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Will implementation of green gas into the gas supply be feasible in the future?

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HIGHLIGHTS
- The relation between energy efficiency, greenhouse gas reduction and cost price of a green gas supply chain was analyzed.
- Opportunities for improving a green gas supply chain were evaluated.
- Fossil and renewable energy resources are made explicit in energy efficiency definition.
- Switching to green electricity is the major contributor to improving the energy efficiency and greenhouse gas reduction.

ABSTRACT
The energy efficiency, greenhouse gas reduction and cost price of a green gas supply chain were evaluated. The considered supply chain is based on co-digestion of dairy cattle manure and maize, biogas upgrading and injection into a distribution gas grid. A reference scenario was defined which reflects the current state of practice, assuming that input energy is from fossil origin. Possible improvements of this reference scenario were investigated. For this analysis two new definitions for energy input–output ratio were introduced; one based on input of primary energy from all origin, and one related to energy from fossil origin only. The influence of the improvements on greenhouse gas reduction and cost price was assessed too. Results show that electricity (from fossil origin) is the major contributor to energy input in the reference scenario. Switching to green electricity significantly improves the energy efficiency (both definitions) and greenhouse gas reduction. Preventing methane leakage during digestion and upgrading, and re-using heat within the supply chain also show improvements on these parameters as well as on cost price, although their influence is smaller. Decreasing the share of energy crops in the substrate mix shows a negative effect. It is shown that greenhouse gas reduction of more than 80% is possible with current technology. To meet this high sustainability level, multiple improvement options will have to be implemented in the green gas supply chain. Doing so will result in a modest decrease of the green gas cost price.

1. Introduction
Decarbonization of, and increasing the share of renewable energy in the energy supply are important topics nowadays. The EU has set goals in this respect, which meet the vision that people’s well-being, industrial competitiveness and the overall functioning of society are dependent on safe, secure, sustainable and affordable energy [1]. Dutch ambitions on the future energy system are an example of goals on a national level, and are laid down in the Dutch Energy Covenant [2]. The stimulation of decentralized renewable energy production by co-operations is one of the pillars of this covenant: The Netherlands aims for 14% renewable energy production in 2020 (currently 4%) and 16% in 2023. Other pillars in this covenant are saving energy as a means to improve energy efficiency, and greenhouse gas (GHG) reduction (80–95% reduction in 2050).

Biogas and green gas are considered to become part of the future energy system (e.g., [3,4]), not only as an energy carrier, but also as a means to balance supply and demand of energy. At present, in The Netherlands green gas initiatives are often not profitable without subsidies [5–7], but it cannot be concluded plainly that green gas is too expensive. The long term perspectives of
biogas will be strongly determined by possible geopolitical developments and by national and international legislation (e.g., in terms of levels of subsidies, desired energy mix, taxes and sustainability criteria [7]). It is likely that pollution by current fossil energy systems (e.g., coal-fired power plants) will be included more and more in future energy production costs. The existing EU’s and Dutch energy systems need high levels of investment in the future, even in the absence of ambitious decarbonization efforts [1], which may cause uncertainty on future energy prices. Also a possible paradigm shift should be considered. In the current paradigm, gas is a commodity, available from (large) fossil reservoirs. One pays for the amount of gas needed. Within this paradigm, supply flexibility, i.e., the ability to meet energy demand at all seasons and hours, is not a real issue. In a future paradigm with multiple renewable energy resources, balancing supply and demand will be a predominant issue, and flexibility will have to be paid for. Possibilities and costs of flexibility of a green gas supply chain were investigated before [8,9]. Costs will be an important criterion in the future, but questions can be raised on the comparability of the current vs. future, or centralized vs. decentralized energy costs. Given the fact that green gas is considered to be part of the future energy mix, an increasing attractiveness of green gas is clearly not only determined by decreasing costs.

Thus, the question arises how the share of green gas in the energy system can grow. This growth will be stimulated by aiming for the EU and Dutch energy saving and GHG reduction goals from a supply chain design engineering point of view. This is also supported by literature (e.g., [10,11]) and fits within a wider institutional perspective on renewable energy developments [12]. The energy balances of different biogas chains were studied and compared before [13–15], but energy optimizations within each chain were not investigated. Also the needed primary energy PE within supply chains was considered to be from fossil origin, which is not necessarily the case. To the authors’ knowledge, no distinction was made in scientific literature on biogas so far between primary energy from fossil or renewable resources. Considering both, i.e., without making the distinction, is an indicator of engineering energy efficiency. Improving energy efficiency is a sound engineering objective. Only considering the fossil resources is a more direct indicator related to sustainability. Replacement of fossil energy by renewable energy may reduce GHG emissions which is also a sound objective, but it not necessarily improves the energy efficiency as such. Only increasing energy efficiency of supply chains not necessarily leads to reduced energy consumption of end-users. Other policies such as taxation or regulation are required [16]. This must be considered as well, but is outside the scope of our study.

The relation between energy balance, GHG reduction and cost price of a green gas supply chain is analyzed in this study. Three sub questions are defined:

1. Based on definitions of fossil and/or renewable primary energy use, what are the contributors to energy efficiency and GHG reduction of a green gas supply chain?

2. What is the influence of selected modifications of the considered green gas supply chain on reduction of (fossil) energy use and GHG emissions?

3. What are the consequences of these modifications to the cost price of green gas?

This study aims to add knowledge on further improving the energy efficiency and GHG reduction of a green gas supply chain, in relation to costs. The used model, a reference scenario, a consideration and definitions of energy efficiency and GHG reduction, and opportunities to improve these aspects are described in the following section, after which the results are presented and discussed. The study ends with conclusions and recommendations for future research.

2. Method

The considered green gas supply chain was modeled as consecutive transformation blocks, shown schematically in Fig. 1.

This supply chain model has a generic character, based on farm-scale co-digestion of manure and co-substrates. Manure is considered to be a waste stream from milk or meat production. Co-substrates are considered to be (energy) crops. Seeds, (artificial) fertilizers and pesticides are inputs needed for this. The biomass is co-digested in a single stage tank reactor and upgraded to green gas in a water wash upgrading installation. The green gas is thought to be injected into a distribution gas grid (8 bar). Part of the digestate from the digester is used again on the land as a fertilizer for the energy crops, partly replacing artificial fertilizer according to limitations set by Dutch law. The other part is considered waste. Transport comprises transport of manure and co-substrates to the farm, transport of digestate as fertilizer and transport of excess digestate as waste.

CO₂ emissions from the upgrading process are not considered because release of CO₂ is part of the short cycle. CO₂ capture by growing maize is also not taken into account. In the used model GHG emissions of manure are not taken into consideration, because manure is considered a waste stream. From this point of view, GHG emissions from manure could be accounted for in the process of milk production. By expanding milk (or meat) production to include a biogas supply chain, the total system includes avoided emissions of GHG. Other approaches are reported in literature as well (e.g., [18]).

In our study a reference scenario was chosen, based on co-digestion of dairy cattle manure and maize with mass fractions of 50% each. Data of a previous study were used [17]. The functional unit chosen is 300 Nm³/h green gas injection into the gas grid. Cost price calculations are based on net present value of a 12-year project. Used data for this reference scenario are presented in Table 1.

The energy inputs of each transformation block were identified, the needed energy was converted to primary energy (PE). Two distinctions were made:
1. Distinction between direct and indirect energy. Direct energy is the input energy needed for a process. For the reference scenario, direct energy is in the form of diesel, natural gas or electricity (e.g., for transport of co-substrate energy is needed in the form of diesel). Indirect energy may be embodied energy (e.g., in fertilizer, machines or plants), or the energy needed for auxiliary processes (e.g., oil for tractors or trucks). All, except one, transformation blocks use direct and/or indirect energy. Manure is the exception to this, because manure is considered to be a waste stream and only has to be transported to a digester. Both direct and indirect energy are expressed in primary energy (PE).

2. Distinction between total primary energy (PE) need and primary energy need specifically from fossil resources (fossil primary energy, FPE). Except from fossil resources, PE may also be from renewables (renewable primary energy, RPE). In general, for each transformation block:

\[
PE = RPE + FPE
\]

The importance of this distinction is illustrated by using the produced green gas for transport and heating (digester) within the supply chain. This does not necessarily change the PE need of each transformation block, but does change the FPE needed, because fossil resources are replaced by renewable resources. In the reference scenario all needed primary energy PE is considered to be from fossil origin (FPE).

Although other definitions are possible [19,20], energy efficiency is expressed as (fossil) primary energy input–output ratio [13–15]. The output is the net energy available after subtracting the green gas used within the supply chain, i.e., the energy available for injection into the natural gas grid, and is depicted by the higher heating value (HHV) of one Nm³ green gas injected: HHV = 35.63 MJ/Nm³. Two definitions are used in this study:

1. The primary energy input–output ratio (PEIO)

\[
PEIO = \frac{PE_{consumed}}{HHV}
\]

gives insight into the primary energy consumption and is defined as the ratio between the primary energy consumed (PE_{consumed}) at all transformation blocks in Fig. 1 summarized for the injection of one Nm³ green gas into the natural gas grid, and the higher heating value HHV of one Nm³ green gas.

2. The fossil primary energy input–output ratio (FPEIO)

\[
FPEIO = \frac{FPE_{consumed}}{HHV}
\]

is a measure for the fossil energy consumption of all transformation blocks.

The first definition is the most direct indicator of energy consumption. FPEIO changes relatively to PEIO when renewable energy is used within the supply chain. Change of both may influence the costs. Note that our definition of FPEIO corresponds to how PEIO is usually defined in literature (e.g., [13,21]). In the reference scenario, PEIO is equal to FPEIO, as all needed energy is supposed to be from fossil origin.

The used expression for GHG reduction corresponds to prescribed calculations [22,23], and uses a comparator for the fossil fuel replaced by green gas: \(GHG_{comparator} = 0.0838 \text{ kg CO}_2\text{-eq/MJ} \) injected green gas [24]. The GHG reduction is then defined as:

\[
\text{GHG reduction} = \frac{GHG_{comparator} - GHG_{chain}}{GHG_{comparator}} \times 100\% 
\]

where \(GHG_{chain}\) is the GHG emission by the supply chain per MJ injected green gas (based on HHV). The considered greenhouse gases, and how these relate to CO₂-equivalents, are shown in Table 2.

---

**Table 1**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount dairy cattle manure/(t/a)</td>
<td>18,312</td>
</tr>
<tr>
<td>Amount maize/(t FM/a)</td>
<td>18,312</td>
</tr>
<tr>
<td>Production/(h/a)</td>
<td>8000</td>
</tr>
<tr>
<td>Transport costs/(€/km)</td>
<td>1.24</td>
</tr>
<tr>
<td>Load/unload costs/(€/t)</td>
<td>0.50</td>
</tr>
<tr>
<td>Investment costs co-substrate storage/€</td>
<td>549,372</td>
</tr>
<tr>
<td>Investment costs digester/€</td>
<td>1,964,423</td>
</tr>
<tr>
<td>Investment costs upgrading/€</td>
<td>1,207,465</td>
</tr>
<tr>
<td>Investment costs injection/€</td>
<td>269,000</td>
</tr>
<tr>
<td>O&amp;M costs as share in investment/%</td>
<td>5</td>
</tr>
<tr>
<td>Depreciation period/yr</td>
<td>12</td>
</tr>
<tr>
<td>Share of total amount of digestate used as fertilizer/%</td>
<td>40.1</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** The considered green gas supply chain, schematically depicted, based on [17].
For every transformation block in Fig. 1, used data for energy need and GHG emission calculations are shown in Table 3. With the conversion factors in Table 4 the direct energy use in Table 3 can be converted to fossil primary energy use. Indirect energy was considered not to be affected, and is expressed in FPE. Based on literature review and contacting experts in the field of green gas, eight alternative scenarios were identified for optimization of the supply chain, based on the Trias Energetica: saving energy, using renewable energy, clean use of fossil energy [40]. These scenarios were modeled as modifications of the reference scenario. Where applicable, for each scenario the reference scenario is described first. Although we did not do a full LCA, the analysis has similarities to an attributional LCA instead of a marginal LCA [41,42]. We did not take marginal effects into consideration (e.g., in our study, switching to electricity from renewable sources does not mean reduced GHG emissions from a specified fossil power plant type). The alternative scenarios are explained in the following subsections.

### Table 2
Conversion of greenhouse gases to CO₂-equivalents [23].

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>CO₂-equivalent/(kg CO₂eq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>23</td>
</tr>
<tr>
<td>N₂O</td>
<td>296</td>
</tr>
</tbody>
</table>

Based on literature review and contacting experts in the field of green gas, eight alternative scenarios were identified for optimization of the supply chain, based on the Trias Energetica: saving energy, using renewable energy, clean use of fossil energy [40]. These scenarios were modeled as modifications of the reference scenario. Where applicable, for each scenario the reference scenario is described first. Although we did not do a full LCA, the analysis has similarities to an attributional LCA instead of a marginal LCA [41,42]. We did not take marginal effects into consideration (e.g., in our study, switching to electricity from renewable sources does not mean reduced GHG emissions from a specified fossil power plant type). The alternative scenarios are explained in the following subsections.

### Table 3
Used data in the reference scenario.

<table>
<thead>
<tr>
<th>Energy use, direct</th>
<th>Energy use, indirect</th>
<th>GHG emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Co-substrate production</td>
<td>4975 MJ(_{\text{burn}})/(ha a)(^a)</td>
<td>1826 MJ(_{\text{fpe}})/(ha a)(^b)</td>
</tr>
<tr>
<td>Transport truck tank</td>
<td>1.0 MJ(_{\text{burn}})/(t km)(^c)</td>
<td>0.1 MJ(_{\text{burn}})/(t km)(^d)</td>
</tr>
<tr>
<td>Transport truck trailer</td>
<td>1.0 MJ(_{\text{burn}})/(t km)(^e)</td>
<td>0.1 MJ(_{\text{burn}})/(t km)(^f)</td>
</tr>
<tr>
<td>Co-substrate storage</td>
<td>1.7 MJ(_{\text{burn}})/(t km)(^g)</td>
<td>0.8 MJ(_{\text{burn}})/(t km)(^h)</td>
</tr>
<tr>
<td>Digestion</td>
<td>0.4 kW h/Nm(^3) biogas (heating, natural gas)(^i)</td>
<td>0.12 kW h/Nm(^3) biogas (electricity)(^j)</td>
</tr>
<tr>
<td>Upgrading</td>
<td>0.24 kW h/Nm(^3) biogas (electricity)(^k)</td>
<td>0.01 kW h/Nm(^3) green gas (electricity)</td>
</tr>
</tbody>
</table>

### Table 4
Conversion factors. Note that the primary energy use and hence GHG emissions of electricity from fossil resources are significantly more than of diesel and natural gas.

<table>
<thead>
<tr>
<th>Fossil primary energy use</th>
<th>Diesel</th>
<th>Natural gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.25 MJ(<em>{\text{fpe}})/MJ(</em>{\text{diesel}})(^a)</td>
<td>1.1281 MJ(<em>{\text{fpe}})/MJ(</em>{\text{nat.gas}})(^b)</td>
<td>2.5 MJ(<em>{\text{fpe}})/MJ(</em>{\text{el}})(^c)</td>
</tr>
</tbody>
</table>

### Table 5
Methane losses during digestion.

<table>
<thead>
<tr>
<th>Methane losses/%</th>
<th>Quantification method</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assumption</td>
<td>[37]</td>
</tr>
<tr>
<td>1</td>
<td>Assumption</td>
<td>[43]</td>
</tr>
<tr>
<td>2</td>
<td>Assumption</td>
<td>[27]</td>
</tr>
<tr>
<td>3</td>
<td>Assumption</td>
<td>[44]</td>
</tr>
<tr>
<td>0.17–5.46</td>
<td>Measurement</td>
<td>[45]</td>
</tr>
<tr>
<td>3</td>
<td>Measurement</td>
<td>[46]</td>
</tr>
</tbody>
</table>

### 2.1. Digester leakage

Minimizing methane losses at digestion. Values for digester losses as found in literature are presented in Table 5. In the reference scenario 1% of the methane production of the digester is considered to be lost. Note that measured values are often higher. Lack of maintenance shows to be an important cause
for high leakages. The digester methane loss is changed to 0.1% which results in a higher biogas yield. The value is based on proper design and maintenance of biogas plants. It is assumed that this is possible without extra investment costs.

2.2. Upgrading leakage

Minimizing methane losses at upgrading. From the technologies that are currently on the market, water scrubbing is among the technologies with the greatest GHG emission savings [47]. The methane efficiency was changed from 99% in the reference scenario to 99.9%. This is based on available post-treatment technologies which can be implemented to deal with methane slip. These include regenerative thermal oxidation, recuperative thermal oxidation and biological de-methanization. It is assumed that this is possible without extra investment costs.

2.3. Re-use heat

Re-use heat within the supply chain. A pinch analysis [11,48] was performed to explore the possibilities. This showed that 1.2 MJ/Nm$^3$ can possibly be saved by re-using the digestate heat and the compression heat at upgrading for heating the biomass. This scenario implies that digestion and upgrading installations are closely interconnected. Improved insulation of digesters is not investigated separately. The impact would be modest, because heat demand is mainly determined by increasing the biomass temperature to mesophilic conditions. An extra investment of €100K is assumed.

2.4. Digestate fertilizer

Increase of artificial fertilizer replacement by digestate. The rationale of this scenario is that in the reference scenario the largest share of digestate is considered as waste (removal has to be paid for) while energy cost and environmental impact of artificial fertilizer is considerable (e.g., [11]). However, the uptake of nutrients in digestate by crops is limited compared to artificial fertilizer. A somewhat arbitrary 20% increase of digestate use is considered. Savings are mainly caused by lower artificial fertilizer need and partly by not needing to transport digestate as waste (50 km in the model). Transport to arable land increases in this scenario but is less than waste transport.

2.5. Manure 75%

A change to less maize in the mixture. Co-digestion of cattle manure and maize with mass fractions 75% and 25% respectively is chosen.

2.6. Mono-digestion manure

Mono-digestion of cattle manure. Mono-digestion is stimulated in the Netherlands by subsidies [5].

2.7. Green fuel

Using green gas for transport within the supply chain and heating the digester. In the reference scenario, 12.4% of the energy consumption is used for transport, and natural gas is assumed to be used for heating the digester. The extra needed quantity of green gas implies a 14.7% increase in biomass need. Extra investment costs for adapting tractors and trucks, and compression of the gas to 200 bar, are included and assumed to be €200K. The energy (work) needed for compression from 8 to 200 bar is estimated to be 0.45 kWh/Nm$^3$. The PEIO calculated for the reference scenario is also applied to green gas use as a transport fuel.

2.8. Green electricity

Electricity is from renewable resources. Electricity is used at digestion, upgrading and injection. If this is from renewable resources, then fossil energy (FPE) use and GHG emissions are strongly reduced. The factor 2.5 for (F)PE calculation (Table 4) is changed to 1.1 [49]. We assumed no influence on the cost price of electricity.

2.9. Combination

A combination of alternative scenarios which have a positive or non-negative effect on all aspects (F)PEIO, GHG reduction and cost price, was added to explore the limits in improvements.

Changing the methane content of green gas from 89% to a higher value, and thus changing the green gas quality, was not considered [50]. Although the transport of green gas would become more efficient (i.e., more energy per Nm$^3$ transported), it would not influence the supply chain as it was defined. Methane enrichment of biogas by methanization of hydrogen and carbon dioxide might be an interesting option as well (e.g., [51]), but was also not considered. As this technology is still in development, (investment) costs in relation to methane yield are not available.

The alternative scenarios, implemented as modifications of the reference scenario, were analyzed in terms of influence on (F)PEIO, GHG reduction and cost price, and compared to the reference scenario. The calculations were done in the spreadsheet software MS Excel.

3. Results/discussion

As stated before, in the reference scenario PEIO is equal to FPEIO. This is shown in Fig. 2a as a function of scale. The value at the reference scenario is 32.8%.

The increasing PE consumption at increasing scale is caused by increasing transport distances. The share of the consecutive transformation blocks in Fig. 1 in total PE consumption is depicted in Fig. 2b for the reference scenario, where the transport transformation blocks are combined. The largest PE consumption is caused by digestion and upgrading. For the reference scenario, a subdivision in direct and indirect energy is shown in Fig. 3. The share of indirect PE in the total PE consumption is 8.8%.

The large FPE use of digestion and upgrading is caused by a large heating demand (digestion) and electricity use (digestion and especially upgrading) with a relatively large conversion factor of electricity to primary energy (Table 4).

The GHG reduction as a function of scale is shown in Fig. 4a. The decreasing GHG reduction at increasing scale is caused by increasing transport distances for manure, co-substrate and digestate.

The share of the consecutive transformation blocks in Fig. 1 in total GHG emissions is depicted in Fig. 4b for the reference scenario. At this scenario the GHG reduction is 57.8%. For the co-substrate the GHG emissions are caused by direct (fossil fuel use) and indirect (machines, seeds, fertilizer, pesticides) energy use, for transport mainly by fossil fuel use. GHG emissions of digestion are caused by methane emissions (48% of digestion total, the global warming potential of methane is 23 times worse than CO$_2$), electricity use (39%) and heat use (13%). The upgrading share is caused by methane losses (34%) and electricity use (66%). Finally, the emissions at injection are mainly caused by electricity use. The largest shares are caused by methane leakage/slip during digestion.
and upgrading. Because of this effect, the share of transport in GHG emissions is relatively lower than its FPE share in Fig. 2b.

Summarizing, for the reference scenario (scale 300 Nm$^3$/h), (F)PEIO is 32.8%, the GHG reduction is 57.8%, and the cost price was calculated to be 72.0 €/Nm$^3$. The implications of the considered scenarios are shown in Fig. 5.

The first four alternative scenarios (digester and upgrading leakage, re-using heat and increase of digestate as fertilizer) improve the performance of the green gas supply chain, although the influence is modest. These are the only scenarios which show improvements on all considered aspects. The (F)PEIO reductions of the leakage scenarios seem small from a supply chain point of view. From a farmer’s point of view, who operates a biogas plant, the savings may be significant. The leakage scenarios also show that merely aiming for GHG reduction does not necessarily mean a proportional reduction in fossil fuel use at the same time. This again pleads for a distinction between FPEIO and GHG reduction.

The small improvement in (F)PEIO is caused by a more efficient process, so less biomass and hence transport is needed for the same green gas output.

The scenarios Manure 75% and Mono-digestion should be considered with some caution. In the used model, the digestion costs are based on investment costs as a function of produced quantity of biogas. However, in these two cases the share of manure and upgrading, because of this effect, the share of transport in GHG emissions is relatively lower than its FPE share in Fig. 2b.

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The scenarios Manure 75% and Mono-digestion should be considered with some caution. In the used model, the digestion costs are based on investment costs as a function of produced quantity of biogas. However, in these two cases the share of manure and upgrading, because of this effect, the share of transport in GHG emissions is relatively lower than its FPE share in Fig. 2b.

Summarizing, for the reference scenario (scale 300 Nm$^3$/h), (F)PEIO is 32.8%, the GHG reduction is 57.8%, and the cost price was calculated to be 72.0 €/Nm$^3$. The implications of the considered scenarios are shown in Fig. 5.

The first four alternative scenarios (digester and upgrading leakage, re-using heat and increase of digestate as fertilizer) improve the performance of the green gas supply chain, although the influence is modest. These are the only scenarios which show improvements on all considered aspects. The (F)PEIO reductions of the leakage scenarios seem small from a supply chain point of view. From a farmer’s point of view, who operates a biogas plant, the savings may be significant. The leakage scenarios also show that merely aiming for GHG reduction does not necessarily mean a proportional reduction in fossil fuel use at the same time. This again pleads for a distinction between FPEIO and GHG reduction.

The small improvement in (F)PEIO is caused by a more efficient process, so less biomass and hence transport is needed for the same green gas output.

The scenarios Manure 75% and Mono-digestion should be considered with some caution. In the used model, the digestion costs are based on investment costs as a function of produced quantity of biogas. However, in these two cases the share of manure
strongly increases. As the energy content of manure is much less than maize, much substrate would be needed for the same green gas production, i.e., the digester would be larger and more expensive than assumed in the model. So in practice the costs (and embodied energy) will be higher than presented. The obvious impairments of (F)PEIO and GHG reduction are caused by increased transport movements because of the increased needed quantity of manure. If avoided emissions from manure would be taken into account, the results would be different. Avoiding these emissions is one of the reasons to digest manure.

The difference between PEIO and FPEIO becomes clear at scenarios Green fuels and Green electricity. Both scenarios clearly show a reduction in fossil energy use, and thus GHG emissions. Concerning the Green fuel scenario, the energy efficiency as such (PEIO) becomes worse, which may not meet engineering objectives. On the other hand, fossil energy use decreases, which can be considered to be a sustainability improvement. Which of the two prevails, may be an engineering decision. Regarding the Green electricity scenario, the difference is caused by a smaller indirect energy need of green electricity (as embodied energy, which is expressed in FPE).

The higher cost price of scenario Green fuel is mainly caused by the relatively high costs of compression of gas to 200 bar. The high electricity need for this, which is still considered to be from fossil origin, is not advantageous. The net reduction in FPEIO is caused by using green gas as a fuel in the supply chain. Of all scenarios, from a sustainability point of view, green electricity gives the largest improvement of the supply chain.

It is obvious that the results depend on the chosen system boundaries. As stated before, we considered methane emissions from manure to be outside the system boundaries, and did not take marginal effects into account.

4. Conclusions – future research

In the present study an alternative way to present the energy efficiency of a green gas supply chain was introduced. A distinction was made between direct and indirect energy. The share of indirect energy...
energy in total energy consumption is modest. A further distinction was made between primary energy (PE) as such, and the primary energy from fossil origin (FPE). The first is a direct indicator for energy efficiency, the latter is an indicator of energy use from a sustainability perspective. The influence of several scenarios to improve the sustainability of a green gas supply chain was investigated.

An obvious result is that preventing methane losses and reusing heat should always be strived for (scenarios Digester leakage and Upgrading leakage), although on these aspects to date no legislation is known to the authors. Increase of digestate as fertilizer seems promising, but more research is required on aspects like nutrient uptake by plants and soil improvement by digestate. Using compressed green gas for transport within the supply chain would seem obvious, but the costs of compression are very high. Using green gas for heating the digester is more obvious, but was not investigated separately. The effect of using green electricity is evident, a subsidy regime requiring the use of green electricity would significantly contribute to achieving national sustainability goals. At the current state of technology, only the combination of scenarios with a positive score would help to reach long-term goals of more than 80% GHG reduction. In that case the fossil energy use could be significantly reduced. The cost price decrease is modest, but possibilities to make the green gas supply chain more viable seem to be there.

In this study only the injection of green gas was considered. How the results relate to other applications of biogas or green gas remains a subject of future research. Comparison of natural gas replacement with compressed green gas for transport may give other results. Separation of nutrients in the digestate might also open interesting opportunities for further optimizing the green gas supply chain. At least the nitrogen use as a fertilizer might further increase to some 250 kg/ha instead of 190 kg/ha which was used in the study. In the present study only maize was considered as co-substrate. The influence of other co-substrates on cost price and sustainability should be investigated.

A further investigation of embodied energy of plants and machines was not subject of this study. Improvements in the mechanical design of plants and machines, or in the production of artificial fertilizer might open interesting pathways for further ‘greening’ of the green gas supply chain. It does not contribute to fossil energy replacement to a great extent, but to sustainable use of resources in general.

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References


[49] SimaPro 8.0.2.
