AIMS Energy, 5(5): 838-863.
DOI: 10.3934/energy.2017.5.838
Received: 16 June 2017
Accepted: 20 September 2017
Published: 28 September 2017

http://www.aimspress.com/journal/energy

Research article

An economic comparison of dedicated crops vs agricultural residues as feedstock for biogas of vehicle fuel quality

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Abstract: The vast majority of the biofuels presently used in the EU are so called first generation biofuels produced from crops. Concerns of food security, displacement of food crop production and indirect land use change (iLUC) has led to the introduction of measures to reduce the use of first generations biofuels and promote so called advanced biofuels based on feedstock that does not compete with food/feed crops, such as waste and agricultural residues. In Sweden, 60% of the biofuel consumption is already based on waste/residual feedstock, and a unique feature of the Swedish biofuel supply is the relatively large use of biogas for transport, representing 9% of the current use of biofuels. The use of waste/residues dominates the biogas production, but agricultural residues, representing a large domestic feedstock potential, are barely used at present. This could indicate that biofuels from such feedstock is non-competitive compared both to fossil fuels and to biofuels produced from crops and waste under existing policy framework. This study show that without subsidies, the production cost of biogas as biofuel from all non-food feedstocks investigated (grass, crop residues and manure) is higher than from food crops. A shift from food crops to residues, as desired according to EU directives, would thus require additional policy instruments favoring advanced biofuel feedstock. Investment or production subsidies must however be substantial in order for biogas from residues to be competitive with biogas from crops.

Keywords: biogas; biofuel; techno-economic; residues; production cost; EU RED

1. Introduction

According to the EU Renewable Energy Directive (RED), 10% of the fuel used within the transportation sector in the EU should be renewable in 2020, and by 2015, a share of 6.7% was reached [1,2]. The vast majority of these fuels are so called first generations biofuels produced from crops, with biodiesel dominating at 79% [3]. However, the EU's biofuels policy, where the primary goal is reduction of greenhouse gas (GHG) emissions, is much debated. A major criticism is that the use of crop based biofuels causes displacement of food crop production and indirect land use change (iLUC) with impacts on GHG emissions [4]. This discussion has led to an amendment of the EU RED in 2015, with a cap of 7% on the use of crop based biofuels by 2017 and a higher demand on reduction of GHG emissions (60%) for production plants taken in operation after the end of 2015 [5]. In this so called iLUC-directive, iLUC-factors are also introduced, a GHG emission penalty to be included in the reporting for biofuels based on cereal and other starch-rich crops, sugars and oil crops. Together with a higher demand on GHG reduction, some crop based biofuels might not meet the amended sustainability criteria, which might be the reason why a decreased consumption of biodiesel made the EU biofuel consumption as a whole drop with 2% between 2014 and 2015 [3].

Sweden stands out as having the highest share of renewable energy in domestic transport in the EU, with 24% in 2015 according to the calculation rules in the EU RED [2]. The Swedish biofuels supply is partly based on crops, accounting for 40%, but also on biofuels produced from waste and residues [6]. A unique feature of the Swedish biofuel supply is the use of biogas for transport, representing 9% of the biofuels. Biogas can be produced from various types of feedstock such as sewage sludge, municipal and industrial waste, manure, crop residues and dedicated crops. Biogas can also be utilized for different purposes such as heat and power production, as a vehicle fuel, or as a renewable alternative to natural gas in other applications. Which feedstock and utilization pathways that are applied are highly dependent of which policy instruments that are implemented, as demonstrated by a comparison between Sweden and Germany. In Sweden, 63% of the current biogas production is utilized as vehicle fuel, and 95% of the feedstock is municipal and industrial waste and residues [7]. In Germany, representing 50% of the total biogas production in the EU, other policy instruments are applied which results in a completely different biogas system. In fact, only 5% of the biogas is based on waste while the rest is based on crops (52%) and manure (43%) [8,9]. The biogas produced is utilized for heat and power and less than 1% is used as vehicle fuel [9].

To reach the national goal of 70% reduction on GHG emissions in the Swedish transportation sector by 2030, a demand of domestic production of biofuels based on agricultural biomass is foreseen [10–13]. Biofuel production could be based upon a wide range of different crops, which may be more or less suitable depending on which aspects, such as e.g. land use, energy, cost or GHG efficiency, that is prioritized [14,15]. Current EU policy does however prioritize so called advanced biofuels, which are produced from feedstock that does not compete with food/feed crops, such as waste and agricultural residues.

Although agricultural residues represent a large potential, in Southern Sweden dominated by straw, manure and sugar beet tops, only limited amounts are utilized today. This could indicate that biofuels from such feedstock is non-competitive compared both to fossil fuels and to biofuels produced from crops and waste under existing policy framework. Thus, if an increased production of advanced biofuels from agricultural residues is desired, as described in the iLUC-directive, it is important to evaluate the cost aspects under similar and local conditions. Such evaluation could define whether the use of agricultural residues would increase the production cost as compared to biofuels based on crops, and if so, which systems that should/should not be promoted through policy instruments.

The study presented in this paper is related to previously published work with the objective to establish and compare land use efficiency, energy efficiency, economic efficiency and GHG efficiency for biogas derived from agricultural feedstock from a coastal agricultural area situated in southern Sweden. In previous publications, energy input in cultivation, crop yields, and overall energy and greenhouse gas efficiency from field to fuel have been presented [14,15].

In this study, the production costs of biogas of vehicle fuel quality was compared for 8 agricultural crops or residues that are or could potentially be used for biogas production in the investigated region, and which are differently addressed in the iLUC-directive [5];

(1) Four food crops that are mentioned in the iLUC-directive as to be phased out as biofuel feedstock after 2020, and where iLUC-factors will be added in reporting of GHG-reduction; wheat grain, sugar beet, maize and *Triticale*. The latter is a high yielding cereal crop that in this study is harvested green as whole crop silage.

(2) Grass, which has an unclear status at the moment. Grass is not burdened with an iLUC-factor in the iLUC directive, but grass cultivated on arable land for biofuel purposes could potentially fall under the definition as a “crop grown as main crop primarily for energy purposes on agricultural land”, and thus according to the iLUC-directive support for this should be phased out. However, “grassy energy crops” is also listed as a feedstock for the production of advanced biofuels, which is encouraged.

(3) Three agricultural residues: manure, wheat straw and sugar beet tops which are only used in minor amounts for biofuel production in Sweden today. These three are also listed as feedstock for the production of advanced biofuels, and are abundant in the region investigated.

The overall objective is to evaluate how the biogas production costs depends on feedstock, and which aspects of the production costs that dominate for different feedstocks. The production costs are compared to current vehicle fuel prices in Sweden. The analysis also includes the impact of some current policy instruments and the potential outcome if such instruments were implemented for biogas from residues only and not for biogas from crops.

It should be noted that prices might change quickly and vary largely depending on several factors. Therefore, the values presented here should not be considered as absolute and care should be taken when comparing the results with data from other sources.

2. Material and Methods

2.1. System overview

Eight different crops and agricultural residues are evaluated as biofuel feedstock from an economic point of view. The evaluation includes the production of biogas, upgrading to vehicle fuel quality, distribution and filling stations. In addition, storage, distribution and application of digestate, the liquid residue after biogas production, on arable land is included.

Feedstock cost as well as the impact of different features of crops and residues results in different cost to produce and distribute the same amount of biogas. To demonstrate the feedstock-related differences, calculations are based on a process operating on one single feedstock, even if neither biogas production, nor in some cases storage, would be practical for single feedstock.

All gas volumes are given as dry gas at 0 ℃ and 101 kPa, and the lower heating value for methane is used in the conversion to energy units.

2.2. Feedstock

Feedstock properties after storage losses are given in Table 1. Background data, assumptions and references can be found in Appendix A1.

Table 1. Feedstock properties.

	Wheat grain	Beet	Maize	*Triticale*	Grass	Wheat straw	Beet tops	Manure[1]
Dry matter (DM) (%)	86.0	21.5	25.9	35.3	17.1	90.5	12.7	12.0
Volatile solids (VS) (%)	83.4	20.9	24.8	33.4	15.5	85.2	10.5	9.6
CH_4 (m^3/Mg_{DM})	369	372	307	341	243	224	264	170
Macro and micro nutrients (mg/kg wet weight)								
N	18,000	1588	3499	4437	5654	4860	4213	4536
P	4452	234	465	581	633	273	396	873
K	4699	929	1222	2632	3280	9018	2040	4273
S	1330	83	201	266	358	1140	330	309
Fe	24.4	14.0	16.2	12.23	21.07	NA	69.9	53.2
Mo	0.46	0.01	0.06	0.17	0.19	NA	0.06	0.20
Co	NA	0.02	0.01	0.04	0.14	NA	0.07	0.15
Ni	NA	0.11	0.15	0.08	0.33	NA	0.17	0.18

[1] Mix of liquid and solid manure.

2.3. Biogas process

The calculations are based on continuous stirred tank reactor (CSTR) processes, operated under mesophilic conditions (37 ℃), which is the dominating solution in German, full-scale, crop-based biogas plants [16]. The reactors are operated as one-stage processes.

The parameters selected to define the CSTR process are the maximum organic loading rate (OLR), the minimum hydraulic retention time (HRT) and the maximum DM-concentration in the reactor. The output is the active reactor volume. Mineral nutrients of P, S, Fe, Co, Mo, Ni and Se are added if the feedstock provides insufficient amounts to support 5% microbial biomass formation. In additions, a minimum and maximum concentration of total ammoniacal nitrogen (TAN) are set to provide buffering capacity and avoid ammonia inhibition. N is added as carbonic diamide if the concentration is too low. Defining parameters are summarized in Table 2. More details about selected limits and need for mineral nutrients are found in Appendix A2.

Table 2. Defining parameters for the biogas process.

Parameter	**Unit**	**Lower threshold**	**Higher threshold**
Organic loading rate	$kg_{DM\text{-}rem}/(m^3*d)$	-	3
Hydraulic retention time	d	46	-
DM concentration in reactor	%	-	10
TAN in reactor	g/L	1.8	4.0

2.4. Storage and pre-treatment of feedstock

Maize, *Triticale*, grass and beet tops are assumed to be harvested using a forage harvester, transported directly to the biogas plant and ensiled in bunker silos at site. Beet and dried wheat grain is stored off site and transported just in time to the biogas plant. Wheat straw is transported and stored as high-density bales. Liquid and solid manure, delivered just in time with trucks, is handled in a closed building with controlled ventilation to avoid odor disturbances in the neighborhood.

For maize, *Triticale*, grass and beet tops, no additional pre-treatment is included. Beets and grain requires a minor pre-treatment (slicing and crushing respectively). Regarding straw, the feedstock is pre-treated to make the organic material more available for the microorganisms. Although different kinds of pre-treatment are presented in the literature, economic calculations in this study are based on mechanical methods (extruder and hammer mill) used at Danish biogas plants [17,18].

Finally, the use of liquid and solid manure must also fulfill the European directive for the treatment of animal byproducts [19]. To meet these requirements, a mixture of liquid and solid manure is pumped with cutting pumps (to ensure that the particle size is less than 12 mm) to hygienization tanks and heated to 70 ℃ for one hour. Thereafter, the manure is pumped to the reactors while crops and crop residues are fed into the biogas reactor with screw conveyors.

2.5. Digestate

The reactors are assumed to be ideally stirred, giving effluent concentrations equal to those in the reactor. The digestate is stored in covered storage tanks, with a loss of TAN amounting to 1% of N [20]. Storage capacity for crop digestate sufficient for 12-months´ production is included. For manure, a digestate volume corresponding to the amount of liquid manure used as feedstock is assumed to be transported back to existing storage tanks at the farms. For the excess digestate, storage capacity for 12-months´production is included.

2.6. Upgrading of biogas to vehicle fuel quality

Biogas typically contains 50–60% CH_4, 40–50% CO_2 and some contaminants such as hydrogen sulphide, ammonia and particles. Sweden has implemented a standard for biogas utilized as vehicle fuel that requires the removal of contaminants and a methane concentration of 95–99% [21]. Currently, several technologies for the removal of CO_2, also known as upgrading, are commercially available. In Sweden, having 59 biogas upgrading plants in December 2015, 71% of the plants use the water scrubber technology, 8% use pressure swing adsorption (PSA), 19% use chemical scrubbing and 2% use membrane technology [22]. All technologies have different characteristics considering e.g. process energy requirements and methane losses, see Table 3. A more detailed presentation of these and other technologies is e.g. found in Bauer et al. [23] and Hoyer et al. [24].

Table 3. Process energy requirements per volume of biogas and methane losses for different upgrading technologies [9,24].

	Electricity (kWh/m^3)	Heat (kWh/m^3)	Methane losses (%)
Amin scrubber	0.06–0.15	0.5–0.8	0.1
PSA	0.20–0.25	-	1–5
Water scrubber	0.20–0.30	-	0.5–2.0

Different characteristics regarding for instance process energy requirements, methane losses and methane concentration in the upgraded gas affect the economic outcome. Thus, local conditions such as the price of electricity and heat, possibilities to utilize waste heat and the market price for upgraded biogas determine the most favorable technology in each case. Economy of scale, however, has a more general effect on the production cost. As presented in Hoyer et al. [24], there is a clear efficiency of scale concerning the investment cost for upgrading plants up to an installed capacity of approximately 1000 m^3 biogas/h. Increasing the capacity further will have a minor impact on the investment cost per m^3 of installed capacity. A similar efficiency of scale is found for the total upgrading cost [25,26,27]. Although larger plants result in lower upgrading cost per energy unit, a larger biogas plant may also results in a higher transportation cost for feedstock and digestate [28]. Thus, the analysis in this study is based on a biogas plant producing 1000 m^3/h of biogas. With a methane content of 55%, this corresponds to an annual methane production of 172 TJ. Due to low losses of methane and a low consumption of electricity, calculations are based on a chemical scrubber.

2.7. Distribution of biogas of vehicle fuel quality

In Sweden, upgraded biogas is distributed to filling stations by truck (70%) or gas grid (30%) which could be a dedicated biogas grid or the natural gas grid [7]. When distributed by truck, upgraded biogas is compressed to 20–25 MPa and loaded in high-pressure vessels of steel or composite. Biogas can also be liquefied and distributed as LBG (liquefied biogas) although it is not a common solution in Sweden today [29].

When distributed in gas grids, both local dedicated biogas grids as well as the national natural gas grid are utilized today. Most biogas plants inject gas into the low pressure grid (4 bar) but it is also possible to inject into the high pressure grid (80 bar) [29]. Currently, injection to the national grid normally requires that propane is added to adjust the heating value of the biogas to correspond to the distributed natural gas. In this study, calculations are made for biogas injected into the low-pressure natural gas grid. Based on the discussion presented in Börjesson et al. [29] propane addition is not included, assuming conditions as for a dedicated biogas grid.

The final step in the chain of distribution is the methane filling station. In Sweden, 211 filling stations was in operation in the end of 2015. The average amount of gas distributed per station annually corresponded to almost 20 GWh for stations dedicated to busses and 4.5 GWh for public stations [29]. In this study, calculations were based on filling stations distributing 10 GWh annually.

2.8. Energy input

In the following sections, energy input is presented as data measured at the biogas plant, thus as final energy use. This is also used in the economic calculations.

2.9. Biogas production

Process energy input is affected by plant design and operational conditions as well as by characteristics of the feedstock. Process heat requirements depend among other things on process and feedstock temperature, reactor configuration, insulation and heat exchangers as well as on hygienization requirements. In the literature, there are several reports of internal heat demand for biogas plants utilizing different kinds of feedstock. A demand in the range of 70–130 MJ/t has been reported [16,20,30,31,32], but there are also examples where the reported heat demand is as high as 250–330 MJ/Mg [16,33,34]. For comparison, a theoretically calculated heat demand for the feedstocks in the current study (assuming an average feedstock temperature of 8 ℃, a process temperature of 37 ℃ and a specific heat capacity of water and dry matter of 4.18 and 1.0 kJ/kg/K respectively) would be 89–109 MJ/Mg. In addition, heat is required to compensate for losses through the reactor walls and via the biogas produced. These losses are affected by insulation, local weather conditions and reactor configuration etc. Here, the heat demand is increased with 15% to compensate for these losses [31] which gives a calculated heat demand of 102–126 MJ/Mg excluding heat exchangers. For comparison, a recent study of some Danish co-digestion plants found that the net process heat demand was 54 to 72 MJ/Mg of feedstock [17]. Given the numbers calculated here and the ones found in the literature, it is clear that process heat demand varies between different plants depending on feedstock as well as design and operation of the plant. In this study, the calculated heat demand is applied for all biogas plants but the one using manure, where the net heat demand is set to 70 MJ/Mg representing the higher end of the interval presented by Hjort-Gregersen [17].

Electricity is used for feeding, stirring, pumping etc. and the demand is influenced by feedstock type and reactor design. In the literature, reported electricity input varies from 5–41 kWh/Mg [16,20,31–35]. However, when the biogas is utilized for CHP, it is common that reported figures also include parasitic load for the production of CHP, which could represent 9–40% of the total electricity consumption [35]. In a recent study of some Danish biogas plants, the electricity consumption for large scale co-digestion plants was found to be 6–7 kWh/Mg of feedstock [17]. In this study, the internal electricity demand for the biogas production process only is taken to be 8 kWh/Mg wet weight of added feedstock (including water where applicable).

2.10. Upgrading

As presented in Table 3, different upgrading technologies have different energy requirements.

In this study, calculations are based on a chemical scrubber using 0.4 MJ electricity and 2.0 MJ heat per m^3 of biogas.

2.11. Utilization of waste heat

Both the biogas process and the upgrading process require heat. However, the upgrading process also produces waste heat that can be utilized to heat the biogas rector. In total, 75–80% of the heat used in the upgrading process is available at a temperature of 55–60 °C with a return temperature of 35 °C. It is also possible to split this heat stream in two, of which 1/3 is available at 85 °C and 2/3 is available at 55 °C (Karlsson, LE, Läckeby Water AB, personal communication). Thus, the possibility to use this waste heat depends on the temperature required at the biogas plant, where a mesophilic process requires a heat stream at 48 °C [36]. When the feedstock requires 70 °C hygienization, the temperature should be approximately 85 °C [37]. Thus, the waste heat from the upgrading process should be sufficient in both cases. In this study, it is assumed that all available waste heat could be utilized when energy crops are digested, although it is not certain that the biogas plant can reduce the temperature of the heating circuit to the extent required to achieve full utilization. Regarding manure, it is assumed that only the high temperature waste heat could be utilized due to the requirements for hygienization.

2.12. Distribution and filling stations

Upgraded biogas is assumed to be injected into the local low-pressure grid, which requires an increase of pressure from 0.1 MPa to 0.4 MPa. At the filling station, the pressure is increased to 20 MPa. Total electricity consumption is set to 0.03 kWh/kWh of upgraded biogas [29].

2.13. Economic assessment

Considered parameters are feedstock cost, methane potential as well as feedstock properties and how these affect the biogas process, the need for additives and the design of the biogas plant as such. The assessment also includes storage and handling of digestate as well as its potential value when used as a biofertilizer. Finally, the calculated production cost is compared to current market price of vehicle gas at public filling stations.

2.14. Feedstock

The production cost for crops applied in this study, presented in Table 4, includes crop production, harvest, transport to the biogas plant (30 km for grain and 7 km for the other crops) and storage. The production cost for crops does not include the cost for land nor any EU subsidies. Crop yield levels representative for the agricultural area (*Gss*) in southern Sweden are chosen based on the yields used in the assessments of GHG emissions and energy input that have been performed as part of the same research project [14,15,38]. The cost for agricultural residues includes harvest and handling, storage as well as a cost compensation for the removal of nutrients in crop residues as compared to the current practice of leaving the residues in the field. The cost also includes transportation to the biogas plant corresponding to 30 km (straw) and 7 km (beet tops). Regarding wheat straw, the recoverable amount in the region has been calculated to 2.8 Mg_{DM}/ha [39]. According to Valin et al. [40], not more than 33–50% should be removed not to jeopardize soil carbon development. The straw removal used in the present study is 1.6 Mg_{DM}/ha, which represents close to 60% of the total amount, following the assumptions in Rosenqvist [38]. For beet tops, calculations are based on a recovery of 3.0 Mg_{DM}/ha. For comparison, the mean yield in the county of Skåne has been shown to be 3.4 Mg_{DM}/ha, meaning that nearly 90% of the total yield is assumed to be recovered [41].

The calculated cost for crops and residues are based on data presented by Rosenqvist [38] representing price levels of 2016. The reason for using one reference instead of a review of multiple studies is to make sure that calculations are made according to the same methodology and using the same assumptions and background data. For comparison, the calculated cost of wheat grain corresponds to 95% of the Swedish market price for wheat grain in 2016 [42]. For straw, the calculated cost of 91 €/Mg DM corresponds to approximately 5 €/GJ (based on the lower heating value) which is 95% of the average market price for wood chips used for district heating in 2016 [43]. The calculated cost is also comparable of the cost for straw used for district heating in Denmark [44]. As mentioned above, the production cost presented in Table 4 is based on yields representative for southern Sweden, which are relatively high in a Swedish context. Assuming more or less suitable agricultural conditions could decrease the production cost up to 16% or increase it up to 54% for some crops or residues (data not shown here) [38]. Given these uncertainties, the impact of different feedstock costs is included in the sensitivity analysis.

Regarding manure, it is assumed that manure is available at the farm free of charge for the biogas producer, resulting in a transport cost only. The transportation cost is calculated based on assumed loading capacity, time to load and unload, cleaning of the truck, average speed and distance. Based on the assumptions and method presented in Appendix A4, the average one-way distance is calculated to 24.7 and 22.7 km for liquid and solid manure respectively. The resulting transport cost corresponds to 4.3 and 2.9 €/Mg respectively. For liquid manure, the transportation cost also includes return transport of digestate.

Table 4. Production/recovery cost for crops and crop residues (€/Mg_{DM}) [38].

	Wheat grain	Beet	Maize	Triticale	Grass	Wheat Straw	Beet tops	Manure	
								Liquid	Solid
Yield (Mg_{DM}/ha)	6.5	11.2	10.0	7.5	10.0	1.6	3.0	-	-
Machinery	59	72	55	65	49	60	33	-	-
Mineral fertilizers	40	26	39	21	47	10	36	-	-
Transport	7	15	20	20	20	14	52	-	-
Other	51	68	46	40	32	6	8	24	15
Total	**156**	**180**	**160**	**146**	**149**	**91**	**129**	**24**	**15**

2.15. Pre-treatment and handling of feedstock

Wheat grain, beet and straw are treated before fed into the reactor. In a recent study, the cost for pre-treatment of straw at Danish biogas plants was calculated to 17–43 €/Mg wet weight depending on technology, scale and level of utilization [17]. The average cost was 31 €/Mg which could be compared to the average cost of 10 €/Mg for pre-treatment of solid manure [17,18]. With a straw DM content of 90.5% (Table 1), the cost for pre-treatment of straw is set to 34 €/Mg_{DM} in this study. For further comparison, the cost for extrusion of grass has been calculated to 40 €/Mg_{DM} [45]. For wheat grain and beet, the cost for crushing and slicing is set to 0.9 €/Mg [38]. The time required for handling of feedstock at the biogas plant is set to 1.5 minutes/Mg for grain and straw, 3.8 minutes/Mg for maize, *Triticale* grass and beet tops and 2 minutes/Mg for solid manure [46]. The cost of personnel is set to 30 €/h.

2.16. Additives

The costs of additives in the biogas process are 1.1 €/kg (N) and 2.2 €/kg (P) based on mineral fertilizer costs [38]. For S and Fe, the cost are 3.0 €/kg and 4.1 €/kg respectively based on price estimates in April 2017 (Brenntag Nordic AB, Malmö; Kemira Kemi AB, Helsingborg; Yara AB, Köping). Micronutrients (Co, Mo, Ni and Se) are applied as individualised mixtures, for each feedstock (from Schaumann BioEnergy GmbH, Pinneberg) at a fixed cost of 21,600 € per biogas plant and year for 1600 kg of mixture, independent on variations of micronutrients in the mix.

2.17. Investment costs

The specific investment costs for biogas plants designed to process energy crops varies in the literature depending on scale, material, feeding technique, etc. Data presented by FNR [16] show that the investment cost for 41 biogas plants varies from 209–895 €/m^3 active volume, including the CHP unit, which on average represents 22.5% of the total investments. However, when comparing biogas plants of similar design and features, efficiency of scale is clear, albeit limited for larger biogas plants [47]. For large-scale biogas plants, treating approximately 10,000–100,000 t of maize (90% of the feedstock) and manure (10% of the feedstock), the investment costs, not including production of CHP, vary from 82 to 114 €/t [25]. Assuming a VS content of 33.6% for maize and 6.4% for manure, investment costs were recalculated to €/m^3 active reactor volume as shown in Figure 1, by assuming an OLR of 2.5 $kg_{VS\ added}/m^3/d$ [25,47]. The investment cost for a biogas plant with an active reactor volume of 7000 m^3 would with this method be calculated to 309 €/m^3. For comparison, FNR [48] presents data for biogas plants with an active reactor volume of 7000 and 7200 m^3. Not including the cost for biogas utilization and digestate storage, the investment is approximately 320 €/m^3. Since the calculated investment cost, as presented in Figure 1 is only a few percentage lower, the equation for the curve shown in Figure 1 is applied for all plants using energy crops and crop residues.

For the biogas plant using manure as feedstock, there will be additional investments for odor control (building, ventilation, filters etc.) and hygienization. The investment cost would therefore be higher. For such biogas plants with a reactor volume of 13–16,000 m^3, the investment cost has been calculated to 400–480 €/m^3 [49]. For comparison, the calculated investment cost for a biogas plant based on manure and with a reactor volume of 32000 m^3 is approximately 470 €/m^3 (Andersson, S. Biogas Sydöstra Skåne AB, personal communication). Given these numbers, the investment cost for large-scale manure based biogas plants could be 50–100% higher per m^3 reactor than biogas plants using crops. In order not to underestimate the investment cost for manure based biogas plants, the investment is calculated with the same method as applied in Figure 1 and then doubled.

The investment costs for covered digestate storage tanks are set to be 30 €/m^3 [50].

For the amine scrubber, with an installed capacity of 1000 m^3/h, the investment cost is set to 2.0 million € including a wood chips boiler [29].

The investment in filling stations is estimated to 830,000 € for a station with an annual capacity of 10 GWh. Thus, the total investment in filling stations is set to 4.2 million € [29].

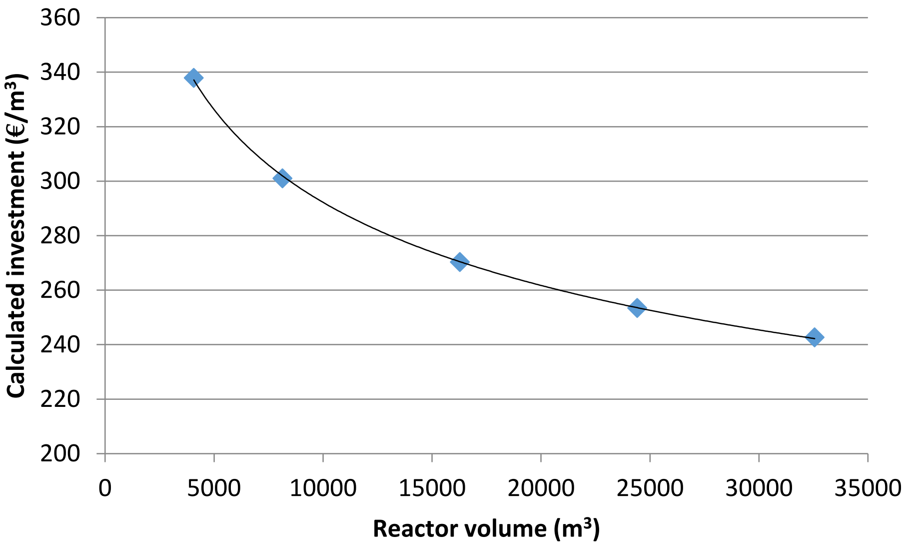

Figure 1. Calculated investment cost.

2.18. Capital cost

The weighted average cost of capital (WACC) is set to 6% and the depreciation period is set to 15 years for all installations [29].

2.19. Process energy

Process heat is produced on site in a wood chip boiler. The cost for wood chips is set to 21 €/MWh based on the average price paid by district heating plants in Sweden in 2014–2016 [51]. Assuming a boiler efficiency of 85% and a cost for operation and maintenance of 1.7 €/MWh [29] the cost for heat is calculated to 26 €/MWh excluding cost of capital (included in the investment cost). Based on the average electricity price in 2015 and 2016 for industries using 2–20 GWh annually, the cost for electricity used in the biogas system is set to 55 €/MWh [52].

2.20. Operation and maintenance

For large-scale biogas plants treating agricultural feedstock, such as energy crops and manure, the costs of operation and maintenance of the biogas plant reported in the literature vary between approximately 5–10% of the investment, corresponding to approximately 5–10 €/t [25,31,53] including personnel, insurance, service and repairs etc. In this study, labor costs for feedstock handling is calculated separately and the costs of operation and maintenance are set to 5% of the investment. For the upgrading, the cost for operation and maintenance, excluding process energy, is set to 3% of the investment [54]. Operation and maintenance of the digestate storages are set to 0.5% of the investment [50].

2.21. Digestate

The economic value of the digestate produced depends on the concentration of nutrients and the cost of alternative fertilizers available to the farmer. Different crops and soil type will also require different fertilization, which affects the economic value of the digestate. Based on discussions with industrial actors in Ireland, Smyth et al. [53] estimate the net value to be 4 €/Mg for digestate from the digestion of grass, not including transport and storage. According to Brown et al. [31], a conservative assumption is that the value of the digestate equals the cost of transport and spreading. In this study, the cost of storage and transport of the digestate is included in the biogas production cost.

The transportation distance is calculated in the same ways as for manure, see Appendix A4, assuming that the biogas plant is in a center of a circle. The size of the circle is calculated based on the average share of arable land in the county of Skåne (41%) and assuming that 30% of the arable land surrounding the biogas plant is fertilized with digestate. The amount digestate spread per hectare will depend on P and TAN content where the maximum amounts added are limited to 22 and 150 kg/ha respectively to comply with Swedish legislation for organic fertilizers [55]. Thus, the transportation distance varies depending of the content of the digestate.

In order to present the impact of the value of the digestate in the overall economic calculation, two values are applied. As a minimum value, it is assumed that the farmer is given the digestate free of charge. As a maximum value, the nutrients in the digestate (N, P and K) are valued as mineral fertilizers with a market price of 1.1, 2.4 and 0.8 €/kg, respectively [38]. This maximum value is, however, reduced by the cost of spreading the digestate. The cost of spreading liquid manure could vary from 1.7 to 3.8 €/Mg depending on how it is spread [56]. Based on this interval, the cost for spreading of digestate is set to 2 €/Mg. Regarding the digestate from manure, P and K are not affected by the biogas process, and digestion gives no added value. Organically bound nitrogen is, however, mineralized to TAN, so TAN concentration is higher in the digestate than in the untreated manure. The value of this additional TAN is used in the calculation of the maximum economic value. Also, the cost of spreading digestate is reduced by the cost that would have been generated by spreading the untreated manure, which is set to 2 €/Mg for liquid manure and 3.5 €/Mg solid manure [56]. Any additional investments that might be required at individual farms in order to deliver manure and receive digestate are not included.

2.22. Distribution and filling stations

The cost for gas grid distribution is set to 8.9 €/MWh and the cost for operation and maintenance of the filling stations is set to 5.6 €/MWh [29].

2.23. Policy instruments

The production and utilization of biogas is affected by a wide range of policy instruments [57]. In Sweden, there are energy and carbon dioxide taxes on fossil fuels from which renewable vehicle fuels such as biogas are exempted as long as the sustainability criteria in the EU RED are met and the biofuel is not overcompensated as compared to the market price of fossil fuels. However, these exemptions are only approved by the European Commission until 2018 for liquid biofuels and 2020 for biogas [58,59]. To meet EU regulation, a reduction quota system has been suggested for low-blend biofuels [60]. It is, however, not yet (June 2017) clear which policy instrument that will be applied for high blend or pure biofuels such as biogas.

In addition to these tax exemptions, there is a production subsidy for biogas from manure which could be as high as 12 €/GJ. However, the subsidy can vary between years, since all producers must share the available funds, which are fixed until the year 2023. It is also possible to apply for different kinds of investment subsidies. However, according to EU regulation, none of these subsidies can be given to biogas plants using energy crops as feedstock [61,62,63]. The potential impact of these subsidies is demonstrated in the sensitivity analysis.

Finally, the calculated biogas production cost is compared to current average market price of compressed biogas (CBG) and natural gas (CNG) as well as gasoline and diesel including the tax exemption applied until 2020. Since there are restrictions in EU regulations regarding the support of biofuels from food crops, the same comparison is also made with full taxes on biogas from these feedstock.

2.24. Vehicle fuel market prices

The market price of vehicle fuels more or less change on a daily basis. The prices presented in Table 5 reflect the situation in 2016, including current policy instruments, at public filling stations. Diesel and CBG/CNG have similar market prices and petrol is approximately 15% more expensive.

Table 5. Market price of diesel, petrol and CBG excl. VAT (€/GJ) [6,29,64].

	Diesel	Petrol	CNG	CBG
Fuel price	12.9	15.3	24.2	30.9
Energy and CO_2-tax	17.0	20.5	6.7	-
Total price	**29.9**	**35.8**	**30.9**	**30.9**

3. Results and Discussion

3.1. Feedstock amounts, reactor dimensions, additives and digestate content

The feedstock requirements to reach a biogas production corresponding to 1000 m^3/h, or 172 TJ/year are shown in Table 6. The result from the dimensioning of the biogas process will apart from the demand for feedstock be a requirement of active reactor volume and in some cases a need for water and additives. The required addition of nutrients reflects the low concentrations of some essential nutrients that are present in some of the crops. The required addition for individual micronutrients can be found in Appendix A3. Apart from biogas, the process will also generate digestate. Calculated amounts, nutrient content and transport distance are also given in Table 6.

Table 6. Resulting process requirements, feedstock and transport demand.

	Wheat grain	Beet	Maize	Triticale	Grass	Wheat Straw	Beet tops	Manure
Process								
Feed-in, wet [Mg/a]	15,200	60,160	60,720	40,010	119,130	23,730	143,540	236,200[1]
Feed-in, DM [Mg/a]	13,070	12,960	15,700	14,130	18,710	21,470	18,270	28,340[2]
Water [Mg/a]	41,270			650		90,350		
Active reactor volume [m^3]	10,200	10,200	10,200	10,200	15,000	14,400	18,100	29,800
Additives [kg/a]								
Fe	450	130	70	410		NA		
N		71,340				190,810		
P						5440		
S		330						
Micronutrient mixture	1600	1600	1600	1600	1600	1600	1600	1600
Digestate								
Amount (t/yr)	45,290	48,980	49,540	29,480	107,950	102,900	132,370	225,000
N-tot (kg/t)[3]	6.0/6.0	2.0/3.4	4.3/4.3	6.0/6.0	5.5/5.5	1.1/3.0	4.6/4.5	4.8/4.7
TAN (kg/t)[3]	4.0/3.9	0.3/1.8	1.9/1.8	2.8/2.8	3.2/3.1	0.0/1.8	3.0/3.0	3.1/3.1
P (kg/t)	1.5	0.3	0.6	0.8	0.6	0.1	0.4	0.9
K (kg/t)	1.6	1.1	1.5	3.6	3.3	2.1	2.2	4.5
Field application [Mg/ha/a]	14.7	76.5	38.6	27.9	36.8	84.7	50.2	24.0
One way transport distance [km]	7.7	3.5	5.0	4.5	7.6	4.9	7.2	6.6[4]

[1] Whereof 64,410 t/a is solid manure

[2] Whereof 12,880 t DM/a from solid manure

[3] Nitrogen concentrations are given both as based on concentration in crop after processing and as concentration after addition (if applicable) and storage loss (1% of N-tot at storage under roof cover [65]).

[4] An amount of digestate corresponding to the delivery of liquid manure (171,770 t/a) is assumed to be delivered back to the farm with the return transport. This transport distance is for the additional 53,230 t/a of digestate for which new storage capacity is built and that is applied at fields in the vicinity of the biogas plant.

3.2. Economy

The calculated cost for production and distribution of biogas, as presented in Table 7, range from 24 to 33 €/GJ, including the full value of the NPK in the digestate and not including any subsidies. Thus, biogas from all feedstock but grass and straw could meet the average market price of 31 €/GJ CBG. Since this is the average market price and the calculated biogas cost is only slightly higher, it might be possible to find local markets where biogas from all feedstock could be competitive. The economical margins for grass, manure, straw and beet tops are however very small or non-existing. The feedstock cost is based on the amount of feedstock required to produce 172 TJ annually and includes the production cost presented in Table 4 and the methane yield given in Table 1. Due to the difference in methane yields, the feedstock cost per MJ of fuel for straw is i.e. only marginal lower than the cost for wheat grain even if the DM-based feedstock cost is much lover for straw.

Table 7. Investment and production cost.

	Wheat grain	Beet	Maize	Triticale	Grass	Straw	Beet tops	Manure
Investment cost (k€)								
Biogas plant	2972	2971	2971	2972	4111	3964	4808	14,618
Digestate storages	1359	1469	1486	884	3239	3087	3971	1597
Upgrading plant	2000	2000	2000	2000	2000	2000	2000	2000
Gas grid injection	100	100	100	100	100	100	100	100
Filling stations	4167	4167	4167	4167	4167	4167	4167	4167
Annual cost (k€)								
Feedstock	2045	2283	2513	2068	2787	1945	2351	1013[1]
Feedstock handling	11	120	121	80	238	18	287	64
Feedstock pre-treatment	14	53	-	-	-	738	-	659
Nutrients and water	45	103	23	24	22	301	22	22
Capital	1091	1102	1104	1042	1402	1371	1549	2315
Electricity	198	200	200	189	230	228	243	202
Heat	125	125	125	125	137	130	162	125
Gas grid distribution	425	425	425	425	425	425	425	425
Operation and maintenance								
Biogas	149	149	149	149	206	198	240	731
Digestate storage	7	7	7	4	16	15	20	8
Upgrading	60	60	60	60	60	60	60	60
Filling stations	265	265	265	265	265	265	265	265
Digestate transport	71	60	67	39	168	138	201	-
Total	**4505**	**4953**	**5059**	**4471**	**5955**	**5832**	**5825**	**5883**
Annual revenue								
Digestate	329	76	129	170	594	192	541	396
Production cost (€/GJ)[2]	24.3	28.4	28.7	25.0	31.2	32.8	30.7	31.9
Production cost (€/GJ)[3]	26.2	28.8	29.4	26.0	34.6	34.6	33.9	34.2

[1] Transport cost only, including return transport of digestate

[2] Including the value of NPK in the digestate

[3] Excluding the value of NPK in the digestate

The economic value of the digestate has different impact in different systems, see Figure 2. In general, the value of the digestate depends on the concentration of nutrients and the amount of nutrients in relation to the amount of biogas produced. For beet, maize and straw the value of the digestate reduces the overall cost with a few percent only, mainly due to the relatively low concentration of nutrients. Notice that the value of the digestate from straw is low even if considerable amounts of N and P has been added for process stability reasons. Without these additives, the digestate would not have any economic value. For grain, grass and beet tops, the value of the digestate reduces the cost with up to 10% due to the higher nutrient amounts. Digestate from *Triticale* has a high concentration of nutrients but because of a high methane potential the total amounts and thus the economic impact is low. Biogas from manure is a special case where not only the increased share of TAN adds to the economic value but also the avoided cost for spreading of solid manure.

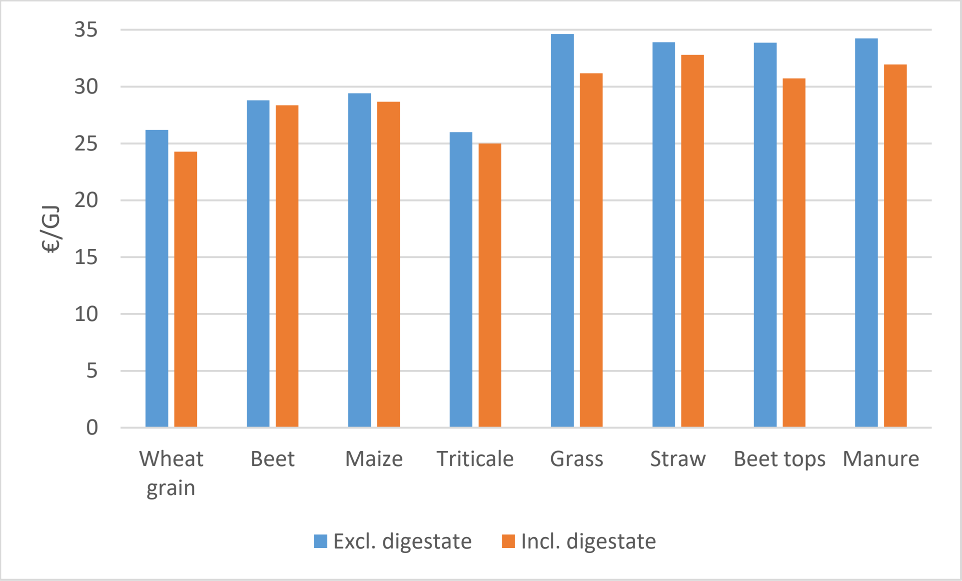

Figure 2. Production and distribution cost for biogas from crops and residues with and without the value of the digestate.

3.3. *Biogas from crops vs residues*

One of the main objectives with this paper is to analyze the difference between biogas systems based on three different kinds of feedstock (crops with an iLUC-factor; grass and residues). The assessment shows that biogas systems based on cereal crops (wheat grain and *Triticale*) results in the lowest cost while crop residues, grass, and manure gives the highest. Considering the overall cost for the biogas systems analyzed here, feedstock and feedstock pre-treatment represents approximately 40–50% of the total cost for production and distribution of upgraded biogas from crops and crop residues and less than 20% for systems based on manure.

However, the overall cost presented in Table 7 include upgrading and distribution of biogas, which, with the system design applied here, is not affected by the choice of feedstock. Considering only costs related to biogas production and digestate handling, the feedstock cost represents an even higher share of the production cost, as seen in Figure 3. The choice of feedstock does however not only affect the feedstock cost as such. The features of the feedstock, such as biodegradability, content of micro- and macronutrients and water also affect the need for additives, reactor dimensions as well as storage, transport and economic value of the digestate. Compared to the cost for the feedstock (including pre-treatment), differences in the need for additives and reactor dimensions etcetera has, however, a relatively small impact. Thus, the feedstock with the lowest cost (including pre-treatment) compared to its methane potential is likely to result in the lowest production cost, see Figure 3. Of the analyzed feedstock, manure partly constitutes an exception to the latter two statements. The feedstock cost per produced methane is low, however, due to the low conversion degree to methane a large volume of inert material is treated, making the cost of capital and the cost for operation and maintenance high. This shows the dual importance of high conversion to methane.

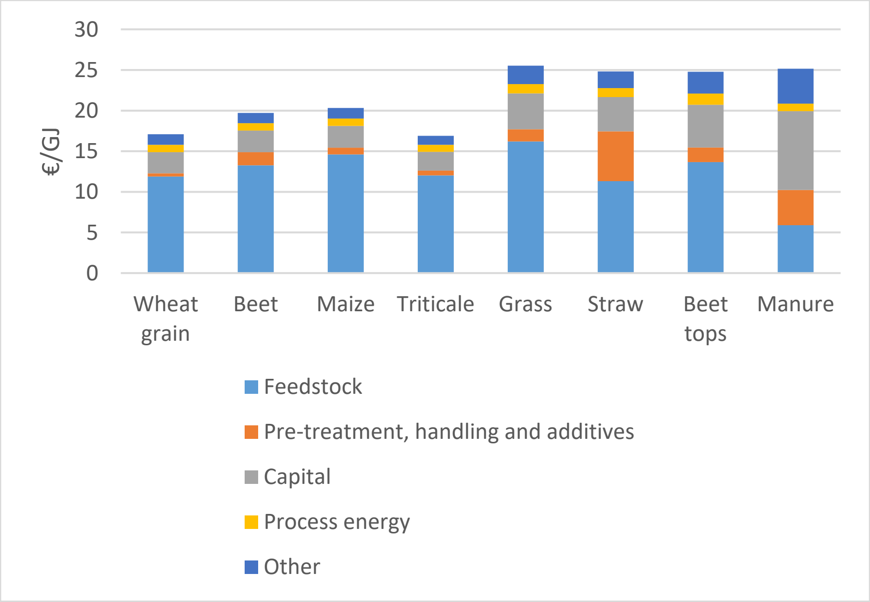

Figure 3. Production cost for biogas from crops and residues excluding upgrading and distribution.

3.4. Uncertainties in calculated production costs

The calculated biogas production cost depends on a number of estimations and assumptions. For the biogas systems analyzed in this paper, the production cost is dominated by the cost of feedstock, capital and in some cases pre-treatment, see Table 7 and Figure 3. For energy crops, the feedstock cost depends on local agricultural conditions, which may vary between different regions but also between different years. However, the feedstock cost is not only related to the actual production cost for the crop but also to the market value for the crop and the farmer's alternative use of land which may vary over time. For crop residues, the cost for handling and storage may also vary depending on local agricultural conditions and transport distance to the biogas plant. For manure, the feedstock cost applied in this study consists of transportation costs only. Thus, changing the transportation distance, the average speed or the loading capacity would have a direct impact on the feedstock cost. If there is need for investments in farm installations, this would also increase the cost. Regarding the cost of capital, this is affected by the investment cost as such, which depends on the specific plant design as well as the current market situation for construction projects of that kind. Also, the cost of capital is affected by the interest and depreciation time applied which e.g. depend on the perceived risk seen by the investor. Therefore, the cost of capital could vary over time but also between different projects. Given these uncertainties, the production cost is calculated for scenarios where the cost of capital and feedstock is changed by ± 50%, see Figure 4 and 5. Although these changes have a high impact on the overall production cost, they do not change the conclusion that biogas from energy crops has a lower production cost than biogas from residues and manure. When biogas is produced from straw and manure, pre-treatment and additives also represents a substantial and relatively uncertain part of the total production cost. Reducing these costs would increase the competitiveness of these feedstocks. However, the cost for pre-treatment and additives must be reduced with more than 75% before biogas from straw have a lower production cost than biogas from wheat grain.

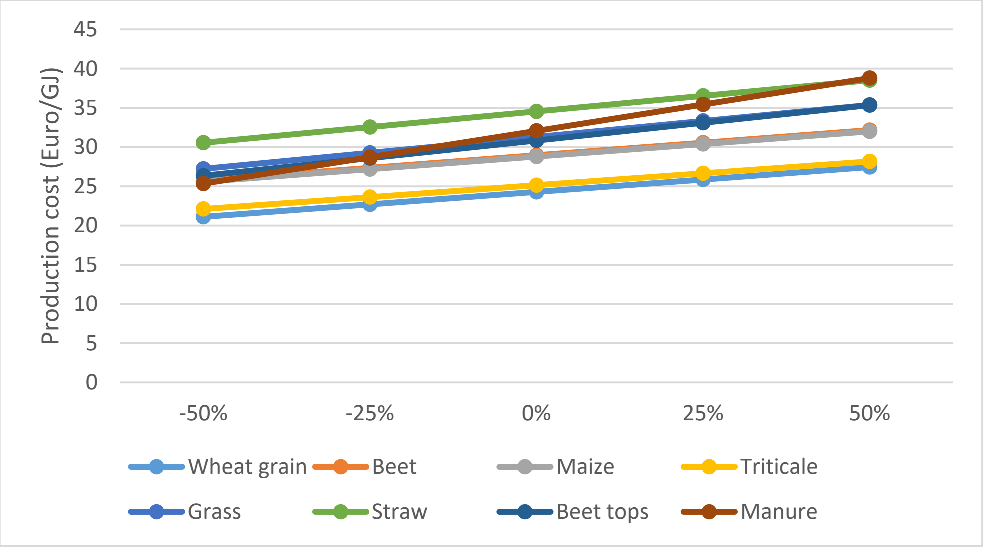

Figure 4. Biogas production cost when capital cost is changed by ±50%.

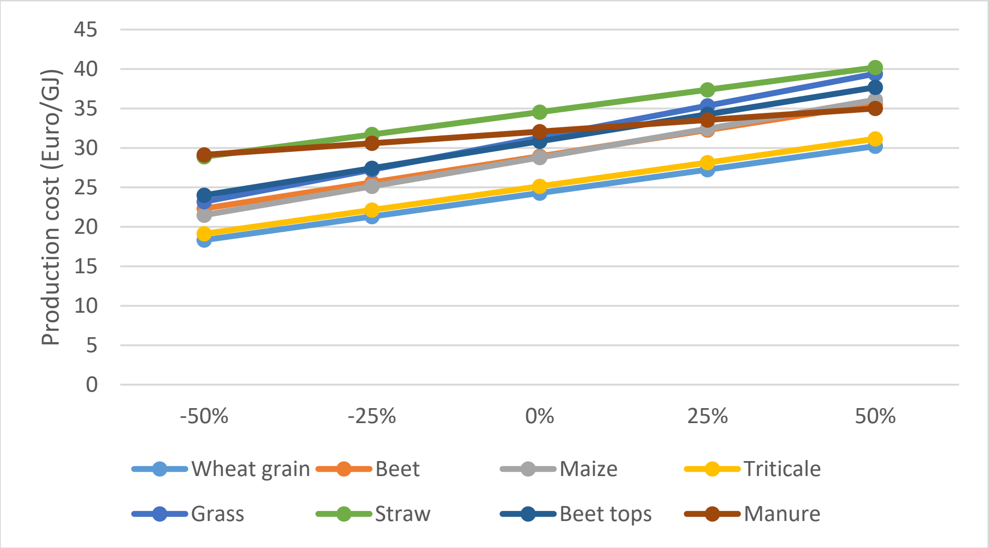

Figure 5. Biogas production cost when feedstock cost is changed by ±50%.

In Table 8, the break-even cost of capital and feedstock is also presented for each biogas system. Since the distribution cost applied in this study is based on a relatively well established market, where each filling station distribute 10 GWh annually, calculations are also made for a scenario where the volume is 5 GWh, representing a less developed market. For biogas produced from wheat grain and *Triticale*, the capital cost could be increased with 41–106% before the production cost equals the current market price. If the feedstock cost is changed instead, the cost could be increased with 29–57%. For biogas from straw, the cost of capital and feedstock must be reduced by 22–41% and 90% respectively to match the current market price.

Table 8. Calculated break-even cost for capital and feedstock with an annual distributed volume of 10 and 5 GWh per filling station.

	Production cost (€/GJ)[1]	Capital cost (k€)		Feedstock cost (€/t DM)	
		Calculated[1]	Break-even	Base case	Break-even[2]
Wheat grain	24.3–26.8	1091–1520	2247	157	245–212
Beet	28.4–30.9	1102–1531	1557	180	215–182
Maize	28.7–31.2	1104–1533	1506	160	186–158
Triticale	25.0–27.5	1042–1471	2074	146	219–189
Grass	31.2–33.7	1402–1830	1373	149	147–125
Straw	32.8–35.3	1371–1800	1063	91	76–56
Beet tops	30.7–33.2	1549–1978	1597	129	131–108
Manure	31.9–34.4	2315–2744	2159	36	30–15

[1] Reducing the distributed volume from 10 GWh to 5 GWh at each filling station increase the annual capital cost with 429 k€ or 2.5 €/GJ.

[2] The interval represents the feedstock cost that results in a total cost for production and distribution of 31 €/GJ depending on the distributed volume at each filling station.

3.5. *Impact of policy instruments*

As mentioned earlier, different policy instruments affect biogas production and utilization. In the following, the impact of current investment and production subsidies as well as the exemption from CO_2- and energy taxes applied in Sweden is presented.

The calculated cost presented in Table 7 and the comparison between crops and residues presented in Figure 2 and 3 does not include any subsidies. Including them would reduce the cost and increase the competitiveness for biogas versus other fuels. Since both the investment subsidy as well as the production subsidy are unavailable for biogas plants using food crops they might also affect the comparison between different biogas systems.

The impact of an investment subsidy on the cost for production and distribution of biogas is presented in Figure 6. The investment subsidy is set to 30% of the total investment for all biogas systems analyzed but the ones using wheat grain, *Triticale*, maize and beet. For these systems, only filling stations are subsidized.

These assumptions reduce the difference between crops and residues, although straw and grass still give the highest cost and wheat grain the lowest. Since the cost of capital represents a high share of the total cost for biogas from manure, this is the feedstock where an investment subsidy has the highest impact. However, the production subsidy for biogas from manure could have an even higher impact. Including a production subsidy of 6 €/GJ (50% of the maximum subsidy) instead of an investment subsidy gives an overall cost of 26 €/GJ. In that case, biogas from manure would be the biofuel with the lowest cost excluding biogas from wheat grain and *Triticale*.

In general, biogas from straw, grass and beet tops is not economically competitive to biogas from crops such as wheat grain and *Triticale*, even if investment subsidies are included. Compared to current market prices of fossil fuels, all biogas systems also seems to be competitive, some with very small margins, if investment subsidies are included, see Figure 7.

Implementing these investment subsidies at the same time as biogas from food crops is burdened with the same energy- and CO_2-taxes as natural gas used as a vehicle fuel, biogas from beet tops and manure would have the lowest cost. With the feedstock cost applied in this study, biogas from wheat grain would, however, still be competitive as compared to fossil fuels. Since wheat grain is easier and cheaper to transport than the other feedstock analyzed here, these result could also be more generally applicable.

It should, however, be pointed out that the conditions described in this paper are not representative of Sweden in general. The conditions for producing crops and collect crop residues are likely more favorable than in many other parts of the country. Also, the availability of manure is high in the region analyzed here. The biogas volumes sold on each filling station is also higher than current average representing a more developed biogas market.

Since the difference between the calculated cost and current market price is relatively small, especially for residues, small changes in the assumptions made here might also change the conclusion that biogas can compete with fossil fuels from an economic point of view. Due to this uncertainty, long term and clearly defined policy instruments will be necessary for actors to invest in the kind of biogas systems analyzed here.

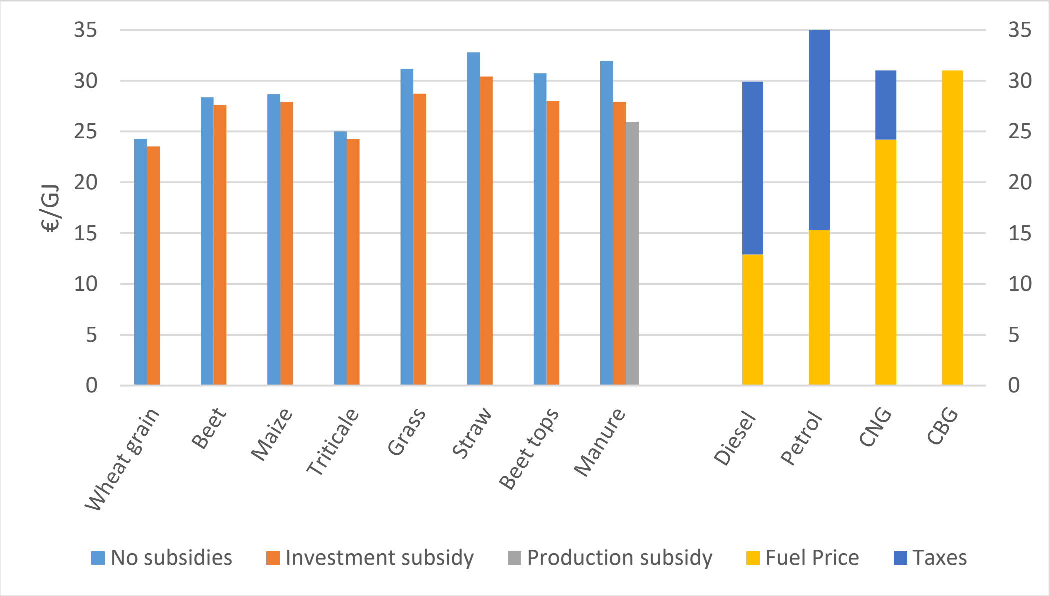

Figure 6. Production cost for biogas from crops and residues with and without subsidies and compared to current market prices of vehicle fuels.

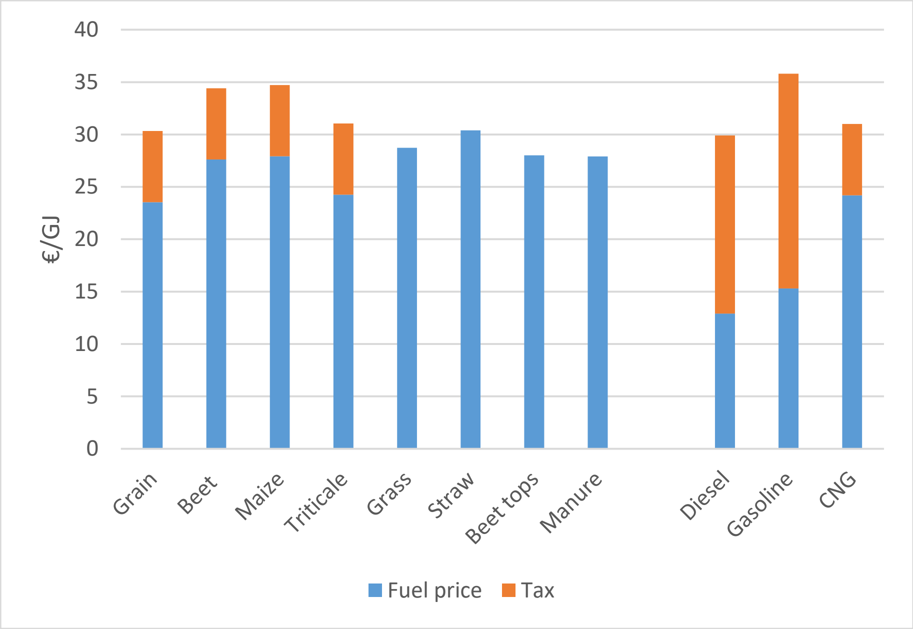

Figure 7. Calculated production cost for biogas including investment subsidies and full CO_2- and energy tax for biogas from food crops compared to current market prices of fossil vehicle fuels.

4. Conclusions

When producing biogas from crops or residues, the choice of feedstock has a high impact on the overall cost for production and distribution.

Biogas from *Triticale* and wheat grain can be competitive to fossil fuels even without subsidies. However, EU directives set out goals to favor the production of biofuels from waste and residues to that from dedicated energy crops. Without investment and production subsidies, biogas from grass, crop residues and manure is more expensive than biogas from several food crops. Even with current subsidies biogas from wheat grain and *Triticale* are economically more competitive than biogas from grass, wheat straw and beet tops. A shift from food crops to residues as biofuel feedstock, as desired according to EU directives, would thus require additional policy instruments favoring biogas from residues. Current production subsidy for biogas from manure could, however, make manure the most interesting feedstock from an economic point of view.

An alternative or complementary approach could be to keep the current tax exemption for energy and CO_2-taxes for biogas based on desired feedstock and not for biogas from crops. Even with this action, biogas from food crops could be more or less competitive to residues. This policy alone would also result in very small or non-existing economical margins for biogas production from all analyzed feedstocks.

The reason to produce biofuels is to reduce different kinds of environmental impact. In this case, the main objective is to replace fossil vehicle fuels with biofuels that give large GHG emission reduction. When different policy instruments are discussed, it is important to keep this in mind. Given the policy instruments implemented today, biogas from both food crops and crop residues could, in some cases, compete with fossil fuels from an economic point of view. These instruments are, however, only implemented for a few more years and investments in biogas systems require a longer time perspective. Thus, strong and long-term policy signals are required if a future increase in production of biogas as an advanced biofuel is desired.

Acknowledgements

The funding from the Swedish Research Council Formas for the interdisciplinary research project Crops 4 Biogas (Resource efficient production of renewable energy carriers from energy crops) is gratefully acknowledged. We thank our co-workers in that project for interesting and fruitful discussions.

Conflict of Interest

All authors declared that, there is no conflict of interest in this paper.

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