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LCA OF WASTE MANAGEMENT SYSTEMS

The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains

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Abstract
Purpose The BioValueChain model facilitates the calculation of environmental impacts throughout the value chain for production of biogas from organic waste and manure in Norway. This paper describes the methodology of the model, presents the results based on general data and performs a sensitivity analysis for the input data.
Methods The model is based on life cycle assessment methodology and defines the boundaries of the system and a set of default parameter values which can easily be changed to obtain relevant results for a specific region or a specific biogas plant.
Results and discussion The general results from application of the model show that the application of biogas and digestate, including the assumption regarding which products are substituted, has significance for the results. The sensitivity analysis reveals that results for global warming potential (GWP) appear to be less sensitive for the different parameter values than the other environmental indicators. Increased biogas production from source separated organic household waste and manure from cattle and pigs appears to be an appropriate greenhouse gases (GHG) mitigation measure for Norwegian conditions if the biogas substitutes fossil fuels and if the digestate substitutes mineral fertiliser.
Conclusions The results underline the need for the use of specific data, especially for transport distances, biogas potential and efficiency of biogas plant. Furthermore, in order to decrease the uncertainty of the results, more research is required into ways of modelling and quantifying direct emissions from the storage and application of manure and digestate on land.

Keywords Biogas · Food waste · LCA · Manure · Organic waste

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1 Introduction

1.1 Biogas production in Norway

Biogas production was introduced by the Norwegian government through a white paper (The Norwegian Department of Agriculture and Food 2009) as a contribution towards the reduction of greenhouse gases (GHGs) in the agricultural sector. The paper announced the ambition of utilising 30 % of the manure from livestock on Norwegian farms for biogas production by 2020. In 2008, a biogas potential study revealed that manure from livestock comprised about 42 % of the theoretical Norwegian biogas potential (Raadal et al. 2008). Currently, Norwegian biogas plants are most commonly run on sewage sludge and organic waste. Using sewage sludge as substrate limits the use of the digestate as required by The Norwegian organic fertiliser ordinance (2003), thus the focus in the model described in this paper has been on manure from cattle and pigs as well as organic waste.

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Life cycle assessment (LCA) is commonly applied to quantify and assess the environmental impacts from different waste management systems and biogas production value chains. A review of LCAs concerning the treatment of organic waste revealed that there are significant variations in the results, and that the results are strongly dependent on system boundaries, methodological choices and variation in input data (Bernstad and la Cour Jansen 2012). A review of LCA studies performed on municipal solid waste management systems in general revealed that results are strongly dependent on local conditions (Laurent et al. 2014a). This underlines the need for the use of specific data when applying LCA to decision support, and the importance of a consistent and well-documented methodology. The BioValueChain model presented in this paper establishes a framework for the performance of LCA on biogas value chains and facilitates specific analysis for a specific region or plant through variation of the relevant parameters.

In recent years, various waste models that can estimate the environmental impacts of waste management options have been developed to contribute to decision support. Examples are the Danish EASEWASTE (Kirkeby et al. 2006) which has been further developed and renamed EaseTech (Clavreul et al. 2014), and the Swedish ORWARE (Dalemo et al. 1997; Eriksson et al. 2002). Both EasteTech and ORWARE contain separate modules for biological treatment of organic waste as described in Boldrin et al. (2011), Dalemo et al. (1997) and Sonesson et al. (1997), but none of them currently include properties for other substrates such as manure. The inclusion of manure implies the defining of other reference scenarios and the involvement of additional life cycle stages such as storage.

The conditions for biogas production in Norway differ from other European countries because of relatively low electricity prices, high fuel prices, a cold climate and the scattered location of small scale farms. This may have an effect on the incentives for biogas production and the environmental impacts, for example transport and direct emissions from the storage and spreading of biomass. The BioValueChain model was developed to meet the need for a Norwegian model that could calculate the environmental impacts throughout the value chain of biogas production for different substrates and a combination of substrates.

1.2 Objective of the paper

The objective of this paper is to describe the BioValueChain model, the methodology applied and the defined system boundaries, and to present generic results to show how the model contribute to optimising biogas value chains with regard to environmental impacts. The model contains a large number of predefined parameters for each substrate in each life cycle stage. Example of these parameters would be transport distances for substrates and digestates, the amount and mix of substrates, energy use and efficiency of the biogas plant and the use of the produced biogas and the digestate. The parameters in the model may easily be changed to perform analysis for specific biogas plants or for specific regions with a certain mixture of the different substrates. The model is developed in the LCA software SimaPro 8.0.3 (PRé 2014).

The purpose of the BioValueChain model is to simplify local case studies in specific regions or for specific biogas plants. This is achieved by creating an LCA infrastructure and a pool of general data which can be changed according to local conditions. The results shown in this paper aim to identify the hot spots for environmental impacts from biogas value chains and where emphasis should be made on gathering specific data when doing assessments for a specific region. In addition, the model work aims to document where there are data gaps and where more research is required in order to decrease uncertainty and to increase the robustness of the results.

2 Methods

2.1 Life cycle assessment methodology for waste management systems

LCA is known as a method for estimating the environmental impact of a product or a service throughout the value chain from raw material extraction to production, use and waste treatment. The methodology is standardised in ISO 14044 (International Organization for Standardization (ISO) 2006) and described in literature such as European Comission JRC (2010); Baumann and Tillman (2004) and Curran (2012). For LCA of waste management systems, the “raw material extraction” normally starts when the consumer discards the waste, as described in Finnveden (1999). The upstream life cycle stages are excluded because when comparing different waste management options, the upstream activities are regarded as independent of the waste management option and thus are assumed equal for all scenarios. This is common practice in waste management LCA models (Gentil et al. 2010). Although manure is useful and valuable to the agricultural sector, it may be regarded as a waste product from the production of meat or milk in an LCA context. It can therefore be analysed with the same methodology as organic waste. Environmental impacts from the operation of the cattle farm, such as energy use for barns and nutrition of the cattle, are allocated to the main products (meat, milk etc.), and is seen as being outside the system boundaries of the biogas value chain.

Biogas production may be considered to be open loop recycling, as the organic waste is recycled into new products: biogas which may be used as fuel in vehicles or to generate heat and electricity, and digestate which may be used for soil improvement or as fertiliser. The new products represent possible replacements for fossil alternatives. In order to envisage these additional functions, the model applies system expansion (Finnveden 1999; European Comission JRC 2011; Laurent et al. 2014b) where the avoided impacts of the replaced products are credited as negative emissions.

As described in the literature, for example Finnveden (1999), Gentil et al. (2010), Laurent et al. (2014a) and Laurent et al. (2014b), when system expansion is applied, careful consideration is required when making assumptions as to what the recycled material will replace, and in the case of energy generation, what the alternative energy carrier(s) might be.

2.2 Purpose of the model

The purpose of the biogas model is to facilitate the evaluation of the environmental impacts of specific Norwegian biogas value chains, by changing the parameters from average/generic values to specific values. This result in reduction of the effort entailed each time options are compared regarding, for example, the localisation of a biogas plant, choice of different technologies, treatment options for a specific amount of manure/waste or documentation of the overall impact from the treatment of organic waste and manure in a certain region.

This corresponds to a micro/meso-decision support analysis, or situation B study, according to the technical guide to Life Cycle Thinking and Life Cycle Assessment (European Comission JRC 2011), as it aims at optimising the waste management system at a local/regional or plant-specific level. The model may also be applied to the accounting of environmental impacts, also referred to as situation C in European Comission JRC (2011). The model is not intended to be applied for meso/macro-decision support analysis to change the national objectives for biogas production, but it may, however, serve as a decision support tool on how best to achieve the existing national objectives and meet the policy requirements through optimisation, measures and instruments. In addition, specific regional analysis may create a knowledge base which can contribute to overall national strategies.

2.3 Functional unit and system boundaries

Functional units of biogas systems are normally related to the amount of biogas or energy generated, or the amount of waste treated. Treatment of waste is normally considered as the main function when performing LCA of a waste management system (European Comission JRC 2011). In Norway, the primary motivation for the treatment of manure in a biogas plant is assumed to be that it is a GHG mitigation measure, as the market demand for biogas and digestate is moderate or nonexisting. In addition, by considering the waste treatment as the main function, allocation issues between the two products in the system (biogas and digestate) are avoided.

> The functional unit for the model is hence defined as: Treatment of a specific amount of Dry Matter (tonnes DM per year) of organic substrates of a given mix (organic waste and/or manure) in a specific region, including avoided emissions caused by the generated products when substituting materials and energy carriers.

The choice of a functional unit that is based on the amount of waste treated is common practice for LCA of waste management systems (Laurent et al. 2014b) and LCA waste models (Gentil et al. 2010). The reference flow in the model is one tonne DM in each substrate (including the corresponding water content). The results shown in this paper are presented per reference flow.

As shown in the flow chart in Fig. 1 and Tables 1 and 2, the life cycle stages are as follows: storage of substrate (only for manure); transportation to plant; pre-treatment (removal of non organic material and treatment of the

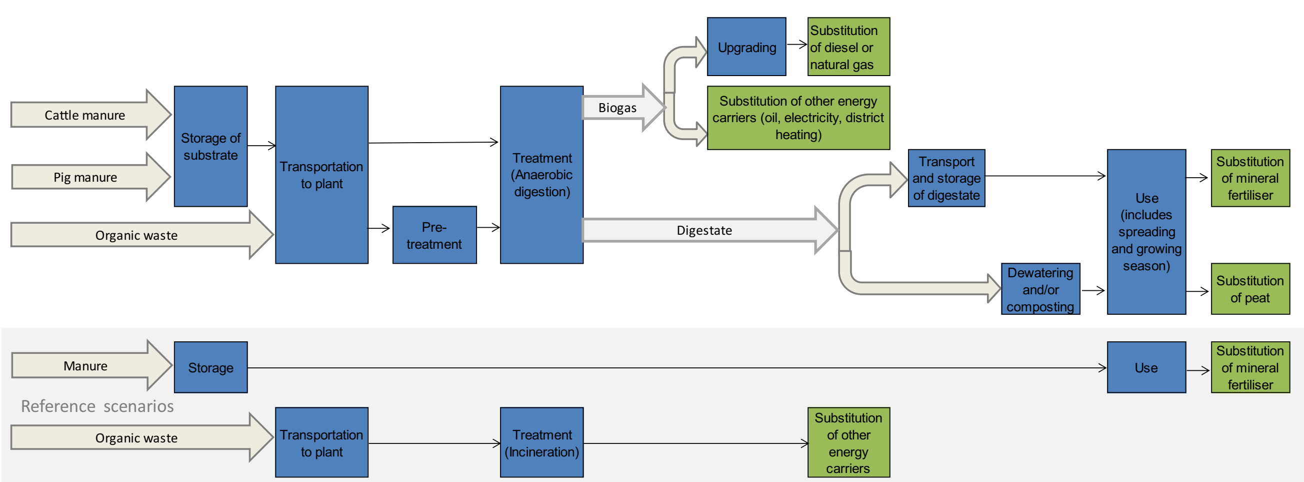

Fig. 1 Flow chart for biogas value chains and reference scenarios

Table 1 Activities and direct emissions for each life cycle stage for the biogas scenarios

		Storage of substrate	Collection and transport to plant	Pre-treatment	Treatment (anaerobic digestions)	Upgrading	Substituted product, biogas	Transport and storage of digestate	Dewaterin and/or composting	Use of digestate (application on land)	Substituted product, digestate
Biogas scenarios	**Direct emissions from biomass**	Emissions of NH3 CH4 and N2O (assumed covered storage for biogas scenarios)			Assumed no diffuse emssions	Methane loss		CH4 and NH3, N2O (assumed covered storage for biogas scenarios)	Emissions from composting (if relevant) Direct emissions from dewatering and wastewater treatment	Liquid digestate: emissions of N2O and NH3 during and after spreading as fertiliser	Uptake of carbon in soil
	Environmental impacts from processes and activities		Service, maintenance, infrastructure vehicle and road	Electricity use per tonne DM, treatment of reject (incineration) and avoided emissions from recovered energy. Reject composition assumed to be similar to municipal solid waste. Transport of substrate from pre-treatment to biogas plant (if relevant).	Electricity and heat use per tonne DM. The biogas potental for the substrates that goes into the biogas plant is multiplied by a "realistic output" factor (dependent on technology, retention time, efficiency of plant) and for production of heat and or electricity from biogas also a efficiency coefficient and delivery coefficient (energy sold/energy generated).	Electricity use per Nm3 biogas to upgrading	Avoided production and use of relevant energy carrier: electricity, distict heating and/or heat from oil or coal. Upgraded biogas may substitute diesel or natural gas.	Transportation vehicle.		Electricity or diesel use stirring and spreading equipment	Avoided production of mineral fertiliser for direct use of digestate and avoided production of peat for composted digestate
	Outside system boundaries	Capital good: storage			Capital good: biogas plant	Capital good: upgrading equipment		Capital good: storage		Capital good: stirring and spreading equipment	

The text in bold is a description of the data in the following column or line

Table2 Activities and direct emissions for each life cycle stage for the reference scenarios

		Storage of substrate	Collection and transport to plant	Pre-treatment	Treatment (incineration)	Upgrading	Substituted product, energy recovery	Transport and storage of digestate	Dewaterin and/or composting	Use of manure (application on land)	Substituted product, manure
Reference scenarios Manure	Direct emissions from biomass	Emissions of NH3 CH4 and N2O								Emissions of N2O and NH3 during and after spreading as fertiliser	Uptake of carbon in soil
	Environmental impacts from processes and activities		Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Electricity or diesel use stirring and spreading equipment	Avoided production of mineral fertiliser
	Outside system boundaries	Capital good: storage								Capital good: stirring and spreading equipment	
Reference scenarios Organic waste	Direct emissions from biomass				Emissions from combustion of organic waste						
	Environmental impacts from processes and activities	Not relevant	Service, maintenance, infrastructure vehicle and road	Not relevant	Treatment of slag (landfill) and construction, maintenance and end of life for incineration plant.	Not relevant	Avoided production and use of relevant energy carrier: electricity, distict heating and/or heat from oil or coal.	Not relevant	Not relevant	Not relevant	Not relevant
	Outside system boundaries										

reject, normally only for organic waste); treatment (anaerobic digestion); upgrading of biogas (if relevant); avoided burdens from energy carriers replaced by biogas, storage of digestate (if relevant); dewatering and/or composting of digestate (if relevant); use of digestate products (includes emissions from spreading and throughout growing season) and avoided burdens from production and use of fertiliser or soil improvement products replaced by digestate.

The environmental impacts from energy used for pre-treatment and anaerobic digestion are allocated between the different substrates based on the DM content in the model. The model has various options for substitution of energy carriers: diesel or natural gas (when upgraded), Norwegian district heating mix, Nordic electricity mix and heat from oil and coal.

As shown in Table 3, the general scenarios presented in this paper represent different use and substituted products for biogas and digestate, relevant to Norwegian conditions. The model allows for the analysis of biogas production for a mix of substrates (as in most biogas plants) and a mix of products (heat, electricity and upgraded gas). In order to ensure transparent results, for the generic results in this paper, the environmental impact for each substrate and for each end product is presented separately. The three options for the utilisation of biogas are the generation of heat, electricity or fuel for vehicles. In the case of heat production, both the substitution of Norwegian district heating mix and heat from oil is analysed. In the case of the generation of electricity from biogas, it is assumed that the electricity substitutes the NORDEL production mix. This is due to the existence of a common Nordic electricity market. For upgraded biogas, it is assumed that biogas substitutes diesel because it is probable that the increased upgrading of biogas in Norway will result in the replacement of buses currently running on diesel. The digestate is assumed to replace mineral fertiliser when used as fertiliser, and peat when used as compost.

Table 3 General scenarios analysed

Reference			Treatment	Avoided product (heat)	Avoided product manure
0	Organic waste		Energy recovery	District heating mix (NO)	
0	Manure		Used as fertiliser		Mineral fertiliser
Scenario			**Treatment**	**Avoided product biogas**	**Avoided product digestate**
A	Organic waste	Manure	Biogas production	District heating mix (NO)	Mineral fertiliser
B				Heat from oil	
C				Electricity (NORDEL)	
D				Diesel	
E					Compost (dewatered digestate)

The text in bold is a description of the data in the following column or line

A reference scenario that does not include biogas production has been defined for each of the substrates in the model, reflecting the most common practice in Norway. This is necessary in order to "benchmark" the environmental impacts from the biogas value chain. For organic waste, the life cycle stages for the reference scenario include transportation, incineration and avoided burdens from the substitution of energy carriers. In the case of manure, the life cycle stages are storage, use (including emissions from spreading and throughout the growing season) and avoided burdens from the substitution of mineral fertiliser.

2.4 Life cycle inventory

As described above, the BioValueChain model contains default basis values representing best estimates of all activities and direct emissions in each life cycle stage, as listed in Appendix A (Electronic Supplementary Material). In Table 1, the principal activities and the direct emissions included in each life cycle stage in the model are described. Default data for direct emissions are best estimates for Norwegian conditions based on literature data. The estimation of emissions from biomass during storage and application on land is challenging because emissions are largely related to site-specific issues such as climate, type of storage (size and cover/no cover) and time.

The assumed properties of the substrates are shown in Table 4. Properties for organic waste (such as the DM content, amount of reject during pre-treatment and biogas potential) are for source-separated organic household waste (SSOHW), but the model can also include organic waste from other sources, as long as the values are altered according to the properties.

The model applies LCI data from the EcoInvent 3 allocation default database for background data such as transport processes, incineration and energy generation (Swiss Centre for Life Cycle Inventories 2014). The NORDEL production mix is applied as the default electricity mix. The Norwegian district heating mix has been modelled on the basis of national statistics for Norwegian district heating for 2012 (Tekniske Nyheter DA 2013). For composted digestate, the default assumption is its application in gardens and parks as soil improvement, and peat is therefore substituted. The calculation is then based on the carbon content in the compost and the plant accessible amount of C in the digestate. It is assumed that a certain amount of the carbon in the compost is stored in the soil.

The amount of substituted energy is calculated by the model based on the biogas potential of each substrate, the biogas digester's ability to release this potential ("realistic output"), the efficiency coefficient for energy conversion and the proportion the produced energy that is sold. It is assumed that liquid digestate substitutes mineral fertiliser. The amount replaced is based on the nitrogen content of the digestate and the amount of plant accessible nitrogen. It is possible to adjust the biogas output as a result of the (often) positive effects of codigestion of substrates.

2.5 Life cycle impact assessment

The model is currently able to analyse the following environmental impacts: global warming potential (GWP), abiotic depletion of fossil fuels (ADPfossil) and acidification potential. The model has also been applied to cumulative energy demand, but this impact category will not be presented in this paper. Other impact categories may be presented, but to ensure correct results, use of other indicators than those specifically mentioned above requires a check for the potential need for more data, especially on direct emissions from the biomass.

The model applies GWP characterisation factors from IPCC 2013 for a 100-year perspective as implemented in SimaPro 8.0.3 (PRé 2014) and the CML-IA method v.3.01 (Leiden University 2013) for the other environmental impact categories. Biogenic CO_2, from biomass, is given a characterisation factor of 0. This is because the organic substrates analysed does not contribute to an increase in the concentration of carbon in the

Table 4 General data for substrate properties in the model

	Description	Unit	Basis values biogas			Reference			Comments and references
			SSOHW	Manure		ER of SSOHW	Manure		ER=energy recovery
				Cattle	Pig		Cattle	Pig	
Substrate properties	Dry matter content in substrate	–	0.33	0.08	0.08				Assumptions based on Daugstad et al. (2012), Carlsson and Uldal (2009) and Eklind et al. (1997).
	Biogas potential (volume based)	Nm^3/tonne DM	600	260	330				
	Carbon content in DM substrate	kg/tonne DM	400	400	400		400	400	
	Methane content in produced biogas	–	0.63	0.65	0.65				
	Nitrogen content in DM substrate	kg/tonne DM	23	48	75		48	75	
	Lower heating value per kg organic waste	MJ/kg				2.3			Frøiland et al. (1999)

atmosphere as the carbon was "recently" removed from the atmosphere. It is possible to apply the model to calculate results using other assumptions for the biogenic CO_2 characterisation factor. Similarly, the biogenic CH_4 has been given a characterisation factor of 25.25 kg CO_2-equivalents/kg, while fossil methane has the factor 28. According to normal practice, abiotic depletion of fossil fuels is related to the lower heating value (LHV) expressed in MJ per kg of m^3 fossil fuel.

Phosphorous is a limited resource, but despite this, emissions into the environment may cause pollution to water and create the growth of algae and death of fish. Emissions of phosphorous during and after application of manure, digestate and mineral fertiliser on land are largely dependent on soil conditions, created by, for example, the history of phosphorous fertilisation, soil type, redox conditions and other factors, and less on the actual application of phosphorous fertilisers. For this reason, these effects were not quantified in the EaseWaste model for organic waste (Hansen et al. 2006). Drainage and surface losses of phosphorous have been measured for Norwegian conditions with regard to crop rotation, fertilisation, soil tillage and plant protection, and it is concluded that the fertilisation level appears to have no significant effect. The important factors identified were time of soil tillage, time of application of manure and type of plant cover in the autumn (Eltun et al. 1996). According to Bøen (2013), the application of waste-based products to soil are in practice usually decided by criteria other than the P-fertiliser. Measurements have shown a small loss of phosphorous from digested biosolids (0.1–0.3‰) (Bøen 2013). Composted food waste showed significantly higher losses, but still low compared to the amount of P supplied. It is therefore not likely that biogas production, where liquid digestate is used as a fertiliser, will lead to considerable increase in eutrophication potential compared with the use of mineral fertiliser or of manure as fertiliser. The scenario that includes dewatering and composting of the digestate may lead to a magnification of the phosphorous concentration, making the emissions more difficult to predict, especially in comparison with the reference scenario of organic waste, which is incineration. To be able to quantify emissions of P, a specific region or a specific farm must be assessed, resulting in challenges in establishing default emission values in the BioValueChain model. Results for eutrophication should thus be presented for specific cases, and application of the model to calculate results for eutrophication will be subject to further research and is not a part of the scope of this paper.

Land use is increasingly used as an environmental indicator, especially with regard to bioenergy and biofuels. This is connected to ethical issues related to the use of farmland for energy instead of food purposes. Since the model focuses on the production of biogas from waste products and not energy crops, the inclusion of land use as an indicator has not been prioritised. Land use may, however, be included in the future if it is shown to be relevant.

Heavy metals may be of concern when applying digestate from organic waste and manure on land that is used to cultivate food products. The Norwegian organic fertiliser ordinance (No. 11) (2003) prohibits the use of digestate as fertiliser if the content of heavy metals is above the permitted threshold values.

3 Results

As the parameters in the model are based on generic and best available data for Norwegian conditions, general results only are presented in this paper. The chief purpose is to demonstrate the way in which results may be presented and the kind of results and conclusions that can be achieved when applying the model. Where conclusions are to be drawn for a specific region, the parameters must be altered to region specific values. The results presented below do, however, give an indication of hotspots and where there is a significant need for specific data. They also reveal the need for further research, where there are data gaps, and show where average or generic results may be applied if specific data is not available or if the data is too resource consuming to collect.

3.1 Global warming potential

Figure 2 shows the net global warming potential (GWP) results for each of the substrate types for the different uses of the biogas and the digestate. The biogas production scenarios result in a higher net benefit than the reference scenario for all three substrates, except for the scenario with dewatering of the digestate (including composting and waste water treatment) for the manure substrates. The most desirable option for all substrates is the upgrading of biogas for transport purposes (diesel is substituted) together with the use of liquid digestate as fertiliser (mineral fertiliser is substituted).

Figure 3 shows the GWP results split into life cycle stages. Only the reference and the best and worst cases are shown for each substrate. The avoided burdens from use of biogas and digestate have significant influence on the results. It follows, therefore, that the end product downstream from the digester, together with the assumptions regarding substitution, is of great importance. In addition, assumptions concerning the loss of nitrogen and carbon along the value chain (pre-treatment, digester, upgrading and dewatering/composting) are important, as these affect the substitution effect of the biogas and digestate produced.

All direct emissions of CH_4 and N_2O have considerable impact on the GWP. These include those from storage of

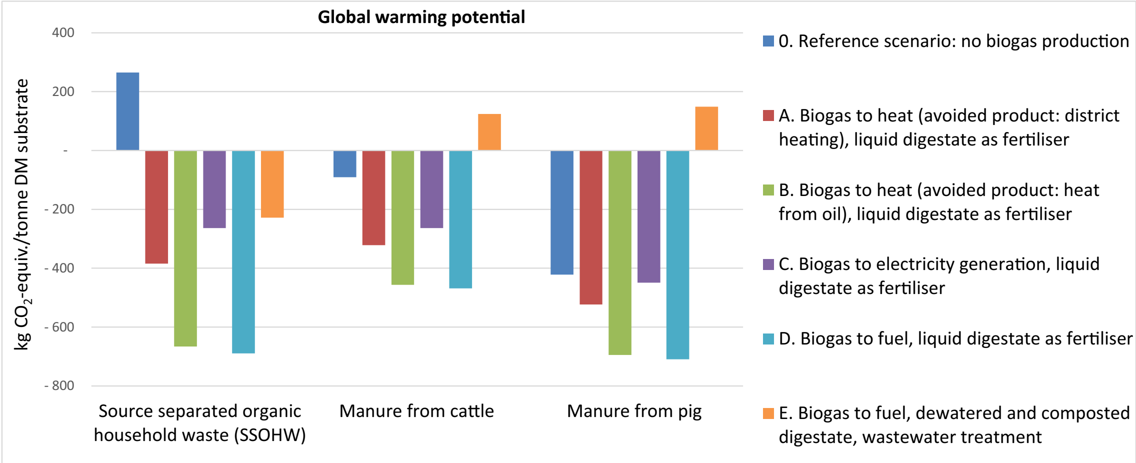

Fig. 2 Global warming potential results per tonne DM substrate

digestate and manure substrates, and the application of digestate to soil. This also applies to emissions of N_2O from wastewater treatment in the scenarios that includes dewatering.

3.2 Abiotic depletion of fossil fuels

The results for ADP of fossil fuels in Fig. 4 show that biogas production from organic waste results in reduced net use of fossil fuel resources when compared with energy recovery, independent of the way in which the biogas and digestate are utilised. For the manure substrates, some of the biogas alternatives result in increased use of fossil fuels in comparison with the reference scenarios (applying manure as fertiliser), depending on the use of biogas and digestate. This is partly because the reference scenario for manure includes little use of fossil fuels, resulting in a net energy saving as a result of substitution of mineral fertiliser. In addition, the energy content of manure is less than for organic waste, resulting in less substitution of other energy carriers per tonne DM in the biogas scenarios.

3.3 Acidification potential

The results for acidification potential (AP) in Fig. 5 show that the biogas scenarios for organic waste result in higher acidification potential when compared with the reference scenario. However, the biogas scenario where diesel and mineral fertiliser are substituted has only marginally higher acidification potential than the reference. Regarding cattle manure, biogas production has similar or lower acidification potential, depending on the use of the biogas and digestate. For manure from pigs, all biogas scenarios result in a lower impact than the reference scenario. It is the direct emissions of NH_3 that make the greatest contribution. These emissions occur during application of liquid digestate to soil or composting of digestate.

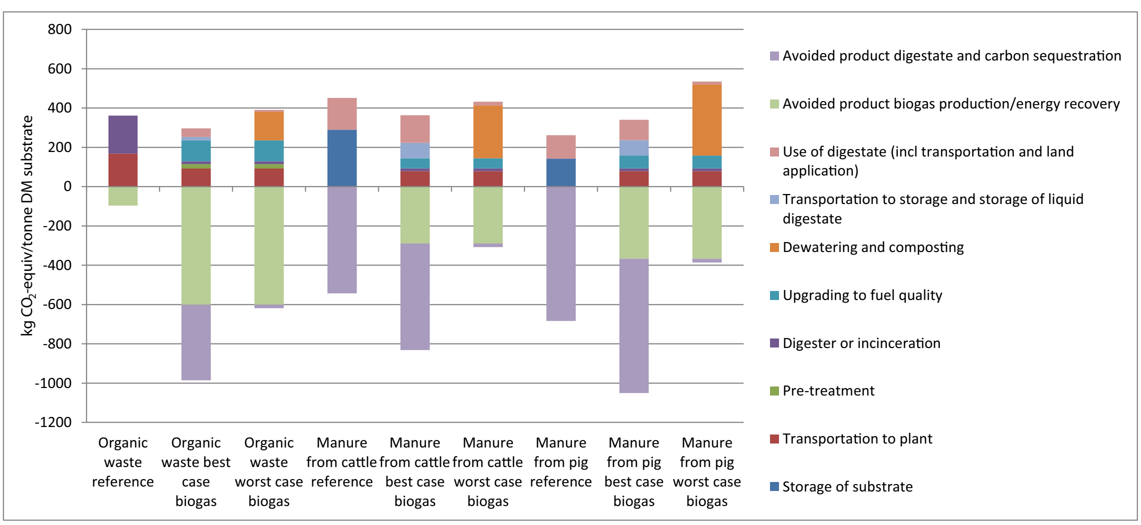

Fig. 3 GWP results per tonne DM organic waste, per life cycle stage

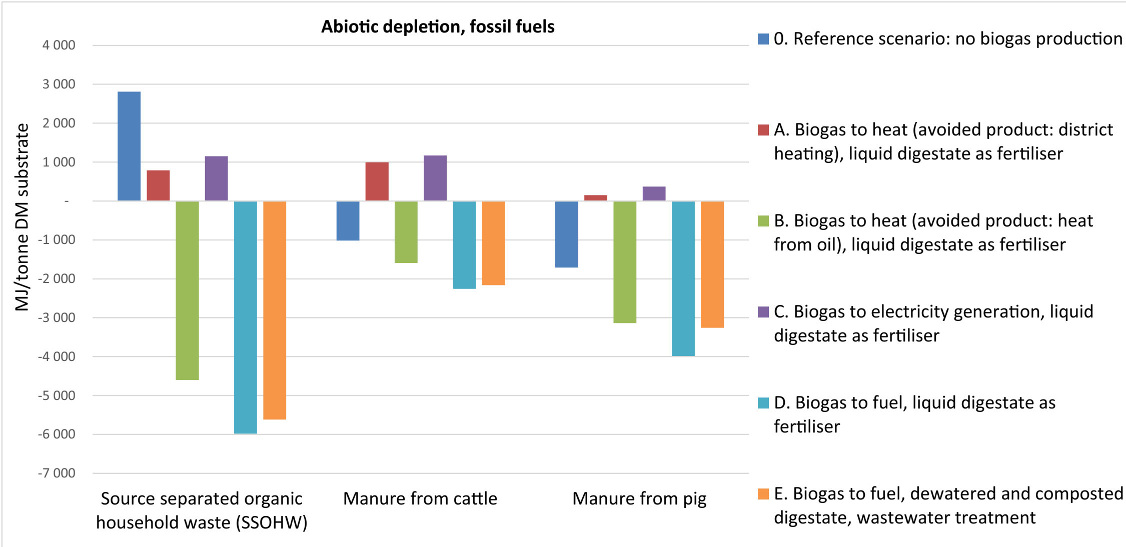

Fig. 4 ADPfossil results per tonne DM substrate

3.4 Sensitivity of parameters in the model

Clavreul et al. (2012) suggest a four-step procedure when performing a sensitivity analysis for LCA on waste systems: sensitivity analysis (perturbation analysis and scenario analysis), uncertainty propagation, uncertainty contribution analysis and combined sensitivity analysis. The purpose of the sensitivity analysis presented in this paper was to evaluate the importance of the different generic parameter values in the model as well as to create a structural approach on how to test the robustness of the conclusion when comparing options for treatment of organic waste and manure.

The sensitivity analysis was limited to the reference scenario and best case biogas scenario (upgrading biogas to fuel quality and use of liquid digestate as fertiliser) as this would seem to be the option that future biogas plants in Norway are aiming for. Moreover, the biogas scenarios have most of the life cycle stages in common. The significance of the substituted products, which is the primary difference, has been discussed earlier in this paper.

The parameters were classified into three main categories: (1) direct emissions from biomass, (2) substrate property values and (3) technology- and operation-based parameters (including transport distances), such as energy use and efficiency (output/loss) throughout the value chain. Minimum and maximum values were estimated for each parameter, based on literature and experience. Setting absolute values on uncertainties can be difficult, especially for parameters such as transport distances, which in principle can be unlimited, and energy use for digesters and pre-treatment facilities because of lack of available ranges for operation data. Best estimates on minimum and maximum values can,

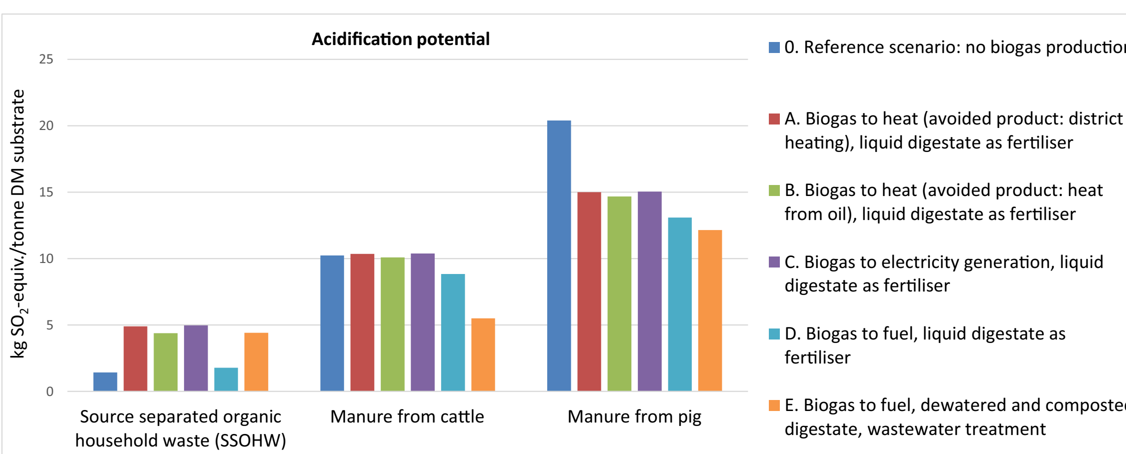

Fig. 5 Acidification potential results per tonne DM substrate

nevertheless, in this context, give a good indication as to whether or not the results are sensitive to each of the parameters.

The model was applied by varying one parameter at a time. The chance in the difference between the reference scenario and the biogas scenario was assessed in order to identify which of the parameters would change the ranking between the scenarios for each environmental indicator. A negative value for change in difference in Table 5 indicates decreased difference between the two assessed scenarios. A positive value indicates an increased difference. If the change in difference is larger than 100 %, the ranking between the two scenarios has changed as a result of the changed parameters. The value of the changed parameters is shown in Appendix B (Electronic Supplementary Material).

The parameters that can alter the ranking of the results (and thus change the conclusion) for one or several of the environmental impact indicators for the minimum and maximum values applied are summarised in Table 5. The results for all the parameters that were tested can be found in Appendix B (Electronic Supplementary Material). The sensitivity analysis shows that the results for GWP appear to be more robust than for the other environmental indicators. The only parameter that can change the conclusion for GWP is increased methane emissions from storage of cattle manure digestate. The results for AP are the most sensitive ones because the difference between the two scenarios is small for the default values in the model, thus only small changes in values are required to change the conclusion. AP results are sensitive for emissions of NH_3 for all substrates and for values that affects how much diesel the biogas from organic waste can substitute, such as efficiency of plant and biogas potential. The results for ADP of fossil fuels are sensitive for transport distances of manure substrate and manure digestate.

It is a challenge that the need for specific data is important for the direct emissions. As direct emissions of CH_4 and NH_3 from storage and application on land are strongly dependent on local conditions such as storage size, time, temperature, type of soil and agricultural practice, these input values are challenging to estimate for actors in the value chain, such as biogas plant owners and farmers.

In the results presented in chapter 3.1 to 3.3, heat generated by the incineration of organic waste was assumed to substitute the Norwegian district heating mix, based on the LHV of organic waste, the efficiency coefficient for the incineration and the ratio between sold heat and the amount of heat produced. These assumptions were tested through the variation of the values for LHV and the sold heat ratio (estimated maximum values). In addition, scenario analysis with a marginal perspective, where the heat produced replaces oil, was performed. The results showed that results for GWP and ADPfossil are quite robust, and the conclusion remain unchanged (the biogas scenario still substantially better.) The marginal perspective results in a further reduction I AP of the reference scenario, resulting in a wider gap between the biogas scenarios and the reference scenario.

These uncertainties would imply that the input data should be as specific as possible when applying the model for case studies. As only one parameter was changed at a time in this analysis, it is important to be aware that the added effect of change of several parameters could have a considerable impact. For case studies, a specific sensitivity analysis should be carried out to test the robustness of the conclusions. In the case of direct emissions, further research is required to decrease the uncertainties and to ensure that the emission factors are relevant for the local conditions.

4 Discussion

The results show significant variation in the environmental effects of biogas production, depending on type of substrate, and the way in which the biogas and digestate are utilised. As a general assumption, biogas production represents an appropriate measure to reduce greenhouse gas emissions from waste and manure management in Norway when digestate is used as fertiliser and biogas is upgraded and used in the transport sector. Non-optimised value chains may, however, have serious environmental impacts, for example emissions from the storage of substrates and digestate. Use of biogas for heating and electricity purposes is generally less desirable for Norwegian conditions. The substitution of fossil energy carriers has a marked impact on the results. It is thus important that the assumptions regarding substitution reflect the system in the specific region. In the same way, any assumption regarding biogas potential and carbon and nitrogen content in the substrate, and loss and efficiency throughout the value chain, must be as specific as possible. It is recommended that more than one substitution alternative for replacement of energy carriers is included, especially for the generation of heat and/or electricity.

The optimisation of biogas value chains with regard to the reduction of greenhouse gases may lead to an increase in other environmental impact categories. Knowledge of these consequences is important so that decision makers make well-informed decisions and avoid unnecessary trade-offs. In general, the results for AP seem to be more sensitive than GWP and ADPfossil due to small differences between the results for AP for each scenario and uncertainties in direct emissions of NH_3.

The sensitivity analysis showed that any variation of input parameters may alter the conclusions as to which scenarios are preferable. Specific data should always be used when possible. This particularly applies to parameters for transport distances, efficiency of biogas plant and the biogas potential for

Table 5 Summary of the sensitivity analysis

		GWP			AP			ADPfossil		
Substrate	Changed parameter (technology and operation)	kg CO_2-equivalents/tonne DM substrate			kg SO_2-equivalents/tonne DM substrate			MJ/tonne DM substrate		
		Difference between reference and biogas	Change in difference		Difference between reference and biogas scenario	Change in difference		Difference between reference and biogas scenario	Change in difference	
Source separated organic waste	Basis parameters	−954	–	–	0.35	–	–	−8792	–	–
	Increased transport distance, substrate	−827	−128	−13 %	0.97	0.62	176 %	−6922	−1870	−21 %
	Reduced efficiency, biogas plant	−869	−86	−9 %	0.82	0.47	134 %	−7625	−1166	−13 %
	Increased efficiency, biogas plant	−1040	86	9 %	−0.12	−0.47	−134 %	−9958	1166	13 %
	Decreased NH_3 emissions, application on land	−954	0	0 %	−1.40	−1.76	−500 %	−8792	0	0 %
	Reduced, biogas potential, substrate	−752	−203	−21 %	1.67	1.32	376 %	−5547	−3244	−37 %
	Increased biogas potential, substrate	−1157	203	21 %	−0.97	−1.32	−376 %	−12,036	3244	37 %
Cattle manure	Basis parameters	−377	–	–	−1.39	–	–	−1247	–	–
	Increased transport distance, substrate	−142	−235	−62 %	−0.24	−1.16	−83 %	2331	−3578	−287 %
	Increased transport distance, digestate	−142	−235	−62 %	−0.24	−1.16	−83 %	2331	−3578	−287 %
	Increased CH_4 emissions, storage digestate	13	−390	−103 %	−1.39	0	0 %	−1247	0	0 %
	Increased NH_3 emissions, storage digestate	−377	0	0 %	1.68	−3.07	−220 %	−1247	0	0 %
	Reduced emission NH_3 manure/substrate	−377	0	0 %	0.61	−2.01	−144 %	−1247	0	0 %
Pig manure	Basis parameters	−288	–	–	−7.31	–	–	−2272	–	–
	Increased transport distance, substrate	−53	−235	−82 %	−6.15	−1.16	−16 %	1306	−3578	−157 %
	Increased transport distance, digestate	−53	−235	−82 %	−6.1	−1.16	−16 %	1306	−3578	−157 %
	Increased NH_3 emissions, storage digestate	−288	0	0 %	5.03	−12.3	−169 %	−2272	0	0 %
	Reduced emission NH3 manure/substrate	−288	0	0 %	0.77	−8.08	−111 %	−2272	0	0 %

Change in difference: negative value: decreased difference between the two scenarios. Positive value: increased difference. Change in difference > -100% means change in ranking of the two scenarios and thus change in conclusion about which option is most favorable (reference scenario and biogas scenario)

substrates. In addition, direct emissions from storage and spreading have appreciable variations. Simple measures such as the use of storage covers to minimise emissions of CH_4 may have noticeable effect on the results for the entire value chain. These highly site- and time-specific direct emissions are difficult for non-experts to estimate. This pinpoints the need for further research into ways in which direct emissions can be reduced and the development of models that can estimate direct emissions as a function of the type of fertiliser applied for different types of local conditions (soil properties, type of farm and agricultural practice).

Appropriate abatement measures on a national level in Norway appear to be increased use of organic waste and manure for biogas production (exploit more of the total potential), as long as there are incentives for the actors to use biogas in the transport sector to substitute diesel, and incentives to substitute use of mineral fertiliser by digestate. There is a need to explore further how to utilise the digestate in the most optimal way and how the practices of storage and application on land can be optimised to reduce direct emissions.

5 Conclusions

The BioValueChain model has been developed to facilitate evaluation of the environmental impacts of various types of biogas value chains in different regions or for specific plants in Norway. The model may also be applicable to other countries as long as the relevant electricity mixes are applied and the relevant assumptions are made regarding substitution when defining scenarios. Collection of specific data should include estimation of direct emissions from storage and application on land for the specific climate and agricultural practice.

When applying the model, effort should be made to use specific data, especially with regard to the following: transport distances, efficiency of biogas plant and emissions from storage of manure and digestate and application of manure and digestate on land. Further testing of the model and the collection of data relating to the operation of pre-treatment facility, digester and upgrading facility will be carried out in order to validate the generic parameter values in the model.

The model work has revealed a need for more research into emissions from biomass during storage and into the application of digestate for the various substrates. Work should also be carried out in order to establish which parameters affect these emissions, to decrease uncertainties and to be better able to estimate the emissions in the different regions.

The model will be applied for case studies on specific regions and for specific biogas plants in Norway. Furthermore, the model will be combined with an economic model looking at the economic situation and need for political measures for the actors in the value chain.

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