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DUTCH GAS DISTRIBUTION GRID GOES GREEN: DECISION SUPPORT TOOL FOR LOCAL BIOGAS UTILIZATION

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ABSTRACT

A Decision Support Tool (DST) has been developed that will aid Distribution Service Operators (DSOs) in their decision making process on which investments to make in the gas distribution grid in order to facilitate the use of biogas. The DST considers both the conversion of biogas to electricity as well as upgrading the biogas to green gas and consequently injecting it into the gas grid. Based on a starting configuration - i.e. a gas grid, gas consumers connected to this grid, and biomass locations -, in combination with several building blocks - e.g. a digester installation, an upgrading plant, and a CHP installation -, the tool generates several solutions to utilize the biomass. The DST generates solutions and determines for each solution two performance criteria: CO_2 emission reduction and costs. Showing these solutions, gives the DSOs insight in the available options and which trade-offs can be made.

A case study has been performed for the gas grid of the Dutch municipality of Zutphen. This case study showed that cost-wise there is a preference for centralization, i.e. digesting biomass at a central location and upgrading the biogas at a central location to green gas. Furthermore, conversion of biogas to electricity led to the highest CO_2 emission reduction, but also to the highest cost.

Furthermore, the case study showed that the DST basically works, and that it is a good way to explore the possible investment options. The tool however needs further improvements. For instance, more performance indicators (e.g. energy usage and reliability) will be included. Furthermore, the interaction with the electricity grid will be incorporated and multiple gas qualities in the distribution grid will be introduced. Also more boundary conditions should be added to the DST, for instance taking the topology of the area into account when laying pipelines.

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1. INTRODUCTION

It is expected that the Dutch gas distribution grid will face several significant changes in the near future. Among others, it is expected that the share of green gas, will increase significantly (from the current 0.1% to 12% in 2020); instead of gas of one quality (Groningen gas), gas of different qualities will flow through the grid (Russian, Norwegian, Algerian, LNG, and green gas); and the network will become smarter, i.e. will become a grid that actively controls and monitors gas pressure, gas flow, and gas quality.

Investments in the gas distribution grid are required to cope with these expected changes. In our previous paper [1] we stated that the preferred investment option is largely dependent on the local situation and the preferences of the Distribution Service Operator (DSO). This makes that there is a large number of possible options. Therefore, we proposed the development of a Decision Support Tool (DST) that will aid in the decision making process of choosing the best investment option for the distribution grid. The DST will give advice, tailored to the local situation, on possible investment decisions in the gas distribution grid.

The DST will provide insight in the available investment options by showing the advantages and disadvantages of each solution, e.g. large CO_2 emission reduction but also high costs. Although the tool should give a clear view on the possible options, the eventual choice on which investment to make has to be made by the DSO.

In this paper we will present a prototype of the DST and give a proof of principle. The prototype will be referred to as DST in the remainder of this paper. The DST focuses on the production of green gas from (co-)digestion and has reduced functionality compared to the eventual DST. The research question this paper attempts to answer is whether the proposed DST is a good way to advice on the possible investment options for the Dutch gas distribution grid. We answer this question by performing a case study.

The remainder of the paper is outlined as follows. First, section 2 elaborates on the green gas production process from co-digestion and which investment options are available to allow for the injection of green gas into the distribution grid. In section 3 the method used is described. Next in section 4, the proof of principle of the DST will be given by applying the DST to a case study. In this case study optimal ways to use biomass in the Dutch municipality of Zutphen are investigated. In section 5 conclusions are drawn on the DST and the performed case study. Finally in section 6 recommendations for further research are given. It elaborates on the planned adaptation of the DST and research that could be done with the eventual DST.

2. INVESTMENT OPTIONS FOR THE GAS DISTRIBUTION GRID

The process steps for the production of green gas are shown in Figure 1. The first step is to collect manure and co-substrate, e.g. agricultural crops, swill, or other waste products. Secondly, the manure and co-substrate are digested in the digester installation where biogas is produced. The digestion process produces biogas, consisting of 50 - 65% methane [2] (for comparison Groningen gas consist of 83% methane). The next step is the upgrading process which removes unwanted components, e.g. hydrogen sulphide, hydro carbons, and ammonia from the biogas and increases the methane content in order to obtain gas with a Wobbe-index similar to that of Groningen gas. Biogas with a similar quality as natural gas is referred to as green gas. Once the gas is at the desired quality, the gas can be injected into the gas grid. Besides upgrading the biogas to natural gas quality, it can also be converted to electricity in a Combined Heat and Power (CHP) installation.

Choices concerning the optimal utilization of biomass consider among others:

- Digest the biomass locally at the farm, or transport it to a central location where it will be digested at a larger scale?
- Convert the produced biogas from the digestion process to electricity, or to green gas?
- If the biogas will be converted to green gas, will this be done locally adjacent to the digester installation, or will it be transported by a pipeline to a central location where also biogas from other locations is converted to green gas?
- Where to inject the green gas? Into the 40 bar grid, or into the 8 bar grid?

These are some of the choices to be made considering the utilization of biomass. The DST developed in this paper takes this into account and explores as much options as possible to find the optimal solutions for the required investments. Hence, the problem to be solved by the DST comprises, among others, an allocation problem, a layout problem, and an investment problem. The next section elaborates on the method employed by the DST to solve this problem.

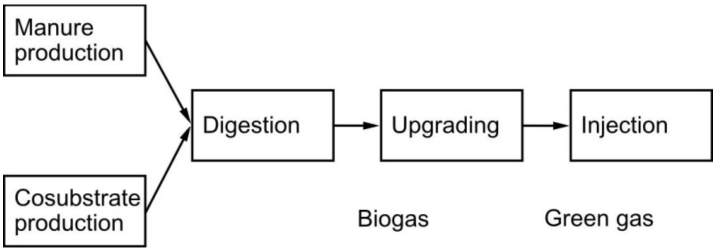


Figure 1: Green gas supply chain [3]

3. DECISION SUPPORT TOOL

This section describes the method underlying the DST. In section 3.1 the method of the DST is described. In the sections 3.2 - 3.6 each step of the method is described in more detail.

3.1. Method

In Figure 2, the method of the DST is shown schematically. Given a starting configuration - composed of an existing gas grid, gas consumers with specified gas demand, and biomass locations with availability -, the DST explores options to utilize the biomass. The decision variables that are available to the DST are derived from the building blocks. For the basic DST described in this paper, the building blocks are: gas pipelines, manure transport, digester installations, an upgrading plant, injection stations, a compressor station, and a CHP installation. All the building blocks are scalable, i.e. the size can be adjusted to the required size. Section 3.2 and appendix A elaborate on the building blocks.

In the *Generate solution* step, the DST generates a solution by choosing where to place a certain building block, what the size of this building block is, and how these building blocks are connected to each other and to the existing configuration. This step is described in more detail in section 3.3. In the *Validation* step (see section 3.4) the DST checks whether the pipeline capacity is sufficient to transport the gas at all times and maintain a certain minimum gas pressure level in the grid for the generated solution. If this is not the case, the solution is rejected, and a new solution is generated.

If, however, the solution is accepted, the two performance criteria - CO_2 emission reduction and costs - are determined in the *Analysis* step, see section 3.5. The previously described steps are repeated for a, by the user defined, number of times. Then in the *Results* step, among the generated solutions that are valid, the set of pareto optimal solutions is selected and plotted, see section 3.6 for more details.

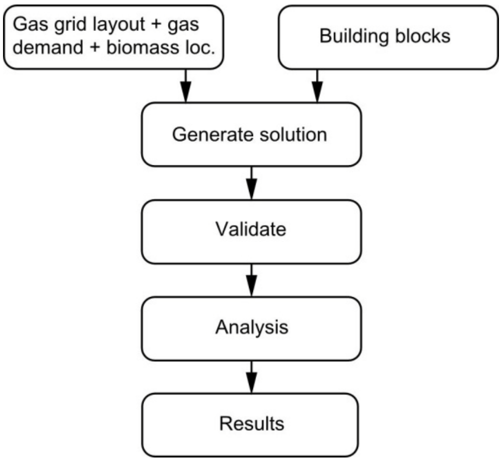


Figure 2: Method

3.2. Building blocks

To generate solutions, there are several building blocks available to the DST. Below the building blocks are listed and described in further detail. As mentioned before, when allocating the building blocks they can be scaled to the preferred size. In appendix A, it is indicated how the relevant parameters scale with the increase or decrease in size of the building block.

Biomass transport: If the biomass is not digested locally, but instead digested at a central location, the biomass needs to be transported. This is done by a "biomass transporter". When assessing the performance criteria cost and CO_2 emission reduction, only the energy use is taken into account for biomass transport.

Pipelines: Pipelines can be used for the transport of biogas or green gas. For this building block, the diameter, the operating pressure, and the costs of laying a pipeline are important.

Digester installations: The digester installation converts the biomass into biogas. Parameters of importance for the digester installation are the investment costs, the amount of biomass required to produce 1 m^3 of biogas, the amount of energy used for the production of 1 m^3 of biogas, and the operational costs. For this case study we use a digester installation that uses a biomass mix consisting of 90% manure and 10% maize [4].

Upgrading plant: In the upgrading plant, the methane content of the biogas is increased from 57% to 90%. Parameters of importance are, among others, how much green gas can be produced from 1 m^3 of biogas, and investment and maintenance costs. For this case study we use a Pressure Swing Adsorption upgrading plant [4].

Injection station: Once the gas is at the right quality, the gas needs to be compressed at the right pressure - 8 or 40 bar for this case study - and injected into the gas grid. Parameters of importance are the inlet pressure, the outlet pressure, the compression rate, and the investment and operational costs. Both injection stations are listed in appendix A.6.

Compressor station: If the gas offtake in a certain grid is insufficient to consume all the green gas injected, the DST can add a compressor station to feed the gas to a higher grid. In this case study, the DST checks whether the gas offtake in the 8 bar grid is sufficient to consume all the green gas injected. If this is not the case, a compressor will be added that transports gas from the 8 bar grid to the 40 bar grid. It is assumed in the case study that the gas offtake in the 40 bar grid is sufficient. The compressor station is listed in appendix A.6.

CHP installation: If the DST chooses that the biogas should not be upgraded to green gas, but instead be converted to electricity this will be done by a CHP installation. A CHP installation converts biogas into heat and electricity. For this case study we will assume that the heat cannot be utilized.

3.3. Generate solutions

In this step, a large number of possible solutions are generated. The decision tree belonging to the Generate solution method is schematically shown in Figure 3. Below, each step of the method is described in more detail.

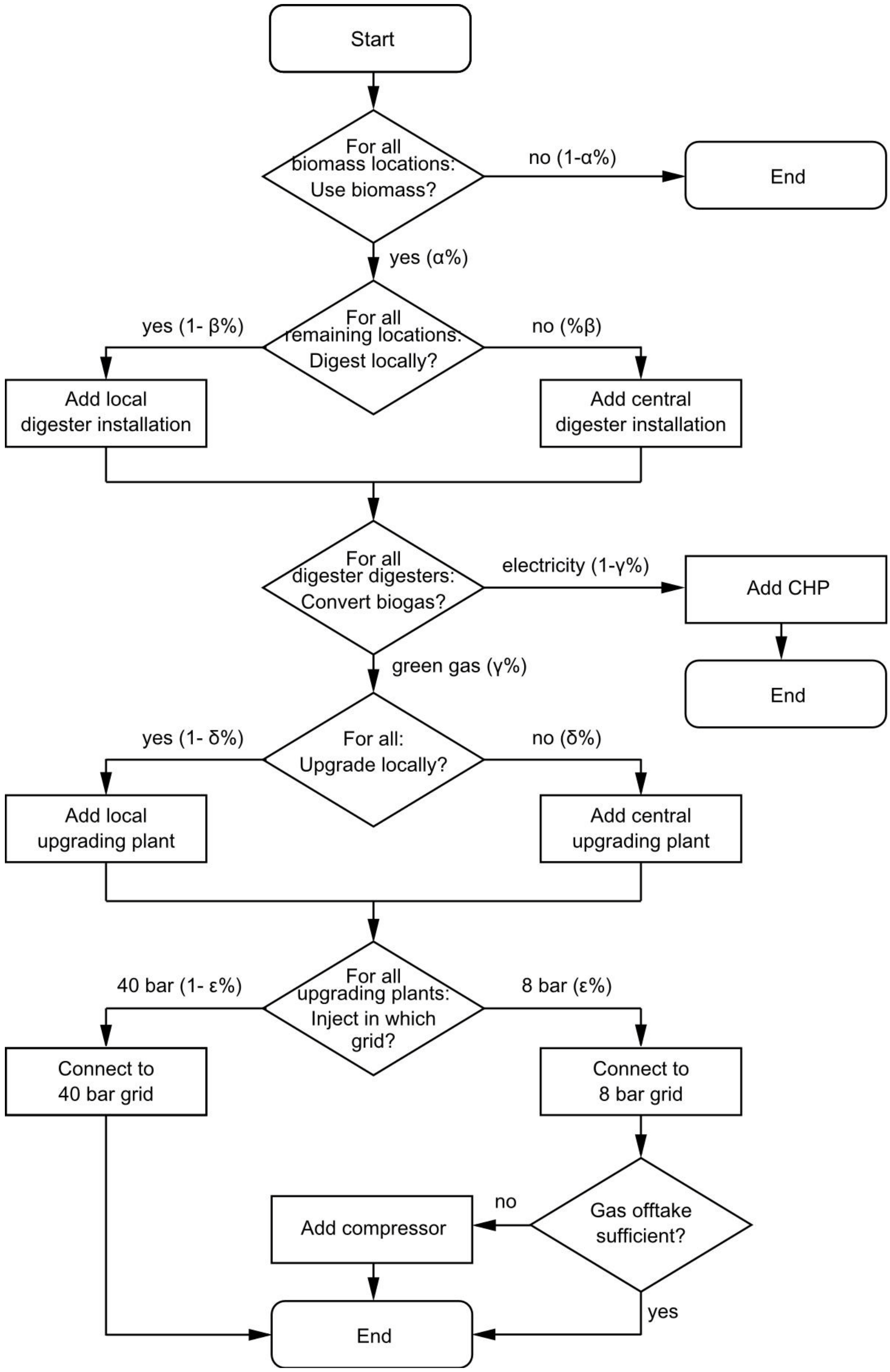


Figure 3: Decision tree for the generation of solutions

Step 1: For each biomass location, choose whether to use the biomass. The biomass is utilized with chance α%. This step is repeated till for all biomass locations it is decided whether the biomass will be utilized or not.

Step 2: Of the locations which biomass will be utilized, choose whether to digest the biomass locally or at a central location. Biomass is digested at a central location with chance β%. This again is repeated till for each location is decided whether its biomass will be digested locally or at a central location.

A digester is allocated to all the locations where the biomass is digested locally. For the locations which biomass will be digested centrally, a pool with biomass locations is created. Till this pool is empty, the DST picks a random number which is the number of biomass locations that will share a central digester installation. Among these biomass locations one is chosen where the digester installation will be placed. Along with this, the DST decides on the routes for the biomass transport from the biomass location to the central digester installation. This step can result in multiple central digester installations.

Step 3: Once all the digester installations have been allocated, the tool chooses for each digester installation what to do with the biogas. With chance γ% the biogas will be upgraded to green gas, and with chance $(1-\gamma)$% the biogas will be converted into electricity in a CHP installation. If the biogas will be converted into electricity, a CHP installation is allocated at the corresponding digester installation location.

Step 4: For all the digester installation locations which biogas will be upgraded to green gas, the tool chooses whether the biogas should be upgraded locally or at a central location. With chance δ% the biogas will be upgraded centrally.

For the locations where the biogas will be upgraded locally, an upgrading plant is allocated adjacent to the digester installation. For the locations which biogas will be upgraded centrally, again a pool is created. The DST generates a random number which indicates how many digester installations will share an upgrading plant. This is repeated until the pool is out of upgrading plants. Among the digester installation locations that share an upgrading plant, one will be picked randomly to which the upgrading plant will be allocated. In this step also the pipelines are laid that will transport the biogas to the central upgrading plant. This step can result in multiple central upgrading plants, and consequently multiple separate biogas networks.

Step 5: For each upgrading plant, the DST will choose whether the green gas will be injected into the 8 bar grid or will be fed to the gas receiving station (GRS) - which connects the 40 bar grid to the 8 bar grid by reducing the pressure from 40 bar to 8 bar. The gas will be injected into the 8 bar grid with chance ε%. The DST allocates the injection stations adjacent to the upgrading plant, and also lays the required pipelines to transport the green gas to the 8 bar grid or the GRS.

Step 6: The DST checks whether the gas offtake at each hour during a year is sufficient to consume all the green gas that is injected into the 8 bar grid. If the gas offtake shows to be insufficient, the DST adds a compressor that will inject gas from the 8 bar grid into the 40 bar grid in times of green gas surplus. It is assumed that the gas demand in the 40 bar grid is sufficient.

Each time a building block is placed, it will be scaled to the required size. The reason we chose to use random generation instead of total enumeration is the fact that the possible number of solutions would explode in any real sized problem and therefore, the problem would become insolvable.

The values for the variables α, β, γ, δ, and ε are set by the user. Since, finding the right values for the variables is a matter of trial and error, it can be quite cumbersome for the user to find the best configuration of values for the variables. Therefore, in a later version of the DST we want to incorporate an algorithm that adjusts these parameters automatically in such a way that the solution space is explored optimally. Furthermore, procedures can be incorporated in the DST to explore the solution space in a smarter way.

In addition, in a later version of the DST more design knowledge will be incorporated to reduce the size of the solution space. Adding design knowledge prevents the DST from generating solutions that are known to be non-optimal beforehand.

In the next step the generated solution will be validated.

3.4. Validate

This step verifies whether the capacity of the pipelines is sufficient to provide every consumer with gas. For this step an interface has been created with IRENE Pro 4.1 [5], which is a tool created by Kiwa Gas Technology that can be used for gas grid calculations and analysis. IRENE Pro 4.1 uses the Hardy Cross iterative calculation method, based on the two laws of Kirchhoff. If the analysis performed by IRENE Pro 4.1 shows that the capacity of the gas grid is insufficient, this solution will be rejected. Otherwise, the solution will move on to the *Analysis* step, where the performance criteria will be determined.

3.5. Analysis

In this step the two performance criteria will be determined. The performance criteria are annual cost and annual CO_2 emission reduction. The values and equations given in appendix A are used to calculate these performance criteria.

The costs are calculated as yearly costs [€/year]. Therefore, costs that are given as initial investment costs have to be converted to annual costs. We do this by assigning a useful life to the building block. For the conversion of present cost to annual cost, we use an interest rate of 6%. Furthermore, when we have to deal with different useful lives we use the repeatability assumption to deal with this, see [6] for a more elaborate discussion on the conversion from present cost to annual cost and the repeatability assumption.

For the CO_2 emission reduction, we calculate the annual kilograms of CO_2 saved. We have determined the CO_2 emission of natural gas, and for each m^3 of green gas added to the gas grid we subtract the CO_2 that would otherwise have been emitted using natural gas. The reason that this does not result in 100% CO_2 reduction is the fact that we also incorporate the increase in CO_2 emission due to the energy required for the production of green gas. In a similar way, we calculate the CO_2 emission reduction for the conversion of biogas to electricity. We determined the average CO_2 emission of 1 MJ of electricity, and for each MJ of green electricity that we produce, we can subtract that amount from the total annual emission. In addition, when digesting manure also a significant amount of CH_4 is prevented from being emitted into the air. Therefore CH_4 emission reduction is taken into account for the CO_2 emission reduction. We assume that per kilogram of biomass that is digested, 20 grams of CH_4 is prevented from being emitted [7].

3.6. Results

The performance criteria of all generated solutions that were found to be valid were determined in the previous step. So each valid solution has a value for cost and CO_2 emission reduction. In this step among all solutions, the set of pareto optimal solutions is chosen [8]. A pareto optimal solution is a solution that could not score better on one performance criteria without deteriorating another performance criterion. In other words, a solution is called pareto optimal if there does not exist another solution which has a better performance for at least one of the objective functions and an equal performance for the other objective functions. In our case study this would result in a set of solutions each with its own trade-off between cost and CO_2 emission reduction.

4. CASE STUDY

To demonstrate that the DST is a good way to provide insight in the available investment options and aids in the investment decision process we performed a case study. For our case study we used the gas distribution grid of the Dutch municipality of Zutphen.

In this section we first describe the starting configuration, i.e. the existing gas grid, the gas demand of the consumers connected to this grid, and the available biomass locations (subsection 4.1). Next in subsection 4.2 the results of this case study are presented and discussed. Finally, in subsection 4.3 conclusions are drawn on the performed case study.

4.1. Starting configuration

Gas grid topology: For this case study we consider the 8 bar grid of Zutphen and the GRS that connects the 40 bar grid to the 8 bar grid. Figure 4 shows the 8 bar grid, the GRS, and also the district stations that reduce the pressure from 8 bar to 100 mbar. The black square indicates the GRS; the dots in various tones of grey indicate the district stations.

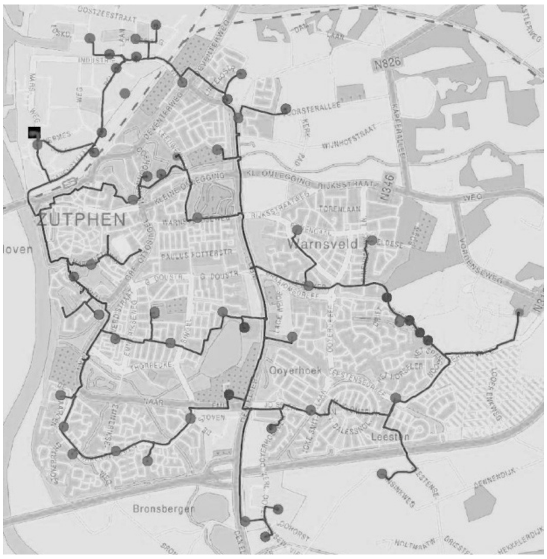


Figure 4: 8 bar grid of the municipality of Zutphen [10]

Biomass locations and availability: In the region of Zutphen there are on average 119 cows on a farm and each cow produces around 14,000 kg of manure per year. Taking the average to be the case for each farm, this leads to a biomass availability of 211 kg biomass/hour (including 10% maize). With the aid of Google Earth, we identified 21 cattle farms in the municipality of Zutphen and the corresponding GPS coordinates. The biomass locations together with the 8 bar grid were incorporated in the DST. Figure 5 shows the biomass locations together with the 8 bar grid, as represented in Matlab [9]. In Figure 8(d), an explanation is given for the symbols used.

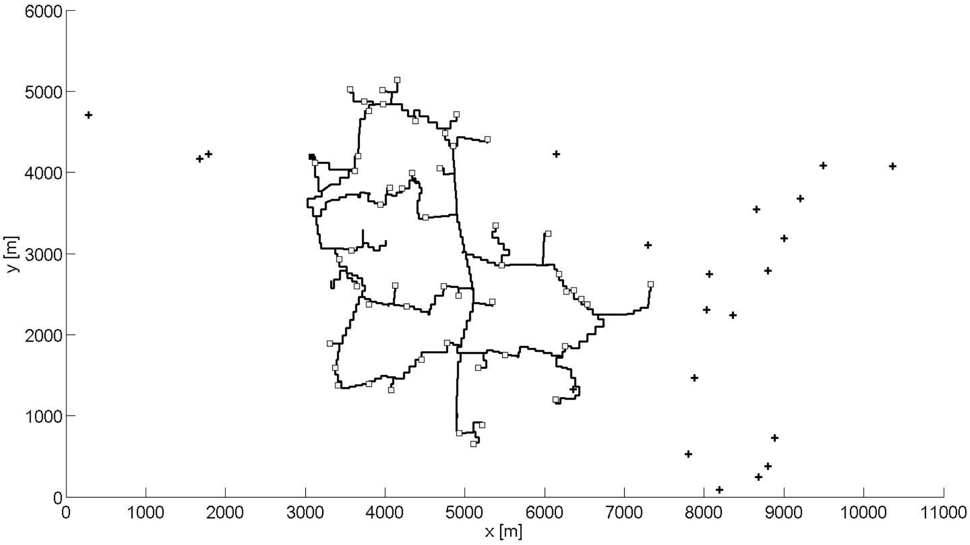


Figure 5: 8 bar grid and biomass locations as represented in Matlab

Gas demand: Figure 6 shows the gas throughput of the GRS connected to the 8 bar grid of Zutphen. Since we do not have detailed information of each individual customer or district station, we choose to distribute the gas demand equally among the 52 district stations that reduce the pressure from 8 bar to 100 mbar.

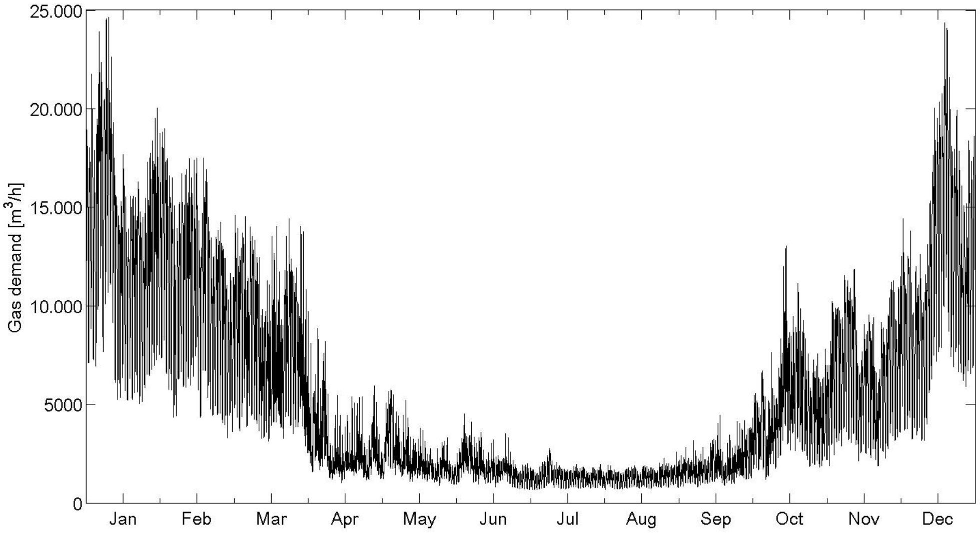


Figure 6: Hourly gas throughput of the GRS of Zutphen in 2009 [10]

4.2. Results

For the generation of solutions the variables that determine the chances (see subsection 3.3) are varied. The following values are assigned to the variables:

- For α: 0.25; 0.5; 0.75; 1
- For β, γ, δ, and ε: 0; 0.25; 0.5; 0.75; 1

This leads to $4 * 5^4 = 2500$ possible options. For each option we let the DST generate 10 solutions. This leads to a total of 25,000 generated solutions.

Figure 7 shows in grey the performance indicators for all the solutions generated by the DST for this case study. The set of pareto optimal solutions is indicated with black, which comprises 137 solutions. As can be seen, all solutions generated by the DST are unprofitable.

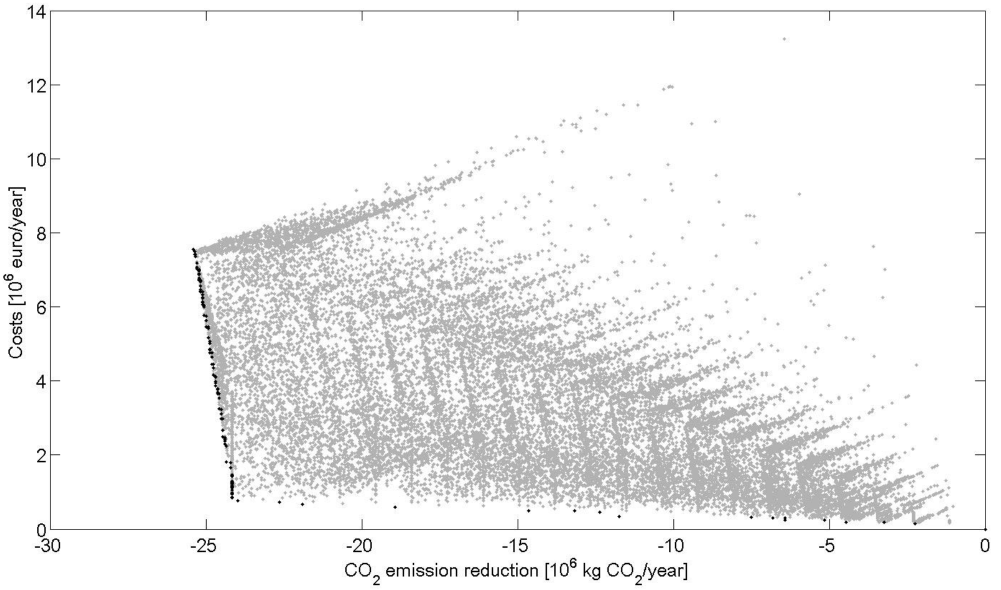
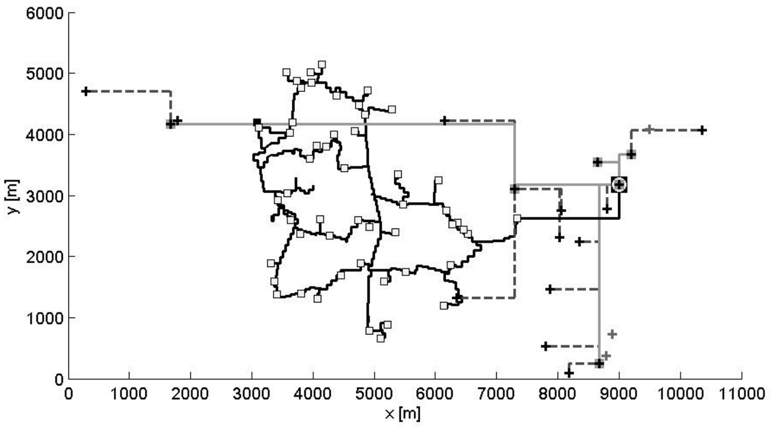


Figure 7: Values of performance indicators for all generated solutions for both runs. Pareto optimal solutions are indicated with black

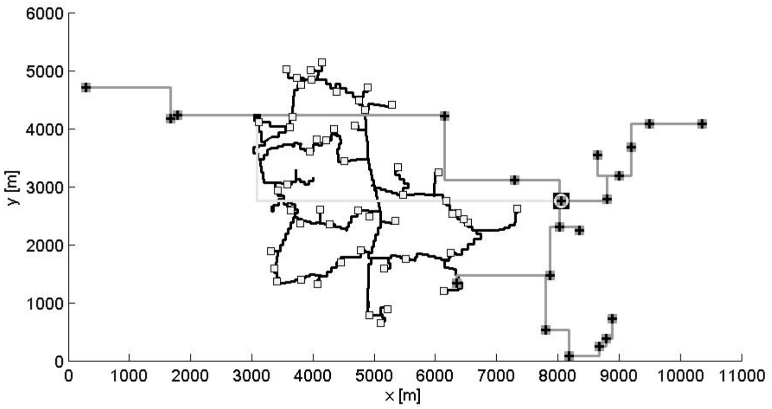
Figure 8 shows three examples of the pareto optimal solutions and in Figure 8(d) the legend belonging to the solution representation is shown. In addition, in Table 1, the performance indicators of these three solutions are shown. In the table, the total yearly CO_2 emission reduction is split up in the CO_2 emission reduction due to the CH_4 that is prevented from being emitted by digesting the manure; the CO_2 emission reduction due to the replacement of fossil energy by renewable energy; and the CO_2 emission increase due to the energy required for the production of green gas or green electricity. The table splits the total yearly cost into investment costs, operational costs, energy costs, biomass costs, and energy retail profit.

	Solution 1	**Solution 2**	**Solution 3**
Total CO_2 reduction [10^6 kg/year]	18.9	24.2	25.4
CO_2 reduction by not emitting CH_4 [10^6 kg/year]	19.3	22.5	22.5
CO_2 reduction by energy replacement [10^6 kg/year]	1.44	1.68	2.91
CO_2 emission by energy usage [10^6 kg/year]	1.80	0.04	0.02
Total costs [10^3 €/year]	596	841	7,540
Investment costs [10^3 €/year]	473	1,140	774
Operational costs [10^3 €/year]	218	563	7,950
Energy costs [10^3 €/year]	651	4.89	1.87
Biomass costs [10^3 €/year]	116	136	136
Energy retail profit [10^3 €/year]	861	1,000	1,320

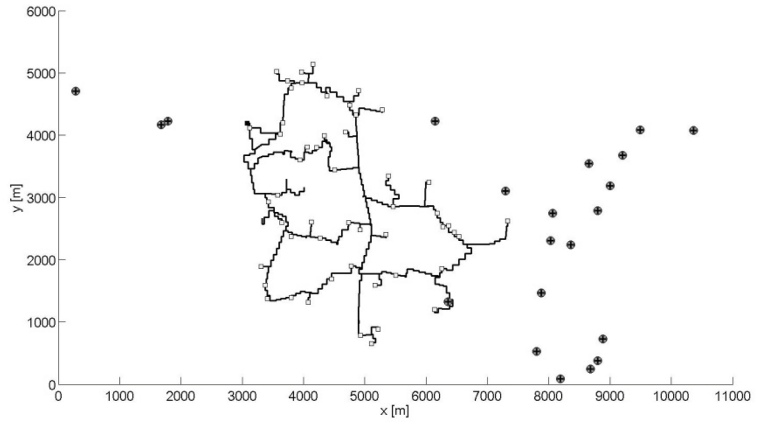
Table 1: Performance indicators for the three example solutions



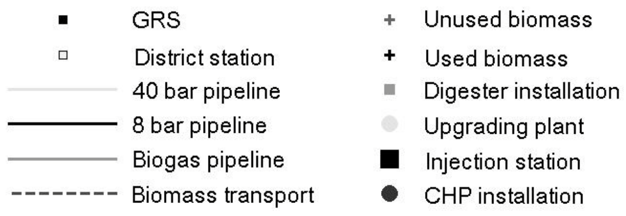
(a) Solution 1



(b) Solution 2



(c) Solution 3



(d) Legend

Figure 8: Examples of pareto optimal solutions

Figure 8(a) shows solution 1. Of the three selected pareto optimal solutions from Figure 8, this is the solution with the lowest yearly cost, but also with the lowest CO_2 emission reduction. In total 18 biomass locations are used in this solution. Of these 18 biomass locations, 12 transport there biomass to a digester installation located elsewhere. There are 5 digester installations that digest biomass of multiple biomass locations, and one digester installation digest only the biomass available at its own site. The biogas produced by these 6 digesters is transported by means of a biogas pipeline to one central upgrading plant. The green gas produced by the upgrading plant is injected into the 8 bar grid. Of the three solutions this one requires the highest energy costs ($6.51*10^5$ €/year compared to $4.89*10^2$ and $1.87*10^2$ €/year). This is caused by the energy required for the transport of biomass.

Figure 8(b) shows solution 2. This solution has a higher yearly cost but also a higher yearly CO_2 emission reduction compared to the first solution. In this solution, the biomass of all 21 locations is utilized. At each location the biomass is digested locally. The biogas produced by each digester is transported by means of a biogas pipeline to one central upgrading plant. The green gas produced by this upgrading plant is injected into the 40 bar grid.

Figure 8(c) shows solution 3, which is the top left pareto optimal solution of Figure 7. This solution has the highest CO_2 reduction of all generated solutions. Of the three solutions shown in Figure 8, it has the highest yearly cost. As can be seen, the biomass of all locations is used. At each biomass location a digester installation is assigned. The biogas produced by each digester installation is converted to electricity by means of a CHP installation, which are all located adjacent to the digester installation.

Examination of all 137 pareto optimal solution shows that when we move on the CO_2 emission reduction axis from right to left (see Figure 7), we start with configurations where a small number of biomass locations is utilized, and a significant amount of the biomass is transported to a central digester installation (see for instance Figure 8(a)); moreover the biogas is often transported by means of biogas pipelines to a central upgrading plant. As we reach the vertical line, the biomass of all locations is used and the biomass transport slowly vanishes in the solutions. Instead, most of the biomass is digested locally. Furthermore, the biogas produced by the digester installation is increasingly transported by biogas pipelines to one or more central upgrading plants (see for instance Figure 8(b)). Then as we move upwards on the vertical axis, the number of CHPs gradually increases till on the top left side of the graph, the biogas of each digester is converted into electricity.

Finally, an observation that can be made from Table 1 is that the largest share of the total CO_2 reduction is due to the methane that is not emitted. The replacement of fossil energy by renewable energy is only responsible for a small share of the total CO_2 emission reduction.

4.3. Conclusions

Figure 7 showed the performance indicators of the 25,000 generated solutions. Of those 25,000 solutions, 137 solutions were found to be pareto optimal. None of the solutions found in our preliminary model is profitable.

From observing the pareto optimal solutions, of which Figure 8 showed three examples, we found that cost-wise there is a preference for centralization. Digesting biomass at a central location, and upgrading the biogas at a central location was shown to be the most cost-efficient way of utilizing biomass.

From a CO_2 emission reduction perspective the central digestion of biomass is, however, unwanted, since this results in extra CO_2 emission due to the transport fuel required to transport the biomass. Furthermore, the conversion of biogas to electricity by a CHP results in more CO_2 reduction than conversion of biogas to green gas. This is mainly due to the fact that the CO_2 emission of one MJ of "fossil" electricity use is higher than the CO_2 emission of one MJ of natural gas use.

The amount of green gas produced in each of the pareto optimal solutions never exceeded the gas demand in the 8 bar grid. Hence, the addition of a gas compressor was not necessary.

Furthermore, we found that preventing CH_4 from manure from being emitted is responsible for the largest share of CO_2 reduction. The replacement of fossil energy by renewable energy is responsible for only a small part of the total CO_2 emission reduction.

5. CONCLUSIONS

The case study showed that application of the DST is a good way to provide insight in the available investment options. Once the starting configuration is loaded into the DST, it generates a multitude of solutions. And the plots easily show how each solution performs compared to the other solutions. Hence, the tool promises to be of great added value to the DSOs.

There are however some drawbacks. It was quite cumbersome to translate the gas grid layout provided by Alliander to a format which can be used by the DST, it took us around 10 hours to implement. In a future version, this should be automated. Furthermore the text based user interface was not optimal either. Especially, when the DST will be used by one of the DSOs, this will be a barrier in using the tool. With these drawbacks in mind, we suggest several improvements for our DST in the next section.

6. FURTHER RESEARCH

This paper showed the proof of principle of the DST. The final DST will have improved functionality. First of all, when looking at the ease of use of the DST, incorporating the gas grid topologies should be automated. At the moment, this is done manually and proved to be quite cumbersome - the 8 bar of Zutphen grid took about 10 hours to implement. In addition, the user interface should be improved. At this moment the tool is executed from the Matlab command window. In the future we want this to be a graphical user interface to improve the ease of use.

The number of building blocks should be expanded: more types of for instance digester installations and upgrading plants should be added to the database of building blocks. The number of performance indicators will also be expanded with at least: energy usage and reliability. Also we want

to incorporate interactions with the electricity grid; what investment can be made in the gas grid in order to complement the electricity grid. Furthermore, we want to incorporate multiple gas qualities in the gas distribution grid and how this will affect the optimal investment option in the grid.
Furthermore, the tool should take more real life boundary conditions into account. For instance, the pipelines that are laid by the DST should better incorporate the topology of the surroundings. For the solution generation, we want to add more design knowledge to it. This will prevent that the DST will generate a solution that is beforehand known to be sub-optimal. Hence, this design knowledge will reduce the solution space that the DST has to explore. Furthermore, we want to implement several procedures for the solution generation that allow a smarter way of exploring the solution space. This will prevent that the DST focuses on a too narrow part of the solution space.

When looking at research to be performed with the DST, we want to perform a thorough sensitivity analysis on the parameters of the building blocks and the general parameters of the model. This will demonstrate how these values influence for instance the economic feasibility of a green gas project. An interesting aspect would be to see how the required gas quality influences the costs of green gas projects. Would a broader Wobbe band reduce cost of a green gas project?

APPENDIX A. MODEL

A.1. General

Description	Value	Unit
Interest rate (MARR) [10]	6	%/year
Economic life of biogas project	12	years
Gas retail price [11]	0.2938	€/m^3 green gas
CO_2 emission natural gas	2.00	kg CO_2/m^3 natural gas
Green gas subsidy [12]	0.905	€/m^3 green gas
Electricity retail price [11]	0.021	€/MJ
Cost of electricity [11]	0.021	€/MJ
CO_2 emission of electricity generation [13]	0.169	kg CO_2/MJ
Green electricity subsidy [12]	0.0558	€/MJ
Cost of transport fuel [14]	0.027	€/MJ
CO_2 emission of transport fuel [15]	0.074	kg CO_2/MJ
Capacity of a biomass transporter [15]	20,000	kg
Energy use of a biomass transporter [15]	14.4	MJ/km
Cost of biomass [4]	0.0035	€/kg biomass
CH_4 emission biomass [7]	0.02	kg CH_4/kg biomass
CO_2 equivalent CH_4	29	kg CO_2/kg CH_4

Table 2: General parameters

A.2. Pipelines

The table below indicates the average price for laying a pipeline; they also include overhead costs within the DSO [10]. The actual prices vary significantly depending on the location where the pipeline is laid. In the equation for the investment costs, W indicates the diameter of the pipeline [m].

Description	Value	Unit
Investment cost	$1679W^2+71.73W+62.84$	€/m
Maximum pressure	8	bar

Table 3: Pipeline parameters

A.3. Digester installation

Below the data of two digester installations is given, the input for both is a biomass mix composed of 90% manure and 10% maize. The output of the digester installation is biogas which contains 57% methane. Both digesters are identical with the difference that the second digester has a compressor with it which is used to feed biogas to a biogas pipeline. Furthermore, the costs for both digesters include the cost for the desulphurization of the biogas, which is a required step whether or not the biogas is directly fed to an upgrading plant or is first injected into a biogas pipeline. Data is derived from [4]. X is the biogas output in m^3/hour.

Description	Digester 1	Digester 2	Unit
Investment cost	$3287.3X+206{,}370$	$-0.169X^2+3659.5X+280{,}360$	€
Biomass input	28.43	28.43	kg/m^3
Energy usage	0.02889	0.0651	MJ/m^3
Operational costs	$514.5X+18{,}750$	$514.5X+21{,}333$	€/year
Desulphurization costs	$9.17*10^{-6}X^2-0.0093X+3.1$	$9.17*10^{-6}X^2-0.0093X+3.1$	€ct/m^3

Table 4: Digester installation parameters

A.4. Upgrading plant

The upgrading plant is a PSA upgrading plant. Y is the biogas input m^3/hour. The output of the upgrading plant is green gas which contains 90% methane. The values are derived from [4]

Description	Value	Unit
Investment costs	$1.0117Y+901.67$	10^3 €
Green gas output	$0.614Y$	m^3/year
Energy use	$555.6Y$	€/year
Operational costs	$0.026667Y+27.867$	€/year

Table 5: Upgrading plant parameters

A.5. CHP installation

Below the data used for the CHP installations is given, the data is derived from [16]. Z is the output in kW of the CHP installation.

Description	Value	Unit
Investment costs	$4639Z^{-0.333}$	€
Biogas input	0.079365	m^3/MJ
Major overhaul every six years	13.295Z+2755.7	€/year
Maintenance costs	$432.8Z^{0.7781}$	€/year

Table 6: CHP installation parameters

A.6. Gas compressor

Below the data for three compressor types is given. The first compressor compresses gas from 1 bar to 9 bar and is an injection station that injects green gas in the 8 bar grid (see section 3.2). The second compressor compresses gas from 9 bar to 41 bar and is used to feed gas from the 8 bar grid to the 40 bar grid in times of green gas surplus (see section 3.2). The third compressor compresses gas from 1 bar to 41 bar and is an injection station that that injects green gas in the 40 bar grid. V is the compression rate of the compressor [m^3/h].

We obtained investment prices, operational costs, and energy usage for several compressors that compress gas from 1 bar to 9 bar from [17]. We fitted a line to the investment costs. For the other two compressors we assumed similar investment costs. Furthermore, we extrapolated the energy use of these compressors by the assumption that it is an adiabatic process, and that the energy efficiency is equal for all compressors.

Compr. #	Investment costs [€]	Energy use [MJ/m^3]	Useful life	Operational costs [€/year]
1	$-0.169V^2+372V+58,994$	0.0339	25	2320
2	$-0.169V^2+372V+58,994$	0.0686	25	2320
3	$-0.169V^2+372V+58,994$	0.0218	25	2320

Table 7: Gas compressor parameters

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Table 6: CHP installation parameters

Table 7: Gas compressor parameters