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DESIGN SUPPORT TOOL FOR BIOMETHANE SUPPLY CHAINS AND GAS DISTRIBUTION GRIDS

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ABSTRACT

The Dutch gas distribution infrastructure faces several significant changes in the near future. One of the major changes is the production and injection of biomethane into the gas distribution grid. The distribution system operators (DSOs) have to make investments in the gas distribution grid in order to facilitate the injection of biomethane. Numerous design choices have to be made for the biomethane supply chain and gas distribution grid. These choices, which are made in the design process, largely depend on the local situation and the DSOs' preferences. In order to support this decision making process, this paper presents a Design Support Tool (DST) that aids actively the generation of design solutions for the biomethane supply chain and gas distribution grids for user-defined regions. The focus of the paper is set on the functionality of the tool and how it can be used to improve the design process in which multiple stakeholders are involved.

Keywords: Design Support Tool, Biomethane Supply Chain, Gas Distribution Grid

1 INTRODUCTION

After the discovery of the Groningen gas field in 1959, with an initial volume of 2.8 Tm^3(n) one of the largest gas fields in the world, the Dutch gas sector was shaped and the foundation of the current Dutch gas infrastructure was laid [1]. Nowadays, the gas infrastructure forms a crucial part of the Dutch energy system, as about half of the primary energy demand is met by natural gas. The gas distribution system, which is part of the gas infrastructure, distributes approximately 20 Gm^3(n) per year. With 98% of Dutch households connected to the gas distribution grid, the penetration of the gas distribution infrastructure is impressive, as compared to other countries.

The Dutch gas distribution grid is facing a changing gas market. Up to now, the gas distribution grid's sole function is to distribute (one type of) natural gas to gas consumers, and it is merely composed of pipelines and valves. Due to anticipated changes in the gas market, this situation will change in the near future. One of the major changes is the production and injection of biomethane into the gas distribution grid. Biomethane is gas with burning properties similar to natural gas, but is produced from renewable sources. The Dutch Distribution System Operators (DSOs), which are responsible for the distribution grids, will have to make investments to assure that the functionality of the gas distribution grid complies with the future requirements of the gas grid. Therefore, research is required on what the needed investments are for the gas distribution grid, in particular with regard to biomethane. Numerous design choices have to be made for the gas distribution grid and biomethane supply chain, and the best choice will depend largely on the specific situation and on the preferences of the DSOs. In order to support this decision making process, a new Decision Support Tool (DST) is proposed that will aid the design process of the biomethane supply chain and the gas distribution grid. The DST supports designers by automatically generating the space of possible biomethane supply networks for a given location. This solution space can then be assessed by the different stakeholders (i.e. DSOs, farmers, municipalities) by comparing the different performances and incorporating the constraints that follow from their perspective on the implementation of such a system. The DST can be applied to different geographical regions and network characteristics.

This paper is outlined as follows. Section 2 describes the biomethane supply chain. Section 3 describes the decision making modeling approach as well as the design engineering model implemented in the

DST. Section 4 presents the results of applying the DST for designing biomethane supply chains in a rural region in the Netherlands. Finally, Section 5 provides a discussion on the possible industrial implementation of the DST.

2 DESIGNING BIOMETHANE SUPPLY CHAINS

Biomethane is produced by digesting wet biomass. Commonly, manure is digested in combination with a co-substrate, for instance, agricultural crops, swill, or other waste products. This process is referred to as co-digestion [2]. In Figure 1, the supply chain for biomethane from co-digestion is shown. The feedstock for the co-digestion process is manure and co-substrate. The digestion process produces biogas, consisting of 50 – 65% CH_4 [3]. The upgrading process removes unwanted components (for instance, H_2S and H_2O) from the biogas and increases the CH_4 content in order to obtain gas with the required Wobbe index. Once the gas is at the desired quality, it can be injected into the gas grid. The digestion and upgrading processes are technically robust and commercially proven technologies.

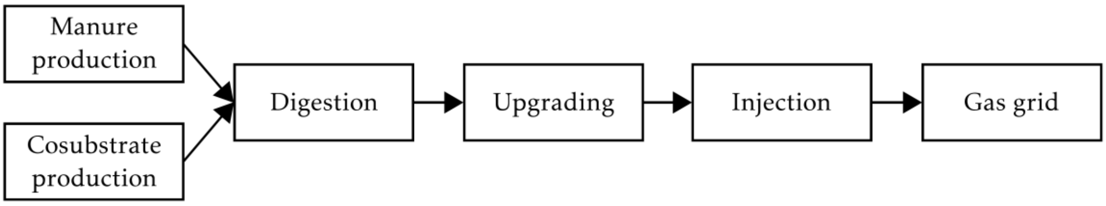


Figure 1: Biomethane supply chain [4]

Biomethane installations using the digestion process to generate biogas are small-scale (the average capacity in the Netherlands is approximately $600m^3(n)/h$ [5]). Therefore, it is economically not feasible to inject the gas into the transportation grid, since the costs for the connection to the transportation pipeline and for compression are too high. Hence, the biomethane is injected into the distribution grid. The cost for injection of biomethane into the distribution grid is lower since the length of the connection will be shorter (the distribution grid has a finer mesh and therefore, needs usually a shorter connecting pipeline) and compression costs are lower since the distribution grid is operated at a lower pressure than the transportation grid. However, injection of biomethane into the distribution grid might lead to problems in balancing the gas demand and biomethane supply, since the volume of the gas flow in the distribution grid is significantly lower than in the transportation grid. As a consequence, the injection of biomethane can result in congestion in the distribution grid. Furthermore, biomethane production often takes place in rural areas, where gas demand is lower than in urban areas. Finally, due to seasonal fluctuations the gas demand in summer is lower than in winter. The difference between summer and winter demand is about a factor 10, if there are no industrial customers connected to that distribution grid. Since the biomethane production process is very inflexible, and therefore, the volume of produced biomethane can hardly be varied during the year, the gas demand in summer becomes the limiting factor. The design of biomethane supply chains has to take these factors into consideration. As these factors are different for different locations, specific solutions are required for each case.

3 THE DESIGN ENGINEERING MODEL OF THE DST

In order to automate the design of biomethane supply chains, a design engineering model has to be assembled. Design engineering models serve as general knowledge template for large and complex design tasks. In this sense, one design engineering model can be used to determine design solutions for any problem that can be formalized using its variables and relations. This section describes the approach that was used to model the biomethane supply chain and the resulting engineering design model that was implemented into the DST.

3.1. Modeling Approach

According to the engineering modeling approach in Jauregui-Becker [6], the following parts in the model are distinguished:

- Elements: the physical parts of the design, which perform certain (sub)functions of the design. For example, a digester installation is one of the elements in the model.

- Topological relations: Indicate how the different elements of the model can be connected to each other. For example, a digester element can be connected to an upgrading plant element. But a digester element cannot be connected directly to the gas grid, since the biogas from the digester does not comply with the specifications on gas quality.
- Scenario parameters: the environmental influences in the model. For example, in this model, the subsidy given for biomethane is a scenario parameter.
- Embodiment variables: the variables that need to be instantiated (that is, are assigned a value) by the design method to obtain a candidate solution. For example, the size of the digester installation that is installed at a certain location is an embodiment variable.
- Analysis: Entails the equations used to derive the performance indicators of a candidate solution. For example, the equation that determines the energy usage of a digester installation.
- Performance indicators: Indicate the quality of a candidate solution. For example, CO_2 emission reduction is one of the performance indicators in this model.

3.2. The Design Engineering Model

This section presents a summary of the design engineering model implemented into the DST.

PERFORMANCES

In this model, the most important performance indicators of the biomethane supply chain are NPV (net present value), Net energy production [kWh/a] , Biomethane cost [€/m^3(n)], CO_2 emission reduction [t/a], CO_2 cost [€/kg]. The detailed models used for calculating these performances can be found in [7].

ELEMENTS AND TOPOLOGY

Figure 2 summarizes the elements and its topological relations conforming the biomethane supply chain. The elements are the physical parts of the biomethane supply chain. All these elements have been installed in practice in the Netherlands, with the exception of the gas storage, which has not yet been installed on gas distribution scale.

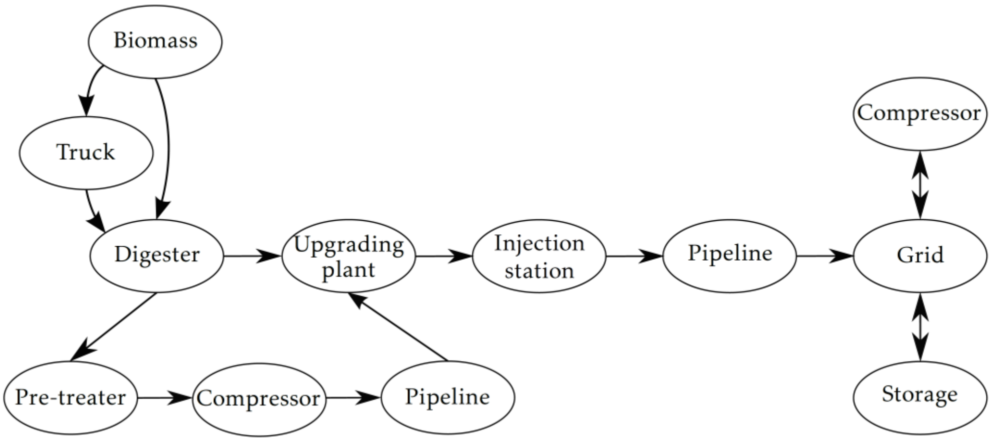


Figure 2: Elements of the biomethane supply chain and their topological relations

As can be seen in Figure 2, there are two options for the available biomass:

1. The biomass can be digested locally at the same site as the biomass production location (farm).
2. The biomass can be transported by truck to a central location, where biomass of multiple biomass locations is digested.

In the digester, biomass is converted to raw biogas, which contains 50 to 75% CH_4 [2]. This CH_4 content is too low, to allow the biogas to be injected in the gas grid. Therefore, this gas needs to be upgraded to natural gas quality in an upgrading plant. There are two options to get the biogas from the digester to the upgrading plant:

1. The raw biogas can be upgraded locally at the same site as the digester.
2. The raw biogas can be upgraded at a central location, where the biogas of multiple digesters is upgraded. For this option, first some unwanted components (H2S and H2O) are removed in the pre-treatment step, to prevent corrosion in the next two steps. Next, the compressor compresses the biogas to the right pressure to transport the biogas through a pipeline to the upgrading plant.

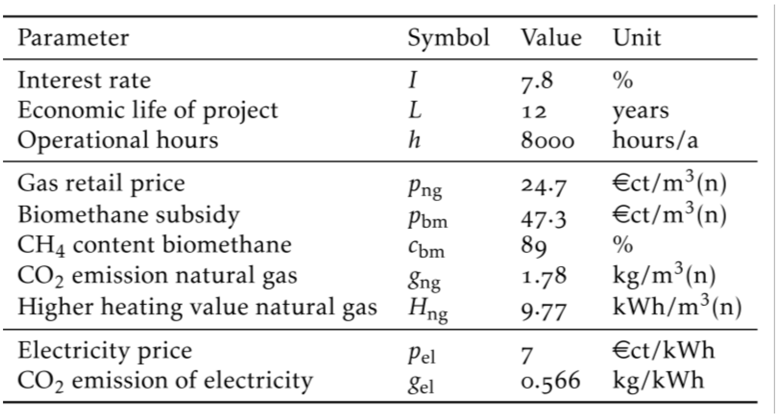
In the upgrading plant, some unwanted components are removed, and part of the CO_2 is removed such that the CH_4 content is increased to 89% [2]. After the upgrading step, quality and flow of the biomethane is measured in the injection station. This step also adjusts the biomethane to the right pressure. Finally, through a pipeline, the biomethane is injected in the gas distribution grid. If the gas demand in the gas grid is always higher than the biomethane production, no further steps are required. If this is not the case, three options exist to deal with this balancing issue:

1. Add a compressor to compress the surplus biomethane to an upstream gas grid, such that the biomethane is also consumed by the gas consumers of this grid.
2. Connect a gas storage to the grid. The gas storage buffers surplus biomethane, and releases it once the gas demand exceeds the biomethane production.
3. A third option, which is not explicitly shown in Figure 1, is using the line-pack flexibility of the gas distribution grid. That is, the pipelines of the grid can be used as a small buffer for excess biomethane, by operating the pressure dynamically.

EMBODIMENT AND SCENARIO VARIABLES

Each one of the afore described elements is composed itself by several embodiment variables. The embodiment and scenario parameters were derived from literature that lists parameters of elements of the biomethane supply chain, such as capital cost, operational cost, and energy usage. However, these variables are omitted in this paper as its technical description is out of the scope of this paper. Furthermore, the values that each embodiment variable can obtain is chosen from a discrete set of possibilities. This resembles reality, where, for instance, a farmer that wants to buy a digester, can only choose from a limited number of available types. Furthermore, it allows a designer of the biomethane supply chain to add more digester types to the model. Compared to an embodiment which values are derived from a continuous energy or cost function, an advantage of the discrete set is that each building block can have its own characteristics. For instance, the set of possible embodiment values of the digester element can consist of a set of digesters that perform well on energy usage which is complemented with another set that scores worse on energy usage but better on economic performance.

The scenario variables required to specify one biomethane supply chain network design problem can be classified into 2 groups. On the one hand, some general parameters are defined that are part of the model but do not apply to any of the elements in specific, such as depreciation period, interest rate, biomethane subsidy, and electricity price. Table 1 shows the considered variables and their projected values for the Netherlands. A more detailed description on how this values were chosen can be found in [7]. On the other hand, a start configuration of the current gas distribution grid and biomass locations and its related biomass availability for the regions of interest is also needed.



Parameter	Symbol	Value	Unit
Interest rate	I	7.8	%
Economic life of project	L	12	years
Operational hours	h	8000	hours/a
Gas retail price	p_{ng}	24.7	€ct/m^3(n)
Biomethane subsidy	p_{bm}	47.3	€ct/m^3(n)
CH_4 content biomethane	c_{bm}	89	%
CO_2 emission natural gas	g_{ng}	1.78	kg/m^3(n)
Higher heating value natural gas	H_{ng}	9.77	kWh/m^3(n)
Electricity price	p_{el}	7	€ct/kWh
CO_2 emission of electricity	g_{el}	0.566	kg/kWh

Table 1: Scenario parameters. Soources [8, 9, 10, 11, 12, 13]

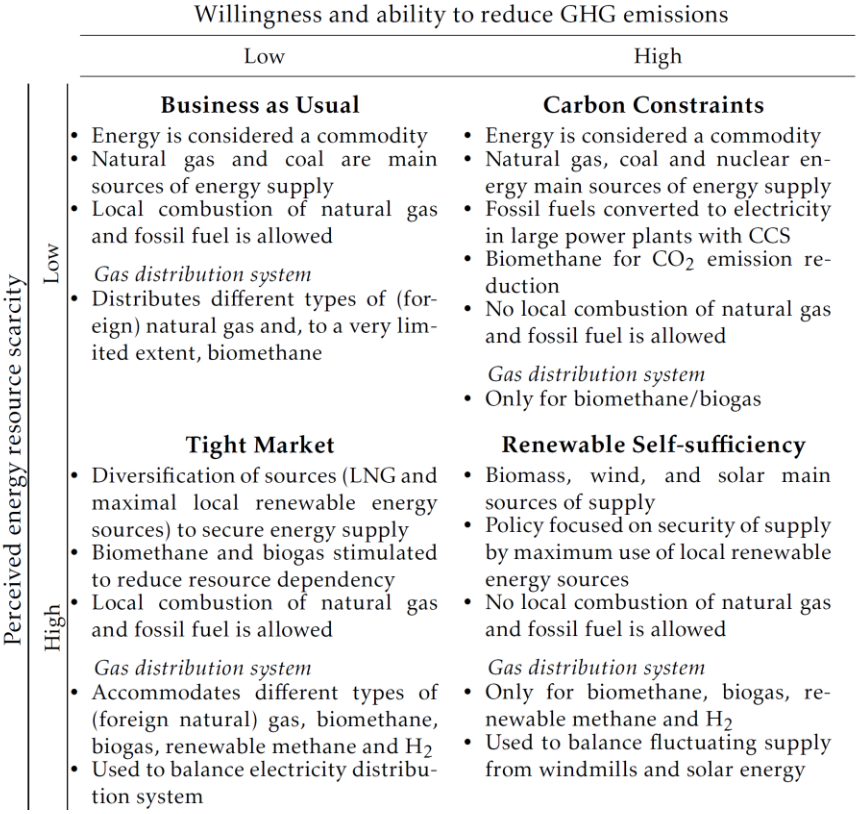
4 THE DESIGN SUPPORT TOOL

From the previous section it can be concluded that many development options for the biomethane supply chain exist. However, the preferred solution for the biomethane supply chain depends to a great extent on the specific situation and preferences of the stakeholders involved. This makes the design process a complex and time consuming process. In order to support this complex process, a Design

Support Tool (DST) has been developed. The DST generates for each specific situation a number of candidate solutions by automatically determining the number and types of elements, assigning values to the embodiment parameters and calculating the performance indicators of each of the generated solutions. Each solution has its own advantages and disadvantages, which are balanced by performance indicators –for instance CO$_2$ emission reduction and net present value (NPV). Showing the performance indicators of each solution, provides the engineer insight in the available solutions and eases the evaluation process and the choice for the eventual solution. The philosophy of generating sets of feasible solutions and then integrating different perspectives and criteria for selecting the most appropriate one is funded on the principles of lean design. According to it, engineers take more effective and efficient decisions by considering sets of solutions instead of continuously trying to optimize one. This practice has enabled companies like Toyota presenting productivity rates four times better than their rivals. This section provides the results of applying the DST to the design of supply chain networks for a real rural area in the Netherlands. Different solutions are generated for different future gas requirements and scenarios.

4.1. SHOWCASE

Previous research performed in relation to the project this paper belongs to resulted in the determination of 4 plausible future scenarios of the Dutch energy system in the year 2015, as depicted in Table 1 [14]. As the gas distribution network infrastructure is likely to be shaped according to these scenarios, in this paper we have chosen to provide biomethane supply chain solutions for the 4 cases. Furthermore, this is done for an initial configuration of the gas distribution systems of a rural region in the Netherlands: Noord-Drenthe (consisting of the municipalities: Assen, Midden-Drenthe, and Aa en Hunze). The actual gas distribution grid, hourly gas demand patterns, and biomass locations corresponding to this region was used. As such, the analysis presented in this paper also demonstrates the usefulness of the DST for this real situation. The current layout of the gas distribution grid shown in Figure 5(a) was provided by the DSOs. Here, only the layout of the high-pressure distribution grid – whose operating pressure is higher than 200 mbar(g) – was used, as this is the most suitable for injecting biomethane. The total gas demand in 2012 was 0.13 Gm$_3$(n)/a, the farmers' average biomass availability was 779 kg/h, the number of farmers was 49, the biomethane potential was 32 Mm$_3$(n)/a and the potential biomethane share is 24.3%.



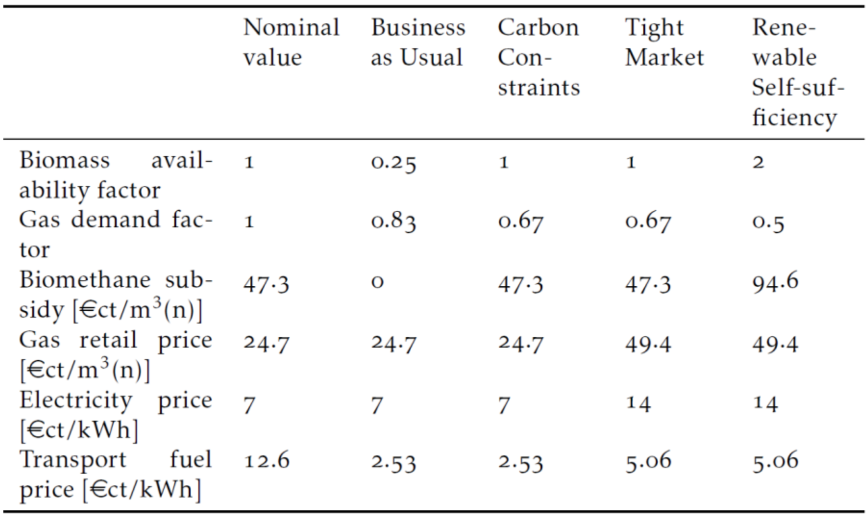
		Willingness and ability to reduce GHG emissions	
		Low	High
Perceived energy resource scarcity	Low	**Business as Usual** • Energy is considered a commodity • Natural gas and coal are main sources of energy supply • Local combustion of natural gas and fossil fuel is allowed *Gas distribution system* • Distributes different types of (foreign) natural gas and, to a very limited extent, biomethane	**Carbon Constraints** • Energy is considered a commodity • Natural gas, coal and nuclear energy main sources of energy supply • Fossil fuels converted to electricity in large power plants with CCS • Biomethane for CO$_2$ emission reduction • No local combustion of natural gas and fossil fuel is allowed *Gas distribution system* • Only for biomethane/biogas
	High	**Tight Market** • Diversification of sources (LNG and maximal local renewable energy sources) to secure energy supply • Biomethane and biogas stimulated to reduce resource dependency • Local combustion of natural gas and fossil fuel is allowed *Gas distribution system* • Accommodates different types of (foreign natural) gas, biomethane, biogas, renewable methane and H$_2$ • Used to balance electricity distribution system	**Renewable Self-sufficiency** • Biomass, wind, and solar main sources of supply • Policy focused on security of supply by maximum use of local renewable energy sources • No local combustion of natural gas and fossil fuel is allowed *Gas distribution system* • Only for biomethane, biogas, renewable methane and H$_2$ • Used to balance fluctuating supply from windmills and solar energy

Table 2: Scenarios per degree of willingness and ability to reduce GHG emissions and perceived energy resource scarcity [from 14]

4.2. Scenario dependent variables

Energy prices will go up when there is a perceived scarcity of energy. Similarly, subsidy for biomethane will be higher when there is a willingness to reduce CO_2 emissions or when there is a perceived energy scarcity. As a consequence, some of variables, when there is a perceived energy scarcity, the hourly gas demand is likely to be lower than currently the case, and also more biomass resources are likely to become available to produce renewable energy. Hence, depending on the four scenarios, the values for biomass availability and hourly gas demand in the three nominal start configurations presented in the previous subsection are subject to change.

The values for these scenario dependent variables are listed in Table 2. As can be seen, in the Business as Usual scenario, biomass availability is only 25% of the nominal situation. It is assumed here that in this scenario only one fourth of the farmers that have biomass available in the nominal situation want to use their biomass for biogas production. This was achieved by omitting 3 out of 4 farmers from the nominal start configuration, which was done randomly. Furthermore, biomass availability in the Renewable Self-sufficiency scenario is double that of the nominal situation. This availability was achieved by letting the farmers have 25% extra biomass available. The remaining 75% extra biomass comes from 1 or 2 biomass centers that have imported biomass available. These are located near harbors. Finally, biomass availability in the Carbon Constraints and Tight Market scenarios is equal to the nominal situation. So biomass-wise the start configuration for these scenarios is identical to the nominal start configuration. The hourly gas demand in 2050 for each future scenario is found by multiplying the nominal hourly gas demand by the gas demand factor (moet dit niet ergens gedefinieerd worden?), which is given in Table 3. Finally, in the Carbon constraints and Renewable Self-sufficiency scenarios, the gas grid is adjusted to biogas quality. So no upgrading of the biogas is needed. In the DST this will be simulated by setting the cost for upgrading at zero.



	Nominal value	Business as Usual	Carbon Constraints	Tight Market	Renewable Self-sufficiency
Biomass availability factor	1	0.25	1	1	2
Gas demand factor	1	0.83	0.67	0.67	0.5
Biomethane subsidy [€ct/m^3(n)]	47.3	0	47.3	47.3	94.6
Gas retail price [€ct/m^3(n)]	24.7	24.7	24.7	49.4	49.4
Electricity price [€ct/kWh]	7	7	7	14	14
Transport fuel price [€ct/kWh]	12.6	2.53	2.53	5.06	5.06

Table 3: Values of the scenario dependent variables

4.3. Results

For each scenario and each region, 10,000 candidate solutions were generated. To make a choice among the 10,000 solutions, only the pareto optimun solutions were considered. In this way, the set of candidate solutions became much smaller. In addition, only selected solutions with a positive NPV have been selected. Finally, if net energy production or CO_2 emission reduction was one of the objectives, the solution with the highest net energy production or CO_2 emission reduction (but with a positive NPV) would be selected. In this section, the results are discussed per region.

BUSINESS AS USUAL

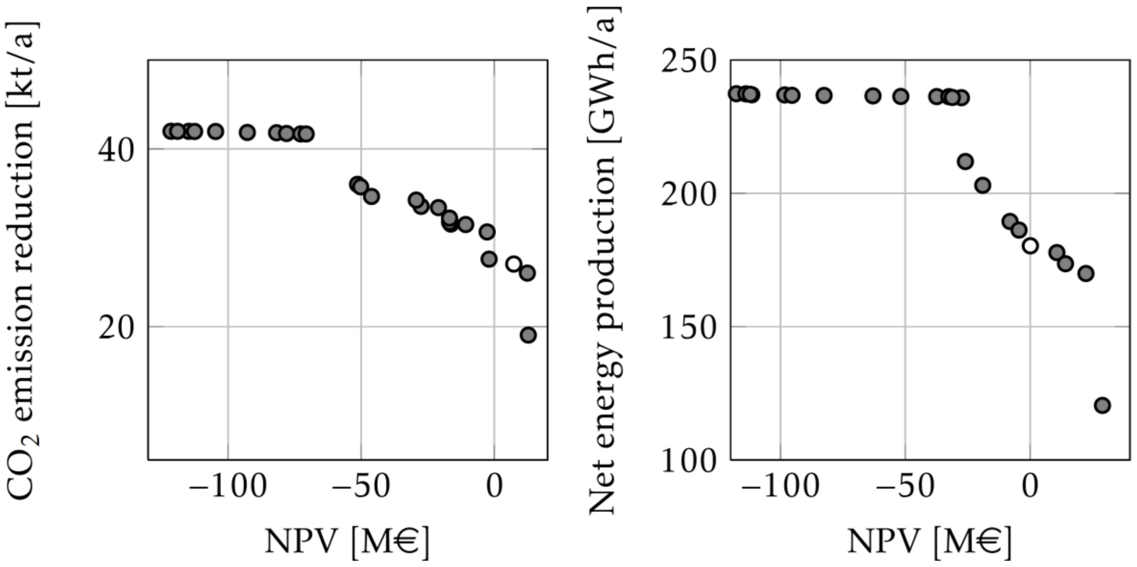
None of the 10,000 solutions generated for the Business as Usual scenario had a positive NPV. So the best solution is the start configuration, with an NPV of zero. Hence, in this scenario, there will be no biomethane production and the gas distribution infrastructure remains as it is.

CARBON CONSTRAINTS

Figure 3(a) shows the NPV and CO_2 emission reduction of the non-dominated solutions in the Carbon Constraints scenario. The design of the preferred solution is shown in Figure 5(b). It has four digestion centers that are supplied with biomass from other locations by means of trucks. Each digester installation has its own upgrading plant. As can be seen, of only a limited number of locations the biomass is used. This is due to the low hourly gas demand in this region, which requires expensive gas balancing measures to further increase the biomethane production. Already, there are two gas storages in operation that buffer the biomethane in times of surplus. However, adding more storage capacity would result in a negative NPV.

TIGHT MARKET

Figure 3(b) shows NPV and net energy production of the non-dominated solutions in the Tight Market scenario. The design of the preferred solution is shown in Figure 6(a). This solution has five digester installations, of which three are central digesters to which biomass is transported from other locations. Each digester installation has an upgrading plant on site. Compared to the preferred solution in the Carbon Constraints scenario, more biomass is used. This is due to the higher compensation for biomethane in the Tight Market scenario: the biomethane subsidy is the same but the gas retail price is double that of the Carbon Constraints scenario. Furthermore, since more biomass is used, also more gas needs to be stored in this scenario.



(a) (b)

Figure 3. Performance indicators of the non-dominated solutions in the Carbon Constraints and Tight Market scenarios. The solutions chosen and presented in Figure 5(b) and 6(a) are given in white.

RENEWABLE SELF-SUFFICIENCY

NPV, net energy production, and CO_2 emission reduction of the non-dominated solutions in the Renewable Self-sufficiency scenario are shown in Figure 4. Of the solutions with a positive NPV, the one that has both the highest CO2 emission reduction and highest net energy production has been chosen. Its design is shown in Figure 6(b). In this solution more biomethane is produced than in the preferred solutions in the Tight Market and Carbon Constraints scenarios. However, even in the Renewable Self-sufficiency scenario, which has the highest incentive to produce biomethane, not all biomass is used. The biomass from the biomass center is not used either.

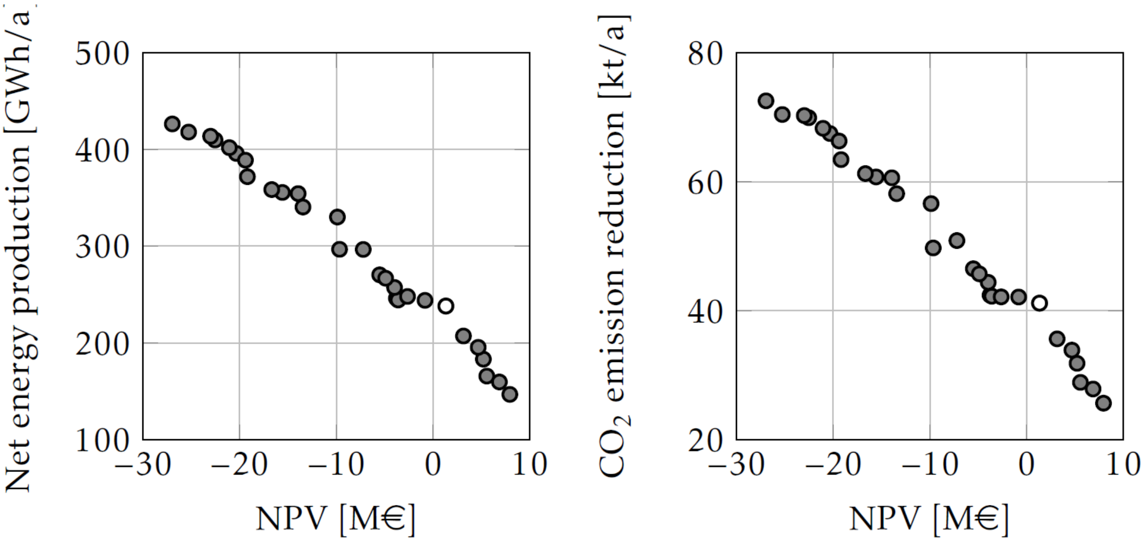


Figure 4: Performance indicators of the non-dominated solutions in the Renewable Self-sufficiency scenario. The chosen solution is given in white.

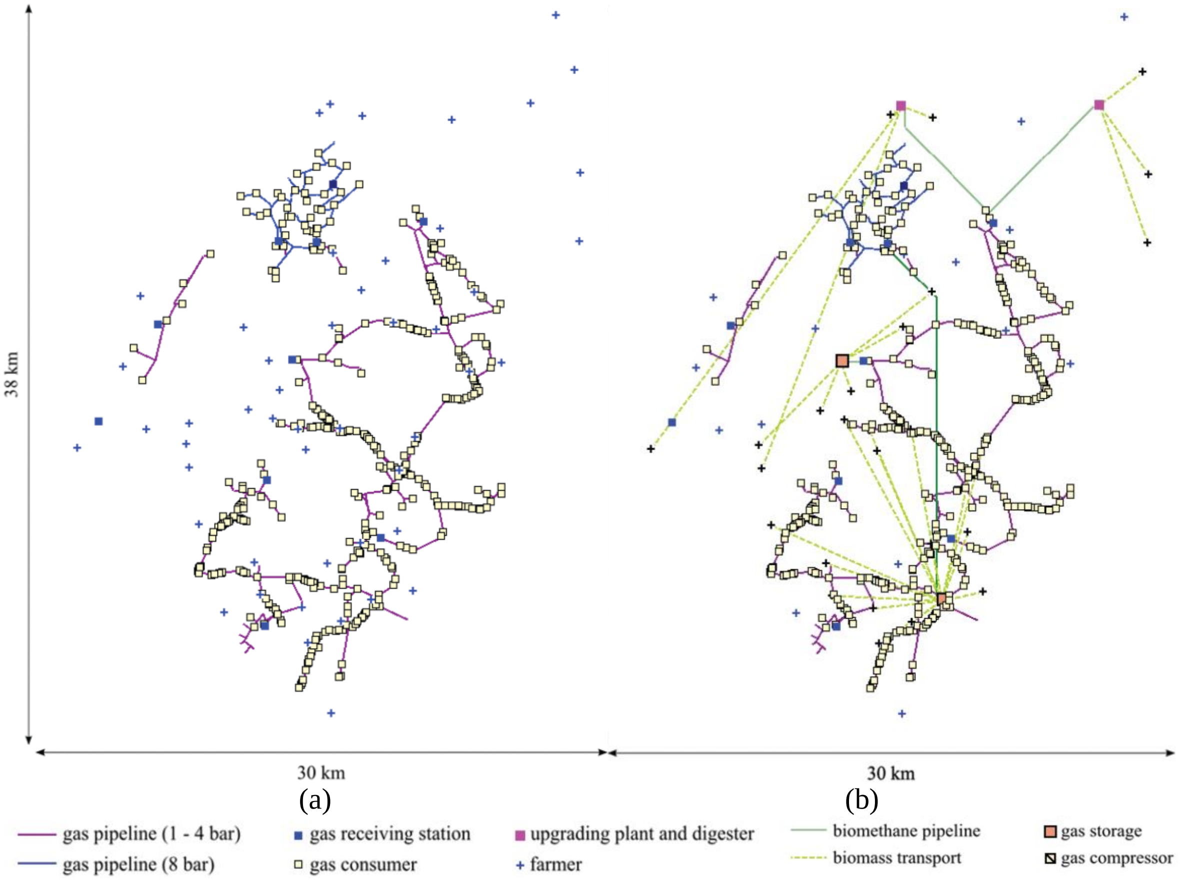


Figure 5: Gas distribution network: (a) initial configuration, (b) design of the chosen solution in the Carbon Constraints scenario

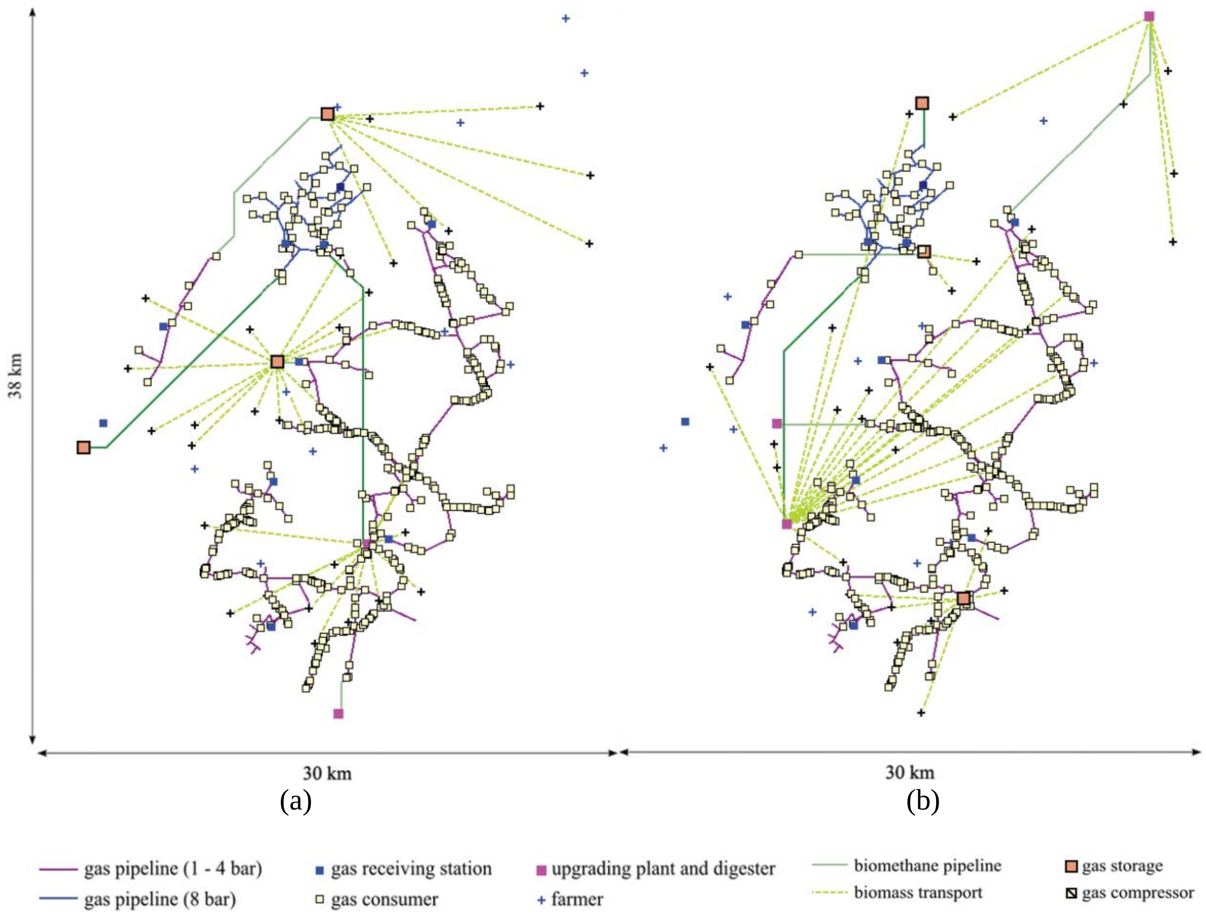


Figure 6: Gas distribution network: (a) design of the chosen solution in the Tight Market scenario (b) Design of the chosen solution in the Renewable Self-sufficiency scenario.

5. DST APPLICATIONS

The DST is envisioned to be used (1) for cases where one or more biomass owners want to use their biomass for biomethane production and (2) for making strategic decisions on the future biomethane infrastructure, without immediate interest from biomass owners.

For the first option, several biomass owners are interested in producing biomethane and injecting it into the gas grid of the DSO. Several other stakeholders are also involved in the design process, such as DSOs, municipalities, and citizens living near the biomethane production location. When preparing the DST for a certain case, first the available elements have to be added to the DST, biomass locations have to be defined, and from existing files available to the DSOs the gas distribution grid and gas consumption have to be loaded. Next, the performance indicators which are of interest for the stakeholders are chosen, and are used to determine the non-dominated solutions. Performance indicators of interest are, for instance, the profit of a biomass owner, investments in the gas grid, and the number of biomass transport movements. Next, using the DST, a large number of solutions are generated and their performance indicators are determined. The performance indicators give insight into the available solutions and allow stakeholders to make trade-offs between different options.

For the second option, the DST is used to make strategic decisions on the future biomethane supply chain. This option gives the DSOs insight in what the consequences will be when biomass owners in a certain region want to use their biomass to produce biomethane in the coming years. This allows DSOs to see ahead, and make investment decisions that look beyond the first biomass owner that knocks on the DSO’s door to inject biomethane. As such, the solution chosen for the first biomass owner(s) that wants to inject its biomethane into the gas grid might not seem the best or cheapest option. But this solution might prove to be a good option when subsequent biomass owners also want to inject their biomethane into the gas distribution grid.

CONCLUSIONS

The DST has the potential to create value for the DSOs, other stakeholders and society. First, the DST reduces the complexity of the design process. It allows the user to choose its own performance indicators and these performance indicators again give insight in the solution space. As such, it increases acceptance among different stakeholders for the chosen design, by showing the advantages and disadvantages of each solution. Ultimately, this improves the quality of the chosen solution. Secondly, society benefits, since solutions can be chosen that no longer only optimize the profit of the biomass owner. Instead, a solution can be chosen that is most beneficial for society (for example, lowest societal cost). Thirdly, the strategic use of the DST allows the DSOs to look further than the first biomass owner when investing in the gas grid. Later on, these higher initial investments might prove cost-effective when subsequent biomass owners also want to inject their biomethane. Finally, by reducing the time to come to an embodiment design of the biomethane supply chain, the DST shortens the overall design process. It does this, by automating several tasks. For instance, it allows easy addition of new values for elements of the biomethane supply chain and it can quickly generate a large number of solutions. Integrating the DST with existing files further reduces the time to come to a design for the biomethane supply chain.

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REFERENCES

[1] J. Schenk. Groningen-gasveld vijftig jaar: kloppend hart van de Nederlandse gasvoorziening. Boom, Amsterdam, 2009.

[2] T. Al Seadi, D. Rutz, H. Prassl, M. K¨ottner, T. Finsterwalder, S. Volk, and R. Janssen. Biogas handbook. University of Southern Denmark Esbjerg, Esbjerg, 2008.

[3] J.-h. Welink, M. Dumont, and K. Kwant. Gas van aardgaskwaliteit uit biomassa - Update van de studie uit 2004. Technical report, Senter Novem, 2007.

[4] J. Bekkering, A. A. Broekhuis, and W. J. T. van Gemert. Optimisation of a green gas supply chain–a review. Bioresource technology, 101(2):450–6, Jan. 2010.

[5] AgentschapNL. www.b-i-o.nl, Accessed at 5-11-2013.

[6] J. M. Jauregui-Becker, H. Tragter, and F. van Houten. Structure and models of artifactual routine design problems for computational synthesis. CIRP Journal of Manufacturing Science and Technology, 1(3):120–125, Jan. 2009.

[7] T. Weidenar. Designing The Biomethane Supply Chain Through Automated Synthesis. PhD thesis. University of Twente. 2014.

[8] AgentschapNL. Bio-energie – Output – Groen Gas, 2011.

[9] P. Forster, V. Ramaswarmy, P. Artaxo, T. Berntsen, R. Betts, D. Fahey, J. Haywood, J. Lean, D. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland. Changes in Atmosperic Constituents and in Radiative Forcing. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors, Climate change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, chapter 2. Cambridge University Press, Cambridge, 2007.

[10] S. Lensink, J. Wassenaar, M. Mozaffarian, S. Luxembourg, and C. Faasen. Basisbedragen in de SDE + 2012. 2011.

[11] H. Levinsky and M. van Rij. Gaskwaliteit voor de toekomst. KEMA, Groningen, 2011.

[12] MilieuCentraal. Energieprijzen. http://www.milieucentraal.nl/themas/energie-besparen/energieprijzen

[13] SenterNovem. Cijfers en tabellen 2007. 2007.

[14] T. D.Weidenaar, E. Bekkering, and R. van Eekelen. Scenarios for the Dutch gas distribution infrastructure in 2050. Working Papers of the Energy Delta Gas Research, ISSN 2213-6169, Groningen, 2012.