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Lessons from spatial and environmental assessment of energy potentials for Anaerobic Digestion production systems applied to the Netherlands

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HIGHLIGHTS

- There is a substantial gap between bio-energy potential and net energy gain.
- For reaching production goals the green gas utilization pathway is preferable.
- Environmental sustainability favors the waste management pathway.
- Renewable energy production goals and environmental sustainability do not always align.
- There is a gap between top–down regulation and actual emission reduction and sustainability.

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ABSTRACT

Anaerobic digestion (AD) can play an important role in achieving the renewable energy goals set within the European Union. Within this article the focus is placed on reaching the Dutch local renewable production goal set for the year 2020 with locally available biomass waste flows, avoiding intensive farming and long transport distances of biomass and energy carriers. The bio-energy yields, efficiency and environmental sustainability are analyzed for five municipalities in the northern part of the Netherlands, using three utilization pathways: green gas production, combined heat and power, and waste management. Literature has indicated that there is sufficient bio-energy potential in local waste streams to reach the aforementioned goal. However, the average useful energy finally produced by the AD production pathway is significantly lower, often due to poor quality biomass and difficult harvesting conditions. Furthermore, of the potential bio-energy input in the three utilization pathways considered in this article, on average: 73% can be extracted as green gas; 57% as heat and power; and 44% as green gas in the waste management pathway. This demonstrates that the Dutch renewable production goal cannot be reached. The green gas utilization pathway is preferable for reaching production goals as it retains the highest amount of energy from the feedstock. However, environmental sustainability favors the waste management pathway as it has a higher overall efficiency, and lower emissions and environmental impacts. The main lessons drawn from the aforementioned are twofold: there is a substantial gap between bio-energy potential and net energy gain; there is also a gap between top–down regulation and actual emission reduction and sustainability. Therefore, a full life cycle-based understanding of the absolute energy and environmental impact of biogas production and utilization pathways is required to help governments to develop optimal policies serving a broad set of sustainable objectives. Well-founded ideas and decisions are needed on how best to utilize the limited biomass availability most effectively and sustainably in the near and far future, as biogas can play a supportive role for integrating other renewable sources into local decentralized energy systems as a flexible and storable energy source.

1. Introduction

The European Union has set high goals for renewable energy integration in the near future [1,2]. Within this context, Anaerobic Digestion (AD) can play an important role as it is capable of processing a multitude of biomass feedstocks, whilst producing both

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Nomenclature

AD	Anaerobic Digestion	GHG	Green House Gasses
CHP	combined heat and power	(P)EROI	Process Energy Returned on Invested
oDM	organic dry matter	GWP100	Global Warming Potential 100 year scale
FM	fresh matter	Pt	environmental impact in EcoPoint
PJ	peta joule (10^{15} J)	LCA	Life Cycle Analysis
GJ	giga joule (10^9 J)	aLCA	Attributed Life Cycle Analysis
MJ	mega joule (10^6 J)	kgCO$_2$eq	kilograms of carbon dioxide equivalent
Mg	mega gram (equivalent to metric tonne)	Nm^3	normal cubic meter (volume at 1 bar 0C)

energy in the form of biogas, and fertilizers in the form of digestate. Biogas can be seen as a renewable and flexible energy carrier which is storable and can be transformed into electricity, heat, or upgraded to green gas (biogas upgraded to natural gas quality) [3]. Digestate can be processed to produce quality fertilizers for use in agriculture [4]. AD has been successfully implemented in the treatment of several biomass feedstocks and is already established as a reliable technology in Europe [5]. In the year 2014 around 4% of the total energy supply within Europe was produced through biomass, and this is expected to grow significantly in the future [6]. However, the need for feedstocks will most likely also increase as a result, and the majority of the additional supply is expected will come from agricultural land [6]. Therefore, questions can be raised regarding the achievability, efficiency, and sustainability of the biogas production pathway when utilizing specially cultivated energy feedstocks and transporting them over longer distances. The choice of feedstocks, technologies, and the operational values of AD pathways (e.g. feedstock, transport, process) have a significant influence on the environmental impact [7–13], and the increased biomass use can claim valuable arable land for cultivation [6] and/or effect biodiversity [14].

Within the aforementioned context, focus could be placed on alternative feedstocks which: do not have other applications except as energy sources; do not have an extensive environmental impact; and, are locally available (e.g. manures, organic wastes, natural grasses, harvest remains) [13,15–19]. Studies have indicated that there is a sufficient amount of local waste feedstocks within the Netherlands to achieve the Dutch decentralized renewable goals of 40 PJ by 2020 [20]. One recent study concluded that locally available biomass waste streams can provide up to 66 PJ annually of energy within the Netherlands [21]. Other studies indicate: natural resources (e.g. roadside grass, natural grass reed) can provide around 12 PJ [22] to 13.5 PJ annually [23]; waste streams from agro-industry potentially hold another 14PJ annually [24]; overall, a range between 53 up to 94 PJ per year will be available by 2020 [25]. However, the aforementioned studies often ignore the energy required in the process of extracting energy from the biomass and the environmental impacts of the process. In order to make more reliable environmental assessments of biogas systems from feedstocks, specific local and regional conditions have to be included [7], which fit a unique geographic location with dispersed availability and quality of biomass. LCA studies on local implementation of AD focusing on single waste flows (e.g. food, vinasse, agro-food waste, municipal solid waste) have indicated environmental benefits over fossil resources [15–18,26,27]. However, the LCA studies do not focus on utilizing the multitude of locally available waste products for reaching decentralized renewable production goals. Additionally, the question could be raised, from an environmental perspective, whether to focus on quantity or quality of production: quantity, focusing on producing the largest amount of useful energy; or quality, achieving the highest efficiency or creating the biggest reduction of greenhouse gas emissions and environmental impacts. Currently, regulations in the Netherlands are mostly focused on quantity (e.g. the production of green gas, heat and electricity) [20].

Thus, research is still needed to assess the overall renewability, sustainability, and possible energy yields of biogas production pathways operating on locally available waste feedstocks. Understanding the local availability of biomass, the subsequent, related biogas production pathways, and the best sustainable practices can support decentralized renewable integration as AD can play an important role as a waste treatment system which also produces a flexible energy carrier. One indication can be whether the goal of the Dutch government is achievable and whether the focus should be placed merely on quantity or also on quality of energy production from an environmental sustainability perspective. This article aims to contribute to a proper assessment of the overall renewability, sustainability, and possible energy yields of biogas production pathways operating on locally available biomass waste flows. The goal will be affected by assessing and evaluating the local availability of organic waste materials within five municipalities in the northern part of the Netherlands. For these five locations, the following procedure is followed: first, the available biomass waste flows and bio-energy potentials are determined; second, the net energy yields from three biogas production and utilization pathways are calculated; third, the net average yield of the five municipalities are compared to the required yield to reach the Dutch goal of 40 PJ; and finally, the emissions and environmental impact are determined. Additionally, the effect of an increased percentage of manure in the feedstock for the digester is analyzed in terms of efficiency and environmental impacts. The lessons learned from the case study will be discussed in the conclusion.

2. Methods

The assessment of the complete biogas production pathway will be performed through the use of a method for calculating the sustainability of AD production pathways and the sustainability of feedstocks and process optimization (described in [13,28]) and Life Cycle Analysis (LCA). The LCA analysis is undertaken in accordance with European guidance and DIN EN ISO 14040 to 14044: 2006 [29]. The environmental impacts were obtained through the use of the SimaPro v8.0 (2013) utilizing the Eco Invent database v3.0 (2013) as endpoints.

2.1. System boundary

Dutch regulation states that at least 50% of the feedstock fed into the biogas production pathway must be composed of manure sources (e.g. cow, pig, chicken manure), while the remainder can be filled up by other biomass sources (e.g. harvest remains, roadside grass, or maize). Environmental impacts are taken into

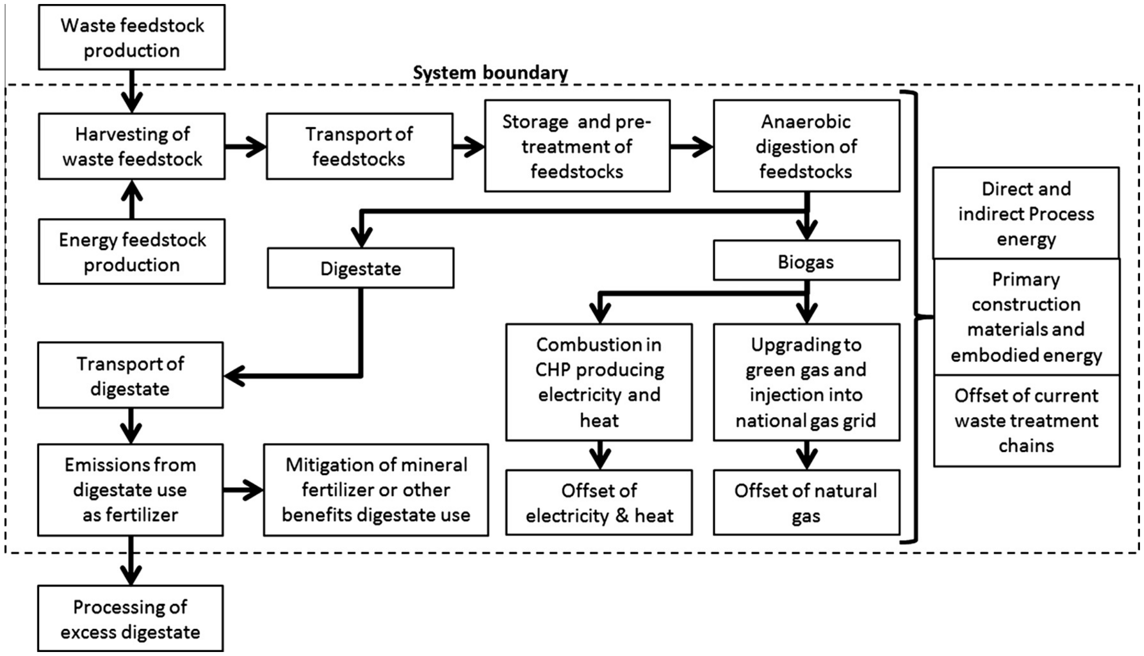


Fig. 1. System boundaries of biogas production and utilization pathways, included aLCA.

account when they are in direct service of the biogas production pathway (e.g. production, processing, and transport), which include the direct impact of consumption, the indirect impacts of production and transportation, and the required embodied energy in the shape of installations and infrastructure (Fig. 1) [13]. The digestate produced will be returned to the biomass sources as fertilizer and transport of the digestate is included. The processing of excess digestate is not included. Within this research, impact mitigation resulting from the replacement of current waste treatment chains is taken into account (e.g. seasonal storage of manure) including the upgrading process of digestate into a fossil fertilizer replacement [13].

2.2. Municipalities

Five municipalities located in the North of the Netherlands are selected where the biomass potential is assessed (Fig. 2). These municipalities vary from urban areas with a high population density to rural, agricultural and dairy farming areas, representing the diversity of land usage in the Netherlands (Fig. 2). The research is focused on the northern part of the Netherlands as it lays within the scope of the Flexigas project [30] and the project partners responsible for managing and processing biomass flows. However, the calculation method discussed in this article can be used for all areas when sufficient data is available. The data regarding biomass availability in the Netherlands, used in this article, is available per municipality by the Bureau of Statistics of the Netherlands [31].

2.3. Method for determining the local biomass potential

Due to geographical differences in biomass potential within the selected areas a calculation method is used for determining the average biomass potential. The total biomass potential present within a local municipality is divided by the total land surface of the municipality to obtain an average potential per square kilometer. This method thus averages the distribution of biomass over the surface of one municipality. With the biomass yield per square kilometer known, the land surface required to feed a representative farm scale digester of 20,000 Mg/a, can be determined (Fig. 3). With the surface area known, the average transport distance for the manure and the feedstocks can be determined (discussed in Section 4).

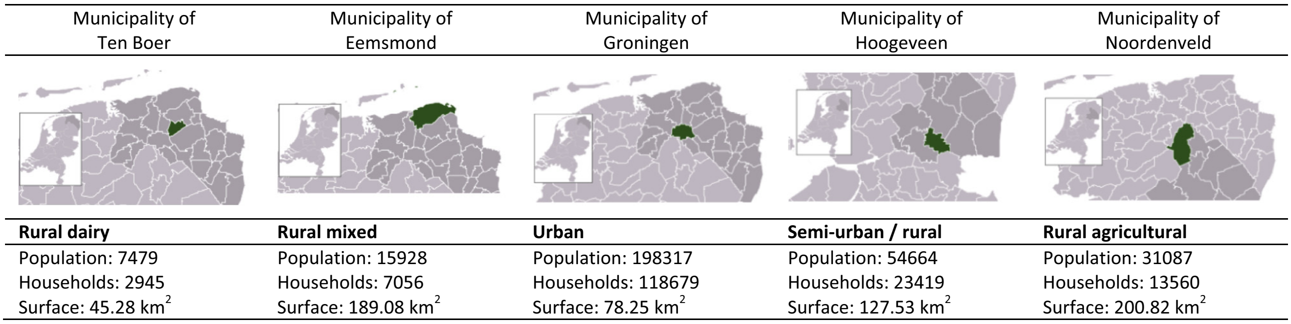
2.4. Expressions of the results

The bio-energy potential per municipality will be expressed in GJ/km^2. The process efficiency, carbon footprint and sustainability of the biogas production pathway, will be expressed by three indicators per GJ of energy produced: (Process) Energy Returned on Energy Invested or (P)EROI, the carbon footprint in GWP 100 year timeframe, and the environmental impact in ReCiPe 2008 Eco indicator. The specific choice for the above-named indicators and a clear description thereof are discussed in Pierie et al. [28]. The results will be compared with reference scenarios (e.g. intensively cultivated maize, Groningen natural gas, and electricity from the Dutch national grid).

3. Biomass inventory

An inventory of biomass waste streams availability has been performed for five local municipalities (Fig. 2). The bio-energy potentials of the feedstocks are retrieved from Pierie et al. from Table 2 [13]. These represent readily available and easily usable feedstocks for farm scale digester installations. However, small scale waste flows, other agricultural waste flows, and waste flows from the food industry are not included in this inventory. For the biomass availability in the municipalities (Table 1) a lower and upper limit are taken into account in two scenarios:

(1) *Minimum availability scenario:* will focus on the biomass waste flows which are already in use or very easily used as feedstock in the AD process, for instance when infrastructure or management processes are already in place and only need minor modification.
(2) *Maximum availability scenario:* all the available biomass waste flows are utilized as feedstock, including biomass waste flows which need additional energy for collection.



Municipality of Ten Boer	Municipality of Eemsmond	Municipality of Groningen	Municipality of Hoogeveen	Municipality of Noordenveld
Rural dairy	**Rural mixed**	**Urban**	**Semi-urban / rural**	**Rural agricultural**
Population: 7479	Population: 15928	Population: 198317	Population: 54664	Population: 31087
Households: 2945	Households: 7056	Households: 118679	Households: 23419	Households: 13560
Surface: 45.28 km^2	Surface: 189.08 km^2	Surface: 78.25 km^2	Surface: 127.53 km^2	Surface: 200.82 km^2

Fig. 2. The municipalities chosen for assessment of local bio-energy potential.

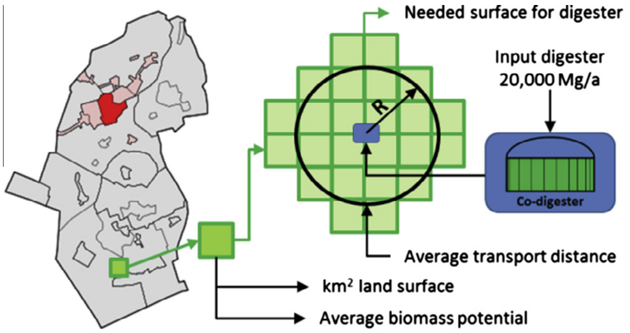
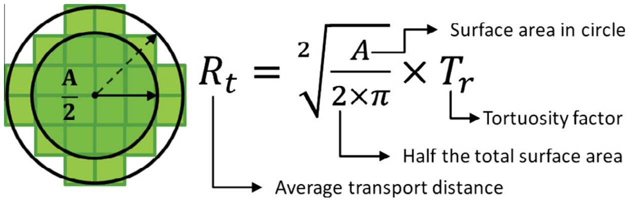


Fig. 3. Calculation method used to determine biomass and biogas potential for the municipality of Noordenveld.



$$R_t = \sqrt[2]{\frac{A}{2\times\pi}} \times T_r$$

Fig. 4. Calculation method used to determine the average transport distance.

4. Biogas utilization pathways

All feedstocks and scenarios use the same AD plant setup, located on or near a farm with a total biomass input of 20,000 Mg of fresh matter (FM) per year [13]. The produced biogas is utilized in three different pathways: green gas, combined heat and power (CHP), and waste treatment. The manure/feedstock ratio in the digester will be kept at 50% manure and 50% biomass feedstock. The feedstock ratios are determined by the surface area needed to supply the digester, set as a circle around the location (Fig. 3). The average transport distance will be based on half the surface area of the biomass circle and a tortuosity factor, which represents inefficiencies in transport e.g. winding roads, multiple pickup locations, etc. (Fig. 4), [34]. For the manure and feedstock sources a tortuosity factor of 1.5 is used [35]. For municipal organic waste, which is collected on individual house level through a bin system, a tortuosity factor of 20 is used. For the minimum availability of grass a tortuosity factor of 5 is used, and for the maximum availability a factor of 10 is used, due to the additional transport needed for collecting small patches of natural or roadside grass [34]. The effect of the assumed tortuosity factors will be discussed in the sensitivity analysis section (Section 6).

The solid feedstocks are mechanically pre-treated with a hammer mill in order to improve the digestion and the biogas potential of the feedstock [36]. Grass and municipal organic waste are sieved for foreign debris (e.g. plastics, rocks). Additionally, municipal organic waste will be pasteurized to remove unwanted biological contaminants (Table 2).

4.1. The green gas production pathway

Within the green gas utilization pathway, the main product is green gas of natural gas quality for injection into the national gas grid. Part of the produced biogas will be used in a small boiler to produce the needed heat for the digestion process. The remaining biogas will be upgraded to green gas through the use of a highly selective membrane upgrader system (see Table 1 in [13]). A gas pipe transporting the green gas over a distance of one kilometer

Table 1
Biomass waste flows selected as feedstocks for biogas production pathway.

(1) *Manure:* Dairy manure is readily available in the northern part of the Netherlands. Chicken manure, however, is less available and also has a higher biogas potential due to its higher oDM. The manure availability will be similar for both the current and maximum availability scenario.
(2) *Grass feedstock:* Natural grasses can be found spread throughout local municipalities. Natural grasslands and road embankments are already in use and are relatively easy to harvest and therefore make up the current availability. The remainder of grass, for instance in small parks and green spaces, is more difficult to harvest and collect and will be added to the maximum scenario.
(3) *Harvest remains:* During harvests of sugar beets and potatoes, organic material is left on the fields containing parts of the plant and root system which can be used as feedstock for the digester. In the minimum scenario around 50% of the remains, consisting of the plant are used, and in the maximum scenario 100% of the available remains from sugar beets and potatoes, consisting of the plant and root system, are used.
(4) *Straw from grains:* Straw is a product often used as bedding material for livestock in stables. As other systems (e.g. separated manure, rubber mats) slowly replace part of the market for straw, some degree of overproduction and remaining stocks can result. Unused straw can be utilized as a feedstock. In the minimum scenario around 10% of the total produced straw is available for use as feedstock. In the maximum scenario all produced straw is available as feedstock.
(5) *Municipal organic waste:* Municipal waste is collected, on average, every two weeks in the Netherlands through the use of a waste bin system. However, most of the organic municipal waste (83%) finds its way into the normal waste flow. Only a small percentage of organic waste is collected directly (17%), comprising of kitchen and garden waste [32]. The minimum availability scenario will be made up from the currently collected organic municipal waste. The maximum availability will contain all the organic waste including the fraction normally found in the normal waste stream. Within this context a separate collection system is used for collecting the organic waste and to prevent contamination of the biomass. The organic dry matter content (oDM) of waste on average is 18% with a biogas and methane yield of respectively 260 and 156 Nm^3/Mg oDM [33].

Table 2
Main values used for pretreatment of feedstocks.

Feedstocks	Grass	Waste	Sugar beet tops	Potato tops	Straw	Unit	Sources
Energy use screening unit[a]	5.4	5.4	–	–	–	MJ/Mg FM	[37]
Energy use hammer mill[a]	20	20	20	20	20	MJ/Mg FM	[36,37]
Energy use pasteurization[b]	–	162	–	–	–	MJ/Mg FM	[38]

[a] Electricity consumption only.
[b] Electricity use 5 MJ/Mg FM and heat use 157 MJ/Mg FM.

to the injection point and the electricity (Average grey electricity mix of the Netherlands, Table 6) needed for the process is incorporated.

4.2. Combined heat and power

In the combined heat and power (CHP) utilization pathway the main products are electricity and heat (see Table 3 in [13]). The produced electricity and heat is firstly used to supply the energy demand of the AD process itself, and the remainder is put on the national electricity grid and on a local heat grid. Within this pathway all the produced heat is considered as useful energy. For both electricity and heat an additional cable and pipeline of one kilometer is incorporated for transportation to the injection locations.

4.3. Waste management optimization

The waste management utilization pathway will produce both green gas and CHP. The CHP unit will power and heat the AD process and the digestate upgrading process, which produces fossil-equivalent quality fertilizers. Any remaining heat demand will be supplied by the biogas boiler. The remaining biogas will be upgraded to green gas, which is firstly used as transport fuel for the trucks delivering the feedstocks, thereby replacing diesel use, and the remainder will be injected into the national gas grid. Additionally, a large share of the digestate (90%) is separated into a thin and thick fraction (Table 3). The processed thin and thick fractions (the former, after upgrading) will be used to replace fossil fertilizers (Table 4) [6,39]. The remaining 10% of the digestate will be used on-site, replacing manure fertilization on the pasture but not replacing fossil fertilizers.

4.4. Reference scenarios

The results from the analysis will be compared to two reference scenarios in order to indicate efficiency and sustainability.

1. *Fossil reference scenarios:* The reference scenarios are based on Groningen natural gas and the grey electricity average mix of the Netherlands (Table 5), which includes production, required infrastructure (natural gas and electricity network), and combustion of the gas when used.
2. *Maize reference scenario:* The maize silage used as a feedstock is specially cultivated for use in the biogas production pathway (Table 6). Therefore, agricultural field work and the use of fossil fertilizers and pesticides during cultivation are incorporated. Maize will be incorporated in the model as a reference using the same biogas production and utilization pathways as described in Section 4. The maize will be transported over an average distance of 50 km [3].

5. Results

In the following section the results are discussed, starting with the overall bio-energy yields and the efficiencies of the utilization pathways, followed by the (P)EROI and environmental impact of the pathways, and finally, the effect of increasing the percentage of manure in the feedstock is discussed. The figures used to express the results are based on the descriptions in Table 7 (scenarios are described in Section 3).

Table 3
Main values for digestate handling, separation of digestate in thin and thick fractions, and thin fraction upgrading.

Main components waste management pathway	Value	Unit	Source
Energy requirement separator[a]	4.68	MJ/Mg FM	[40]
Energy requirement evaporator[b]	231	MJ/Mg FM	[41]
Water removed from fraction in evaporator	90%	%	[41]

[a] Based on an electric separator.
[b] Based on vacuum evaporator system operating on a heat pump.

5.1. Theoretical energy yields

The theoretical bio-energy yield of the municipalities per square kilometer is strongly dependent on the nature of the space available for biomass growth, the types of biomass available, and population density. The average theoretical bio-energy yield of the selected municipalities is around 1614 GJ/km^2, which is comparable to the national average indicated in literature (1400–2500 GJ/km^2) as discussed in the introduction (Table 8). However, only around 64% (1038 GJ/km^2) of the biomass available is utilized as a feedstock (Table 8). The gap can partially be traced back to the high amount of manure available, of which only small amounts are used as feedstock, often due to low biogas yields and difficulty in collection and transport. Therefore, a municipality with a high number of dairy farms can have a high theoretical bio-energy yield with only low utilization realized (e.g. municipality of Ten Boer). Agricultural activity can also lead to higher utilization of bio-energy yield (e.g. municipality of Eemsmond) (Table 8). Furthermore, the local theoretical bio-energy yield from waste flows is fairly constant and without the use of agricultural land or intensive farming will most likely not increase significantly in the coming years; therefore, the bio-energy yield can be seen as a set amount.

5.2. Energy efficiency process

The efficiency of the AD process and utilization pathways determines the amount of energy which can be extracted from the feedstock. The average energy extracted varies: 73% as green gas, 57% as heat and power, and 44% as green gas in the waste management pathway (Fig. 5). This lowers the average energy yield of the municipalities to 757 GJ/km^2 as green gas. There will be differences in yields between municipalities, depending on available feedstock, transport distance, etc. (Table 8). Within the utilization pathways the green gas pathway is capable of retaining the largest share of energy from the feedstock, due to minimal losses (e.g. leakage, heat), (Fig. 5a). However, the energy needed for the production of green gas is substantial: over a quarter of the produced biogas is needed for the production of heat, and over a third of external energy is required for the process itself (e.g. transport,

Table 4
Main values for production of fossil fertilizers replaced by upgraded digestate.

Fertilizers replaced	Nitrogen as N	Phosphate as P_2O_5	Potassium as K_2O	Units	Source
Required energy for fertilizer production	75.90	27.9	12.9	MJ/kg	[42,43]
Emission during fertilizer production	12.60	2.22	2.30	$kgCO_2$ eq/kg	[42,43]
Environmental impact during fertilizer production	1.77	0.76	0.24	Pt/kg	[42,43]

Table 5
Values used as reference for Groningen natural gas and grey electricity.

	Carbon footprint ($kgCO_2eq$/GJ)	Environmental impact (Pt/GJ)	Source
Natural gas[a]	54.6	6.2	[42,43]
Grey electricity[b]	177	28.2	[42,43]

[a] Natural gas produced from the Groningen gas field and surrounding gas fields in the Netherlands, including infrastructure.

[b] Grey electricity, based on the average mix of electricity produced in the Netherlands in 2014, including infrastructure.

Table 6
Main properties of energy maize feedstock.

Feedstock	Biomass yield (Mg/ha)	Organic Dry Matter (% of FM)	Biogas potential (Nm^3/ Mg oDM)	Methane potential (Nm^3/ Mg oDM)	Sources
Energy maize	45	30	606	322	[44–46]

Table 7
Scenario indications in Table 8 and Figs. 6–8.

Municipality	Minimum	Maximum
Ten Boer	Ten Boer_min	Ten Boer_max
Eemsmond	Eemsmond_min	Eemsmond_max
Groningen	Groningen_min	Groningen_max
Hoogeveen	Hoogeveen_min	Hoogeveen_max
Noordenveld	Noordenveld_min	Noordenveld_max

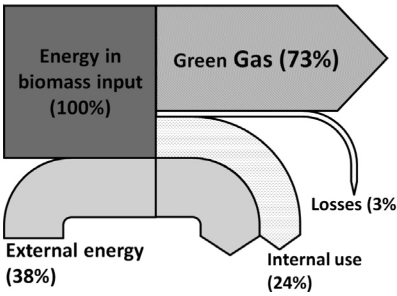


Fig. 5a. Average efficiency of the green gas utilization pathway.

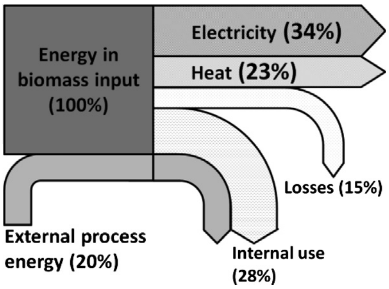


Fig. 5b. Average efficiency of the CHP utilization pathway.

electricity and the embodied energy) (Fig. 5a). The CHP pathway retains relatively less energy from the feedstock. This process includes higher losses, primarily in the form of non-recoverable heat. Also, a larger portion of the produced heat and electricity is used internally (than in the green gas pathway), which will result in lower final energy production, but also lower external energy requirements (Fig. 5b). Finally, the waste management pathway has the lowest energy yield as green gas. The losses are comparable to the heat and power scenario as the pathway also contains a CHP unit. The internal energy consumption is larger, due to the upgrading of digestate to fertilizer and the replacement of transport fuel with green gas; this, however, also results in the lowest final energy production and external energy demand (Fig. 5c). Within the aforementioned context, from a target oriented approach (e.g. 40 PJ in the year 2020 [20]) the green gas utilization pathway would be most capable in achieving the highest energy production.

Table 8
Bio-energy yields, energy in feedstocks, and net energy yields of the utilization pathways per municipality.

Municipality	Average[a] (GJ/km^2 a)	Ten Boer (GJ/km^2 a)		Eemsmond (GJ/km^2 a)		Groningen (GJ/km^2 a)		Hoogeveen (GJ/km^2 a)		Noordenveld (GJ/km^2 a)	
	Average	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Bio-energy yield	1614	2472	3412	897	2732	436	757	1172	1900	1259	1887
Energy in feedstock[b]	1038	719	1673	659	2563	252	562	277	1018	631	1285
Green gas	757	576	1305	475	1949	161	214	192	672	488	944
CHP	591	460	1039	361	1525	122	187	147	510	384	734
Of which electricity	350	247	573	218	863	85	187	93	342	214	434
Waste management	453	390	900	233	1194	90	44	110	382	306	587
Energy demand[c]	20,955	5273		3026		122,971		14,889		5475	
Of which electricity	2838	714		410		16,653		2016		741	
Of which natural gas	18,118	4559		2616		106,318		12,873		4733	

[a] The averages are calculated considering the total bio-energy yield of the municipalities divided by the total land surface of the municipalities and the average between the minimum and maximum scenario.

[b] The bio-energy in the feedstock used as input in the digester installation.

[c] Calculated using the energy consumption for an average household in the Netherlands: electricity 3050 kW h/a, gas 1200 Nm^3/a [31], excluding shops and industry.

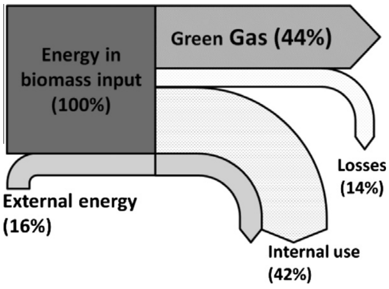


Fig. 5c. Average efficiency of the waste management pathway. (Replaced energy in fertilizers (0.9%) and green gas used as fuel for transport (0.2%) is included in internal use.)

5.3. Process energy returned on energy invested

The efficiency of the process, feedstock availability, and quality, combined with the external energy inputs, strongly influence the process energy return on energy investment or (P)EROI. Feedstocks with low biogas potentials or which need energy-intensive processing will negatively affect the (P)EROI. For instance, the municipality of Groningen has a very low (P)EROI due to the high ratio of organic municipal waste, which requires high energy inputs (e.g. transport, screening, pasteurization). When waste use is maximized in Groningen, more energy is needed in the production process than can be obtained (Fig. 6). However, this is not taking into account the energy already required by the waste industry currently in place. For the municipality of Ten Boer the (P)EROI is higher due to a larger share of natural and roadside grass in the feedstock. Therefore, from an efficiency standpoint, one could be selective in the feedstocks used in the production pathway. Furthermore, there are also differences per utilization pathway. The green gas pathway is able to retain the most energy from the available biomass, however, higher use of external process energy has a negative effect on the (P)EROI compared to the CHP and waste treatment scenarios (Fig. 6). Heat and power production has a high overall efficiency in most scenarios due to the low external energy requirements. However, when the produced heat from the CHP unit cannot be completely utilized, due to lack of demand in some municipalities, the overall efficiency will go down. Overall, the (P) EROI of the waste treatment pathway is highest due to the low use of external energy in the process and the displacement of fossil fertilizers (Fig. 6). Production and utilization pathways with internal energy production and consumption positively influence the (P) EROI, however, they produce lower net energy from the feedstocks.

5.4. Environmental assessment

The environmental impacts of the biogas production and utilization pathways are strongly linked to external energy consumption often based on fossil energy, leakages of biogas or green gas, the combustion of biogas, the mitigation of greenhouse gas emissions when feedstocks are left on the field or stored in manure tanks, and the replacement of fossil fertilizers which are often produced from, or with the aid of, fossil fuels. Furthermore, the quality of the feedstock and the corresponding processing also influences the environmental sustainability. In municipalities where larger amounts of municipal organic waste are processed the impacts are higher due to a larger energy requirement. For example, the effect of using large shares of municipal organic waste can be clearly observed in the municipality of Groningen; where, in the maximum scenario, around 18% of the total feedstock is composed of municipal organic waste, which lies on average around 2% per municipality. The large external energy requirements needed for processing the waste has a significant effect on the emissions (Fig. 7) and the environmental sustainability (Fig. 8) of the process. Environmental impacts and emissions also differ between utilization pathways. On average, the green gas production pathway has the highest impacts, which can be traced back to its higher external energy requirements. In the waste treatment pathway where all emissions saving actions are combined (e.g. internal energy production, green gas fueled transport, mitigation of emissions, replacement of fossil fertilizers) the overall emissions and environmental impacts are significantly lower. In some cases, more impact is avoided in the process than is produced, resulting in negative environmental impact (Fig. 8). However, when more energy is

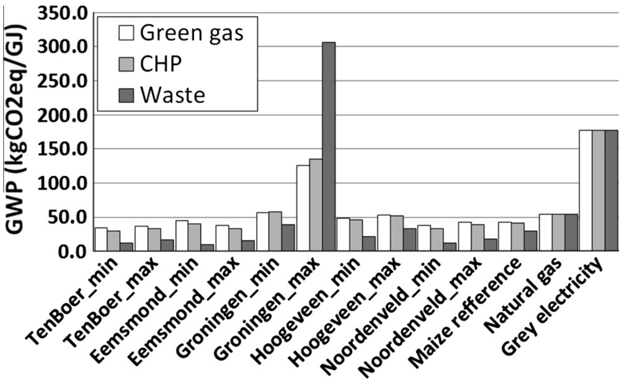


Fig. 7. The emissions per municipality.

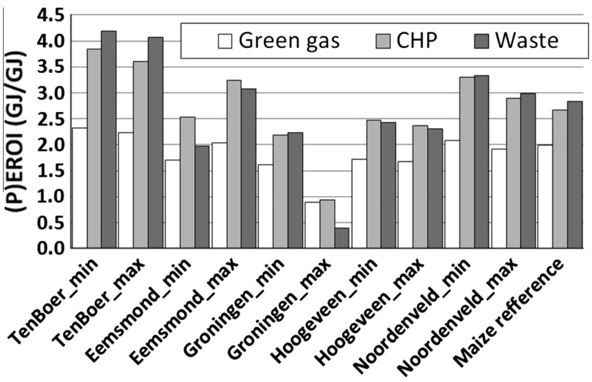


Fig. 6. The (P)EROI of the AD utilization pathways per municipality.

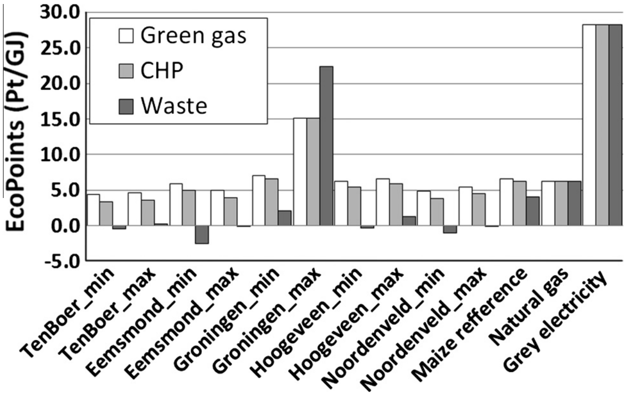


Fig. 8. Environmental impact per municipality.

required in the process than is produced, the impact increases well above the reference of energy maize, natural gas and even grey electricity (Fig. 8, municipality of Groningen). Therefore, care should be taken in feedstock selection and/or renewable energy should replace fossil energy inputs. Also, the maximum biomass scenario (Section 3) on average performs less well in efficiency and environmental impacts, indicating that some biomass feedstocks are not worth collecting (e.g. small patches of biomass). Overall, the environmental footprint is strongly influenced by the feedstocks used, the design of the production, and the utilization pathway.

5.5. Increase of manure as feedstock

As previously indicated in this article, on average only 64% of the bio-energy potential is used as feedstock for the AD process (Section 5.1), which can be partly traced back to unused manure waste flows. Feedstocks containing over 50% of manure are often not used, due to the low biogas yields and high process costs of manures. In the municipality of Ten Boer (and to a lesser extent in Hoogeveen and Noordenveld) the availability of cow manure far outweighs the availability of waste feedstocks, and provides an additional source of biomass. However, the lower energy potential of manure can have an effect on the environmental sustainability of the production pathway. Therefore, for the municipality of Ten Boer the manure input in the digester was increased from 50%, by increments of 5%, up to 100% (although the values above 80% are no longer representative and are not presented here) to see the effects of higher percentages of manure in the feedstock (Fig. 9).

Results indicate that, for both the green gas and CHP pathway, increasing the manure fraction of the feedstock generally has a negative effect (Figs. 9a and 9b), with only the environmental impact of the CHP pathway being slightly lowered (Fig. 9c). Due to the higher percentage of manure, the energy in the feedstock steadily lowers, but the energy input in processing (e.g. transport, heating, stirring) stays the same, resulting in overall negative effects (Fig. 9a). For the waste treatment pathway the efficiency drops sharply as a higher percentage of the produced energy is required by the process itself (Fig. 9a). However, avoided emissions from manure and the replacement of fossil fertilizers can significantly reduce emissions and environmental impact (Fig. 9c). If, for instance, the required external energy input is supplied by renewable resources, then the environmental sustainability would further increase. At this point the waste production pathway ceases to be a net energy producer. However, from an environmental perspective waste management is preferable (Figs. 9b and 9c).

6. Sensitivity analysis

Using organic material in a biological process inherently creates variations. Where possible, values used in the model are similar to each other (e.g. in the biogas production pathway). When comparing scenarios, similar settings will cancel out sensitivities in the used values. However, the variables used to define the biomass feedstocks and the biogas utilization pathways will differ. Within the variables selected for the sensitivity analysis, the methane potential proved to be the most sensitive. The amount of methane produced finally determines the energy output from the AD process. oDM content proves to be a very important variable in transport, storage and processing. The lower the oDM content, the more water (and other materials not contributing to methane production) are transported, heated, and stirred. The complete sensitivity analysis is described in Pierie et al. [13]. Also, within this article tortuosity factors are used to simulate winding roads used for grass

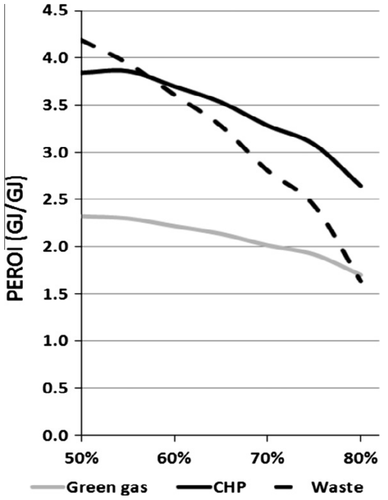


Fig. 9a. (P)EROI variable manure input in the municipality of Ten Boer.

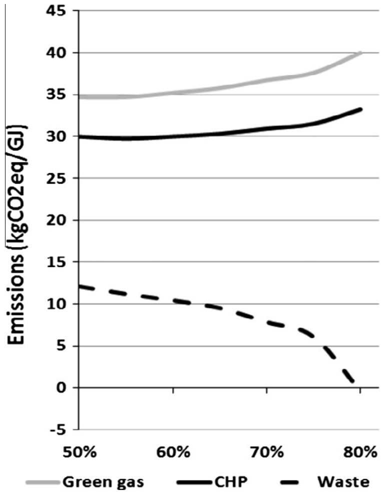


Fig. 9b. Emissions variable manure input in the municipality of Ten Boer.

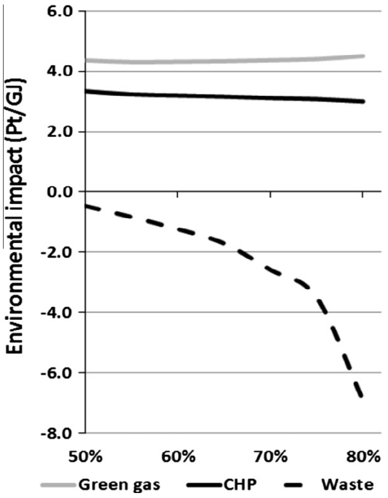


Fig. 9c. Environmental impact variable manure input in the municipality of Ten Boer.

and municipal solid waste collection (see Section 4). The sensitivity regarding the tortuosity factors on grass and municipal organic waste, compared to average transport distances, only accounts for an average difference on the expressions of 5% for green gas, 8% for CHP, and 4.5% for the waste treatment pathway, with a maximum difference of 10%, 14%, and 7% respectively in the municipality of Groningen. The impact of transport is thus substantial, depending on the scenario and location; however, it is not a dominant factor. The municipality of Groningen is most affected due to the high percentage of municipal organic waste within the feedstock. Within the aforementioned context, the energy requirement of pasteurizing the organic waste is also significant. The results of this study are considered to be representative of bio-energy production, on average.

7. Discussion

Energy production through AD is a promising method for producing a renewable and flexible energy carrier. However, the production and utilization pathways are complex systems, containing multiple factors and variables which must be taken into account. The accuracy of the results presented in this article depends strongly on the quantity and quality of the data it contains, which comes from both literature and case studies. However, these sources still contain a wide range of data. Therefore, the model used for calculating the results was extensively validated before being implemented. In order to give an overview and gain more transparency, three specific impact factors are chosen to express the efficiency and environmental impact; however, the indicators cannot provide detailed information regarding specific environmental impacts (e.g. acidification). The expression (P)EROI behaves nonlinearly due to its dividing element in the equation which will cause it to behave exponentially. The biomass potential used in this article is based on data from the Dutch bureau of statistics, which represents an average potential. Specific biomass potentials are often difficult to quantify and differ by season and specific location. Furthermore, the biomass potential is spread out evenly over the municipality for determining average transport distances. The effects of multiple feedstocks in combination with digestion are not well documented and can have an effect on the biogas potential of the individual feedstocks. Cutting natural areas and embankments can have an effect on the natural wildlife, which is not considered within this article. In addition, the biomass described in this article could have other uses (e.g. stable flooring, animal feed) which must be considered. The locations chosen for this research lay within the scope of the Flexigas project [30] and the project partners responsible for managing and processing the biomass flows, which does not necessarily make them realistic averages for the whole of the Netherlands. The quantity and quality of the various types of biomass differ per chosen location; however, the calculation method discussed in this article can be used for most areas with sufficiently available data. Municipal organic waste is used as a feedstock within this article; currently the quality is substandard and the digestate therefore cannot be used as fertilizer; however, when separated and collected correctly, quality will be sufficient. Transport distances are difficult to quantify and normalize; therefore, within this article tortuosity factors are used, although transport distances can differ significantly per specific location. Also, in this article all the energy from the CHP unit is utilized; however, heat produced in a CHP unit cannot always be fully utilized as demand must be present and may fluctuate.

8. Conclusion

Anaerobic digestion of bio-waste flows can play an important role in achieving renewable goals set within the European Union. Literature indicated that there is sufficient bio-energy potential in local waste streams to reach the Dutch goal for local renewable energy production of around 40 PJ in the year 2020. Within the case study, however, the average useful energy retained is significantly lower. Only around 64% of available biomass is utilized as a feedstock, often due to low quality and difficult harvesting conditions. Utilization of biomass can be increased by using higher amounts of manure in the feedstock. However, increasing the share of manure has a negative impact on the (P)EROI of all utilization pathways. Furthermore, of the potential bio-energy input in the three utilization pathways considered in this article, on average: 73% can be extracted as green gas; 57% as heat and power; and 44% as green gas in the waste management pathway. When utilizing AD biogas production pathways a significant gap arises between bio-energy potential and net energy gain, demonstrating that the Dutch goal cannot be reached using AD and local biomass waste flows alone. The green gas utilization pathway is preferable for reaching production goals as it retains the highest amount of energy from the feedstock. However, environmental sustainability factors favor the waste management pathway. High use of internal energy, green gas for transport, mitigation of emissions, and the replacement of fossil fertilizers with upgraded digestate significantly reduce Green House Gas (GHG) emissions and environmental impact. The main lessons drawn from the aforementioned are twofold: there is a substantial gap between bio-energy potential and net energy gain; and there is also a gap between top down regulation and actual emission reduction and sustainability. Therefore, a full life cycle-based understanding of the absolute energy and environmental impact of biogas production and utilization pathways is required to help governments to develop optimal policies which effectively support the European Union in achieving renewable energy and GHG emission reduction goals within the context of climate policy, as described in the EU energy directive and the EU roadmap 2050 [1,2]. Decisions will need to be made on how to utilize the limited biomass availability most effectively and sustainably, in the near and far future, as biogas can play a supportive role for integrating other renewable sources into local decentralized energy systems as a flexible and storable energy source.

Appendix A

See Tables A1–A7.

Table A1
Biomass yields per type.

Feedstocks	Grass	Organic waste	Beet tops	Potato tops	Straw	Unit	Sources
Yield per hectare	22	–	40	20	4.1	Mg FM[a]/ha	[36,47–50,3,51]
Production per person per year	–	79	–	–	–	kg/person	[31]

[a] Fresh matter.

Table A2
Biomass potential per square kilometer.

Municipality	Ten Boer (Mg/km^2)		Eemsmond (Mg/km^2)		Groningen (Mg/km^2)		Hoogeveen (Mg/km^2)		Noordenveld (Mg/km^2)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Mixed manure dairy/pig	3975.3	4019.4	677.0	756.3	447.3	536.7	2054.4	2132.8	1474.0	1523.8
Solid manure poultry	22.1	22.1	31.7	31.7	0.0	0.0	7.8	7.8	24.9	24.9
Municipal waste	3.7	21.6	2.9	16.8	15.5	91.2	8.5	49.7	4.2	24.5
Natural grasses	228.3	487.8	31.8	338.8	76.9	137.3	58.7	257.5	158.0	318.2
Tops sugar beets	8.8	17.5	136.2	272.4	3.0	6.0	22.2	44.3	27.8	55.5
Tops potato	0.0	0.1	162.2	324.4	2.5	5.1	31.5	63.0	60.5	120.9
Straw	3.6	36.3	11.4	113.9	0.3	3.3	0.7	6.5	0.6	6.5
Total feedstock	244.4	563.3	344.5	1066.3	98.2	242.9	121.5	421.2	251.0	525.6

Table A3
Biogas potential of the selected feedstocks.

Feedstock	Organic dry matter (% of FM)	Biogas potential (Nm^3/Mg oDM)	Methane potential (Nm^3/Mg oDM)	Sources
Cow manure	6.4	350	180	[52]
Poultry manure	41.6	212	127	[52]
Municipal organic waste	18.3	260	156	[33]
Natural and roadside grass	23.5	560	297	[36,48]
Sugar beets tops	10.3	420	302	[50]
Potato tops	11.1	420	302	[49,53]
Straw from grain	82.0	341	174	[3,51]

Table A4
Input in digester per scenario.

Municipality	Ten Boer (Mg/a)		Eemsmond (Mg/a)		Groningen (Mg/a)		Hoogeveen (Mg/a)		Noordenveld (Mg/a)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Cow/pig manure stable	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0
Cow/pig manure source	7284.5	7795.9	7266.8	7890.4	8188.0	8188.0	7542.4	8001.8	7196.2	7714.3
Poultry manure	903.5	392.1	921.2	297.6	0.0	0.0	645.6	186.2	991.8	473.7
Municipal waste	150.5	384.1	83.1	158.0	1579.1	3756.5	695.9	1180.6	165.6	465.3
Grass meadow	9341.1	8659.3	923.5	3177.4	7825.7	5652.0	4831.1	6115.1	6294.7	6054.6
Sugar beet tops	358.2	310.8	3953.6	2554.3	303.7	245.6	1825.5	1053.0	1105.4	1055.9
Potato tops	1.8	1.6	4709.0	3042.3	257.6	208.4	2593.6	1496.0	2408.4	2300.5
Straw wheat	148.4	644.1	330.6	1068.1	34.0	137.5	53.9	155.3	25.9	123.6
Total feedstock	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000

Table A5
Transport distances used for feedstocks.

Municipality	Ten Boer (km)		Eemsmond (km)		Groningen (km)		Hoogeveen (km)		Noordenveld (km)	
Main feedstock	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Manure cow/pig	0.9	0.9	2.3	2.2	2.8	2.6	1.3	1.3	1.6	1.5
Poultry manure	3.8	2.5	3.2	1.8	6.0	3.8	5.4	2.9	3.8	2.6
Municipal waste	36.1	23.8	30.4	17.3	56.9	36.2	51.2	27.5	35.6	24.6
Grass	12.8	16.8	10.8	12.2	20.1	25.6	18.1	19.4	12.6	17.4
Feedstock remainder	3.8	2.5	3.2	1.8	6.0	3.8	5.4	2.9	3.8	2.6

Table A6
Percentage of input for digestate management.

Municipality	Ten Boer (%/a)		Eemsmond (%/a)		Groningen (%/a)		Hoogeveen (%/a)		Noordenveld (%/a)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Manure cow/pig at farm	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Manure cow/pig source	36.4	39.0	36.3	39.5	40.9	40.9	37.7	40.0	36.0	38.6
Manure poultry	4.5	2.0	4.6	1.5	0.0	0.0	3.2	0.9	5.0	2.4
Waste	0.8	1.9	0.4	0.8	7.9	18.8	3.5	5.9	0.8	2.3
Grass	46.7	43.3	4.6	15.9	39.1	28.3	24.2	30.6	31.5	30.3
Feedstocks	2.5	4.8	45.0	33.3	3.0	3.0	22.4	13.5	17.7	17.4
Total feedstock	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table A7
Land use and biomass availability data local municipalities.

		Ten Boer	Eemsmond	Groningen	Hoogeveen	Noordenveld
Totals per municipality						
Total population	total	7479	15,928	198,317	54,664	31,087
Total households	total	2945	7056	118,679	23,419	13,560
Total land surface	ha	4528	18,908	7825	12,753	20,082
Manure production						
Mixed manure dairy	Mg/a	179,000	124,000	34,000	212,000	262,000
Solid manure beef	Mg/a	1000	1000	1000	3000	3000
Thin manure meat calf's	Mg/a	0	1000	0	20,000	19,000
Solid manure poultry	Mg/a	1000	6000	0	1000	5000
Thin manure pigs	Mg/a	–	1000	0	23,000	7000
Thin manure breeding pigs	Mg/a	–	1000	0	4000	5000
Manure animals remainder	Mg/a	2000	15,000	7000	10,000	10,000
Municipal organic waste						
Municipal organic waste	Mg/a	979.749	3185.6	7139.412	6341.024	4911.746
Municipal areas						
Train surface	ha	–	37	68	24	–
Road surface	ha	106	431	460	473	347
Airfield surface	ha	–	–	–	28	–
Burial site	ha	6	17	62	25	14
Parks	ha	10	28	434	108	27
Sport parks	ha	22	43	183	160	110
Urban garden	ha	0	–	57	16	5
Recreation area	ha	–	–	39	13	24
Camping grounds	ha	–	7	10	42	205
Natural areas						
Forrest area	ha	47	1643	282	1326	3631
Grass from road shoulders	ha	14.76	154.38			518.01
Open and dry natural terrain	ha	–	1071	–	97	826
Open and wet natural terrain	ha	1	456	42	58	207
Agriculture						
Natural grasslands	ha	447.73	351	125.81	80.16	340.04
Temporal grasslands	ha	466.82	776.13	45.28	1075.86	1316.94
Fallow fields	ha	59.58	145.25	12.58	4.15	68.58
Grains	ha	400.71	5252.34	63.75	203.51	318.3
Sugar beets	ha	19.82	1287.51	11.67	141.39	278.64
Potatoes	ha	0.2	3067	19.8	401.76	1214.13

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