Uncertainties in the Development of Unconventional Gas in the Netherlands

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Abstract. *Unconventional gas has raised debates all over the world following its considerable contribution to the natural gas production of some countries such as the US. The Netherlands, which is a prominent gas producer in the Western Europe, also considers unconventional resources as an alternative to conventional production, which is estimated to significantly decline in the next 25 years. However, the development of unconventional gas in the Netherlands is surrounded by several uncertainties. In addition to parameter uncertainties, uncertainties in the boundaries and structures of the models used in the analysis of this future development play an important role. This study aims to investigate the effects of such uncertainties on the production rate of unconventional gas, by combining the Exploratory Modeling and Analysis method with four different SD models. The results show a wide range of production rate possibilities, where the variety is mostly caused by the model uncertainties. This study can be extended with more model alternatives, and the results of this study can be used in further analysis for robust policy making.*

Keywords. *System dynamics, exploratory modeling and analysis, unconventional gas, natural gas, uncertainty*

1 Introduction

Natural gas is one of the major energy resources on the world, and expected to continue to be so in the next 120 years due to the availability of large amounts of reserves (IEA 2011). However, as the global reserves are reallocated to satisfy the demand of economically growing countries (IEA 2011) and local gas reserves decrease, the security of gas supply in some regions or countries is threatened. Unconventional gas, the gas produced from more challenging reservoirs, such as shale gas, tight gas and coal bed methane has emerged as a promising solution for such security of supply or import dependency problems. In the United States, it has made a drastically positive impact by constituting 20% of the gross gas production in 2009 whereas that was only 5% in 2005 (EIA 2011). This situation has drawn attention in other regions of the world, including the Netherlands. However, unconventional gas development in the Netherlands is surrounded by several uncertainties and deep uncertainties, mostly matching with the ones identified in (Eker and van Daalen 2012a, forthcoming) at the European level. These uncertainties are mainly about the cost and price developments which determine economic viability, the attitude of investors and authorities, and public acceptance issues due to environmental risks.

Deep uncertainty is defined by Lempert et al. (2003) as a situation where there is no sound knowledge or agreement of the actors involved in the decision making process on the following three aspects: "(1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes." The second aspect of this definition is especially important in computational uncertainty analysis for the generation of outcome scenarios. Following that, Kwakkel et al. (2010) define deep uncertainty as "being able to enumerate multiple alternatives without being able to rank order the alternatives in terms of how likely or plausible they are judged to be." Also, Kwakkel et al. (2010) list the locations in the model-based decision support where uncertainty may exist as the *system boundary, conceptual model, computer model (model structure, parameters inside the model, input parameters to the model), input data, model implementation and processed output data*.

According to these definitions, it can be said that the development of unconventional gas in the Netherlands is full of deep uncertainties, for which a set or range of alternatives can be derived but the likelihood of these alternatives is not known due to the imperfection of knowledge or the disagreement of actors. Eker and van Daalen (2012b, forthcoming) assume the first and the third aspects in the definition of Lempert et al.(2003) namely the conceptual model and the desirability of outcomes as certain, and investigates the effects of deep uncertainty present in the *computer model* (parameters inside the model and the model structure to some extent) on the development of unconventional gas in the Netherlands. The single model used in that study assumes a particular model boundary, although the model boundary is subject to uncertainty since there is a less extensive representation even in the literature. Also, this model is based on a particular investment making structure of the exploration and production companies. Yet, this structure is also uncertain since it is not fully known and varies from company to company.

The availability of different representations of exploration and production structure even in the literature, and of different investment making mechanisms indicate uncertainty in the system boundary, i.e. the depth of decomposition, and in the conceptual model, hence the model structure, as well. Therefore, the impact of such model boundary and structure uncertainties arises as an important question in addition to the parameter uncertainties inside the model. As a complementary to (Eker and van Daalen 2012b, forthcoming), this study aims to investigate the effects of such deep model boundary and structure uncertainties on the development of unconventional gas in the Netherlands. For this purpose, the Exploratory System Dynamics Modeling and Analysis (ESDMA) methodology is adopted, and four different models are used, with parameter uncertainties common in these models or specific to each of them.

In this paper, the following section explains the ESDMA methodology. The four different system dynamics models are described in Section 3, and the results of the uncertainty analysis are presented in Section 4 with emphasis on the explanation of the behaviors generated by these different models. The paper ends with a discussion of the results and conclusions in Sections 5 and 6.

2 Method: Exploratory System Dynamics Modeling and Analysis

Generally speaking, Exploratory Modeling and Analysis (EMA) is defined as "a research methodology that uses computational experiments to analyze complex and uncertain systems" (Bankes, Walker, and Kwakkel 2010). It has been developed in the last two decades as a model-based decision support tool for decision making under deep uncertainty (Bankes 1993), (Agusdinata 2008). The approach of EMA to the treatment of uncertainty is scenario-based, which means that (all) potential outcomes which result from what-if assumptions are explored instead of searching for the most likely future. Following this approach, EMA enables simultaneous consideration of a huge number of uncertainties, exploration of a huge number of future scenarios by propagating the effects of these uncertainties through the models to the outcomes of interest, and generation of robust policy options which perform well in any of these future worlds. As mentioned before, EMA is a research methodology, rather than a modeling methodology, and several types of models can be used in an EMA study for scenario generation.

EMA can provide several advantages over well-known uncertainty analysis methods (Agusdinata 2008): Compared to sensitivity analysis, EMA is more comprehensive, because in EMA uncertainties not only in the parameter values but also in the other elements of the models are taken into account. Also, EMA shows not only which parameters significantly affect the output, but also at which values or in which ranges they do, whereas sensitivity analysis can do only the former. Compared to scenario analysis, it can be said that EMA and traditional scenario analysis are based on the same notion of what-if assumptions, but EMA generates a huge number of scenarios and helps avoiding assumptions about the relevancy of scenarios to limit their number. Lastly, EMA differs from Monte Carlo simulation or other statistical and stochastic methods with respect to their conceptual grounds. The latter uses well-defined probability distributions to represent uncertainty and yields a probability distribution for the outcome of interest. However, based on the definition of deep uncertainty for which well-defined probability distributions cannot be assigned, EMA is built on a scenario-based approach rather than a probabilistic approach.

Regarding the generation of scenarios in an EMA study, the most important matter is the internal consistency and plausibility. Based on justifiable causal relations, system dynamics provides possible plausible behaviors of dynamically complex systems, hence internally consistent scenarios for them. Therefore, it is valuable to combine SD with EMA. This combination, named Exploratory System Dynamics Modeling and Analysis (ESDMA), enables generation of a huge number of plausible scenarios for an EMA study, and enhances the limited uncertainty analysis, mostly in the form of sensitivity analysis, in an SD study. Various examples of ESDMA application can be seen in (Pruyt and Kwakkel 2011; Pruyt, Logtens, and Gijsbers 2011; Pruyt and Hamarat 2010), while Hamarat and Pruyt (2011) illustrate the use of ESDMA especially to investigate the model structure uncertainty.

In this study, on the one hand, SD is chosen to study the dynamics of unconventional gas development due to its appropriateness to represent the feedback-rich gas system with the fundamental relations between supply, demand and investments. On the other hand, EMA is chosen for uncertainty analysis due to its ability to generate a huge number of scenarios by setting various parameter values and function forms on various model structures, and to analyze the results of these scenarios.

3 Model Description

As mentioned before, the primary objective of this paper is to explore the effects of model boundary and model structure uncertainty on the outcomes of interest by using the case of unconventional gas development in the Netherlands. For this purpose, four alternative models have been developed, each containing the corresponding parameter and function uncertainties. These four models will be explained in this section. The entire equation list of Model 2, which is the most extensive one, can be found in Appendix I, whereas the others can be derived from this.

3.1 Model 1: The Base Model

Unconventional gas differs from conventional gas only in terms of production techniques and related socio-economic issues. Because of that, to investigate the development of unconventional gas, only the upstream of the gas industry, e.g. exploration and production, is included in the model. The upstream sector of the gas industry is modeled based on the field lifecycle which is composed of exploration, appraisal, development and production phases (Jahn, Cook, and Graham 2008), and in correspondence with the resource and reserve terminology of the Society of Petroleum Evaluation Engineers (2002). Fig. 1 shows this structure, which can also be used for representing the conventional gas lifecycle. *Prospective resources* are undiscovered but assumed to be technically and economically recoverable resources according to geological estimations. Once the presence of prospective resources is proven with exploration drilling activities, they are named *contingent resources* if they are technically recoverable but uneconomic, and they can become *undeveloped reserves* immediately if they are also economically recoverable. Depending on fluctuations in price and cost, some reserves may become uneconomic to develop, or some contingent resources may become economically recoverable, hence reserves. Although they are economically recoverable, undeveloped reserves are used for recovery only if they are prepared for production with the construction of production wells, and become *developed reserves*. *Production rate* is formulated as the minimum of *developed reserves* and the annual *demand for unconventional gas*, with the assumption that there is no capacity limit on the production.

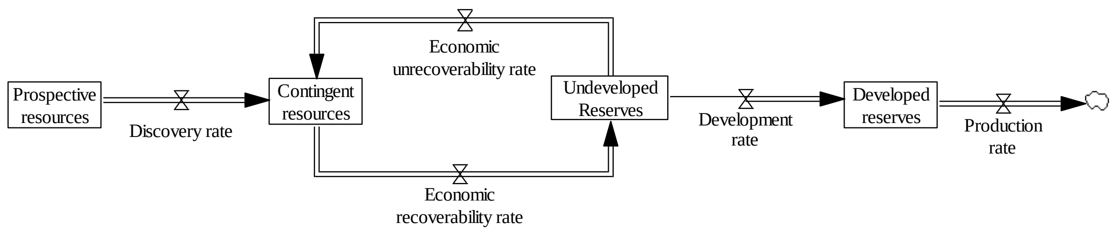

Fig. 1. The representation of the gas field lifecycle

There is no unique definition of economic recoverability since it depends on the individual investment decisions of firms. As an aggregate economic recoverability definition at the system level, in this model, undeveloped reserves are assumed to be at the breakeven level which makes potential revenues equal to development costs with current price and cost values, and continuously adjusted according to that.

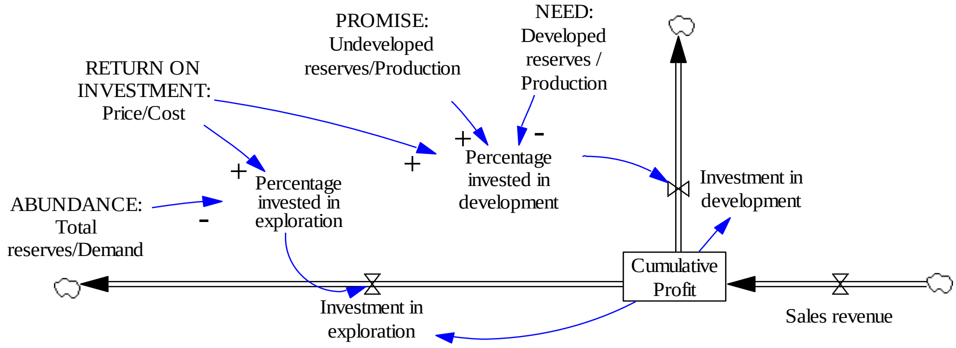

Fig. 2. Investments in the model

Certainly, the extent of new discoveries and the development rate depends on the investments made in these activities by the industry. In this model, these investments are assumed to be percentages of the cumulative profit obtained from the sales, and the percentages are assumed to be related with four factors as shown in Fig. 2. Firstly, following the existing SD models about natural gas (Naill 1974), (Chyong Chi, Nuttall, and Reiner 2009) the ratio of wellhead price to the total unit cost of exploration and development is assumed to indicate the general profitability in the industry, which increases investments in both exploration and development. The ratio of total reserves to the demand indicates abundance and inhibits investments in exploration. Investment in development increases if undeveloped reserves are promising to maintain the production rate, which is represented by the ratio of undeveloped reserves to the production rate. Lastly, the ratio of developed reserves to the production rate indicates the availability of reserves to maintain the production, which in turn shows the need for developing more.

Demand is an important factor which affects investment decisions and production rate. In this model, the total of domestic and export demand is assumed to change with a steady fraction and also depending on price changes. Since conventional gas production will be continuing as the primary source, the demand specifically for unconventional gas is formulated as the difference between the total demand and conventional production assuming that this deficit is desired to be covered first by the unconventional domestic production rather than imports. Fig. 3 is a simple depiction of this mechanism.

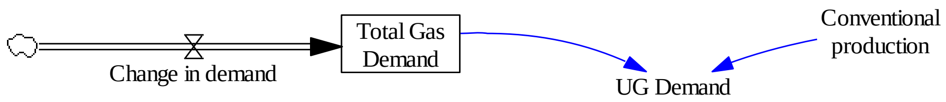

Fig. 3. Total and unconventional gas demand

In the existing gas or petroleum resource models (Naill 1974), (Chyong Chi, Nuttall, and Reiner 2009) the relation between investments and exploration or development rates is modeled via the unit cost of exploration or development, i.e. the cost per cubic meter of gas. This formulation is adopted in the base model in the form of the following equations:

$$Desired\ discovery\ rate = DELAY1\left(\frac{Investment\ in\ exploration * Success\ fraction}{Unit\ exploration\ cost}, Discovery\ delay\right) \quad (1)$$

$$Discovery\ rate = min\left(\frac{Prospective\ resources}{TIME\ STEP}, Desired\ discovery\ rate\right) \quad (2)$$

$$Development\ rate = min\left(\frac{Undeveloped\ Reserves}{TIME\ STEP}, \frac{Investment\ in\ development\ activity}{Unit\ development\ cost}\right) \quad (3)$$

Discovery rate and *development rate* are formulated as independent from the stock variables that they deplete. However, these rates cannot actually be more than the amount of *prospective resources* and *undeveloped reserves*, respectively. In such cases where the desired value of discovery and development are greater than what is actually present, only the present amount, the stock value, can be realized. Based on the assumption that all the remaining amount will be discovered or developed with the current efforts, that is, the stock values will be drained in one time unit, these two outflows are formulated as the minimum of desired and available amounts as in equations (2) and (3).

To illustrate how the different sectors of the model are connected and how the behavior of the main outcome of interest, namely the *production rate*, is determined, Fig. 4 shows the feedback loops which directly affect the *production rate* in Model 1. Two positive loops via *revenues* and *developed reserve production ratio* which indicates the need for development, and two negative loops via the *undeveloped reserve production ratio*, which indicates how promising the undeveloped reserves are, can be seen in this figure. For distinction, negative loops are shown in bold. The loop formed with the links from the *production rate* to *investment in exploration*, then to discoveries and finally to the *development rate* is excluded from this view for simplicity since this mechanism is similar to the one via investment in development.

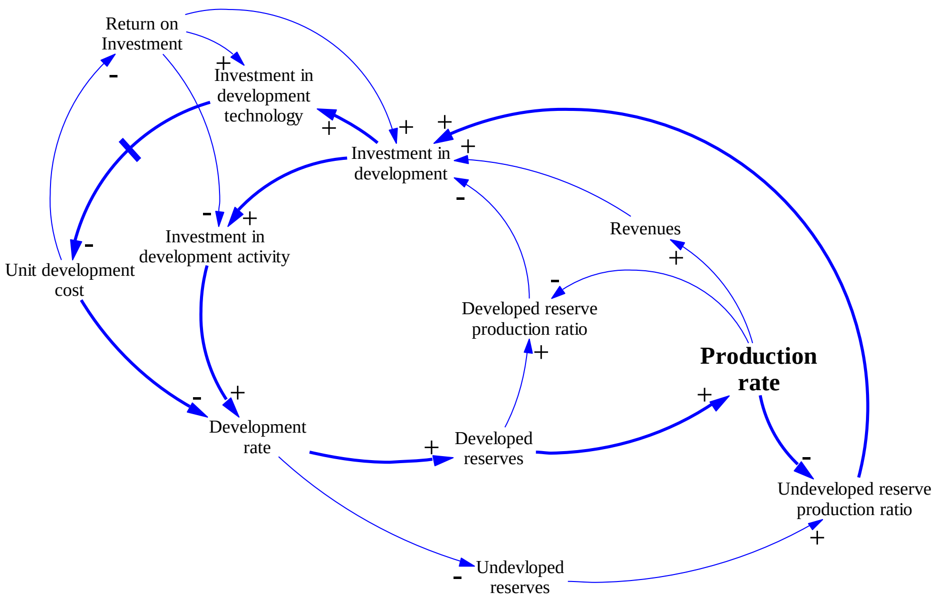

Fig. 4. Feedback loops directly affecting the production rate in Model 1

3.2 Model 2: Well Construction

Besides the aggregate investment-driven discovery and development structure of the base model, the use of investments for land acquisition and well construction which leads to the discovery and development of reserves can be explicitly modeled, as well. The development of unconventional gas requires drilling a higher number of wells due to low recovery amounts per well compared to conventional gas, and this leads to issues like large land requirements, large public opposition and long delays in the licensing procedure. The structure with wells enables including the uncertainties regarding these issues in the model more explicitly. Fig. 5 shows the core of this structure where exploration wells which result in discoveries are improved to become production wells or stimulate the construction of new wells.

Having the number of producing wells as a variable in the model is important also in terms of computing the production capacity, which limits the production rate. The production rate of a single well is recorded to logarithmically decline in the US shale plays (IEA 2009). Based on this, the total production capacity is also modeled with a logarithmic decline mechanism, whereas it is increased by a certain amount for each new production well. This structure is depicted in Fig. 6.

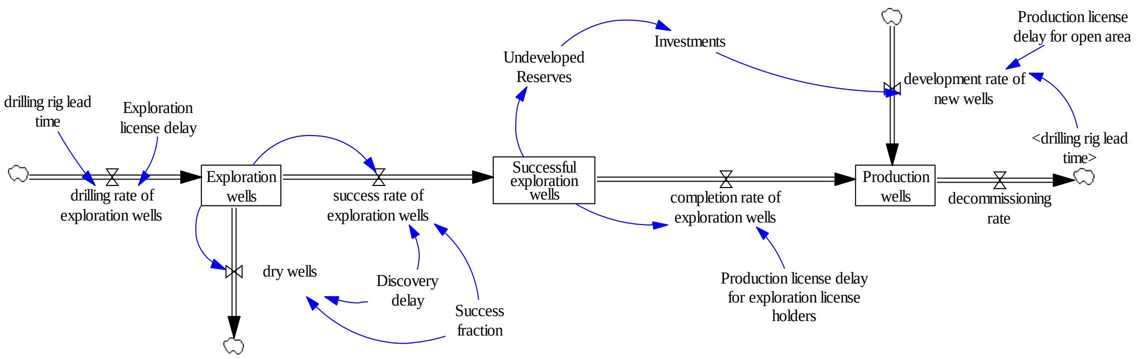

Fig. 5. The representation of well drilling in the model

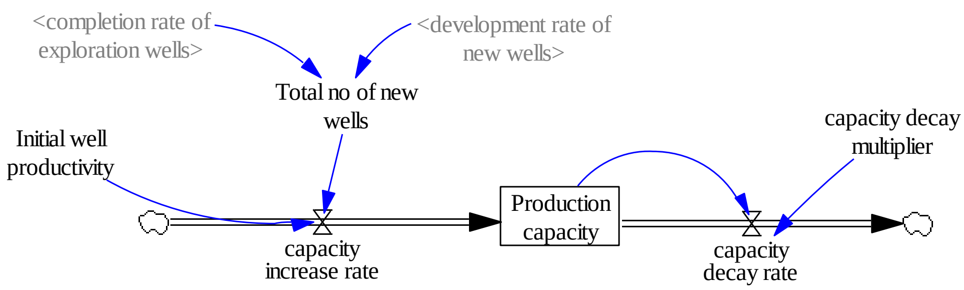

Fig. 6. The total production capacity depending on the number of wells

In the base model, discovery and development rates are formulated as the ratio of corresponding investment amount to the unit cost of activity. In this model, they are formulated as follows:

$$Discovery\ rate = \\ min\left(\frac{Prospective\ Resources}{TIME\ STEP}, Average\ discoveries\ per\ well * Success\ rate\ of\ exploration\ wells\right) \qquad (4)$$

$$Development\ rate = \min\left(\frac{Undeveloped\ Reserves}{TIME\ STEP}, Average\ Estimated\ Ultimate\ Recovery\ per\ well * Total\ no\ of\ new\ wells\right) \quad (5)$$

The construction of new exploration and production wells is dependent on the investments made in these activities, and the cost of each type of well together with the land cost. It is assumed that half of the investments are expended on land acquisition (Geny 2010), and the remaining amount determines the construction rate of the corresponding type of wells, e.g. exploration or production, under the restriction of the land size that could be obtained.

Similar to Fig. 4, Fig. 7 shows the main feedback loops that govern the behavior of the *production rate* in Model 2. Balancing loops are again in bold. The ones existing in the previous model despite the difference of a few variables regarding the well construction are shown in black, whereas the new two ones formed due to the *production capacity* mechanism are in blue.

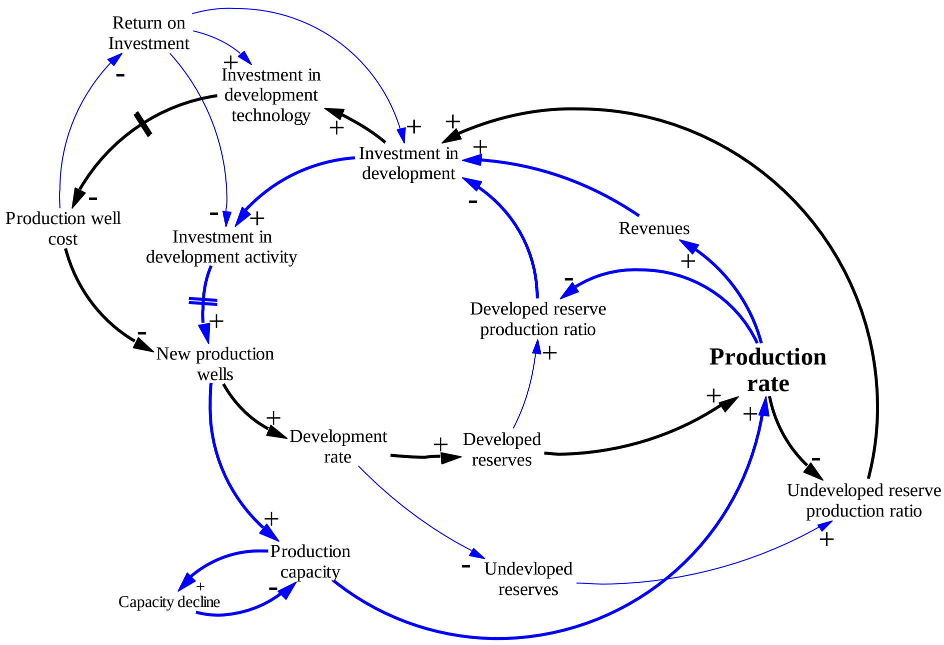

Fig. 7. Feedback loops directly affecting the production rate in Model 2

A more detailed uncertainty analysis and policy testing on this model can be found in (Eker and van Daalen 2012b, forthcoming).

3.3 Model 3: Demand-oriented investments

Following (Naill 1974), Model 2 assumes that the investment decisions are made according to the ratio of developed and undeveloped reserves to the current production rate, as an indicator of need and promise, respectively. This structure implies the investors' desire to maintain the current production rate. However, in the case of unconventional gas where initial production rates are low, this structure may inhibit the investments by showing the need less than it is, and some investors may prefer to consider the ratio of reserves to demand. Thus, a third model structure alternative is developed. This structure differs from the second one only in terms of taking the ratio of developed and undeveloped reserves to the unconventional gas demand as the inputs of effects of need and promise on the development investments, respectively. This mechanism results in elimination of one negative loop via the *undeveloped reserve production ratio*, and one positive loop via the *developed reserve production ratio*. The remaining two positive loops (via *investment in development activity* and *production well cost*) and one negative loop (via the *production capacity*) are shown in bold in Fig. 8.

3.4 Model 4: Constant Investments

In Model 2, it is assumed that investments in exploration and development are financed by only the revenues collected by unconventional gas sales, despite an initial amount of capital. The findings of (Eker and van Daalen 2012b, forthcoming) has shown that this business model is not able to provide investment levels sufficient to obtain considerable production rates, because low production rates result in low revenues and low investments, decreasing after the use of initial capital. In this fourth model alternative, the source of investments is assumed to be external, instead of revenues. Also, the amount of investments is assumed to be independent of the reserves, demand or production rate. Hence, the feedback mechanisms existing in the previous models are all omitted in this model. Fig. 9 shows the remaining causal links which influences the *production rate* in Model 4.

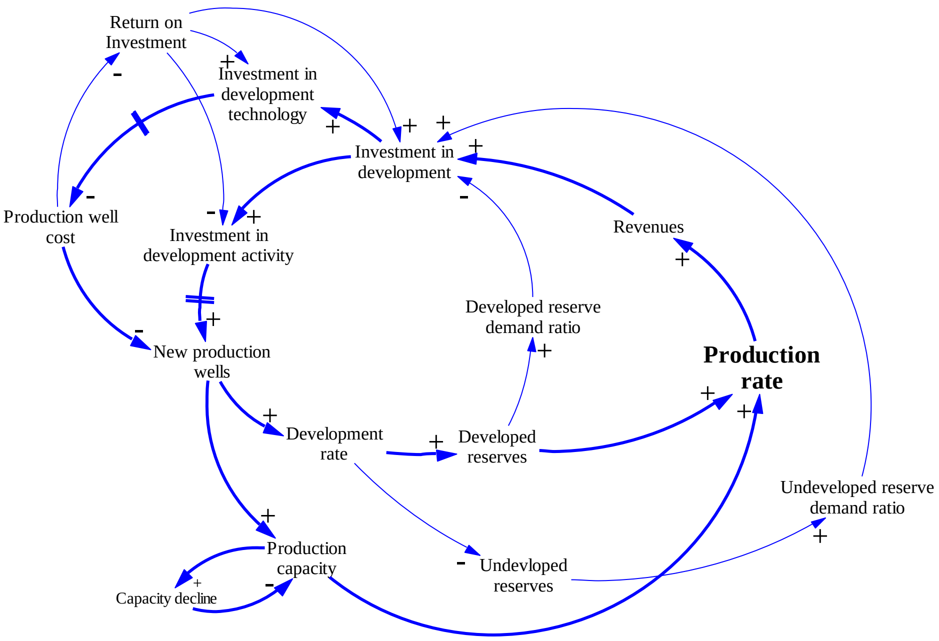

Fig. 8. Feedback loops directly affecting the production rate in Model 3

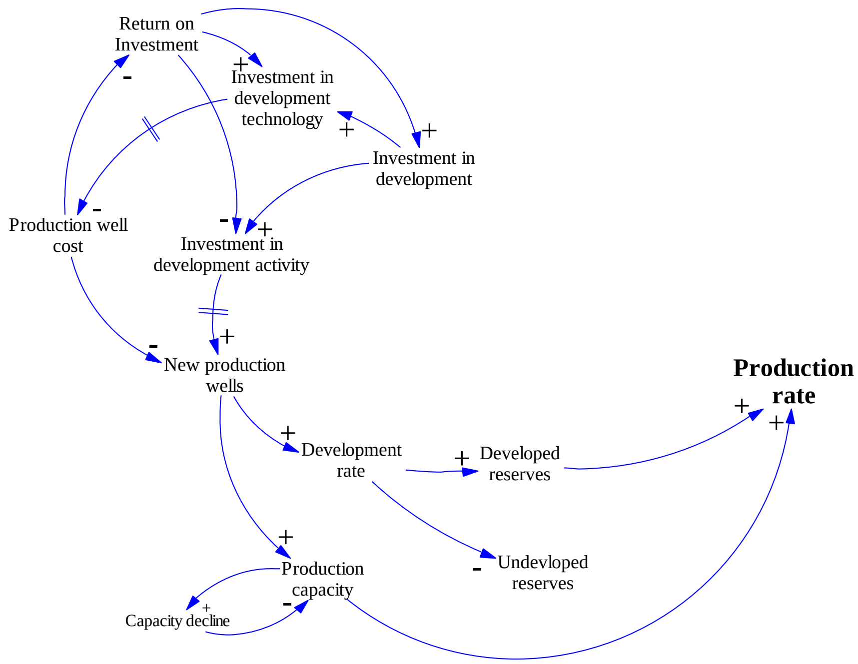

Fig. 9. Causal links affecting the production rate in Model 4

4 Results

The models are built in Vensim and quantified based on the data obtained from the Dutch conventional and the US unconventional gas production records. The uncertainty ranges of parameters and alternatives of graphical functions in each model are given in Appendix II. Each model is simulated 10000 times for the time period 2011 until 2050, and each of these simulations shows the outcomes of a different combination of corresponding uncertainty values and alternatives. A shell written in Python is used to communicate with Vensim, to make the experimental designs, based on Latin Hypercube sampling in this case, and to visualize the outputs.

Fig. 10 shows the 10000 possible trajectories of production rate in the case of each model structure alternative, with the distribution of their end states at the right. It is important to remind that y-axis scales of these plots are different. Fig. 11 provides the envelopes of the production rate values, i.e. the range between the minimum and maximum values it may take.

The production rate behavior created by the first model is a rapid increase at the beginning and then decline in most of the cases, but the smoothness of the curves is disrupted. Although high production rates may be obtained especially at the peaks of a few cases (around 50 bcm/year), the end state values, namely the production rates in 2050, are below 5 bcm/year, which indicates an insignificant long-term contribution to the gas supply in the Netherlands. Against the several positive loops that govern the behavior of the production rate, there may be two causes of the decline behavior observed in almost all of the 10000 cases: Either the inadequacy of revenues for the investment after the initial capital is consumed; or the two balancing feedback loops that makes the undeveloped reserves less promising as the production rate increases, and reduces the investments made in development.

Despite several parameter and function uncertainties, the common behavior created by the second model in 10000 experiments is an increase followed by decline, with different amplitudes and peak times. The maximum production rates that may be obtained are much lower than those in the case of Model 1. In the majority of the cases, the production rate is below 10 bcm/year throughout the next 40 years, and ending with values below 2 bcm/year in 2050. These findings again point out a pessimistic future for the gas supply in the Netherlands from unconventional resources. The reasons behind such similar behavior patterns can be traced back to the intervening positive and negative feedback loops depicted in Fig. 7. The variety in the peak times, which are mostly later than those in the case of Model 1, is ascribed to the introduction of delays with the well construction mechanism, whereas the production capacity mechanism seems to be responsible for the lower maximum values than those of Model 1.

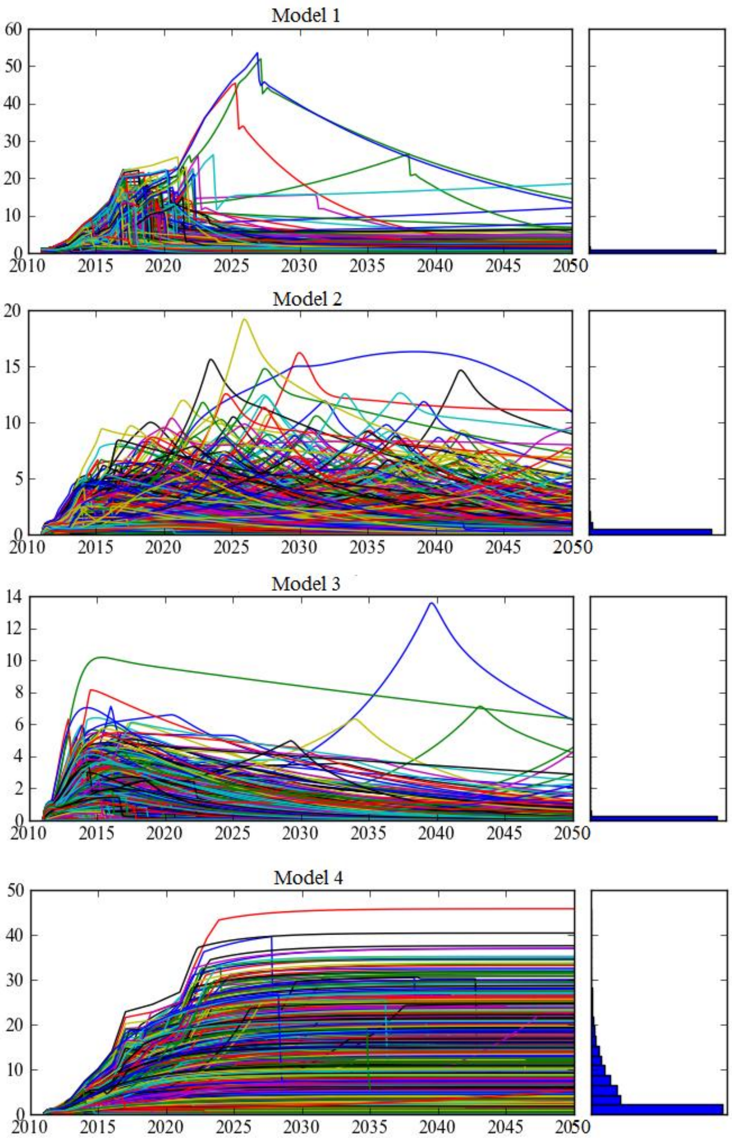

Fig. 10. Possible trajectories of production rate for four models, with end state densities

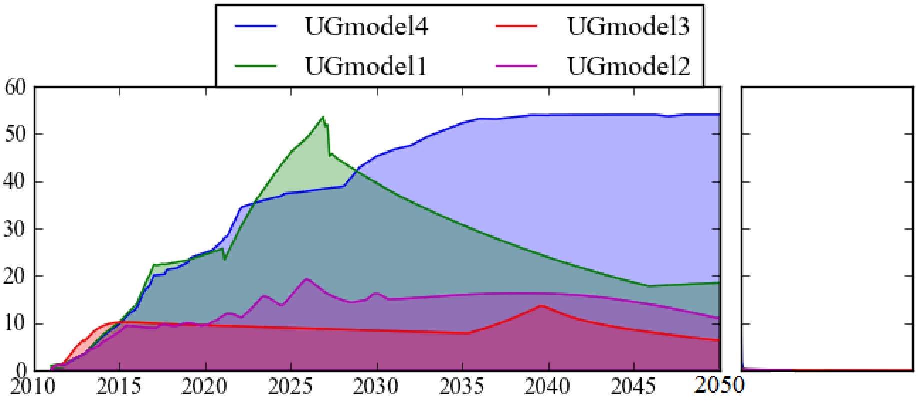

Fig. 11. Envelopes of production rate for four models, with end state densities

Similar to the second one, Model 3 generally demonstrates an initial increase and then decline, but with the rapid rises in the earlier stages of the time horizon in almost all cases. In other words, the variety in the peak times is observed to disappear after the elimination of two feedback mechanisms as shown in Fig. 8 despite the presence of well construction delays. Moreover, maximum values of the *production rate* are lower than those generated by the second model, except the first 10 years. Although demand orientation in the investments is expected to create higher *production rates*, such low values can be explained with the *undeveloped reserves* being less promising to meet the high demand values and causing low investments, even if the unavailability of *developed reserves* indicates more need. This narrower outcome range, and also very low end states below 1 bcm/year indicate a minor supply of unconventional gas, in contrast to the desired levels.

The last model structure alternative generates more optimistic future possibilities. Although the majority of cases result in less than 5 bcm/year production rates in 2050, the number of possibilities which result in production rates above 10 bcm/year is higher compared to the other model structures. Also, all possibilities generated by this model show an increasing pattern in the production rate. These results can easily be attributed to the removal of causal links between the production rate and investments and elimination of the corresponding feedback loops.

For further understanding of these different behaviors, the resulting ranges of the driving factors behind the production rate, namely the *UG demand, developed reserves* and the *production capacity* can be examined. The trajectories of *UG demand* are similar for each model, and demonstrate usually increasing patterns as in Fig. 12. The uncertainty ranges of *developed reserves* and *production capacity* are shown in Fig. 13. *Developed reserves* generally demonstrate a rapid increase, then decline to very low values similar to the trajectories of *production rate* in the case of Model 1, while they generally show an increasing pattern till very high values in other models. While abundant *developed reserves* are present on the one hand, on the other hand, *production capacity* trajectories are very similar to those of production rates generated by Models 2, 3 and 4.

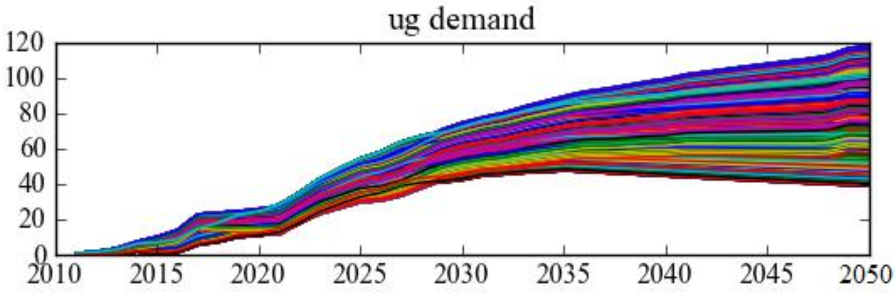

Fig. 12. The uncertainty range of *UG Demand*, common in all four models

This implies that production capacity is the most influential factor on the production rate even in the presence of uncertainties and different model structure. Moreover, the influence of *UG Demand* on the *production rate* can be best seen in the smoothness differences between the *production rate* and *production capacity* trajectories generated by Model 4.

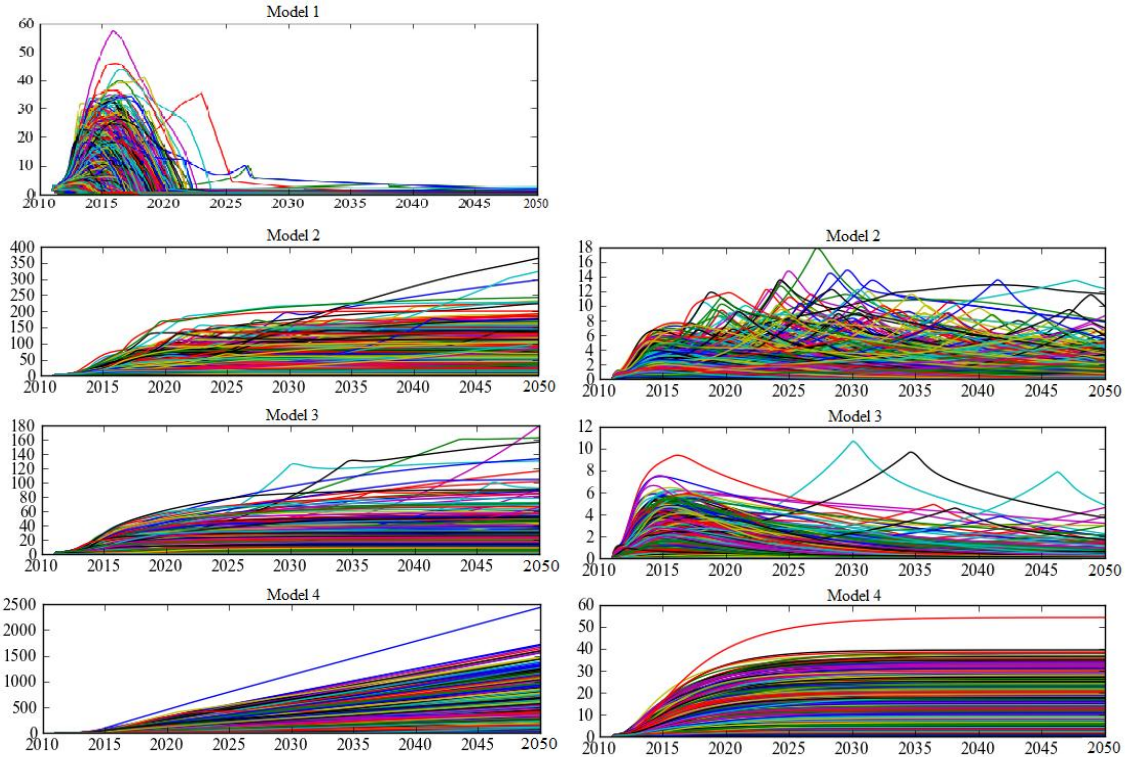

Fig. 13. The uncertainty ranges of *developed reserves* (left) and *production capacity* (right)

5 Discussion

The experiment results presented in the previous section revealed that the effect of parameter (including table functions) uncertainties on the outcome of each model is numeric, rather than behavioral, i.e. Model 2 creates a rapid increase, then decline in the production rate, whereas Model 4 creates a non-decreasing pattern similar to s-shaped growth in almost all of 10000 cases. Although such effects of uncertainty may not be important for behavioral analysis purposes, the uncertainty in the values and in the timing of each value is important for policy makers.

As for the model uncertainty, it has been observed to cause both numerical and behavioral differences in the outcome. Model 1 and Model 2 were two alternatives of model boundary uncertainty, and they resulted in behaviorally similar but numerically significantly different outcome ranges. Model 3 was an alternative to Model 2 to represent the uncertainty in the decision making criteria of investors and yielded significant numeric differences in the outcome range, too. Model 4 was another alternative to Model 2 with differences in investment making mechanism, and the outcome range obtained from it was both behaviorally and numerically different.

6 Conclusion

The first conclusion that can be derived from this study is that uncertainties in the boundaries and structures of the models used for generating future possibilities may lead to very different outcomes. Hence, such uncertainties should be taken into account in model-based decision making, as well as parameter uncertainties.

Besides, the contribution of EMA to this study has been valuable, because it allowed generation of possible behaviors that could not be generated in a conventional SD study. In other words, an SD study with a standard uncertainty analysis could result in relatively high or relatively low production rates only, but EMA showed that there is a huge span of possible outcomes, which tend to accumulate around low values.

In terms of the development of unconventional gas in the Netherlands, the first and third models resulted in promising production rates in the early stages, whereas the second model produced a large possibility span of the timing of maximum production. Despite some favorable but not too likely outcomes which are also not sufficient to fill the gap between demand and conventional production, all three models showed the production rate evolving towards very low amounts in 40 years. This finding can be interpreted as negligible long-term benefits from unconventional gas for the Dutch gas industry. Although the future scenarios generated by Model 4, where investments in unconventional gas are continuously high, are more optimistic, the majority of the future possibilities again result in very low values which are not considered as significant contributions to the total gas supply.

There were two arguments in this paper about the cause of low production rates: First, the insufficiency of revenues to provide necessary investments after the initial capital is depleted, and second, low production capacity values. Regarding the former, the investors are recommended to use capital from external sources for a longer time, as in the fourth model. For the latter, focusing the technical research and development studies on the well productivity in order to enhance production capacity is advised as another policy option.

In this study, a limited number of model alternatives is taken into account. However, this analysis can be continued with a more extensive set of model alternatives, to analyze the uncertainties caused by differences between the worldviews of stakeholders or investors, by different model boundaries and by different structural assumptions. The models developed in this study can also be used in analyses for making robust policies.

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Appendix I: Model Equations

*Parameters and graphical functions are not listed in this section, since they are given in Appendix II.

Undeveloped reserve production ratio = IF THEN ELSE(Smoothed Production rate>0, Undeveloped Reserves/Smoothed Production rate, 3)

Smoothed Production rate = smooth(Production rate,1)

Developed reserve production ratio = IF THEN ELSE(Smoothed Production rate>0, Developed reserves/Smoothed Production rate, 2)

Total no of new wells = development rate of new wells + completion rate of exploration wells

Production capacity = INTEG (capacity increase rate-capacity decay rate, 0)

capacity increase rate = Total no of new wells*Initial well productivity

Development rate = min(Average EUR per well*Total no of new wells , Undeveloped Reserves/TIME STEP)

capacity decay rate = Production capacity*capacity decay multiplier

Production rate = min(min(Production capacity, UG Demand), Developed reserves/TIME STEP)

Cumulative Profit = INTEG (Sales revenue - Investment in development - Investment in exploration, Initial investable)

Actual completion expense = Production well cost*completion rate of exploration wells

completion rate of exploration wells = min(Successful exploration wells,Investment in development activity/Production well cost)/Production license delay for exploration license holders

km2 to acre= 247

Land cost per acre=Land cost per km2/km2 to acre

Production well cost= DELAY1I(Initial production well cost*effect of technology on development cost,RD delay, Initial production well cost)

Total development cost=Production well cost+Land cost per newly developed well

development rate of new wells=min(Production wells constructable,Money left for dev well const/Production well cost)/drilling rig lead time

Money left for dev well const=max(Development investment when land was requested-Development land cost,0)

adjustment breakeven UR= Breakeven value of undeveloped reserves*(Wellhead Price-Unit development cost)/Unit development cost

Contingent resources= INTEG (Discovery rate+Economic unrecoverability rate-Economic recoverability rate, 200) drilling rate of exploration wells=min(Exploration wells constructable,Money left for well construction/exploration well cost)/drilling rig lead time

Development investment when land was requested=
DELAY FIXED (Investment in development activity-Actual completion expense,Production license delay for open area, 0)

Breakeven value of undeveloped reserves= INTEG (adjustment breakeven UR, 2)

Economic unrecoverability rate=max(0, Undeveloped Reserves-Breakeven value of undeveloped reserves)

Economic recoverability rate=min(Contingent resources/TIME STEP, max(0, Breakeven value of undeveloped reserves-Undeveloped Reserves))

Undeveloped Reserves=INTEG (Economic recoverability rate - Economic unrecoverability rate - Development rate, 2)

Money left for well construction=max(Exploration investment when land was requested-Exploration land cost,0)

Exploration investment when land was requested=
DELAY FIXED (Investment in exploration,Exploration license delay,0)

Percentage invested in development=effect of ROI on development*effect of promise on development*effect of need on development*max development percentage

Investment in exploration= max(Percentage invested in exploration*(1-Percentage invested in development)*Cumulative Profit, 0)

Discovery rate=min(Prospective resources/TIME STEP, Average discoveries per well*success rate of exploration wells)

Percentage invested in exploration= effect of ROI on development*effect of scarcity on exploration*max exploration percentage

Land cost per completed well=Exploration land cost/max(completion rate of exploration wells,1)

Land cost per newly developed well=Development land cost/max(development rate of new wells, 1)

Required number of production wells=Undeveloped Reserves/Average EUR per well

desired number of development wells=max((Investment in development activity-Actual completion expense),0)/Total development cost

Production wells= INTEG (completion rate of exploration wells+development rate of new wells-decommissioning rate, 5)

success rate of exploration wells=Exploration wells*Success fraction/Discovery delay

Successful exploration wells= INTEG (success rate of exploration wells-completion rate of exploration wells, 55)

dry wells=Exploration wells*(1-Success fraction)/Discovery delay

Land desired for exploration=max(0,(Investment in exploration/2))/Land cost per acre

Land acquired for exploration=DELAY1(Land desired for exploration*Exploration acceptance fraction,Exploration license delay)

Land acquired for development= DELAY1I(Land desired for development * Development acceptance fraction, Production license delay for open area, 0)

Unit development cost=Total development cost/Average EUR per well

Return on investment=Wellhead Price/Unit development cost

Development land cost=Land cost per acre*Land acquired for development

Production wells constructable=Land acquired for development/area per well

Exploration land cost=Land cost per acre*Land acquired for exploration

Exploration wells constructable=Land acquired for exploration/area per well

Land desired for development=desired number of development wells*area per well

decommissioning rate=Production wells/Average well lifetime

Exploration wells= INTEG (drilling rate of exploration wells-success rate of exploration wells-dry wells, 5)

Change in demand=Steady change-Price related change

Previous years price= DELAY1(Wellhead Price,1)

Price change fraction=(Wellhead Price/Previous years price)-1

Developed reserves= INTEG (Development rate-Production rate, 0.5)

Steady change=Total Gas Demand*Steady demand change fraction

Total Gas Demand= INTEG (Change in demand, 80)

Total reserves=Developed reserves+Undeveloped Reserves

Prospective resources= INTEG (-Discovery rate,Initial value of prospective resources)

Price related change= Total Gas Demand*Price elasticity of gas demand*Price change fraction

Investment in development technology= Investment in development*fraction invested in technology

Investment in development activity= Investment in development*(1-fraction invested in technology)

"Reserve-demand ratio"=Total reserves/max(UG Demand, 0.01)

Sales revenue=Production rate*Wellhead Price

UG Demand= max(Total Gas Demand-Conventional production, 0)

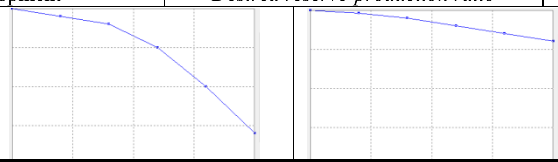
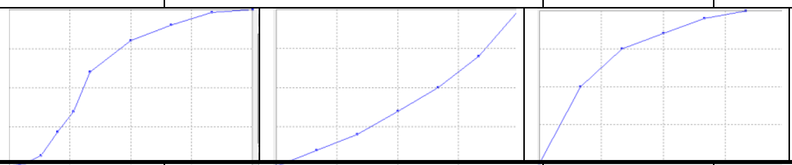
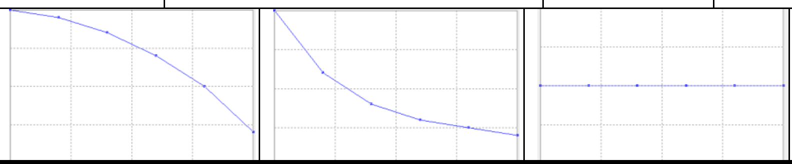
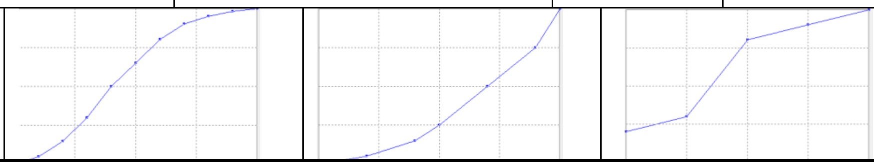
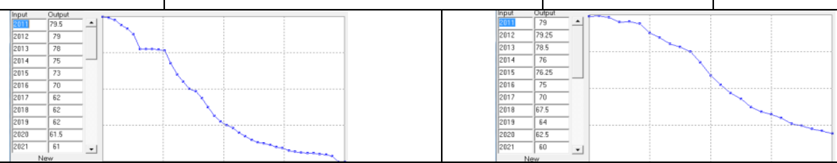
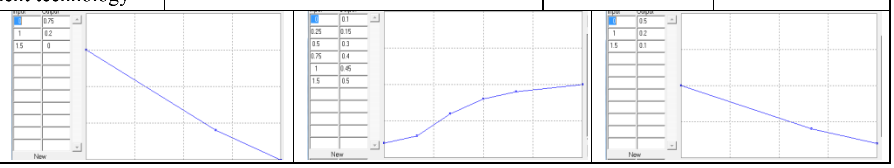
Investment in development= max(Cumulative Profit*Percentage invested in development, 0)

Initial value of prospective resources=CBM recovery factor*GIIP CBM+GIIP Shale*Shale recovery factor+GIIP Tight*Tight recovery factor

Appendix II: Uncertainties in the models and their ranges

The tables below shows the uncertainty ranges of parameters and alternative forms of graphical functions in Model 2. The ones which are not present in the other models are marked.

Uncertainty name	Range	References
Tight recovery factor	0.4 – 0.6	(Muntendam-Bos et al. 2009)
GIIP Tight	Triangular(147,185,228) [bcm]	
Shale recovery factor	0.05 – 0.2	
GIIP Shale	Triangular(48000,110000,230000)	
CBM recovery factor	0.25 – 0.28	
GIIP CBM	Triangular(977, 1417, 2029) [bcm]	
Success fraction	Triangular(0.4, 0.65, 0.7)	(EBN 2011)
Average discoveries per well*	0.5 – 1 [bcm/well]	
Threshold tech. investment	0.01 – 1 [billion euro]	-
R&D delay	0.5 – 3 [years]	-
Initial production well cost*	0.02 - 0.033 [billion euro/well]	(EBN 2011), (Geny 2010)
Steady demand change fraction	-0.01 - 0.01	(GTS 2011), (Energiezaak 2011)
Price elasticity of gas demand	0.3 – 0.5	-
Desired reserve demand ratio	20 – 50 [years]	-
Desired reserve production ratio**	20 – 50 [years]	-
Wellhead price	0.2 – 0.3 [€/m^3]	(EBN 2011), (Geny 2010), (IEA 2009)
max exploration percentage***	0.8 - 1	-
max development percentage***	0.5 – 0.9	-
Initial investable***	10 – 30 [billion euro]	-
Discovery delay	1 – 5 [years]	(Naill 1974), (EBN 2011)
drilling rig lead time*	0.5 – 1 [years]	-
Exploration license delay*	0.25 – 1.25 [years]	(NLOG 2007)
Prod. lic. delay for exp. lic. Holders*	0.25 – 0.75 [years]	
Prod. lic. delay for open area*	0.5 – 1.25 [years]	
Initial well productivity*	0.0075 - 0.025 [bcm/year/well]	(IEA 2009)
capacity decay multiplier*	0.2 – 0.27 [1/year]	(IEA 2009)
Initial exploration well cost*	0.013 - 0.022 [billion euro/well]	(EBN 2011), (Geny 2010)
Average EUR per well*	0.01 - 0.2 [bcm/well]	(Muntendam-Bos et al. 2009), (IEA 2009)
Exploration acceptance fraction*	0 - 0.75	-
Development acceptance frac.*	0 – 0.6	-
area per well*	40 – 320 [acre/well]	(Muntendam-Bos et al. 2009)
Land cost per km2*	0.003 - 0.006 [€/km^2]	(NLOG 2007)

Uncertainty	Input	x axis range	y axis range
Effect of need on development ***	*Developed reserve-production ratio / Desired reserve-production ratio*	0 - 2	0 - 1
Alternatives			1
Effect of promise on development ***	*Undeveloped reserve-production ratio/Desired reserve-production ratio*	0 - 3	0 - 1
Alternatives			1
Effect of scarcity on exploration ***	*Reserve-demand ratio/Desired reserve-demand ratio*	0 - 2	0 - 1
Alternatives			1
Effect of ROI on investment***	*Return on Investment*	0 - 2	0 - 1
Alternatives			
Conventional Production	*Time*	2011- 2050, 2011 - 2035	0 - 80
Alternatives			
Fraction invested in development technology	*Return on Investment*	0 – 1.5	0 – 1
Alternatives			

* Uncertainties which do not exist in Model 1, instead

Unit exploration cost in [0.05, 0.2] billion euros/bcm

Initial development cost in [0.1, 0.3] billion euros/bcm

** Uncertainty which do not exist in Model 3

*** Uncertainties which do not exist in Model 4