



Review

Optimisation of a green gas supply chain – A review

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ABSTRACT

In this review the knowledge status of and future research options on a green gas supply based on biogas production by co-digestion is explored. Applications and developments of the (bio)gas supply in The Netherlands have been considered, whereafter literature research has been done into the several stages from production of dairy cattle manure and biomass to green gas injection into the gas grid. An overview of a green gas supply chain has not been made before. In this study it is concluded that on installation level (micro-level) much practical knowledge is available and on macro-level knowledge about availability of biomass. But on meso-level (operations level of a green gas supply) very little research has been done until now. Future research should include the modeling of a green gas supply chain on an operations level, i.e. questions must be answered as where to build digesters based on availability of biomass. Such a model should also advise on technology of upgrading depending on scale factors. Future research might also give insight in the usability of mixing (partly upgraded) biogas with natural gas. The preconditions for mixing would depend on composition of the gas, the ratio of gases to be mixed and the requirements on the mixture.

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1. Introduction

1.1. Ambitions of the Dutch government

Currently the share of natural gas, 45–50 billion m³ (Energiened, 2007), in primary energy demand in the Netherlands is about 42%, including 14 million m³ of green gas (Welink et al., 2007). Production of heat (40% of the Dutch energy usage) is almost totally depending on natural gas. In The Netherlands the gas use has been stable the last two decades, residential use has decreased slightly the last decade because of isolation and high efficiency burners. The IEA forecasts that till 2030 the gas demand will increase with 2% a year (World Energy Outlook 2005). However, this is a decrease of the growth when compared to the period 1980–2004 (2.6%).

The current share of sustainable energy in The Netherlands is less than 3% (status 2006), and less than 2% of this sustainable energy is (bio)gas (CBS, 2007). The Dutch government aims for a share of 20% sustainable energy and 30% less greenhouse gases in 2020 (compared to the level in 1990, VROM, 2007). Concerning the gas supply chain, the future expectation is that almost 10% of the natural gas can be replaced by green gas (Welink et al.,

2007). Although this does not meet the above mentioned goal of 20% when considering the gas supply system separately, green gas will have an important influence on reaching these goals. On the other hand, published ambitions envision a share of 8–12% of green gas in 2020, 15–20% green gas in 2030 and 50% in 2050 (Wempe et al., 2007). These higher percentages include gasification of biomass (SNG) and hydrogen.

The energy market in the Netherlands seems to move from supply driven to demand driven, at least in part. Customers are becoming more aware how energy is produced and many are willing to pay for 'green' energy. This raises questions about what sustainability comprises. Energy is produced more and more decentrally. In fact, we are talking about a transition instead of optimisation or innovation (Geels, 2002).

The above considerations, in addition to matters of decreasing availability of fossil fuels and security of supply, justify research into the dynamics of the gas market. In order to understand the aforementioned transition and to investigate what is necessary for a transition, it is wise to investigate the total gas supply chain from producers of gas, transport, distribution to demand side (end users of gas).

Till now biogas is mainly converted to electricity. For small quantities this seems the most practical way of conversion, and till recently this was the only conversion of biogas which was subsidized by the Dutch government. However, basically there are four routes to transform biogas to useful energy:

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Nomenclature/definitions

Primary energy Coal, peat, oil, gas, combustible renewables and waste, hydro, nuclear, other (including geothermal, solar, wind, and ambient heat production), definition according to IEA

Green gas Biogas which is upgraded to natural gas quality
SNG Synthetic Natural Gas, consists of mainly CH₄, produced by gasification of coal or biomass followed by methanisation

1. Production of electricity.
2. Production of heat.
3. Production of heat and electricity.
4. Upgrading to green gas and injection in the gas grid.

A way of comparing these transformations is to calculate the savings of natural gas of every transformation. The sequence of these transformations when rated to decreasing energy efficiency, in terms of saving natural gas, is given below (with a rough indication of natural gas savings, see also [Welink et al., 2007](#)). It is convenient to compare the transformations of biogas in terms of energy (MJ) instead of m³ because the heating value of biogas differs from that of natural gas.

1. Production of electricity and heat in a combined heat and power (CHP) installation: 1 MJ of biogas gives 0.50 MJ_{th} thermal energy and 0.38 MJ_e electric energy. The efficiencies are average values from practice. If biogas (and thus a CHP) is not available, the heat would normally have been produced in a local heater (boiler) with an efficiency $\eta_{th} = 0.90$ and the electricity in a power plant with an efficiency $\eta_e = 0.55$ (Combined Cycle). Losses for transport of electricity are not included. This means that for 0.50 MJ_{th} and 0.38 MJ_e 1.24 MJ of natural gas would be needed. So, 1 MJ of biogas would save 1.24 MJ of natural gas. Or, assuming a methane content in biogas of 65%, 1.23 m³ biogas would save 1 m³ natural gas.
2. Heat production: burning 1 MJ of biogas in a heater would give 0.90 MJ_{th}, assumed that this is possible without problems. 1 MJ of natural gas would give the same result. Thus, again with a methane content of 65% in biogas, 1.54 m³ biogas would replace 1 m³ natural gas.
3. Upgrading to green gas and injection into the gas grid: 1 MJ of biogas would give 0.75–0.91 MJ of green gas. The value depends on the way of upgrading. Upgrading not only requires energy for the process itself, but also differences exist to what extent the process is able to separate the methane from other components (methane losses). Anyway, 1 MJ of biogas would save 0.75–0.91 MJ natural gas. Or, 1.69–2.05 m³ biogas would replace 1 m³ natural gas.
4. Production of electricity: this would be done in a gas motor. With an efficiency of $\eta_e = 0.38$, 1 MJ of biogas would produce 0.38 MJ of electric energy. Without biogas the needed electricity would be produced in a power plant. With an efficiency of $\eta_e = 0.55$ (Combined Cycle) 0.69 MJ natural gas would be needed to produce 0.38 MJ (without taking transport losses into account). Or, 2.23 m³ biogas would replace 1 m³ natural gas.

Some remarks can be made about the above comparison. Although CHP and heat production seem the most efficient, the problem is that the heat is often not needed at the location where the biogas is available. This is why these two options are not applied often. Especially for the first option, the question arises why not using a CHP running on natural gas when both heat and electricity are needed, instead of electricity from the grid and heat from a boiler. Then only 1 MJ natural gas would be necessary instead of 1.24 MJ. Of course, the above consideration is only one way of looking at applications of biogas. Another route would f.i.

be to investigate to which rate the distinguished applications would meet sustainability criteria, which would include energy efficiencies of producing biogas or natural gas. In practice, there might be quite different reasons to choose a transformation of (bio)gas. Nevertheless, it seems justified to do research in upgrading biogas to green gas and injecting it in the gas grid. At least it can be said that, from an efficiency point of view, upgrading to green gas and injecting in the grid is much better than producing electricity which is currently, in most cases, common practice. For using biogas as a vehicle fuel the green gas route should be followed as well ([Persson et al., 2006](#)). Also for usage in a fuel cell gas treatment is necessary.

Roughly, the Dutch potential of 10% green gas consists of 1500 million m³ green gas from digestion and 3500 million m³ green gas from gasification ([Welink et al., 2007](#)). Gasification is most promising in large-scale centralized plants. In this paper the focus will be on decentralized gas production. In the current situation (2008) 13 million m³ green gas per annum is produced in four landfill sites and one sewage gas installation. Because waste flows will not significantly increase, it seems reasonable that the green gas production from landfill sites will not exceed 15 million m³, and that the maximum of green gas from sewage gas is 4–5 million m³. Based on available material which can be digested, co-digestion has a green gas potential of 1500 million m³ per annum ([Wempe et al., 2007](#)). So, among the possibilities of digestion, co-digestion has the most significant share. A minor share of this co-digestion consists of swill and other waste products ([Koppejan and De Boer-Meulman, 2005](#)). The major share can be produced by digesting manure and agricultural crops. Therefore, it is interesting to investigate the green gas supply chain based on co-digestion of manure and agricultural crops. [Fig. 1](#) shows how such a supply chain looks like: Manure and cosubstrates are digested, and the biogas is upgraded to natural gas standards and injected into the gas grid.

All activities in producing green gas can be done on one (centralized) or more (decentralized) locations. Many choices can be made, every choice having its transport and storage costs, and a scale of economy can be calculated. In order to get insight in the complexity of such a supply, literature research on the supply chain of [Fig. 1](#) has been done, which is described in the following section. Because of our interest in operational matters of a green gas supply, special focus will be on costs, scale of economy and stability of the processes. After this literature overview, the literature will be discussed and in the final section conclusions are drawn together with a view on future research.

2. Overview literature

Many research programmes on digester gas investigate technologies which are related directly to one of the blocks in the chain of [Fig. 1](#).

2.1. Manure and cosubstrates

Availability of manure and biomass are generally described on a macro-level. Production of manure in the Netherlands is

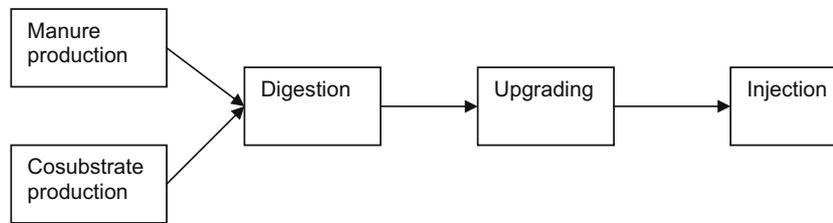


Fig. 1. The chain approach of a green gas supply. The main processes in the chain are shown. Between every block transport and storage can be thought.

investigated by van Bruggen (2008). Koppejan and De Boer-Meulman (2005) investigated the availability of biomass in the Netherlands and abroad (the latter should be imported) in order to meet the need in 2010, and in relation to costs and subsidies. The need is based on all applications of biomass concerning heat and electricity. One of the conclusions is that import is needed to meet the targets, but also that the economy of biomass conversion strongly depends on the prices.

2.2. Digesters

General information about digesters and their role in sustainable energy production is available in several books and documents (see f.i. Deublein and Steinhauser, 2008, and Kool et al., 2005; Klinski et al., 2006; Weiland, 2006). Two approaches seem to be common nowadays to get insight in digestion processes: the experimental approach in which the influence of parameters on digestion are measured, and a more theoretical approach in which digestion processes are modeled in a mathematical way. The latter calculates the biogas production from a given input analysing the chemical structures. Both approaches are presented below. Ward et al. (2008) investigated the state-of-the-art of anaerobic digestion of agricultural resources by literature. The main focus in this research was on the experimental knowledge. An overview of important parameters influencing not only the anaerobic digestion process but also the costs (qualitatively) is listed in Table 1.

The other type of published research is by modeling. Gerber and Span (2008) reviewed and discussed several mathematical models for anaerobic digestion. The existing models vary with respect to their objectives and complexity. Comparatively simple models have been developed to calculate the maximum biogas rate, which theoretically can be produced from organic structures. On the other hand, research has been done in mathematical modeling of anaerobic digestion processes in general, with the aim to develop a generally applicable model. One of these investigations resulted in the Anaerobic Digestion Model No. 1 (ADM1; Batstone et al., 2002). ADM1 is a structured model with disintegration and hydrolysis, acidogenesis, acetogenesis and methanogenesis steps. This model has been applied and modified by Lübken et al. (2007) to simulate energy production of the digestion of cattle manure and renewable energy crops. In this research an energy balance was added, which enabled the calculation of the net energy production. In this energy balance the electrical energy production, mechanical power of the pump and stirrer, thermal energy production, radiation loss and heat requirement for substrate heating were taken into account. It was found that calculations of different kinds of energy losses for a pilot-scale digester showed high dynamic variations. Blumensaat and Keller (2005) used a modified ADM1 to model a two-stage anaerobic digestion. The results of the model were compared to data from experimental pilot-scale experiments with good agreement.

Whatever method is taken, the aim for highest efficiency at the lowest costs is evident. The costs of biogas and electricity

Table 1
Parameters influencing (the costs of) anaerobic digestion processes.

Parameter	Influence on biogas production and costs
Reactor design	Generally three types of reactors can be distinguished: one-stage batch reactors, one-stage continuously fed systems, and two-stage (or multi-stage) reactors in which the hydrolysis/acidification and acetogenesis/methanogenesis are separated. Multi-stage systems seem to be more stable than single-stage systems. Instability can be caused by fluctuations in organic loading rate, heterogeneity of wastes or excessive inhibitors. Multi-stage systems provide some protection against a variable organic loading rate as the more sensitive methanogens are buffered by the first stage (see f.i. Parawira et al., 2008; Mata-Alvarez, 2002). However, multi-stage digesters are more expensive to build and maintain, but are generally found to have a higher performance than single-stage digesters
Mixing	Mixing is done to ensure efficient transfer of organic material for the active microbial biomass, to release gas bubbles in the medium and to prevent sedimentation of denser particulate material. The effect of mixing depends on the type of substrate. In laboratory-scale research it was found that production of biogas was equal for mixed and unmixed digesters when fed with 5% cow manure slurry. With 10% or 15% slurry mixing proved to be effective. Moreover, mixing during start-up was not beneficial (Karim et al., 2005). Also the way of mixing (continuous or intermittent in various intensities) influences the methane production depending on the type of substrate (Kaparaju et al., 2008)
Temperature	Digestion can take place at psychrophilic, mesophilic or thermophilic temperatures. Mesophilic and thermophilic are most commonly applied. Which of these two is the most efficient is difficult to say, there is some evidence that the total methane yield is somewhat higher in a mesophilic process, but that the retention time is shorter in a thermophilic process (Parawira et al., 2007). The heat needed for maintaining the temperature is normally delivered by a gas motor which is used for producing electricity from biogas. In case of upgrading the biogas, instead of producing electricity, the costs for producing heat might be high. Chae et al. (2008) investigated the mesophilic anaerobic digestion of swine manure and showed that methane yield increased with increasing temperature. However, this does not mean the higher the temperature the more optimal, due to the larger energy requirement at higher digesting temperatures. Therefore, careful consideration of the net energy balance between the increased heating energy demands and improved additional methane production at higher operating temperatures must be simultaneously taken into account when deciding the economical digesting temperature
Type of substrate	Co-digestion of manure and biomass increase the methane yield when compared to digesting solely manure (see f.i. Umetsu et al., 2006), but the results are sensitive to many operating parameters: not only the reactor parameters as discussed before but also the type of manure and biomass and ripeness of biomass (Amon et al., 2007, 2 publications).
Pretreatment	Costs highly depend on the type of biomass, energy maize is expensive, while grass as a waste product may have a negative price Pretreatment of biomass is especially useful when these have a high cellulose or lignin content. Pretreatment can be done chemically, thermally or physically. Thermal pretreatment generally takes place at 80–140°. Mechanically decreasing the particle size of biomass increases the methane yield (Mshandete et al., 2006). In both cases the consequences for the costs are evident

production from maize silage in relation to plant size were investigated by Walla and Schneeberger (2008). In this research a model was developed to derive cost curves for the unit costs of biogas and electricity production and for the transport costs for maize silage and biogas slurry. It was found that the least-cost plant capacity depends to a great extent on the local availability of silage maize.

2.3. Upgrading biogas to natural gas quality

Upgrading of biogas is necessary in order to meet requirements which are demanded not only by the application of the gas (burners), but also by the gas grid which transports the gas. In general green gas specifications should meet the local or national requirements. In Table 2 typical values of biogas from co-digestion are compared to the Dutch requirements for gas in the distribution gas grid.

Concerning the requirements in relation to infrastructure, it is known that sulphur and hydrogen influence the integrity of pipelines. But very little literature can be found about gas mixtures or the influence of variations of gas specifications in relation to requirements. However, in order to understand the consequences of injecting other gases into the gas grid than natural gas, much can be learned from recent research in hydrogen (Slim et al., 2006). The effect of hydrogen addition on thermodynamic and transportation properties of the mixture is investigated by Schouten et al. (2004). In this study it was shown that injection of 25% hydrogen may lead to a temperature drop of several degrees, the temperature drop at the pressure reduction stations reduces

by 1/3, and the pressure drop in the transport lines increases only slightly. The influence of hydrogen on combustion properties has been investigated. Coppens et al. (2007) found that in lean flames enrichment by hydrogen has little effect on NO, while in rich flames the concentration of nitric oxide decreases significantly. Changes in the combustion behavior of methane upon hydrogen addition were investigated by Gersen et al. (2008) by characterizing the autoignition behavior of methane/hydrogen mixtures in a rapid compression machine. The experimental results obtained under stoichiometric conditions showed that replacing methane by hydrogen reduced the measured ignition delay time.

Concern exists about pathogens in biogas. Some research has been done into this field (Bisschops and van Eekert, 2008). Possible options to reduce the risk of pathogens include heat treatment of the substrate, longer retention times in the digester and filtration. On the other hand questions must be answered concerning the risks and effects of production steps (f.i. upgrading) on pathogens. Vinneras et al. (2006) sampled condensate water from gas pipes and gas from different parts of biogas upgrading systems. They found that the number of microorganisms found in the biogas corresponds to the original population in natural gas and concluded that the risk of spreading disease via biogas is very low since no pathogens were identified. Practice shows that green gas from landfill sites has been injected in the Dutch gas grid for years without known problems.

So, although much can be said yet about correct requirements, the requirements as listed in Table 2 are generally taken as a starting point to consider upgrading techniques for biogas. The steps

Table 2
Properties of biogas from co-digestion and requirements for gas in the gas grid.

Quality component	Unit	Biogas from co-digestion (typical values)	Requirement from Dutch authority of competition – regional grid – boundary values (NMa, 2007)
CH ₄	vol.%	63 (variation 53–70) ^a 45–75 ^b	–
Higher hydrocarbons	vol.%	0 ^a	–
CO ₂	vol.%	47 (variation 30–47) ^a 25–55 ^b	–
Nitrogen	vol.%	0.2 (variation 0) ^a 0.01–5.00 ^b	–
Upper heating value	MJ/nm ³	–	31.6–38.7
Lower heating value	MJ/nm ³	23 ^a	–
Higher Wobbe-index	MJ/nm ³	27 ^a	43.46–44.41
Water vapour	vol.%	1–5 ^b	–
Water dew point	°C	35 ^b	–10 (8 bar)
Temperature (of injected gas)	°C	–	0–20
Sulphur (total)	mg/nm ³	–	45
Anorganic sulphur (H ₂ S)	mg/nm ³	<1000 ppm (variation 0–10,000) ^a 10–30,000 ^b	5
Mercaptanes	mg/nm ³	–	10
Odor	mg/nm ³	–	>10, nom 18–40
Ammonia	mg/nm ³	<100 ppm ^a 0.01–2.50 ^b	3
Chlorine containing compounds	mg/nm ³	0–5 ^a	50
Fluor containing compounds	mg/nm ³	–	25
Hydrogenchloride (HCl)	ppm	–	1
Hydrogencyanide (HCN)	ppm	–	10
Carbonmonoxide (CO)	mol.%	<0.2 vol.-% ^b	1
Carbon dioxide in dry gas grids (CO ₂)	mol.%	–	6
BTX (benzene, toluene, xylene)	ppm	0 ^b	500
Aromatic hydrocarbons	mol.%	–	1
Oxygen in dry gas grids	mol.%	0 ^a 0.01–2.00 ^b	0.5 (3)
Hydrogen	vol.%	0 ^a 0.5 ^b	12
Methane number	–	>135 ^a 124–150 ^b	>80
Dust	–	–	Technical free
Siloxanes	mg/nm ³	Traces ^b	5 ppm

The data for biogas are taken from:

^a Persson et al., 2006.

^b Doublein and Steinhauser, 2008.

Table 3
Comparison of upgrading techniques for a biogas case containing 65% methane, and including compression to 4 bar gas grid. Data are from Aalderink (2007) and Persson (2003).

Upgrading method	Water scrubbing	Vacuum pressure swing absorption (VPSA)	Membrane	LP Coaab (chemical absorption technique)
<i>Energy need/m_n³ cleaned gas</i>				
Electricity (kWh _e)	0.4 (0.3–0.6)	0.25 (0.3–1.0)	0.14	0.12
Heat (kWh _{th})	0	0	0	0.4
Methane efficiency (%)	97	97	82	99.9
<i>Total efficiency</i>				
Without heat recovery (%)	91	93	80	92
With heat recovery (%)	91	93	96	98

taken for upgrading biogas to green gas (natural gas quality) are usually gas drying, gas desulphurization (removing H₂S), methane enrichment (removing CO₂) and removing other parts (f.i. siloxanes) if necessary. Currently used techniques for upgrading biogas are water scrubbing, pressure swing adsorption (PSA), membrane or cryogenic separation. An overview of these techniques is given by f.i. Hagen et al. (2001), Polman et al. (2007) and Persson et al. (2006). A more extensive evaluation of upgrading techniques including economic aspects can be found in Persson (2003) and Urban et al. (2008). The choice for an upgrading technique is in practice not only determined by investment and operations costs, but might also be affected by matters as availability of water or the market position of a supplier. Some general data on upgrading techniques are given in Table 3.

Research into the water wash upgrading technique has been done by Rasi et al. (2008). The objective of this study was to determine the feasibility of a countercurrent absorption process with a new type of design with a small height-to-diameter ratio (3:1 instead of the more conventionally used 20:1). Absorption columns used in water absorption processes are typically 10 m in height to achieve maximum contact surface between the gas and water phase, and upgrading is done at 9–12 bar pressure. In this study, higher pressure compensated for the lack of column height. With higher pressure, also less water is needed. An interesting method under development is in situ methane enrichment (Lindberg and Rasmuson, 2006, part I + II) because the total cost for in situ methane enrichment digestion is estimated to be significantly lower than the costs for conventional post-digestion upgrading of biogas.

2.4. Injection

Injection of (green) gas into the gas grid normally exists of the following steps:

1. Gas pressure controlling.
2. Gas compression.
3. Gas measurement (flow).
4. Gas storage.
5. Odourising (adding THT).
6. Gas mixing.
7. Gas analysis.

These steps are common practice and are rather straightforward. The costs highly depend on injection location, pressure and quantity.

2.5. The green gas supply chain

Except scientific knowledge on specific 'blocks' in the gas supply chain (Fig. 1), knowledge on behavior of (parts of) the gas supply chain is important. Although not much information is available yet, information on parts of the chain can be found. In a research by (Börjesson, 1996) the energy efficiency in the production and

transportation of different kinds of biomass in Sweden has been analysed in the current and estimated future situation, as well as the change in energy efficiency resulting from a transition from fossil-fuel-based energy systems to biomass-based systems. In this research the energy yields of different crops are investigated, as well as the energy inputs needed, such as motor fuels, and the indirect use of fuels employed in the production of, for example, seeds, pesticides and farming machinery. A table with energy use per km per GJ transported biomass is presented, as well as a table with the net energy yield (energy content of biomass – energy input) based on a fixed transport distance. In this study the energy input per unit biomass was lowest for straw, logging residues and Salix, equal to 4–5% of the energy output. It was also found that a transition from a fossil-fuel-based energy system to a CO₂-neutral biomass-based system around the year 2015 is estimated to increase the energy input in biomass production and transportation by about 30–45%, resulting in a decreased net energy output of about 4%. Berglund and Börjesson (2006) describe the energy performance in the life-cycle of biogas production. The energy content of biogas is compared to the needed energy for growth and transport of biomass and operation of a biogas plant. The results showed that the energy input into biogas systems overall corresponds to 20–40% of the energy content in the biogas produced. The net energy output turned negative when transport distances exceed approximately 200 km for manure. The results are substantially affected by the assumptions made about the properties of the biomass and systems. Also the bottlenecks (technical, legislation, economical) which have to be alleviated in order to preserve the gas market (Wempe et al., 2007) have been investigated. Polman et al. (2007) also give an interesting overview of these bottlenecks: the aspects technology, economy, safety, legal aspects and environment have been investigated for parts of the supply chain: injection, infrastructure, measurement, application. Bottlenecks exist mainly in the area where technology meets economy, and on law and legal aspects.

3. Discussion – challenges

Studies on availability of biomass in a country are valuable in the sense that an overview is achieved of the potential in a country to meet f.i. sustainability goals by using biomass for energy. This is generally known as macro-level knowledge. In this study the major share of the found literature concern techniques for producing or upgrading biogas. These studies are important because a sound understanding of technology is necessary to design cost-effective installations which are able to produce gas that meets the requirements. The knowledge gained in this way can be interpreted as knowledge on micro-level. From a systems design or systems engineering perspective, it is also important to be able to understand the relations between the technologies. At this level, the meso-level, modeling of a green gas supply chain could be done. In order to get a profound understanding of a green gas supply, knowledge on these three levels is necessary. This is illustrated for other systems by f.i. Schenk (2006) and Geels (2002).

We believe that on meso-level still a knowledge gap exists, because little literature can be found thus far on this level. More detailed research would be necessary when insight in a local biomass supply to a digester is needed, which is also recognized by f.i. Walla and Schneeberger (2005, 2008). They investigated economic aspects of biogas plants producing electricity. The aforementioned study by Berglund and Börjesson (2006) seems to be a good starting point to expand this field of investigation, because here a system from growing crops to producing biogas is already analysed. But questions arise about how the knowledge on parts of the green gas supply chain can be combined in order to describe or optimise a green gas supply in a given situation in a specific geographical region. As an illustration: The above mentioned target of 1500 million m³ green gas means that ~2500 million m³ biogas has to be produced annually, assuming that roughly 60% of biogas consists of methane. An average digester on a farm in The Netherlands has an output of ~300 m³ biogas per hour (van Tilburg et al., 2008). Suppose in one year 8500 operating hours are possible. Then each year 2.55 million m³ biogas is produced on one farm. In this case, 2500/2.55 = 980 digesters would be needed in The Netherlands.

Besides questions concerning gas quality and gas production and upgrading technology, new questions arise, such as: are so many digesters desirable, how should these be connected to the grid, can an economy of scale be calculated? It seems logical that the local availability of manure and biomass determine the location of a digester and hence the type and output of a digester. It is evident that for smaller installations these problems would even be more challenging. Insight in the most economic way of digester locations and their capacities is necessary. This could be done by developing an operational model. State-of-the-art knowledge of technologies, which include efficiencies and costs, combined with operations research techniques should give opportunities to obtain insight in optimal locations and capacities of digesters and upgrading plants.

Taking the current discussion in The Netherlands on sustainability into consideration, developing good sustainability criteria seems to be essential for such a model. For the Dutch situation, a good starting point for sustainability criteria seems to be (Cramer et al., 2006). In this document the criteria are divided in six themes: (i) greenhouse gas balance, (ii) biomass should not compete with food, local energy supply, medicine or building materials, (iii) biodiversity, (iv) people, (v) planet, (vi) profit. Part of these criteria should be a sound energy balance for such a gas supply chain for which Börjesson (1996) and Berglund and Börjesson (2006) could be taken as a reference. A mass balance would give insight in (waste) flows in relation to costs. Gerin et al. (2008) consider the energy and CO₂ balance of maize and grass as energy crops for anaerobic digestion. Ecological aspects of biogas production from renewables is also explored by Scholwin et al. (2006). Legislation and environmental aspects should be taken into account. The tension between economic benefits and environmental and social aspects has also been explored by Matos and Hall (2007).

An operational model should give answers on questions like f.i. where to build digesters and to what extent can upgrading installations be built decentrally. With such a model the sensitivity to changes of parameters could be investigated. Finally, challenges for improvement can be investigated systematically, including their usefulness.

Sound requirements on green gas is still a field of research. Polman (2007) states that further research is needed on the influence of bacteria, fosfines, burning behavior of halogenated hydrocarbons and the possibility of microbiological corrosion of piping. The requirements listed in Table 2 seem to be based on calorific values and known influences of some hazardous elements on piping and burner components. A specific mix of components of

the green gas is not required. However, this mix strongly influences aspects like heating value, Wobbe-index, knock phenomena, flame lift, blow out, flashback, soot formation and emissions. Together with an operational model it might be interesting to investigate the possibilities to adapt requirements to region and application.

An interesting field of research might be that fully upgrading of biogas to natural gas is not necessary in many cases. Very little is known about the possibilities of mixing off-spec gas with natural gas off-line. The technical and economic aspects of this should be investigated. The extent to which biogas can be mixed with natural gas depends on the required quality of the mixture and on flows (available quantities) of biogas and natural gas. For the latter an important parameter is the daily and seasonal fluctuation of the demand.

4. Conclusions

The knowledge status of a green gas supply chain on biogas production by co-digestion is reviewed. Although the explored investigations into the several stages from production of manure and biomass to green gas injection into the gas grid are valuable and recommendations for improvement are done, an underpinned view on how such a sustainable gas market would look like on an operational level seems to be lacking. Questions arise about the amount and location of needed digesters, to what extent upgrading installations can be built decentrally, how these should be connected to the gas grid, and about the possibilities of calculating an economy of scale. An operational model, meeting further defined sustainability criteria, should give answers on these kind of questions. With such a model the sensitivity to changes of parameters should be investigated. Challenges for improvement can be investigated systematically, including their usefulness. An interesting outcome might be that fully upgrading of biogas to natural gas is not necessary in many cases. The possibilities of mixing off-spec gas with natural gas in terms of economics should be investigated. Preconditions for mixing would depend on composition of the gas, the ratio of gases to be mixed and the requirements on the mixture. Finally, the risk of pathogens and possible solutions must be investigated further.

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