CHAPTER 2

When does decentralized production of biogas and centralized upgrading and injection into the natural gas grid make sense?

ABSTRACT
The production of biogas through anaerobic digestion is one of the technological solutions to convert biomass into a readily usable fuel. Biogas can replace natural gas, if the biogas is upgraded to green gas. To contribute to the EU-target to reduce Green House Gases emissions, the installed biogas production capacity and the amount of farm-based biomass, as a feedstock, has to be increased. A model was developed to describe a green gas production chain that consists of several digesters connected by a biogas grid to an upgrading and injection facility. The model calculates costs and energy use for 1 m³ of green gas. The number of digesters in the chain can be varied to find results for different configurations. Results are presented for a chain with decentralized production of biogas, i.e. a configuration with several digesters, and a centralized green gas production chain using a single digester. The model showed that no energy advantage per produced m³ green gas can be created using a biogas grid and decentralized digesters instead of one large-scale digester. Production costs using a centralized digester are lower, in the range of 5 €ct to 13 €ct per m³, than in a configuration of decentralized digesters. The model calculations also showed the financial benefit for an operator of a small-scale digester wishing to produce green gas in the cooperation with nearby other producers. E.g. subsidies and legislation based on environmental arguments could encourage the use of decentralized digesters in a biogas grid.

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When does decentralized production of biogas and centralized upgrading and injection into the natural gas grid make sense? 
2.1 INTRODUCTION

The European Union (EU) target to reduce Green House Gases (GHG) emissions by 2020 encourages the use of biomass as a source of renewable energy. The production of biogas through anaerobic digestion is one of the technological solutions to convert biomass into a readily usable fuel. The biogas can, after cleaning, produce heat in a quality adapted burner, or electricity and heat in a Combined Heat and Power (CHP) unit. Biogas can also be transformed into green gas by upgrading. Green gas has the same quality as natural gas, in our case Dutch natural gas, and can replace natural gas. Injection of green gas into the natural gas grid allows the use of the natural gas grid for long distance transport and balancing demand and supply by storage [1]. At this moment biogas is mainly produced in single digester plants and used in a CHP. To contribute to the EU-target, the installed biogas production capacity and the amount of farm-based biomass, as a feedstock, has to be increased [2-4].

Research has been done to optimize the supply chain of biogas and green gas from biomass. The biomass supply chain for biogas production and for a green gas production unit has been described extensively (e.g. Refs. [5-7]). In addition, others describe the different steps within the chain, the production of biomass i.e. organic dry matter per ha, the transport and logistics of biomass (e.g. Ref. [8]), the performance of the digester and the treatment and upgrading of the biogas (e.g. Ref. [9]). A recent review is available [10].

However, in the above-mentioned papers, the authors presented results for biogas produced by a single digester. The size of this one digester is adjusted to the available feedstock and to the required output of biogas. These papers do not show results for the production of biogas from several digesters, spread in a region, from which the produced biogas is collected to be processed in a joined upgrading and injection facility. The produced biogas can be transported from decentralized digesters to an upgrading and injection facility by dedicated pipelines i.e. a biogas grid or a biogas network. Large-scale production of green gas has a scale advantage for the capital costs and energy use for the digester or upgrading and injection facilities. On the other hand, the transport and logistics of the biomass and digestate give a scale disadvantage for costs and energy use [11].

In a given region a configuration of several small-scale decentralized digesters and a centralized upgrading and injection plant could combine the scale advantage in capital costs and energy use, avoiding the scale disadvantages regarding transport and logistics of biomass [12]. Furthermore large scale digestion introduces environmental drawbacks, e.g. a high number of transport movements at the digester is needed to collect the biomass and to remove the digestate [11].

In Section 1.2 an overview of the information available on biogas grids is presented. It was found that this information is mostly available only from project reports and feasibility studies. Many of the case studies are specific for a certain region. Some studies cover the distribution of biogas from a single digester to one or more users, e.g. CHP units. Other studies take the existing natural gas grid as a starting point, and discuss the impact on this natural gas grid caused by the injection of green gas. In contrast, we evaluated a general operational model to describe the green gas production chain that consists of several digesters connected to an upgrading and injection...
facility by a biogas grid. The model calculates costs and energy use for 1 m³ of green gas in the complete chain, with the volume of gas at an absolute pressure of 0.101325 MPa and a temperature of 273.15 K [1]. The number of digesters in the chain can be varied to find results for different configurations. The aim of the study is to evaluate the impact of different configurations, i.e. the number of digesters, on the costs and energy use. More specifically, we are interested to find out how results differ for a chain with decentralized production of biogas, a configuration with several digesters, and a centralized green gas production chain using a single digester.

### 2.2 BIOGAS GRID, STATE OF THE ART

Bärnthaler et al. [13] gave a detailed description and calculations for distribution of biogas through a micro grid. A small size digester (32.5 to 250 m³h⁻¹) produces the biogas. Different types of micro-grids are considered, including a rural village and a light industrial area, with and without connection to the natural gas grid. Technical solutions, biogas storage, a simulation and profitability are discussed. Also Austrian legal aspects and subsidies can be found. Furthermore an Austrian case study shows engineering and economic aspects for a local biogas grid in Güssing [14]. It is shown that a biogas grid may increase profitability of a biogas plant. A biogas grid enables the efficient use of heat produced by CHP in district heating.

Swedish, Danish, Belgian and Dutch parties participated in a study to reduce the risks associated with design choices for biogas network configurations [15]. This study gives an inventory of current practices in several countries in Europe. Besides cost analysis and technical evaluation of specific cases, the authors emphasized risk identification and assessment. It is concluded that the safety regime of the natural gas grid should apply. In addition, extra measures need to be taken e.g. because of the corrosive and poisonous nature of biogas, and there is risk of overpressure. Based on the assessment of typical cases it is concluded that construction of biogas pipelines requires a relatively large investment, and that the transport costs of manure could be crucial to the profitability of the business case.

In the Netherlands, the Distribution Service Operators (DSO) initiated projects to study the impact of integrating the biogas production into the natural gas distribution grid. Because of an increase in the share of green gas, a change in the gas distribution grid is foreseen. Weidenaar [16] used a simulation. In his model, the end use of the biogas is either upgrading and injection into the gas grid, or production of power by CHP. The aim is the development of a Decision Support Tool (DST) that can be used to evaluate costs and CO₂-reduction. The methodology of this first study started from an existing gas grid. The potential biogas supply and demand in the province of Noord-Holland is shown in a survey [17]. Nine local biogas grids were suggested to connect the production units and users. Another case study [18] examined the grid area of the DSO Endinet in the Dutch province Noord-Brabant. This study aimed at the full potential of digesting all manure available in this area; the effect of adding some maize for co-digesting is included. Green gas injection is analysed for different pressure levels in the natural gas grid. The
gas demand profile showed a summer surplus of biogas. Technical solutions for the mismatch were compared and an indication of costs was given. The case study assumed that all biogas is upgraded and injected into the natural grid and the focus was on this specific grid area. The infrastructural investments by the DSO in several scenarios were calculated. Smits et al. [19] presented a feasibility study for a local biogas grid, that is used to distribute the biogas. Several alternatives are presented and the inventory of the components needed in the grid is shown. Similar work for other local initiatives can be found [20, 21].

Klocke et al. [22] presented results for green gas production with a biogas collection pipeline for the German region Nordrhein-Westfalen. The emphasis was on environmental issues; in particular water quality is addressed in relation with the digestate processing. This study gives technical and economical results, but also the business model and a communication concept. It is concluded that a sustainable green gas system in the region is possible, if a plan is made using an integrated approach. In another report a case study for a micro biogas network can be found [23]. The report gives details on the implementation of CHP-units to serve a heat distribution system in the built environment. Other case study summaries can be found in presentations by engineering firms [24, 25].

Concluding from this overview, we state that earlier biogas grid studies were predominantly case studies, either for a certain area or in combination with an existing natural gas grid. The distribution, and not the collection, of biogas is often addressed. We did not find any reports showing the energy consumption associated with a biogas grid as part of a green gas production chain. Table 2.1 summarizes some of the information on the sources in this section.

Table 2.1: Summary biogas grids, state of the art

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>&lt; 250</td>
<td>1</td>
<td>d1</td>
<td>e1, e2</td>
<td>f1</td>
<td>1.13 … 7.525</td>
<td>h1, h3, h8</td>
</tr>
<tr>
<td>14</td>
<td>approx. 850</td>
<td>1</td>
<td>d1</td>
<td>e2</td>
<td>f1</td>
<td>3.155</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>150 … 2050</td>
<td>1, 2, 5 and 1</td>
<td>d1, d2</td>
<td>e1</td>
<td>f1, f2</td>
<td>3.6 … 29</td>
<td>h1, h2, h3</td>
</tr>
<tr>
<td>16</td>
<td>depending on farm size</td>
<td>variable</td>
<td>d2, (d1)</td>
<td>e2</td>
<td>f2</td>
<td>variable</td>
<td>h1, h5</td>
</tr>
<tr>
<td>17</td>
<td>approx. 75 (farm based)</td>
<td>approx. 80 in 9 separate grids</td>
<td>d1, d2, d3, d4</td>
<td>e2</td>
<td>f1, f2</td>
<td>5 &lt; 65</td>
<td>h1, h4, h5</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>-</td>
<td>d2</td>
<td>e2</td>
<td>(f2)</td>
<td>-</td>
<td>h1, h5</td>
</tr>
<tr>
<td>19</td>
<td>400 or 900</td>
<td>1</td>
<td>d1</td>
<td>e2</td>
<td>f3</td>
<td>approx. 0.5</td>
<td>h1, h6, h7, h8</td>
</tr>
<tr>
<td>20</td>
<td>1500</td>
<td>1</td>
<td>d1, d2, d3, d4</td>
<td>e2</td>
<td>f1</td>
<td>&lt; 11</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>-</td>
<td>-</td>
<td>d2</td>
<td>e2</td>
<td>f3</td>
<td>-</td>
<td>h1, h5</td>
</tr>
<tr>
<td>22</td>
<td>250 (125 &lt; 500)</td>
<td>8</td>
<td>d2</td>
<td>e2</td>
<td>f2</td>
<td>29 … 80</td>
<td>h1, h5, h10</td>
</tr>
<tr>
<td>23</td>
<td>50 and 76</td>
<td>2</td>
<td>d1</td>
<td>e2</td>
<td>f2</td>
<td>2.3 or 3.2</td>
<td>h1</td>
</tr>
<tr>
<td>24</td>
<td>210 … 1000</td>
<td>1</td>
<td>d1</td>
<td>e2</td>
<td>f3</td>
<td>1.8 … 20</td>
<td>h1, h6, (h9)</td>
</tr>
<tr>
<td>25</td>
<td>250 to 500</td>
<td>1 (to 4)</td>
<td>d1</td>
<td>e2</td>
<td>f1, (f2)</td>
<td>9 (to 12)</td>
<td>-</td>
</tr>
</tbody>
</table>

A: Reference; B: Digester size m³/h biogas; C: Number of digesters in the biogas grid; D: Final use (d1=CHP; d2=Green gas; d3=Industry; d4=Transport); E: Case study (e1=Typical case; e2=Specific region); F: Functionality (f1=Distribution of biogas; f2=Collection of biogas; f3=Transport only); G: Total length pipeline (km); H: Biomass (h1=Manure; h2=Water treatment sludge; h3=Food waste; h4=Grass; h5=Co substrate; h6=Maize; h7=Glycerin; h8=Industrial waste; h9=Rye; h10=Local available biomass.
2.3 METHODOLOGY

For this study a model was developed to calculate costs and energy use per m$^3$ produced green gas in a green gas production chain with several digesters connected by a biogas grid to an upgrading and injection facility. The model is used to calculate results for different configurations i.e. for different number of digesters used in the chain. In this section a model description is presented. First the model structure is shown, followed by some remarks on logistics and transport of the biomass as part of the production of biogas. The description of the biogas transport shows the assumed grid lay-out and gives details on the calculations of energy use and costs in the grid.

The structure of the model is based on [11] and shown in Figure 2.1. The production of biogas is described using five transformation blocks: Biomass production, Manure & Biomass transport, Manure & Biomass storage, Digester and Digestate handling. In addition to these a separate transformation block takes care of the biogas transport from several digesters to the Upgrading and Injection facility. Upgrading and Injection is found in the third part. The transformation blocks are used to describe the physical stream from left to right. “Auxiliary streams, like energy and finances, are also shown using dotted arrows” (Bekkering et al. [11]).

**Figure 2.1:** A green gas chain based on co-digestion, including biogas transport (adapted from [11]).

### 2.3.1 Biogas production and Upgrading & Injection

The model assumptions for Biogas Production and Upgrading & Injection can be found in Ref. [11]. Only basic data and assumptions on logistics and transport of manure, biomass and digestate are presented here, as logistics and transport are the topic of this study. The biogas is produced at a farm location, using manure and biomass that is available at the farm and in the vicinity. It is assumed that manure and biomass, i.e. maize silage, is collected from a circular area around the farm to provide enough feedstock for the digester. The biomass is assumed to be homogeneous in the area, and 25% of the arable land area is used for growing energy maize.
Maize from the farmer’s own land is transported by tractors. Maize and manure, bought from other nearby farmers, are transported by trucks. In a similar way, digestate that needs to be returned to the land is transported by tractor and truck. In the model, the surplus of digestate is transported by truck to a destruction plant. Figure 2.2 shows the lay-out of the biomass and manure source area.

**Figure 2.2:** Lay-out of the manure and biomass source area.

In Area A, the farmer’s own land (65 ha), tractors are used to transport biomass and digestate to and from the digester, which is located at the centre of the circle. In area B, trucks are used for the transport of manure and biomass to the digester and to return digestate from the digester to the land.

For the average haul distance \( R_{ahd} \) of the biomass for area A, we use:

\[
R_{ahd,A} = \tau_A \cdot \frac{2}{3} \cdot R_A
\]

and for the area B:

\[
R_{ahd,B} = \tau_B \cdot \frac{2}{3} \cdot R_{tot} \cdot \frac{1 - \left( \frac{R_A}{R_{tot}} \right)^3}{1 - \left( \frac{R_A}{R_{tot}} \right)^2}, \text{ with the tortuosity factor } \tau_A = \tau_B = 1.5.
\]

### 2.3.2 The biogas transport

To model the biogas grid for an area, a Star lay-out [22] of the pipelines is assumed (Figure 2.3). The upgrading and injection facility is located at the centre, at the same place as one of the digesters. Biogas from the other digesters in the grid is transported by direct pipelines to this central place. The central place is sometimes referred to as a Biogas HUB or Green Gas HUB.

The next sections show how the costs to build and operate the biogas grid and the energy used for the biogas transport can be found and related to the produced amount of green gas.
Figure 2.3: Star Lay-out of the biogas grid. An example of a configuration is shown. The biogas from four equally sized digesters is collected at the HUB.

2.3.2.1 Energy use for the biogas grid
To transport the biogas in the grid a compressor, placed close to the digester, is used to provide the pressure needed. Basic textbook (e.g. Ref. [1]) calculations show that the pressure drop in a straight pipeline and a circular cross-section depends on the length, the diameter and the capacity of the pipeline. Other data needed in this calculation are density $\rho$ (kg m$^{-3}$) and resistance coefficient $\lambda$ (-). Calculation of the resistance coefficient $\lambda$ depends on the Reynolds number $Re$ dealing with laminar or turbulent flow and absolute roughness $d$ (mm) of the inner pipe; the Prandtl & Colebrook equation was used. The energy needed by the compressor is calculated. In the Appendix the formula [27] and input data are presented. No provision is made for measurement and controlling the pressure in the grid, as the energy use is assumed to be negligible.

2.3.2.2 Costs for the biogas grid
The compressor investment cost function $I$ (in k€) depends on the capacity $C$ (in m$^3$h$^{-1}$) of the compressor (0 MPa to 0.8 MPa): $I = 111.257 + 0.1469 \cdot C$. The measure and control system and the costs to install the compressor are included. Opex is estimated to be 5% of the investments, the same as other installations in the model. The depreciation period in the model is 12 years, corresponding with the Dutch subsidy regime.
Table 2.2: Pipeline diameters and costs

<table>
<thead>
<tr>
<th>outside diameter in mm</th>
<th>inside diameter in mm</th>
<th>€ m⁻¹ easy</th>
<th>€ m⁻¹ moderate</th>
<th>€ m⁻¹ difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>90.0</td>
<td>40</td>
<td>100</td>
<td>160</td>
</tr>
<tr>
<td>160</td>
<td>130.8</td>
<td>80</td>
<td>120</td>
<td>170</td>
</tr>
<tr>
<td>200</td>
<td>163.6</td>
<td>98</td>
<td>134</td>
<td>210</td>
</tr>
<tr>
<td>250</td>
<td>204.6</td>
<td>123</td>
<td>198</td>
<td>258</td>
</tr>
<tr>
<td>315</td>
<td>257.8</td>
<td>135</td>
<td>215</td>
<td>300</td>
</tr>
</tbody>
</table>

Pipeline costs, as shown in Table 2.2, include the costs to install the pipeline. It is assumed that 60% of the pipeline can be easily installed (e.g. in a farmland) and 40% takes more effort i.e. difficult (e.g. passing roads). Maintenance can be taken to be 2% of the investment each year. For the pipelines a longer depreciation period is acceptable; in this model the depreciation period for the pipelines is set at 30 years. The information in this section on biogas grid costs are taken from Ref. [28].

2.3.2.3 Additional information

In the model the pressure calculation in the biogas grid is not influenced by the required pressure for the upgrading and injection. When engineering on a specific case, the pressure can be optimized for the complete sequence of transport of biogas, upgrading and injection [15, 28]. This means that energy use and investments could be lower than predicted by the model.

The investment costs of the pipeline balance with the operational costs of compression. A small diameter requires lower investments in the pipeline, but a higher pressure is needed to support the transport of biogas leading to higher energy costs. On the other hand, a wider pipeline requires higher investment, but lower energy costs. If operational pressures are low, a booster pump may be used instead of a compressor. This could reduce the investment costs for compression significantly. However with the use of booster pumps, the flow of the biogas in the grid is difficult to control [28], therefore this option was not considered.

Before compression and transport, dewatering and removal of H₂S is necessary. For the drying, a passive method is assumed. In case of manure and maize as a source, crude desulphurization can be achieved by internal biological removal in the digester at low investment and operational costs. A relatively small investment of € 5000 per digester is added to the pipeline investment to account for both dewatering and H₂S removal together (adapted from Ref. [15]). For other co-substrates, the levels of H₂S in the biogas can be much higher, resulting in higher investment and operational costs, leading to estimations of cleaning costs from 2.3 €ct up to 16 €ct per m³ biogas [29, 30]).

Safety measures add to investment costs and energy use for the biogas network. These can include safety valves, shutoff valves and a flare. The contribution to costs could be significant [15]. Therefore the investments in the pipelines is increased by k€ 100, to account for a flare. Odorization is considered not to be necessary, as this interferes with the upgrading process [28].
2.3.3 Configurations of digesters

In the model calculations for this article, we consider different sizes of the digester as shown in Table 2.3. The digester for 2036 m³ biogas fits a maximum size of 1200 m³ green gas for an upgrading plant. The digester for 254.5 m³ and 509 m³ biogas represents a small and an average sized farm digester, respectively. The source area radius for the co-substrate, maize, is calculated using data for the northern part of the Netherlands to match the required amount of co-substrate for the digester [11]. The area of the arable land is taken to be 21% of the total land area [31].

Table 2.3: Digester sizes included in the model calculations

<table>
<thead>
<tr>
<th>Biogas m³ h⁻¹</th>
<th>Green gas m³ h⁻¹</th>
<th>Manure Mg a⁻¹</th>
<th>Co-substrate Mg a⁻¹</th>
<th>Source area radius km</th>
</tr>
</thead>
<tbody>
<tr>
<td>254.5</td>
<td>150</td>
<td>9 250</td>
<td>9 250</td>
<td>3.53</td>
</tr>
<tr>
<td>509</td>
<td>300</td>
<td>18 499</td>
<td>18 499</td>
<td>4.99</td>
</tr>
<tr>
<td>1018</td>
<td>600</td>
<td>36 999</td>
<td>36 999</td>
<td>7.06</td>
</tr>
<tr>
<td>2036</td>
<td>1200</td>
<td>73 997</td>
<td>73 997</td>
<td>9.98</td>
</tr>
</tbody>
</table>

Figure 2.3 shows the lay-out of a configuration of four equally sized digesters. The source areas of the digesters touch each other. At the centre of the configuration one digester, upgrading and injection facility are located at the HUB. The pipeline distance from the other three digesters to the central HUB can be seen to be twice the radius of the source area.

2.4 RESULTS AND DISCUSSION

2.4.1 Costs, green gas production 1200 m³ h⁻¹.

The bar chart in Figure 2.4 shows the results of the calculation for four configurations. The total injected green gas is 1200 m³ h⁻¹ for all configurations in this graph. The bar on the right hand side shows results for a centralized green gas production plant. In this case, the biomass, i.e. co-substrate and the manure, is collected at one central digester plant as shown in Figure 2.2. No biogas transport is needed. The other bars show configurations that use a biogas grid. On the left hand side, the decentralized configuration consist of eight digesters, each producing 254.5 m³ h⁻¹ biogas and a biogas grid in a star lay-out as suggested by Figure 2.3. The biogas is upgraded and injected into the natural gas grid. The diameter of the pipeline in a configuration is selected to minimize costs per m³ green gas.

The costs for injection and upgrading are the same for all configurations, showing the centralized upgrading and injection for all four configurations. Other transformation blocks like manure, co-substrate, storage, digestate (waste) also show the same value in the different bars. The choice of configuration does not have any impact on these results. It can be noted that some of these contribute highly to the total costs. In the transformation block Injection the compression of green gas is not calculated, as we assume the green gas is at high pressure when leaving the upgrading facility.
Figure 2.4: Green gas cost structure for decentralized digester configurations with centralized upgrading and injection.

Transport costs, of biomass, manure and digestate, increase from 5.6 €ct m⁻³ for a decentralized biogas grid to 6.9 €ct m⁻³ for a centralized plant. The scale advantage related to the investment and operation of the digester causes a difference in costs; for decentralized digestion these costs are 22.5 €ct m⁻³ and for centralized digestion 16.7 €ct m⁻³. As a centralized plant has no costs related to the biogas grid, the mostly decentralized configuration in these calculations needs 8.0 €ct m⁻³ on average to transport the biogas from the digesters to the HUB. The total costs to produce 1 m³ of green gas ranges from 74.2 €ct (decentralized) to 61.6 €ct (centralized). This result shows that the scale advantage for the digester and the absence of biogas transport costs exceeds the disadvantage of increasing transport costs with scale.

The model indicated that for a decentralized biogas grid the costs per m³ green gas were higher as compared to a centralized green gas production chain. The scale advantage of the investment costs decreased the costs for the larger digester as compared to the smaller digester. Secondly, the costs for the transport of the biogas in a decentralized configuration contributed to this difference. With centralized digestion, however, the costs of transport of manure, biomass and digestate were higher.

The scale advantage of the digester could be over-estimated. The sizing of a biomass utilization facility has been discussed by Jenkins [32]. He suggested that the scale factor might change due to “increasing environmental, safety and other engineering requirements” (Jenkins [32]). The following examples apply to our case. For a large scale digester, the need for
development of new roads and large load and offload facilities could be necessary. Furthermore, sometimes several smaller sized digesters are installed on a plant site instead of one large scale digester, for historical reasons, because of subsidies or to reduce risks in the operation of the plant. Jenkins also associated the congestion of traffic at a large scale installation with extra costs. Some reduction of the scale advantage could also be found in labour costs. Labour costs for small farm scale digesters are usually not attributed to the biogas production, in contrast with large scale digesters, where skilled labour on the plant is required.

The investment costs were responsible for a large part of the biogas transport costs. For the configuration with 8 digesters the shares in the transport costs of 8.0 €ct m⁻³ were 22% for compression energy costs, 13% for O&M (excluding compression energy costs) and 65% for investment costs. The depreciation period for the biogas pipeline was taken to be 30 years. We found that, if the depreciation period for the pipeline is reduced to 12 years, costs for the configuration with eight digesters increased by 2.0 €ct m⁻³.

When transporting biogas in the grid, a large quantity of inert CO₂-gas is transported to be removed at the upgrading and injection facility. A reduction in grid transport costs and energy use is possible, if the CO₂ or part of it, is removed at the digester site. For this purpose, new small-scale upgrading techniques like membrane technology could be implemented to partly or complete upgrade the biogas at the digester site before transporting the enriched biogas to a central upgrading and injection facility for final treatment [8, 33].

2.4.2 Energy use, green gas production 1200 m³h⁻¹

Figure 2.5 shows the results of the energy calculation needed to produce the green gas, again for the four configurations. The total injected green gas is 1200 m³h⁻¹ for all configurations in this graph. The energy use for injection and upgrading is identical for all configurations, showing the same centralized upgrading and injection for all four configurations. The transformation block manure is not shown in this graph, because no energy use is modelled. The choice of configuration does not have any impact on the production of the co-substrate, revealing the same energy use for co-substrate in all bars.

From the energy point of view no scale advantage in the performance of the digester is implemented in the model. The amount for the decentralized and the centralized configurations is 1.235 MJ m⁻³. Energy use of the digester may depend on scale; large scale digesters are more efficient in heat use and less efficient in electricity use [34]. The amount of electricity is less than the heat used. This could mean that the energy use per m³ in the digester of a centralized configuration could be less than the energy use of the digester in a decentralized configuration.
Energy use for transport of biomass, manure and digestate increases from 1.01 MJ m$^{-3}$ for a decentralized biogas grid to 1.32 MJ m$^{-3}$ for a centralized plant. The energy use for the biogas transport in the grid is highest, 0.29 MJ m$^{-3}$, for the decentralized configuration with 8 digesters. The energy use for biogas transport in the configuration with 2 digesters is lower. Because of the larger diameter of the pipeline the pressure drop is smaller and only the biogas of one of the two digesters needs to be transported, the other is located at the HUB. The total energy use to produce 1 m$^3$ of green gas is around 4.85 MJ for all configurations, i.e. 13.5% of the higher heating value of the green gas (35.6 MJ m$^{-3}$).

The energy used for the biogas transport in the configuration with 8 digesters was calculated to be smallest if a pipeline with diameter of 16 cm is used, instead of 11 cm. Energy use decreased by 0.12 MJ m$^{-3}$ to 0.16 MJ m$^{-3}$, while costs increased by 0.8 €ct m$^{-3}$ to 8.8 €ct m$^{-3}$. A larger diameter than 16 cm does not reduce the energy use, as the embodied energy in the pipeline increases with diameter, out balancing the energy advantage in compression. The choice of diameter is often financial, balancing investments versus operational costs.

### 2.4.3 Costs, green gas production 150 m$^3$h$^{-1}$ to 1200 m$^3$h$^{-1}$

Figure 2.6 presents the costs calculated for multiple digesters with centralised upgrading and injection for configurations with 1 to 8 digesters, each producing 254.5 m$^3$h$^{-1}$ biogas. The graph shows the scale advantage of the cooperation of neighbouring digesters in green gas production.
E.g., the costs of green gas in a production chain with a single digester (254.5 \( \text{m}^3\text{h}^{-1} \text{biogas} \)) and an upgrading and injection facility to produce 150 \( \text{m}^3\text{h}^{-1} \text{green gas} \) is 78.8 €ct \( \text{m}^{-3} \). The costs of green gas for the configuration of 5 digesters (each 254.5 \( \text{m}^3\text{h}^{-1} \text{biogas} \)) in a biogas grid leading to a central upgrading and injection facility producing 750 \( \text{m}^3\text{h}^{-1} \text{green gas} \) is 75.2 €ct \( \text{m}^{-3} \), showing the scale advantage of 3.6 €ct \( \text{m}^{-3} \). The scale advantage is mainly caused by the upscaling of the upgrading and injection facility. The biogas grid costs per \( \text{m}^3 \) green gas show a scale disadvantage. It is assumed that for one of the digesters, transport of biogas is not needed. This relative advantage reduces the overall performance of the biogas grid if more digesters are added. The costs for the flare are relatively lower if more biogas is produced in the grid.

![Figure 2.6: Costs for multiple digesters with centralised Upgrading and Injection. The digesters produce 254.5 \( \text{m}^3\text{h}^{-1} \text{biogas each.} \)](image)

### 2.4.4 Other comments

The number of transport movements at the digester plant for a centralized configuration can be high, and provisions to support the logistics may be necessary, e.g., more parking, broader lanes. From an environmental point of view, such a high number is undesirable. In addition to that it can be argued that part of the costs for transport of manure and biomass are socialized. This transport on public roads requires extra investments to improve the roads to make them suitable for the additional traffic and also the costs for maintenance increase. The road owner, usually (local) government, is responsible for these costs.
Collecting biomass and manure from a large area to one digester plant and returning digestate from this digester to the large area again, may induce animal health risks. Hygienisation of the manure may be necessary, causing additional costs. Legislation regarding the nutrient balance on a farm, requires quality measurements of the manure that is leaving the farm. Avoiding these extra costs favours the small-scale decentralized approach.

An advantage of using decentralized digesters, with a biogas grid, can be found in the operational reliability. By spreading the production of biogas over several digester units, instead of using one large-scale digester, the risk of a full operational stop of green gas production is lowered. Maintenance of the decentralized digesters can be scheduled alternately. This could be important if a certain minimum supply is needed at all times.

2.5 CONCLUSION

A model was developed to describe the complete green gas production chain, starting from the sourcing of feedstock for the digester to the injection in the natural gas grid. The model showed that no energy advantage per produced m³ green gas can be created using a biogas grid and decentralized digesters instead of one large-scale digester.

Production costs using a centralized digester are lower than in a configuration of decentralized digesters, when producing the same total amount of green gas. The gap is shown to be in the range of 5 €ct to 13 €ct per m³. The model calculations also showed the financial benefit for an operator of a small-scale digester wishing to produce green gas in cooperation with nearby other producers. It is profitable to combine the capacity needed for upgrading and injection, instead of investing in one’s own upgrading and injection facility.

Subsidies or other financial benefits could fill the gap and encourage the use of decentralized digesters in a biogas grid. Legislation based on environmental arguments like maximizing the number of transport movements at a digester could make large-scale centralized digesting impossible. Considerations such as animal health issues and legislation regarding nutrients can support the individual farmer’s decision for a business model without a large-scale digester shared with others.

Further research could aim at a simulation model for decentralized biogas production in several, connected, biogas grids in a larger region. In this region, demand patterns on electricity and heat have to be matched by the production and distribution of biogas. The use of the biogas grid as a storage facility within the configuration could be implemented in that model. The difference in model results regarding costs per m³ green gas for the configurations depends strongly on the scale effect in digester investment. Research needs to be done to find a more accurate investment function.

2.6 ACKNOWLEDGEMENTS

The authors would like to thank RenQi for facilitating the research as part of the project Flexigas.
2.7 APPENDIX

For the calculation of energy use by the compressor needed for the biogas transport the formula suggested by Damen [28] is used:

\[ W = \frac{ZRT_1}{M} \frac{Nk}{k-1} \left[ \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right] \text{ and } E = \frac{W}{\eta_m \eta_m \times 3600}. \]

\( W \) is the work needed for the compression (kJ kg\(^{-1}\))
\( E \) is the required electrical energy (kWh kg\(^{-1}\)) for compression,

To include electrical efficiency and cooling the energy use for compression is

\[ E_{\text{used}} = E \cdot \frac{\left(1 + \eta_{\text{cooling}}\right)}{\eta_{\text{electrical}}} \text{ in kWh kg}^{-1} \]

with

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<td>( T_1 )</td>
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<td>( k )</td>
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<td>( M )</td>
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<td>( \eta_{\text{electric}} )</td>
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<tr>
<td>( \eta_{\text{cooling}} )</td>
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</tr>
<tr>
<td>( \rho )</td>
<td>density</td>
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</table>

The values for molar mass and density are computed within the model for the digester. The number of compressor stages is taken to be the square root of the ratio of the discharge and suction pressure. If the pressure at the end of the pipeline is equal to the pressure at the inlet of the compressor, the pressure difference, \( \Delta p = p_2 - p_1 \).

For calculation of the pressure drop in the pipeline some input data are summarized:

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<td>Temperature</td>
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</table>
2.8 REFERENCES
