	Dmnl	0.05	(0.05, 0.15)

A piecewise defined linear function with a single extreme point is used to perturb the graphical functions. This function has the following equation form, where *l* is the value of the distortion function at the lower end of x domain, *u* is the upper end value, *m* is the maximum deviation from *l*, and *p* is the point where this deviation occurs.

$$h(x,m,p,l,u)=\begin{cases} l+\dfrac{m}{(p-x_0)}(x-x_0); & x_0 \le x \le p \\ l+m-\dfrac{l+m-u}{x_f-p}(x-p); & p \le x \le x_f \end{cases}$$

The figures below exemplify how a graphical function is varied when multiplied by such a perturbation function with *m=-0.25*, *p=0.6*, *l=0.8* and *u=1.2*. It is important to note that the new graphical function is kept within the boundaries y_{min} and y_{max}, if the distortion causes to exceed these logical limits.



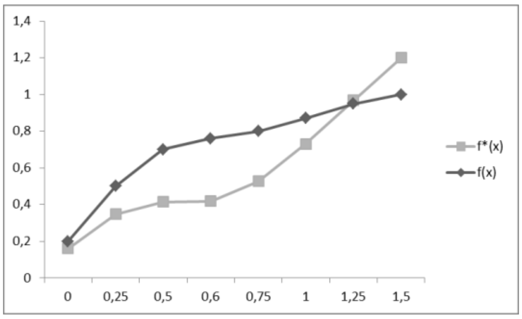


TABLE 2 Base Run Forms and Uncertainty Ranges of Graphical Function in the Model (If no parameter range is stated, this means that the function is not included in the uncertainty analysis)

Notation	Name	Base Run Value	Notes	Uncertainty Ranges of Distortion Parameter
f_{RoI}	RoI Count	(-1,0), (-0.2,0), (0,0), (0.1,0.05), (0.5,0.35), (0.9,0.85), (1,0.92), (1.15,0.97), (1.25,1)	Increasing function of RoI, which implies that negative RoI values are not effective, and the business is considered fully profitable only if RoI exceeds 125%.	
$f_{capacity}$	Capacity Utilization Lookup	(0,0), (0.1,0.1), (0.4,0.4), (0.6,0.6), (0.7,0.7), (0.85,0.83), (0.95,0.89), (1,0.91), (1.5,0.97), (1.8,0.99), (2,1)	A logarithmically increasing function, meaning that capacity utilization is equal to demand till it is 70% of the capacity. After that, capacity utilization decreasingly increases, and full capacity is used if demand exceeds twice the capacity.	
$f_{scarcity}$	Effect of Scarcity on SA Increase	(0.8,0.9), (1,1), (1.2,1.1), (1.3,1.15), (1.4,1.3), (1.5,1.5), (1.6,1.7), (1.7,1.9), (1.8,1.95), (2,2)	Societal acceptance decreases till a limited extent even if there is no scarcity, and increase fraction saturates even if scarcity is high.	m (-0.2, 0.8) p (0.8, 2) l (0.75, 1.25) u (0.75, 1.25) y_{min} 0.675 y_{max} 3
f_{CO2}	Effect of CO_2 on SA	(0,0.5), (0.4,0.55), (0.6,0.6), (1,1), (1.4,1.6), (1.6,1.8), (1.8,1.9), (2,2)	An increasing function, assuming that the response is quicker when CO_2 emissions are around the target, but saturates if it istoo low or too high.	m (-0.25, 0.75) p (0, 2) l (0.75, 1.25) u (0.75, 1.75) y_{min} 0.375 y_{max} 3.5
f_{safety}	Effect of Cumulative	(1,1), (1.2,1.5), (1.5,1.75), (1.8,1.9), (1.9,1.95), (2,2)	Societal acceptance decrease is assumed to be a decreasing function	m (-0.5, 0.5) p (1, 2)

	Production on SA Decrease		of cumulative production due to increasing safety issues, but it saturates at 2 when the cumulative production doubles the initial cumulative production.	l u y_{min} y_{max}	(0.75, 1.25) (0.75, 1.25) 0.5 3.5
f_{price}	Effect of Electricity Demand Supply Ratio on Electricity Price	(0,0), (0.2,0.15), (0.7,1), (1,1.3), (1.5,1.6), (2,1.75), (3,2)	The effect of electricity scarcity on price is assumed to be a logarithmically increasing function since price increase will be limited by imports or regulations.	m p l u y_{min} y_{max}	(-0.5, 1) (0, 3) (0.99, 1) (0.6, 2) 0 4
f_{RMin}	Effect of Reserves on activity rate	(0,0), (0.8,0.8), (0.85,0.84), (0.9,0.88), (0.95,0.915), (1,0.9375), (1.05,0.9575), (1.1,0.9725), (1.15,0.99), (1.2,1)	This function represents the limit on outflow by its stock in the case of development and production rate outflows.		
f_{ER}	Fraction Distribution over cost	(0,0), (100,0.44), (200,0.89), (300,1)	This function shows the percentage of Contingent Resources that are economically recoverable at a certain unit cost value. The values are derived from estimations of the industry (EBN, 2012).	m p l u y_{min} y_{max}	(-0.2, 0.8) (0, 300) (0.99, 1) (0.75, 1) 0 1
f_{PRs}	Effect of Prospects on Exploration Investments	(0,0), (0.1,0.05), (0.2,0.12), (0.3,0.22), (0.4,0.35), (0.5,0.5), (0.6,0.7), (0.7,0.85), (0.8,0.95), (0.9,1.04), (1,1.1)	The industry invests more in exploration if it is estimated that there are remaining undiscovered resources.	m p l u y_{min} y_{max}	(-0.2, 1) (0, 1) (0.99, 1) (0.75, 1.75) 0 2.5
f_p	Effect of Price on Investments	(0,0.2), (0.1,0.25), (0.3,0.35), (0.5,0.5), (1,1), (1.2,1.3), (1.5,1.75), (1.75,1.9), (2,2)	The natural gas industry invests more if higher prices is expected compared to the current price. However, this effect keeps increasing only till the estimated prices doubles the current price.	m p l u y_{min} y_{max}	(-0.2, 0.8) (0, 2) (0.75, 1.25) (0.75, 1.75) 0.16 3.5
f_D	Effect of Demand on Investments	(0,2), (0.1,1.95), (0.5,1.75), (1,1), (2,0.5)	The natural gas industry invests more if demand is higher than the production and less otherwise. In any case, the effect of this factor is limited to twice or half the normal investment.	m p l u y_{min} y_{max}	(-0.5, 0.5) (0, 2) (0.75, 1.25) (0.75, 1.75) 1 3.5
f_{URv}	Effect of Availability on Development Investments	(0,0), (0.5,0.05), (1,0.1), (2,0.25), (3,0.45), (4,0.7), (5,1), (6,1.5), (7,1.8), (8,1.92), (9,1.98), (10,2)	The industry invests more in development if Undeveloped Reserves are promising to maintain the current production rate. If there is no UR, investment is zero, if it can maintain the current PR for 5 years, normal value of investment, and if it is more than 10 years, twice the normal value.	m p l u y_{min} y_{max}	(-0.2, 0.5) (1, 9) (0.99, 1) (0.75, 1.75) 0 3.5
f_{market}	Effect of Market Price on Profit Markup	(0,0.2), (0.5,0.5), (1,0.8), (1.5,0.95), (2.5,1), (3,1.35), (3.5,1.8), (4,3)	This function is used to adjust the wellhead price of natural gas to the market price, hence it is an increasing function.	m p l u y_{min} y_{max}	(-0.2, 0.8) (0, 4) (1, 5) (0.5, 2.5) 0.2 8
f_{RoI}*	Effect of RoI on Upgrading Facility Commissioning	(-1,0), (0,0), (0.1,0.05), (0.5,0.25), (1,0.75), (1.5,1), (2,1)	For the commissioning of biogas upgrading facilities, since RoI is assumed to be the only factor, a function different than RoI count which assumes full response at higher RoI values is used.		
BMS_{dom}	Domestic Biomass Supply	(2010,5.815e+006), (2020,1.71543e+007), (2030,1.7e+007), (2040,1.7e+007), (2050,1.7e+007)	Domestic Biomass Supply is a time dependent function, which is formed according to the forecasts (Panoutsou & Uslu, 2011).	m p l u y_{min} y_{max}	(-0.4, 1) (2010, 2060) (0.8, 2) (0.5, 3) 0 100000000