CHAPTER 1

Introduction
To set the scope for this thesis, some background information on biogas as a renewable energy source is presented. This includes statistics of renewable energy and biogas on a global scale, together with some recent global energy scenarios, and, the statistics on biogas production and its use in Europe. The value chain for biogas, running from efficient production to effective use, covers a large number of research topics and, as a result, a large number of papers and reports have been published in recent years. The current state of art of the technology, including the basics of the biogas production process and a categorization of available biogas plants is presented.

The biogas infrastructure constitutes an indispensable part of this value chain and recent literature covering this area is reviewed. From this the research question for this thesis will be developed.

### 1.1 RENEWABLE ENERGY STATISTICS

#### 1.1.1 Globally

Renewable energy, as part of the global primary energy supply, has increased at an average annual rate of 2.8% in the period 2000-2014 from 55.0 EJ to 80.8 EJ. In 2014 the contribution of renewables to the total primary energy supply was 14.1%, leaving the largest part to fossil energy sources, Table 1.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Coal, Oil, Nuclear</th>
<th>Natural Gas</th>
<th>Renewables; % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>420</td>
<td>278</td>
<td>86.7</td>
<td>55.0</td>
</tr>
<tr>
<td>2005</td>
<td>483</td>
<td>323</td>
<td>98.8</td>
<td>60.9</td>
</tr>
<tr>
<td>2010</td>
<td>542</td>
<td>356</td>
<td>115</td>
<td>71.2</td>
</tr>
<tr>
<td>2014</td>
<td>573</td>
<td>371</td>
<td>121</td>
<td>80.8</td>
</tr>
</tbody>
</table>

Values in EJ, adapted from WBA Global Bioenergy Statistics 2017 [1]

Renewable energy resources include solar, wind, biomass, geothermal, hydropower and ocean. Biogas is produced from biomass by means of anaerobic digestion (AD) and mainly consists of methane and carbon dioxide; the volume percentages for these two parts are in a range of 50% -70% for methane and 30%-50% for carbon dioxide. In addition, water (vapour) and other so-called impurities like hydrogen sulphide, H₂S are contained. The composition and the yield of biogas depends on the type of biomass, the type of digester used in the process and process parameters such as retention time and temperature [2-4]. When the biogas is upgraded to so-called green gas or biomethane, biogas can replace natural gas and has the same quality as, in our case Dutch, natural gas; alternatively biogas can be used to produce electrical power and heat in a combined heat power (CHP) installation.
Table 1.2: Biogas production globally

<table>
<thead>
<tr>
<th>Year</th>
<th>World (EJ)</th>
<th>% of Natural Gas</th>
<th>% of Total</th>
<th>% of Renewable</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0.28</td>
<td>0.32</td>
<td>0.07</td>
<td>0.51</td>
</tr>
<tr>
<td>2005</td>
<td>0.5</td>
<td>0.51</td>
<td>0.10</td>
<td>0.82</td>
</tr>
<tr>
<td>2010</td>
<td>0.84</td>
<td>0.73</td>
<td>0.15</td>
<td>1.18</td>
</tr>
<tr>
<td>2014</td>
<td>1.27</td>
<td>1.05</td>
<td>0.22</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Adapted from WBA Global Bioenergy Statistics 2017 [1]

The quantity of produced biogas is modest as compared to other energy sources. In 2014, global biogas production was around 1% of natural gas and 1.6% of total renewable energy supply, Table 1.2. Production of biogas has increased, from 2000 to 2014, at an annual average of 11.2%, from 0.28 EJ to 1.27 EJ.

In an analysis of the future energy demand, carried out by the International Energy Agency, the “Scenario Sustainable Development” (SSD) is presented. It “outlines an integrated approach to achieve the energy-related aspects of the UN Sustainable Development Goals: determined action on climate change; universal access to modern energy by 2030; and a dramatic reduction in air pollution” Cozzi, L. et al. (2017) [5]. The total energy demand in 2025 and 2040 in this scenario is in the order of magnitude of energy demand in 2016, see Figure 1.1. In contrast to the “Current Policies Scenario”(CPS), this requires an improved energy efficiency and reduction of energy use, i.e. a shift to less energy intensive economic activities, such as services. In SSD the renewable energy supply grows by 5% per year; the share of renewables increases to 60% in electricity production, 21% in transport and 23% in heat by 2040 [5]. In a road map to 2050, published by the International Renewable Energy Agency, a similar conclusion was reached. The share of renewables in the total is estimated at 65% and an energy intensity improvement of 2.8% per annum leads to an energy consumption in 2050 near the energy consumption in 2015 [6]. These scenarios show a substantial role of biomass in the future energy supply, i.e. in 2040 9% and 11% for CPS and SSD respectively, see Figure 1.1. But no estimations of volumes of biogas production are available. Biogas could be used in a gas-fired power plant to add flexibility to the electricity grid. The potential of biogas depends very much on the availability of suitable low cost feedstock e.g. municipal waste and animal by-products. Green gas could be used in the natural gas infrastructure and also add flexibility to the electricity grid [5]. The production of biogas is expected to increase and it is indicated to be used in the transport sector and building environment [6]. An outlook on the energy transition to 2050 states that biomethane is expected to be a transition fuel for residential heating. Furthermore, according to this report there are opportunities for biogas as process energy, as controllable load in electricity and heat generation and as transport fuel; a quantity of 6 EJ in 2050 is foreseen [7].

So, although the share in the future energy supply is small, biogas is expected to play its role in specific applications e.g. to replace natural gas and classic transportation fuels and to provide flexibility in the electricity supply.
Figure 1.1: World primary energy demand [5].

Figure 1.2: Biogas production 2016 in the European Union (EU28); adapted from [8]. For Germany, United Kingdom and Italy the scale has been adjusted.
1.1.2 Biogas production and use in Europe

The total European biogas production in 2016 is 16.1 Mtoe, i.e. roughly half of the global biogas production. In 2016 biogas production has increased with 3% compared to the previous year. Figure 1.2 shows the biogas production for European countries (EU28). Germany has the largest biogas production, followed by United Kingdom and Italy. The Netherlands takes the 6th place, producing more biogas than larger countries as Poland and Spain. Germany has a large share of biogas from “other” sources. This is mainly farm biogas and co-digestion in larger installations. Biogas production in Italy, Czech Republic, the Netherlands, Austria and Denmark show a similar partition of origin.

Large proportions of biogas from sewage sludge are seen in Poland, Spain and Sweden. A large share of landfill biogas is found in United Kingdom, France, Spain and Greece. Production of landfill biogas is declining, as the deposit of organic waste is avoided. The biomass is recycled at a more efficient way, e.g. by using bio-waste as a co-substrate in digestion or by digestion of municipal organic waste directly [8]. There are large differences in biogas production between the EU28 countries. Factors that affect the biogas production in a country could be e.g. size of the countries, population density, level of urbanisation, type of industries, the size of and type of agricultural sector and policies of public authorities.

Production of electricity and heat from biogas is presented in Figure 1.3 and Figure 1.4 [8]. In general the reported gross production of electricity is between 25% and 40% of the biogas production in a country. Electricity in Spain, United Kingdom and Austria is mainly generated in electricity only plants. In other countries, i.e. Czech Republic, Poland, the Netherlands, Belgium, Denmark and Latvia, more than 90% of electricity production from biogas is by CHP. Figure 1.4 shows that heat sold to district heating and industries is mainly produced by CHP. In Germany, Finland, Sweden and Austria more than 30% is produced by heat only plants. For United Kingdom, Spain and Greece heat is reported to be null.

The upgraded biogas that is injected as green gas in the natural gas grid within the EU28 represented 8% of the energy of total biogas produced in EU28 in 2016. For the Netherlands, Sweden and Denmark around 25% of biogas is converted to green gas injected in the natural gas grid. Figure 1.5 shows that Germany has the highest volume of green gas injected, followed by UK and the Netherlands. A map available from [9] indicates the location of injection plants in Europe. Total number of upgrading and injection plants in Europe is around 400, of which half are in Germany [10]. In many EU countries biogas upgrading and injection in the natural gas grid is not implemented. Transport in the natural gas grid may ensure that green gas can be used at a higher efficiency by a chosen end user as compared to use at the biogas production site.
**Figure 1.3:** Gross electricity production from biogas in EU28 in 2016, 1 TWh corresponds to 85.98 ktoe. Adapted from [8]. For Germany, Italy and United Kingdom the scale has been adjusted.

**Figure 1.4:** Gross heat production from biogas in EU28 in 2016; heat sold to district heating networks and industries; adapted from [8]. For Italy and Germany the scale has been adjusted.
Figure 1.5: Injection of green gas in the natural gas grid in 2016; 9 European countries including Switzerland [8]. 1 ktoe corresponds to 11.63 GWh. For Germany and United Kingdom the scale has been adjusted.

Costs for upgrading and injection for individual small scale digesters are high. Feeding in upgraded biogas from small scale digesters may become feasible if biogas from several digesters is collected by biogas pipelines [10]. At 13 fuel stations in Sweden, upgraded biogas is directly sold, without injection in the national gas grid, as fuel to replace fossil fuel in transport. In other countries similar initiatives are present: Germany, Denmark, the Netherlands, each have one of such fuel station, while Finland and Norway have respectively 5 and 2 [9].

In addition to the data presented in the graphs, the EurObserv’ER consortium, a consortium of energy research institutes, presents on its website a description of the European and national policies to “achieve 20% share of final energy consumption to of renewable energy sources by 2020” [11]. Policy and statistic reports EurObserv’er 2017. At European level EU directives and the EU Emission Trading Scheme are examples of measures taken. Also R&D projects and innovation can be supported either by grants or loans. At national level a wide range of support schemes are implemented, as shown in Table 1.3.
Table 1.3: Support schemes to support renewable energy in EU28 [11]

<table>
<thead>
<tr>
<th>Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed-in tariff or Feed-in premium</td>
</tr>
<tr>
<td>Tendering</td>
</tr>
<tr>
<td>Quota obligation with or without tradable green certificates</td>
</tr>
<tr>
<td>Net-metering/net-billing</td>
</tr>
<tr>
<td>Capital subsidy, grants</td>
</tr>
<tr>
<td>Tax regulation mechanism</td>
</tr>
<tr>
<td>Soft loans</td>
</tr>
</tbody>
</table>

Support schemes are used in all but 3 of the EU28 countries to encourage biogas projects. For production of electricity from biogas a Feed-in tariff or Feed-in premium is offered in 22 countries, often in combination with other policy instruments [11]. The eligibility period for the feed-in support differs per country and is in the range of 12 to 25 years [12]. Countries that do not rely on Feed-in tariff or Feed-in premium are: Belgium, Cyprus, Ireland, Malta, Romania and Sweden. In fact Cyprus, Ireland, Malta do not support electricity from biogas. Belgium and Romania both have a Quota obligation and Capital subsidy implemented. Sweden uses a Quota obligation combined with a Tax regulation mechanism [11].

There is no incentive for renewable heat from biogas in 7 countries, i.e. Austria, Cyprus, Ireland, Italy, Malta, Portugal and Spain. In other countries one or several policy instruments are used. Support by means of a Capital subsidy is found in 14 countries. In 4 countries, i.e. Bulgaria, Germany, the Netherlands and United Kingdom, a Feed-in tariff or Feed-in premium for heat is in place [11].

The use of biogas in transport has support in Denmark with a Feed-in Tariff, in Germany with a Quota obligation and in Sweden with a Tax regulation mechanism [8].

1.2 BIOGAS TECHNOLOGY

1.2.1 Anaerobic digestion.

Usually digestion (AD) is described as a four-stage-process whereby each stage is supported by specific micro-organisms. The stages are shown in Figure 1.6.

Figure 1.6: Four stages of methane production by micro-organisms [13].
The micro-organisms live in an environment without oxygen. So production of carbon dioxide is limited by the oxygen available in the substrate and part of the carbon is combined with hydrogen to form methane. The chemistry of the ideal process is described by stoichiometric equations, presented by Buswell, Müller in the 1950s and Boyle some decades later. The relative amounts of carbon, oxygen, hydrogen, nitrogen and sulphur in the substrate are input for a calculation and complete digestion of the substrate is assumed [14]. A more detailed description of production of biogas in a digester is the ADM1-model. In this model two groups of reactions are implemented: biochemical reactions and physico-chemical reactions. The biochemical reactions are a specification of the steps shown in Figure 1.6 including e.g. functions that describe growth of micro-organisms and inhibition of the growth, while the other group of reactions include ion dissociation, ion association and gas-liquid transfer, described by time dependent differential equations [15]. To find a realistic methane potential, Achinas et al. suggest, as an alternative for more detailed and complex modelling, to simply apply a correction factor $f$, equal to $f = 0.8$, on the results for methane production obtained by the Buswell equations [14].

1.2.2 Digester technology

The organic loading rate (OLR) is defined as the amount of biomass, in kg of volatile solids (VS), fed into the reactor per cubic meter of reactor volume; hydraulic retention time (HRT) is the average time the substrate remains in the reactor. The efficient bioreactor aims at high methane production rates and methane yields, at a maximum OLR and minimum HRT, and allows for substantial VS removal at a low parasitic energy demand and low capital and operational costs” (Herrmann, C. et al.) [16].

Digester technology for anaerobic digestion of liquid, slurry, or semi-solid substrates, like manure, differs from anaerobic digestion of substrates with higher solids content, Figure 1.7. For the first type of substrate, with total solids < 15%, the common type of digester is a continuously stirred tank reactor (CSTR). In a continuous process the feedstock is added and digestate is removed. In the reactor, mixing assures good contact between micro-organisms and substrate, but requires relatively high energy. Wash-out of micro-organisms should be avoided by providing sufficient retention time, thus allowing enough growth of these microorganisms. Retention time could be in the range of 20-150 days; a long retention time makes it possible to reach high yields. In high rate systems retention times can be much lower, as the design of the process in these systems facilitates micro-organisms to remain within the reactor. Some examples: In the design of an Anaerobic Contact Reactor (ACR) a sedimentation tank is added to the CSTR, in which biomass settles that can be returned to the reactor, thereby recovering the microorganisms. For the Up-flow Anaerobic Sludge Blanket Reactor (UASBR), mainly used in waste water treatment, micro-organisms are collect as granules in a blanket of sludge in a vertical reactor. In the Anaerobic Filter reactor, a carrier material in the reactor provides surface area for attachment of the micro-organisms, thus forming so-called biofilms.
Substrates with high solids content, total solids > 15%, are processed in a plug flow reactor or in a leach bed reactor. In a plug flow reactor the substrate moves as a plug through a horizontal reactor, with limited mixing. To keep enough micro-organisms in the digester up to 80% digestate is recycled with the feedstock. This reactor shows to be efficient for the organic fraction of municipal solid waste. In a leach bed reactor the feedstock is sprinkled and the effluent, rich with intermediates, is fed in a high rate digester for low solids content. In this way the first two steps of digestion, hydrolysis and acidogenesis, are separated from the other two steps acetogenesis and methanogenesis. This allows for separate optimization of the two stages.

With regard to temperature, digesters may operate at psychrophilic (<20 °C), mesophilic (20 °C - 45 °C) and thermophilic (55 °C - 60 °C) conditions. Most reactors are operated at mesophilic temperature. Thermophilic conditions have advantages and disadvantages; e.g. a higher temperature results in faster degradation of feedstock and improved sanitation to produce pathogen-free digestate; on the other hand the process stability is lower and more energy is needed to maintain the higher temperature. Psychrophilic anaerobic digestion is used in cold climate regions, to avoid the need of additional heat. New reactor concepts are under development [16-19]. Also passive systems are used, e.g. biogas is collected simply from a covered lagoon [18]. Small scale home or household digesters, utilized in parts of Latin America, Africa and Asia [20-22] are within this class. Stürmer (2017) indicates that a large part of the world biogas is produced in many household digesters in India and China [23].

The biomethane potential (BMP) of a wide range of biodegradable materials was measured in a research by Allen et al. Results are presented for first generation i.e. food crops, second generation, e.g. grasses, agricultural and food waste (maize silage is included) and third generation, seaweeds. These results show that a large variation in biomethane potential for one type of substrate is possible, e.g. for Dairy slurry, i.e. manure, as a result of seasonal fluctuations in its composition, Table 1.4 [24].
**Table 1.4:** Biomethane potential of some substrates [24].

<table>
<thead>
<tr>
<th>Substrate</th>
<th>BMP-T L CH₄ kg⁻¹ VS</th>
<th>BMP-M L CH₄ kg⁻¹ VS</th>
<th>SD BMP-M L CH₄ kg⁻¹ VS</th>
<th>BI %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh maize</td>
<td>426</td>
<td>354</td>
<td>13</td>
<td>83</td>
</tr>
<tr>
<td>Maize silage</td>
<td>458</td>
<td>394</td>
<td>14</td>
<td>86</td>
</tr>
<tr>
<td>Dairy slurry, autumn</td>
<td>575</td>
<td>175</td>
<td>14</td>
<td>31</td>
</tr>
<tr>
<td>Dairy slurry, Dec-Jan</td>
<td>606</td>
<td>299</td>
<td>2</td>
<td>33</td>
</tr>
<tr>
<td>Dairy slurry, Feb-Apr</td>
<td>525</td>
<td>214</td>
<td>9</td>
<td>41</td>
</tr>
<tr>
<td>Dairy slurry, summer (2012)</td>
<td>525</td>
<td>238</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>Dairy slurry, summer (2013)</td>
<td>389</td>
<td>239</td>
<td>9</td>
<td>62</td>
</tr>
<tr>
<td>RFW (with grass)</td>
<td>577</td>
<td>274</td>
<td>5</td>
<td>48</td>
</tr>
<tr>
<td>RFW (without grass)</td>
<td>566</td>
<td>368</td>
<td>6</td>
<td>65</td>
</tr>
<tr>
<td>UFW (with grass)</td>
<td>635</td>
<td>297</td>
<td>6</td>
<td>47</td>
</tr>
<tr>
<td>UFW (without grass)</td>
<td>564</td>
<td>344</td>
<td>3</td>
<td>61</td>
</tr>
</tbody>
</table>

RFW = rural food waste; UFW = urban food waste.

BMP-T = theoretical biomethane potential, based on composition of substrate; BMP-M = measured biomethane potential; SD = standard deviation; BI = biodegradable index = BMP-M / BMP-T.

Most European agricultural digesters are designed to produce biogas at a constant rate by feeding a continuous stirred tank reactor at intervals ranging from 15 minutes to several hours. The process parameters like retention time, load, temperature and composition of the substrate are aimed to be constant, producing a steady flow of biogas [25].

### 1.2.3 Categorization of biogas production plants

Lindkvist *et al.* [26] developed a common framework that facilitates sharing of knowledge among European countries. The authors propose a new categorisation of biogas production plants, based on workshops with biogas experts using brainstorming. The authors suggest seven categories out of twenty seven to be the most important ones: substrate, digestion technology, capacity, biogas use, localization, digestate and organization. Subcategories are added; for instance; subcategories under Localization are “Main substrate on-site”, “Substrate pumped”, “Substrate transported by vehicle”; these subcategories concern the input of biomass. Further there are subcategories “Upgrading on-site”, Gas transported by vehicle”, “local gas grid”, “National gas grid”, “Internal use” and “Energy conversion for external use”; these refer to the biogas output of the digester. Options for use of biogas are production of electricity, heat, vehicle fuel, internal use or adding to a national gas grid. For the digestion technology two temperature ranges are used: mesophilic and thermophilic digestion. Figure 1.8 provides an overview of the categorization.
## 1.3 BIOGAS: CURRENT RESEARCH TOPICS

Development of digester technology and research on the potential of different types of biomass is touched upon above. But there are many more research efforts aiming at understanding and improving aspects of biogas production and use. The topics range from biomass availability and biomass collection to biogas use in a combined heat power unit (CHP) or upgrading of biogas to green gas.

Grando et al. [2] use a bibliometric study to evaluate the relation between biogas research and commercial use of biogas knowledge, protected by a patent. For the period 1990 to September 2015 published articles where categorized according to type of substrates. In 2014 more than 500 articles were identified. Patents in the area of biogas production mainly dealt with digester equipment and innovative ways of upgrading biogas. The number of publications on digestion of food waste has risen since 2011. This suggests an increasing interest for waste as a substrate; however the main substrates used in production of biogas in Europe are manure, harvested residues and energy crops like maize. The authors also conclude from their review that in waste treatment, as well in energy and fuel production biogas has a large potential.

In this section we present five recent examples of research studying biogas production. This research aims at increasing biogas production along several routes. 
(1) Substrate pre-treatment of biomass, also implemented to make a wider range of biomass suitable for digestion. Larsen et al. experimentally show that storing wheat straw and green biomass, beet leaves, in a silo could be a pre-treatment method. They demonstrate on lab-scale...
and pilot scale a synergetic effect that increases the biomass potential of a combined substrate [27]. The impact of pre-treatment methods for grass as a co-substrate is reviewed in an article by Rodriguez et al. The pre-treatment methods are described in four categories. First category is “physical”, e.g. chipping, grinding and milling, including ultra-sound and micro-wave. These last two have not shown a positive impact on biogas potential. Secondly “thermal” i.e. heating the feedstock to improve solubility, as well for feedstock sanitisation. Heating at 80 °C can be used to support hyper-thermophilic pre-treatment. Another method described is steam explosion with temperatures of 160 °C to 220 °C. In “chemical” pre-treatment alkalis can be applied to remove lignin while acids are used to solubilize hemicellulose. Generally chemical pre-treatment seems not to be cost effective. Biological pre-treatment, using bacteria, fungi or enzymes, can improve biogas potential considerably; e.g. fungi are used to degrade lignin and cellulose. A similar result could be reached by adding specific enzymes to a digester. A disadvantage of biological pre-treatment is that the process is relative slow and therefore requires a large digester or storage volume.

Pre-treatment methods may be combined [28]. In a review on pre-treatment for food waste the same four categories are presented. But some other pre-treatment methods are mentioned: freeze and thaw, drying, aeration and high voltage pulse discharge are considered. E.g. freeze and thaw could preserve carbon when used in storage of food waste and has some positive effect on methane production. It is concluded that reduction of particle size and thermal pre-treatment is most feasible. Still more pilot scale research is needed to add to the batch-mode laboratory experiment available at this moment [29].

(2) Optimizing the bacteria cultures. Wang et al. connect the structure of the microbial community to different states of the food waste digester system. Microorganisms in high solids content digestion differ from those in low solid content and the effect of pre-treatment on microbial characteristics is discussed. Comparison of micro-organisms present at mesophilic and thermophilic state shows that in a mesophilic state the organisms are more diverse, thereby supporting a more stable process. The authors conclude that measuring composition of microorganisms can be used to monitor the stability of the process. Micro-organisms can be linked to the four stages of methane production, and can be indicators of failure of the digesting process. Experimental research should aim at microorganism growth rate and succession rules. Looking at food waste, factors to include are e.g. high salt and high oil conditions [3].

(3) Alternative digester setup. A research by Wall et al. analyses a two-phase set up of a digester. The first phase consist of the initial two stages, see Figure 1.6, of the digestion process using a Leach Bed Reactor (LBR). The second phase contains the next two stages, implemented in an Up-flow Anaerobic Sludge Blanket Reactor (UASBR). This setup is typically suitable for biomass with high lignocellulose content and can be operated as a demand driven biogas producer. Biogas production is low in operating mode ‘leaching only’, the input to the second phase is reduced or blocked. When high biogas production is needed the UASB reactor can be fully connected in order to produce biogas from the half products leaving the LBR [30].
(4) Influence of processing parameters like temperature. As presented above, Wang et al. show research with respect to the relation of the microbial community and operational conditions, including temperature. Research findings comparing mesophilic and thermophilic conditions show that the diversity is higher in mesophilic digestion providing more stability in the ecosystem of the digester [3]. Luo et al. reported that a temperature disturbance in a biogas reactor had a positive impact on the biogas yield (ca. +10%). After a disturbance a new steady state profile of the microbiology developed, which showed to be more effective [31].

(5) Yield optimisation. Combining some of the aspects considered above, Ma et al. study the bioenergy conversion of food waste, pre-treatment, co-digestion and bioreactor type. They propose to use enzymatic pre-treatment and landfill leachate as a co-substrate in an expanded granular sludge reactor (EGSB) to optimize organic loading rate and organic matter conversion rate [32].

Besides optimization of biogas production, the role of biogas in the energy system, the integration of biogas with other renewable energy sources was studied; two examples are highlighted.

(1) A large share of wind and solar energy could lead to surplus electricity production as a result of the intermittency. Hydrogen produced from this surplus electricity can be introduced in a digester to be combined with carbon dioxide from biogas to make methane. This Bio Power to Methane (BioP2M) process results in biogas with a higher percentage of methane [33].

(2) As explained above for European agricultural digesters the predominant opinion was that feeding rate should not vary too much, although there are several ways to vary biogas production, e.g. changing the loading rate, the volume of biomass in the digester, substrates or temperature [34].

Recent research proposes that an economically more feasible route could be flexible demand-driven electricity production from biogas to accommodate the gaps in power production in a situation of weather dependent energy sources like wind and solar [25]. Mauky et al. demonstrated a demand-driven biogas production at full-scale. By dynamic substrate feeding intraday flexibility up to 50% of the average production was achieved, with long term process stability unimpaired [25]. Flexible biogas production could support flexible power production. But also biogas storage could contribute to flexibility. With low electricity demand, biogas could be stored, while at times with high demand additional biogas can be taken from the biogas storage to generate electricity to meet the total demand. Among other, a biogas transport pipeline infrastructure can be used as a biogas storage.

So far, to our knowledge, only very few scientific studies that consider separation the site of use of biogas and site of production of biogas are published. These studies are reviewed in Chapter 2 [35, 36] and Chapter 3 [37, 38]. Recently, in a case study, O’Shea et al. [39] compared 4 scenarios, S1 to S4, for biogas production from 5 pig slurry farms to produce heat at a single user, a diary industry. The detailed modelling aimed at minimisation of greenhouse gas emission, GHG, by varying the logistics of the process. Slurry can be transported by truck to a centralized digester that is situated close to the user (S1). Secondly the location of the centralized digester
was determined by minimizing the energy consumption for road haulage of the slurry. From this location biogas is transported to the end user by pipeline (S2). Then digesters are at the farms and the biogas transported by pipelines. There are two options. Biogas is collected at a central location, from there it is transported to the user (S3). Alternatively biogas is collected by a pipeline with minimum length (S4). In each scenario the total GHG is calculated based on emission during transport of slurry, the digestion process, compression of the biogas and the transport and spreading of the digestate. GHG is lower in S2 than in S1. Reducing slurry transport and adding biogas transport by pipeline leaves a reduction of 7% in GHG. Decentralized biogas production with biogas transported by pipeline, S3 and S4, reduces GHG by 18% and 19% respectively as compared to S1. Minimization of the pipeline length, as in S4, brings a reduction of 34% in length as compared to S3, so costs are lower in S4. The authors conclude from this study that implementation of decentralized biogas production with biogas grid is preferred.

Hoo et al. [40] developed a spatial-economic model to minimize costs of transport and injection of biomethane into the natural gas distribution grid. The biogas is sourced from landfill, upgraded to biomethane and then transported to service points. Several types of service points users are introduced, each with its own gauge pressure requirement: city gate station (1.8 MPa), district station (345 kPa), Industrial (138 kPa), commercial (30 kPa) and residential (3 kPa). Biomethane is transported from the digester site through pipelines. The pressure at the inlet of each pipeline varies according to service point pressure requirement and length of the pipeline. The total energy demand has to be supplied by the biomethane or from the natural gas grid. Costs of natural gas are summarized in a natural gas tariff. The minimization of total costs is performed using as non-linear programming. In a case study 1000 m³h⁻¹ landfill gas is generated and 3 service points of different types, are considered at distances ranging from 0.5 km to 50 km. The results show that biomethane injection could be feasible at a distance up to 37 km. The model also shows that a location with high gas demand, although it is at a longer distance, could receive a larger part of the biomethane compared to a location more close. The authors conclude that injection of biomethane still needs incentives, e.g. a feed-in tariff or carbon credits, to be feasible.

In The Adaptive Logistics in Circular Economy project (ADAPNER) [41] a green gas production chain is studied with a focus on logistics of biomass and biogas. The project aims at development of a regional logistic network. Biogas is considered to be ‘local to local’, a typical regional product. The transport of biomass and cylinders of compressed biogas is by trucks. Based on the concept of a Cross Chain Collaboration Centre (4C) the logistics is analysed. Other regional flows are integrated. Costs, sustainability and business development are to be evaluated.

In a leaflet published by the International Energy Agency [42] a green gas hub at Wijster, The Netherlands, is displayed. A waste company produces biogas from landfill and from green organic household refuse. The biogas is upgraded to natural gas quality and injected in the natural gas grid. Liquid Carbon dioxide is a by-product. Farmers in the area use their own digester to produce biogas. The biogas is transported by pipeline to the upgrading facility, where it is processed.
## 1.4 BIOGAS PRODUCER-USER VALUE CHAIN

The categorization of Lindquist shows aspects of the biogas-to-user process. Similar aspects were used by Bekkering to model a biogas producer-user chain, see Figure 1.9 [43].

In his thesis Bekkering evaluated the implementation of green gas into the green gas supply. In his model green gas production is represented by transformation blocks. The model was, among other things, used to study costs dependency on digester scale for a green gas chain. It was found that costs at a rate of 1200 m$^3$ h$^{-1}$ production of green gas are around 20% lower as compared to production at a rate of 100 m$^3$ h$^{-1}$. On the other hand it was concluded that the high number of transport movements of biomass and digestate constitutes a disadvantage of large scale digesters. It is suggested that therefore a focus is needed on relative small scale decentralized production systems for biogas and green gas.

So the specific investment costs of a digester are scale-dependent; large scale installations have an advantage. The same applies for the operational energy use of a digester. In general, for a large scale installation biomass needs to be collected from a larger area, involving several farmers or suppliers. Spreading of the digestate on a farmer’s land requires more transport too. With a small scale digester the number of biomass transport movements at the digester is limited. Large scale installation may need dedicated workers to operate; thereby securing high energy efficiency and safety, but increasing labour costs. At a larger scale more participants or stakeholders could be involved. A business model and legislation may be more complex and larger investments may be needed with higher financial risks. Similar arguments apply for an upgrading installation when green gas is produced, or a CHP when the end-use is heat and power production.

Developing decentralized small scale renewable energy production is encouraged by local energy initiatives. These energy cooperatives have increased in number during the last decade in the Netherlands. In his thesis, Timmerman proposes a ‘prosumer community shopping mall’ in order to provide services to these energy cooperatives [44].

![Figure 1.9: A green gas chain based on co-digestion, including biogas transport (adapted from Bekkering et al. [43]); arrows show the routing and the dotted arrows are auxiliary streams.](image-url)
1.5 POTENTIAL CONTRIBUTION OF A BIOGAS INFRASTRUCTURE

From the above it can be summarized that biogas plays a modest role in the total energy supply at European and global scale. Biogas has no intermittency as solar and wind energy have. It can be stored at relative low costs and can replace natural gas, when upgraded. These characteristics make biogas a valuable energy carrier. Biogas research aims at e.g. understanding and improving the anaerobic digestion process, digester technology and the position of biogas in the energy system. Hereby the focus is on single parts of the biogas production-user chain. Other researchers describe the biogas production-user chain as a whole, combining data for steps in that chain.

The research presented in this thesis starts from the green gas chain model as presented in section 1.4. By introducing a biogas infrastructure, decentralized production of biogas at relative small scale can be combined with large centralized use of biogas. Biogas from several production units can be collected at a location where either the biogas is upgraded to green gas, or used in energy production in a CHP. A larger scale induces, in general, lower costs per unit and higher energy efficiency. On the other hand, collection of biogas adds to the overall costs and reduces energy efficiency. Transport of biogas can be done using dedicated pipelines or by container transport [41].

Moreover transport of biogas decouples the location of production of biogas from the location of biogas use. Thereby it facilitates biogas production at an agricultural site and use at a town, village or industrial area where power and heat both may be needed; this may result in a higher overall energy efficiency. An additional advantage is that social acceptance of a digester that is not nearby a residential zone has less complications. In a production chain of green gas, biogas could be transported to an upgrading facility at a site suitable for injection in the natural gas grid. A biogas grid also serves as storage facility.

1.6 THIS RESEARCH

This thesis aims at quantifying the impact of a biogas infrastructure on the biogas producer-user chain. The biogas transport by means of dedicated pipelines is modelled to calculate cost and energy use. A green gas chain model [43] has been extended, as shown in Figure 1.10. Multiple digesters produce biogas that is transported to the end user. End user options are upgrading biogas to green gas and injection of green gas, or biogas use in a CHP. In the model scale advantages as mentioned above are represented. Biogas chains are evaluated at farm scale and at regional scale. Results are acquired using a numerical model for biogas production, biogas transport and biogas use. Incorporation of a biogas grid creates flexibility in the design of a biogas value chain. The modelling is a techno-economic evaluation that can assist to develop options of implementation and business cases. In the research a grid using dedicated pipelines to collect biogas at a central site, a hub, is considered.
**Figure 1.10:** biogas producer-user chain including biogas transport. In red the newly introduced transformations, based on [43].

Within this context this leads to the research question:

- **To what extent can a biogas infrastructure using pipelines support a viable biogas producer-user chain?**

Whereby four sub-questions are formulated:

- **When does decentralized production of biogas and centralized upgrading and injection into the natural gas grid make sense?**
- **What costs and energy use are associated with biogas transport by dedicated pipelines at regional level?**
- **How much and at what costs can biogas be stored in a regional biogas grid?**
- **What are potential advantages in heat and power production when biogas is collected from several digesters using dedicated pipelines?**

These sub-questions come up for discussion in the consecutive chapters.

In Chapter 2 a comparison is made between two green gas production chains at farm scale. The first shows decentralized biogas production, whereby biogas is collected from the digester sites at a hub for upgrading and injection. The second is a production chain whereby centralized biogas production biogas upgrading and injection are at the same site. Costs and energy use are evaluated.

In Chapter 3 costs and energy use for biogas transport in a region are modelled, whereby two different lay-outs of the biogas grid are compared. A star lay-out connects the digesters directly to a hub, while in a fishbone lay-out biogas is collected into a main pipeline that leads to a hub.

Chapter 4 adds to the previous chapter by studying storage of biogas in a biogas grid at regional level; this type of storage is line-pack storage. For the two types of lay-outs, star and fishbone, costs of storage and maximal storage volumes are estimated.

The topic in Chapter 5 is heat and power production at a hub. In a case-study biogas transport costs and CHP scale advantages are quantified to illustrate in what way the implementation of a biogas grid acts on costs of electricity and heat. This case study uses digester production data and locations in a Belgian province. In the last chapter conclusions and an outlook to further research are given.
1.7 REFERENCES


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