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Optimised biogas production from the co-digestion of sugar beet with pig slurry: integrating energy, GHG and economic accounting

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Abstract

Several countries have established a number of increased targets for energy production from renewable sources. Biogas production, which will play a key role in future energy systems largely based on renewable sources, is expected to grow significantly in the next few decades. To achieve these ambitious targets, the biogas production chain has to be optimised to obtain economic viability and environmental sustainability while making use of a diversified range of feedstock materials, including agricultural residues, agro-industrial residues and, to some extent, dedicated energy crops. In this study, we integrated energetic, GHG and economic analysis to optimise biogas production from the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). We found that utilising SB as a co-substrate improves the energy and GHG balances, mostly because of increased energy production. However, utilising SB negatively affects the profitability of biogas production, because of the increased costs involved in feedstock supply. The scale of the processing plant is neutral in terms of profitability when SB is added. The results indicate that medium- to large-sized biogas plants, using low shares of SB co-substrate, may be the preferred solution.

Keywords: mass balance, value chain analysis, economy of scale, silage, transport costs.

Abbreviations:

AD: anaerobic digestion
BMP: biochemical methane potential
CHP: combined heat and power
CSTR: continuous stirred tank reactor
EF: emission factor
GHG: greenhouse gases
HRT: hydraulic retention time
PS: pig slurry
SB: sugar beet pulp silage
TC: total cost
TI: total income
TNI: total net income
TS: total solids
VS: volatile solids
VS_D: degradable volatile solids
VS_{ND}: non-degradable volatile solids
ww: wet weight

1. Introduction

Anaerobic digestion (AD) is one of the most efficient technologies for extracting clean and renewable energy from biomass with high water content [1]. In addition, AD is useful for recycling nitrogen (N) and phosphorus (P) from animal manure, which is in great need worldwide [2,3], and it is also considered to be the most effective technology for reducing greenhouse gas (GHG) emissions from manure management and at a low cost [4,5]. AD is fully integrated into Denmark's long-term strategy to be independent of fossil fuels before 2050 [6,7]. In accordance with this strategy, 50% of all animal slurry must be used in AD by 2020 [8], and 60% of organic waste from public services (up from the current level of 17%) will be collected and utilised for biogas production by 2018 [9]. In 2050, biogas plants are expected to be processing about 42 PJ of biomass, corresponding to >7% of all energy input for Denmark, while 16-22% of all biomass will be routed to energy production [10].

The AD of animal manure is in focus for two reasons: 1) large amounts of manure are available in Denmark [11] and 2) it allows for the better management of N and P nutrients at the regional level. In Denmark, manure is currently collected in the form of slurry, with a water content of about 95% and an organic matter content of ca. 4% [12]. Owing to this high water content, manure can only be used at the present time for biogas production, though hydrothermal liquefaction may represent an alternative to anaerobic biogas production in the future. Manure has a low biogas production potential [13], meaning that its digestion needs to be boosted by a more energetic co-substrate [14]. Suitable co-substrates include other agricultural residues, organic industrial by-products (e.g. from the food industry) and dedicated bioenergy crops.

The amounts of biogas to be produced and the portfolio of biomass materials to be used represent important logistical and management challenges, the combination of which hinders environmentally sustainable and economic viable biogas production in the country. Environmental and energetic issues related to biogas production are depicted rather comprehensively in the available literature, focusing for example on the digestion and/or co-digestion of manure (e.g. Hamelin et al. [15]; De Vries et al. [16]; Lansche & Mueller [17]), municipal organic waste (e.g. Møller et al. [18]; Bernstad et al. [19]; Boldrin et al. [20]; Levis & Barlaz [21]), industrial co-products (e.g. Berglund & Börjesson [22]; Tufvesson et al. [23]), sewage sludge (e.g. Tarantini et al. [24]; Lederer & Rechberger [25]; Nakakubo et al. [26]), energy crops and/or cropping systems (Amon et al. [27]; Gerin et al. [28]; Jury et al. [29]; Schumacher et al. [30]; Blengini et al. [31]; Buratti et al. [32]; González-García et al. [33]). These studies indicate that biogas production from residual biomass is generally environmentally beneficial, but the modelling of biogas from energy crops somehow seems more complex, as it must consider carefully local conditions regarding crop cultivation and the supply chain [34]. The economic viability and optimisation of biogas production has also been investigated in a number of studies (e.g. Walla & Schneeberger [35]; Power & Murphy [36]; Gebrezgabher et al. [37]; Karellas et al. [38]; Stürmer et al. [39]; Brown et al. [40]; Delzeit & Kellner [41]; Møller & Martinsen [42]; Riva et al. [43]; Schievano et al. [44]), indicating that the profitability of biogas production is generally related to factors such as the plant size, the cost of feedstock, initial investment, costs for storage and transportation and biogas yield.

The integration of environmental and economic assessments was only attempted in a few cases. Most of these studies – e.g. Murphy et al. [45], Ayoub et al. [46], Ayoub et al. [47], Luo et al. [48], Santibanez-Aguilar et al. [49], Hennig & Gawor [50] –, however, focus on the use of dedicated energy crops and their conversion in complex and centralised biorefinery systems used for fuel production. Biogas production from residual materials is investigated, for example, in Yabe [51]. These studies nonetheless are static in nature, as the assessments are carried out at the scenario level. When looking at the co-digestion of residual biomass and energy crops, no studies were found to have attempted to optimise biogas production by dynamically modelling individual sub-parts of the biogas chain.

Therefore, the objective of the study presented herein is to develop a joint value-chain, energy and environmental model, to be used for optimising biogas chain production. This model is meant to provide advice to managers and decision makers in the form of a holistic evaluation of risks and benefits in producing biogas using sugar beet pulp silage (SB). This objective is achieved by 1) developing detailed economic, GHG

emission, energy and mass models for the biogas chain, 2) integrating these models into a single framework capable of describing the relationships between economy, energy and emissions, while taking into consideration scaling effects, 3) applying the model to optimise the use of beet roots in manure co-digestion and 4) identifying the optimal scale of the biogas plant.

2. Materials and Methods

2.1. The biogas production chain

As shown in Figure 1, the biogas production chain assessed herein consists of five main process units, including:

- Raw material input: cultivation and harvesting stages
- Pre-treatment: washing, slicing and ensiling
- Transportation: transportation to the biogas plant and transportation to the farm
- Energy production: mixing tank, anaerobic digester, post-digestion plant and combined-heat-and-power (CHP) plant or gas upgrade for the gas transmission net
- Digestate process and fertiliser unit: after-storage and field stages

Sugar beet is first cultivated and then harvested between September and mid- or late November [52]. While harvesting, the root is separated from the beet top and left on the field. Beet roots carry a significant amount of soil, and so a cleaning step is thus required. Cleaning is normally performed at the farm level, but centralised cleaning can occur in some cases. The soil removed from the root is returned to the field. Sugar beets harvested in November are then stored in clamps covered with straw [52]. In February, the roots are chopped finely into beet pulp and moved into silos for 18 months (i.e. until September next year). Ensiling leads to the degradation of some organic pools, so that total solids (TS) and volatile solids (VS) contents change, while GHG are emitted. When needed, SB is collected and then mixed with pig slurry (PS) to a known ratio, and the mixture is then pumped into an AD reactor. PS is the main substrate, whereas SB is the co-substrate providing different benefits to the process: it contains abundant trace elements for microbial growth, it has a strong buffer capacity, thereby helping to maintain pH neutrality, and it is a good diluter for toxic compounds potentially contained in the manure. In the present study, the co-digestion of three mass-based ratios of PS and SB in the feedstock is analysed:

- PSSB-0: 100% PS, 0% SB
- PSSB-12.5: 87.5% PS, 12.5% SB
- PSSB-25: 75% PS, 25% SB

The additional use of SB (i.e. a 50/50 ratio) was attempted in preliminary tests; however, the anaerobic digestion operation was unstable with the accumulation of VFAs and a drop in pH level.

The main product of the digestion process is biogas (i.e. a mix of CO₂, CH₄ and other trace gases), which can be used for electricity and/or heat production, or fed to the natural gas grid. Depending on the final recipient and the energy conversion technology employed, biogas may need to be upgraded to remove most of its CO₂ and other trace compounds. The by-product of the digestion process is a type of slurry called “digestate,” which is typically partly dewatered and further stabilised by means of aerobic composting. The finally cured digestate may be stored further until its final application to agricultural land as a fertiliser and soil amendment agent. The calculations herein considered a field-application scenario where digestate is applied in early spring, prior to seeding a spring cereal crop.

In the biogas production chain, the economy of scale can be a significant factor affecting the profitability of a project. In fact, while production costs per unit of biomass handled may be reduced in large facilities, transportation costs may increase significantly, due to the larger size of the catchment area for the biomass. To assess the scale effect, economic analysis was thus performed on three facilities: small (i.e. using 110,000 Mg of biomass per year), medium (i.e. 320,000 Mg/year) and large (i.e. 500,000 Mg/year). The size of the plant is assumed not to have an effect on mass and energy balances.

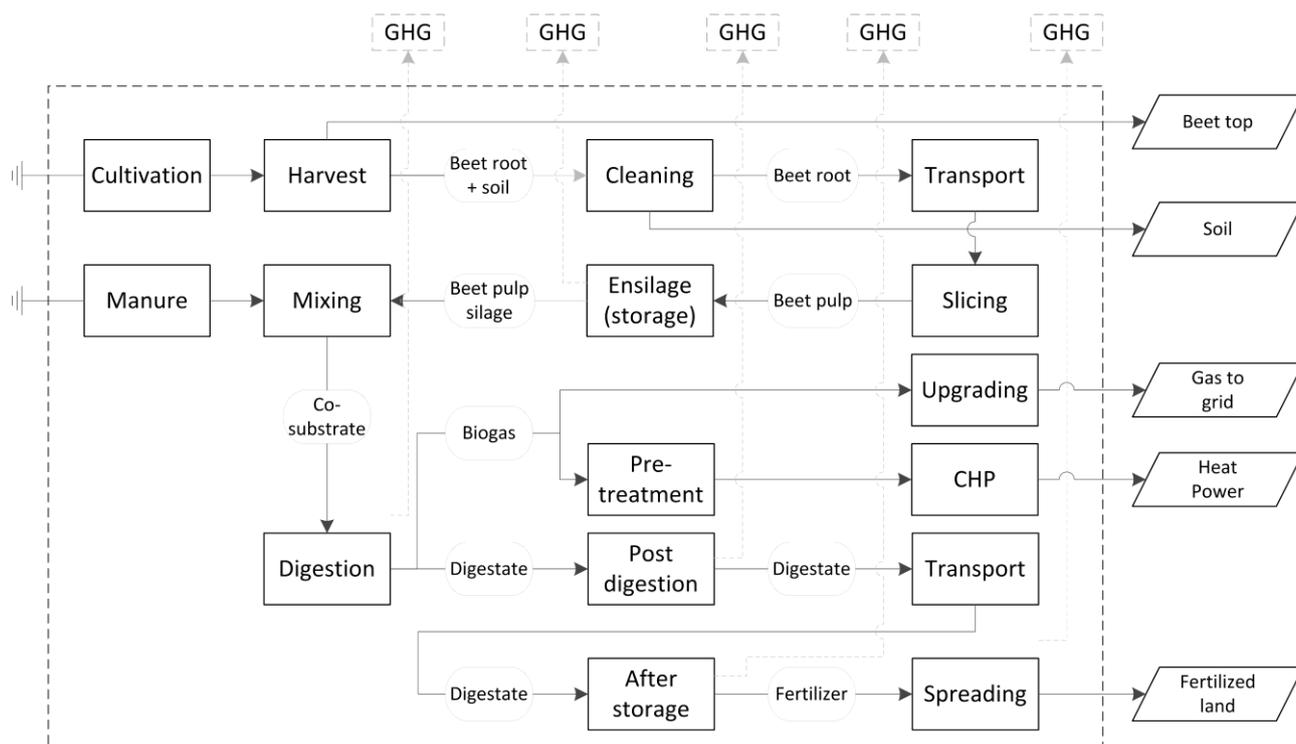


Figure 1 – Overview of the biogas chain model.

2.2. The mass balance model

We based mass balance calculations on both the literature and experimental data. Input and outputs from individual processes in the biogas chain were modelled by tracking digestible (VS_D) and non-digestible (VS_{ND}) components of VS. In the model, we defined lignin as VS_{ND} , as it is non-degradable in an anaerobic environment [13]. The remaining VS (i.e. total VS minus lignin) was defined as VS_D . The basis for the mass balance calculation was 1000 kg of feedstock fed into a biogas digester. The mass balance model included stages shown in Figure 1, as explained in the previous section. We reconciled and displayed mass and energy balances using STAN, a software package used for material and substance flow analysis [53].

For the harvested sugar beet, we used data from Schoups et al. [54] and Thalbitzer [55], to determine mass distribution into roots, tops and soil. Harvested beet root accounted for 70.7% of the total mass, whereas beet tops were 25.6% and soil 3.8%. The total solids (TS) in the root were 226 g/kg, and VS was 208 g/kg. While the top is removed, the root and attached soil are moved further on to the cleaning step. The amount of soil left after the wet washing step was assumed to be 2.1% of TS. Since soil contains mostly ash (85% in TS), the VS concentration is slightly lower than the case where the root is without soil.

We assumed the pulping process would involve no mass loss, and we modelled the storage process for the beet root as employing two sub-processes, both responsible for significant VS degradation (i.e. ~28% and 12% respectively, Table S2 in supporting information) and any subsequent decrease in biogas production during AD. For the sake of simplicity, the two storage sub-processes were represented by one overall storage process in the mass balance model.

We experimentally measured the composition of SB and PS, as well as biogas production data during AD from different sources (details provided in the supporting information). We carried out physicochemical analysis of PS and SB according to the standard procedure (APHA standard method [56], see supporting information), and we determined biochemical methane potential (BMP) according to VDI 4630 (2006). We also investigated the AD of different feedstock mixes using a 20 litre continuous flow stirred-tank reactor (CSTR) in a mesophilic condition (37°C), with a hydraulic retention time (HRT) of 20 days. Data for the

individual co-digestion mixing ratios are presented in Table 1, where it is evident that contributions of VS from SB and PS are considerably different for the analysed scenarios. For example, in the PSSB-25 scenario, 58% of VS is from SB while 42% is from PS, while approximately 63 and 37% of VS originates from SB and PS, respectively, in the PSSB-12.5 ratio. The prime feedstock (i.e. PS) had biochemical methane potentials (BMP) of 296 NL_{CH4}/kg_{VS} (9.42 NL_{CH4}/kg_{ww}). The BMP of SB was 424 NL_{CH4} kg/kg_{VS} (54.8 NL_{CH4}/kg_{ww}). During CSTR experiments, 43.4-55.9% of VS was transformed into biogas (supporting information, Table S5). When only PS was digested, CH₄ production was 9.10 CH₄NL/kg_{ww}, while CH₄ productions from the PS and SB mixtures were 12.3 NL_{CH4}/kg_{ww} and 18.0 NL_{CH4}/kg_{ww} for PSSB-12.5 and PSSB-25, respectively. Using the equation provided by Sommer et al. [4], methane emissions post-storage were estimated at 0.30–1.99 NL_{CH4}/kg_{ww}. Additional details are provided in the supporting information.

Table 1 - Composition of co-feedstock and biochemical methane potentials (BMP) for biogas production at different co-digestion mixing ratio scenarios.

Parameter	Unit	PSSB-0			PSSB-12.5			PSSB-25		
		PS	PS	BS	Co-feed	PS	BS	Co-feed		
Wet mass	g	1,000	875	125	1,000	750	250	1,000		
TS	g	37.7	33.0	22.4	55.4	28.3	44.9	73.2		
	% ww	3.8	3.8	17.9	5.5	3.8	17.9	7.3		
Water	g	962	842	103	945	722	205	927		
	% ww	96.2	96.2	82.1	94.5	96.2	82.1	92.7		
VS	g	31.8	27.8	16.2	44.0	23.9	32.3	56.2		
	% TS	84.4	84.4	72.0	79.4	84.4	72.0	76.8		
Ash	g	5.9	5.2	6.3	11.4	4.4	12.5	17.0		
	% TS	15.6	15.6	28.0	0.0	15.6	28.0	0.0		
VS Pools										
VS _D	g	28.2	24.7	13.8	38.5	21.1	27.6	48.7		
	% VS	88.6	88.6	85.3	86.7	88.6	85.3	86.7		
VS _{ND}	g	3.6	3.2	2.4	5.5	2.7	4.8	7.5		
	% VS	11.4	11.4	14.7	13.3	11.4	14.7	13.3		
Biogas potential										
BMP	NL _{CH4} /kg _{VS}	296	296	424	342	296	424	370		
	NL _{CH4} /kg _{ww}	9.4	9.4	54.8	15.1	9.4	54.8	20.8		

PS: pig slurry; SB: sugar beet pulp silage ; VS_D: degradable VS; VS_{ND}: non-degradable VS; ww: wet weight; TS: total solids; VS: volatile solids; BMP: biochemical methane potential.

2.3. The energy balance model

For individual flows of materials in the system, we assumed an energy content (H_{aw}, ash- and water-free) of 20.5 MJ/kg_{VS} and 26.6 MJ/kg_{VS} for the VS_D and VS_{ND} respectively. As specific data for VS_D and VS_{ND} does not exist, we derived these values through data reconciliation, in order to fit the energy balance with respect to the energy content of the inputs, outputs and biogas production. These estimated values are in accordance with data reported for cellulose/hemicellulose and lignin materials. Energy related to the cultivation and harvesting of sugar beet was 0.334 MJ/kg, taken as cumulative energy demand for the Ecoinvent (v2.2) process 'Sugar beet, from farm'. We assumed the production of PS as being burden-free, meaning that energy and material consumptions utilised for animal growth were excluded from the calculation.

For transportation, we based diesel consumption on estimated driven distances (see later) and assumed a consumption factor of 0.02645 l/tkm (Ecoinvent process 'Transport, lorry >32t, EURO5'). For the energy balance, we assumed that diesel has an energy content of 43.1 MJ/kg, a density of 0.832 Mg/m³ and a cumulative primary energy content of 54.8 MJ/kg (Ecoinvent process 'Diesel, low-sulphur, at regional storage'). We estimated energy consumption during ensilage at 150 MJ/Mg and 6.7 MJ/Mg, based on Ecoinvent processes 'Baling/CH' and 'Loading bales/CH', respectively, and assumed that each bale contained

~1.3 Mg of beet root. The spreading of digestate on land requires 0.26 L/m³ of diesel (Ecoinvent process 'Slurry spreading, by vacuum tanker').

We estimated electricity consumption for operating the biogas plant at 30 MJ/Mg [22], while the energy requirement for heating up the feedstock was estimated at 121 MJ/m³ of slurry (or 1800 MJ/Mg_{TS}). For the estimation, we assumed that the average temperature of the inlet material was $T_{in}=8^{\circ}\text{C}$ and that the slurry had a density and specific heat similar to water (i.e. 1000 kg/m³ and 4.19 kJ/kg/K); additional details are provided in the supporting information. The biogas produced is combusted in an engine (i.e. Jenbacher 420), with conversion efficiencies of 40 and 42% for electricity and heat, respectively [57]. Part of the produced energy is used for operating the plant, while the surplus of electricity and heat is delivered, respectively, to the electricity network and district heating facilities. For electricity, cumulative primary energy was assumed at 2.47 MJ/MJ_{electricity}, as in ELCD process 'Electricity mix, AC, consumption mix, at consumer, 1kV-60kV DK'. For heat, cumulative primary energy was assumed at 1.55 MJ/MJ_{heat}, as reported by the Danish Energy Agency [58].

2.4. The GHG model

We established the GHG balance using the conversion factors for diesel combustion, electricity and heat (reported in Table 2) applied to the individual energy inputs described previously. The loss of biogas due to fugitive emissions from the plant is rather uncertain, as very few measurement studies at full-scale plants have been conducted so far. In the present study, we assumed that the fugitive emission of CH₄ corresponds to 3.1% of the CH₄ production in the biogas plant, as estimated by Flesch et al. [59] for an agricultural biodigester, including storage of the digestate.

We predicted the short-term emission of N₂O using the N₂O sub-model developed by Sommer et al. [4], which considers N₂O emission to be a function of VS in slurry or digestate, reactive slurry nitrogen (N) and soil water potential (ψ). As explained in the supporting information, the model makes use of the VS_D and VS_{ND} introduced in section 2.3. For model calculations of N₂O emissions, we assumed an application rate of 100 kg NH₄⁺-N/ha. Following Sommer et al. [4], the nitrification of reactive N in slurry hotspots was assigned an N₂O emission factor (EF) of 0.5%, and the nitrification of N from digestate or slurry in the surrounding soil was allocated an EF of 0.2%. We calculated total denitrification in the slurry clumps as a function of VS_D in the hotspot, and the resulting N₂O emission was estimated by assuming an EF of 2%. Total N₂O emissions produced by nitrification in clumps and soil, and by denitrification in clumps, were expressed on an area basis but also relative to slurry/digestate VS. The calculation considered a field-application scenario where slurry/digestate is applied in early spring, prior to seeding a spring cereal crop. We assumed an NH₃ loss of 10% during application, and soil-water potential was set to -0.015 MPa, i.e. close to field capacity.

We estimated VS_D in digestate and untreated feedstock from the short-term evolution of CO₂-C after incubating slurry/digestate in soil under aerobic conditions. We assumed that VS_D in applied materials would be fully degraded when CO₂ evolution rates became constant. The six incubation tests included three samples of digested material, two samples of raw feedstock and one control (i.e. only soil); each test included five replicates. The digestate samples were produced in CSTR experiments, as explained in section 2.2. The three samples of digestate corresponded to feedstock mixtures previously described (i.e. PSSB-0, PSSB-12.5, PSSB-25), while the two samples of raw feedstock included undigested PS and SB. The main physicochemical properties of the materials used for the incubation tests are reported in the supporting information (Table S3 and S8), together with a description of the experimental setup (Table S7), the gas sampling procedure, the data analysis and the estimation of N₂O emissions for the analysed scenarios (Table S9 and Table S10).

We converted the emissions of different gases to CO₂-equivalent emissions, by using the following 100-year global warming potentials (GWPs): 1 kg CO₂eq/kg CO₂ for fossil CO₂, 28 kg CO₂eq/kg CH₄ for biogenic CH₄, 30 kg CO₂eq/kg CH₄ for fossil CH₄, 265 kg CO₂eq/kg N₂O for N₂O (according to IPCC [60]) and 0 kg CO₂eq/kg CO₂ for biogenic CO₂ [61].

Table 2 – Emissions factors for energy inputs to the biogas chain.

Process	Unit	Amount	Note, reference
Diesel combustion	kg CO2-eq/liter	3.1	Provision + combustion (Fruergaard et al., 2009)
Electricity production	kg CO2-eq /kWh	0.95	Hard coal, NORDEL (Fruergaard et al., 2009)
Heat production	kg CO2-eq/GJ	72	District heating, natural gas (Fruergaard et al., 2009)

2.5. The economic model

In the following, the economic model is described briefly, while additional details are provided in supporting information. The objective of the economic model was to determine the total net income (TNI) of different scenarios, where we define the $TNI(p_k, M_j, M_k, r_j, j, k)$ as (Equation 1):

$$TNI(p_k, M_j, M_k, r_j, j, k) = TI(p_k, M_k) - TC(M_j, M_k, j, k) \quad (\text{Equation 1})$$

where $TI(p_k, M_k)$ is the total income as a function of the price p_k of output k and the mass M_k of output k ; $TC(M_j, M_k)$ is the total cost as a function of the mass M_j of biomass j and the mass M_k of output k and the index j and k are objects of the set J of input biomass (i.e. PS and SB) and the set K of output (i.e. digestate, biogas), respectively.

2.5.1. Income

Total income $TI(p_k, M_k)$ is the sum of the prices paid for the different outputs and is defined as (Equation 2):

$$TI(p_k, M_k) = \sum_{k \in K} p_k M_k \quad (\text{Equation 2})$$

where M_k is the mass of output k (i.e. digestate, M_{dig} , biogas, M_{gas}) and p_k is the price of output k .

The factor M_k is a function of the process yield, which is in turn a function of different operational parameters, such as feedstock composition and HRT in the process, as explained and estimated in section 2.2. We estimated the prices p_k of the digestate (p_{dig}) and biogas (p_{gas}) based on market considerations. In an agricultural context, digestate has some value because of its fertilising potential and reduced smell in the area. The p_{dig} depends on the specific supplier agreement between the operator of the biogas plant and farmers, thereby including the requirement of the farmer to dispose of the PS.

We estimated p_{gas} in Denmark based on the final use of the biogas and the level of public support. We considered the following two options:

- Biogas is upgraded and fed to the natural gas network.
- Biogas is used locally in a combined heat and power (CHP) plant.

When biogas production exceeds a specific amount, hereby estimated as 3.5 million m³ per year, it was calculated that biogas was upgraded and fed into the natural gas grid. In this case (Equation 3), the selling price of the biogas ($p_{gas,UP}$) is determined by the market price for the natural gas (p^{NG}), the support level (S) and a potential green factor (p^g), corresponding to the market price for "being green", determined from sales of green certificates.

$$p_{gas,UP} = p^{NG} + p^g + S \quad (\text{Equation 3})$$

When biogas is used at a CHP plant, its price ($p_{gas,CHP}$) is a combination of the price of biogas as such and a market power value, as shown in (Equation 4):

$$p_{gas,CHP} = p(p_{NG}, S, p_{HP}) - p_{MP} \quad (\text{Equation 4})$$

where p_{NG} is the price of natural gas, S is the level of public support given to the CHP, p_{HP} is the price of heat and power generated and sold to the market and p_{MP} is the market power value, which depends on the structure of the power market (e.g. user and supplier are monopolist, or alternative supply/production options exist).

2.5.2. Costs

From the biogas plant perspective, total cost $TC(M_j, M_k)$ is expressed as (Equation 5):

$$TC(M_j, M_k) = C_{trans}(M_j, M_k, GP_k) + C_{opex}(M_j, M_{gas,UP}) + C_{capex}(M_j, M_k) \quad (\text{Equation 5})$$

where $C_{trans}(M_j, M_k, GP_k)$ is the transport cost, $C_{opex}(M_j, M_{gas,UP})$ is the operational cost and $C_{capex}(M_j, M_k)$ is the cost of investments. The C_{trans} is a combination of the costs borne for transporting PS and SB to the AD plant, as well as the costs for transporting digestate and biogas away from the plant, as shown in Equation 6.

$$C_{trans}(M_j, M_k, GP_k) = C_{trans,in}(M_j) + C_{trans,out}(M_{man}, M_k, GP_k) \quad (\text{Equation 6})$$

where $C_{trans,in}$ represents the cost of transporting the PS/SB to the AD plant and $C_{trans,out}$ is the cost related to the transportation of digestate and biogas away from the AD plant.

The size of the plant will hence influence transportation costs significantly, as a larger plant will involve longer driving distances, to ensure the supply of the required biomass. To estimate transportation distances according to the size of the plant, the supply area was modelled using concentric circles around the biogas plant, whereby availability and supply cost of PS/SB could be estimated as a function of the radius (i.e. the distance from the plant). With respect to digestate transportation, it was considered that a share of the digestate could be transported back to the some farmers delivering PS. The maximum amount that could be returned to individual farmers was set to 115% of the PS they delivered; any excess sludge would involve additional costs for its transportation to other farmers. A detailed description of the calculation is provided in the supporting information.

Operational expenditures C_{opex} for the biogas plant are estimated as follows (Equation 7):

$$C_{opex}(M_j, M_{gas,UP}) = C_{opex,input}(M_j) + C_{opex,oper}(M_j, M_{gas,UP}) \quad (\text{Equation 7})$$

where $C_{opex,input}$ represents the cost of buying PS/SB beet according to the market prices and $C_{opex,oper}$ is cost related to operating the biogas plant, including the following factors (Equation 8):

$$C_{opex,oper}(M_j, M_{gas,UP}) = C_{basis}(\sum_{j \in J} M_j) + (C_{wear} + C_{pow} + C_{man}) \cdot M_{sug} + C_{opex,UP}(p_{pow}, M_{gas,UP}) \quad (\text{Equation 8})$$

where C_{basis} is the basis cost of a biogas plant with size $\sum_{j \in J} M_j$, C_{wear} is the cost of wear per Mg of SB, C_{pow} is the cost of power per Mg of SB, C_{man} is the cost of manpower per Mg of extra SB and M_{sug} is the total mass of SB. $C_{opex,UP}$ is the cost for biogas upgrading, which is a function of the amount of biogas upgraded ($M_{gas,UP}$) and the price of power (p_{pow}).

Investment costs (C_{capex}) depend on investments related cost-wise to input, production and output. As in this model it is assumed that all transportation is rented (i.e. no investment costs for trucks and other), and the C_{capex} is defined as (Equation 9):

$$C_{capex}(M_j, M_k) = C_{capex,prod}(M_j) + C_{capex,output}(M_j, M_k) \quad (\text{Equation 9})$$

where $C_{capex,prod}$ is the investment cost for production, including the biogas plant, the process heat boiler, the purchase of land, counselling and other elements, and $C_{capex,output}$ is the investment cost for output, including the storage of digestate, the storage of biogas and the biogas cleaning/upgrading facility. The depreciation time for the biogas facility is assumed being 20 years, as recommended by Ea Energianalise to the Danish Energy Agency [62].

3. Results and Discussion

3.1. Mass and energy balance

We reconciled mass balances for the PSSB-0, PSSB-12.5 and PSSB-25 feedstock mixtures, including wet weight, TS and VS. An example of mass balance for PSSB-12.5 is presented in Figure 2 and Figure 3, while remaining figures are provided in the supporting information (section 4).

We found that, when looking at the wet mass, PS represents the most significant flow in all of the scenarios analysed. However, when SB is added to the feedstock in scenarios PSSB-12.5 and PSSB-25, this flow represents the major input of VS and TS into the system. We found similar results in the energy balance (Figure 4), indicating that, as expected, even a relatively small addition of SB significantly increases the throughput of energy in the system while significantly boosting biogas yield (both total production and yield per Mg of input). PS indeed represents a preferable mean for diluting the high content of solids in SB instead of freshwater: besides the significant savings of water resources (and connected expenses), the use of PS as a prime co-substrate provides better nutrient balancing and increased buffering capacity.

Digestate represents the main output of the system, regardless of the feedstock mixture considered, the reason being the substantial amount of water carried as a result. With regards to VS, the situation is rather different, as the majority of VS is converted into gaseous compounds during the AD process. While biogas is used for energy production, the significant amount of gas forming during ensiling represents a loss of energy within the system; this loss, however, is almost unavoidable, as sugar beet storage is needed to ensure the supply of feedstock to the reactor throughout the whole year. The addition of SB to the feedstock mixture has a clear effect on biogas production (per unit of input), which almost doubles – going from PSSB-0 to PSSB-25 (Table 3). This result is a combination of three aspects: an increase in the BMP of the input (Table 3), an increase in VS content in the feedstock (from 3.2% ww in PSSB-0 to 5.6% ww in PSSB-25) and a decrease in the ratio between biogas yield and the BMP (Table 3). The latter suggests that, when adding SB, some adjustments in the digestion process HRT may be needed, to exploit further the methane potential of the feedstock material.

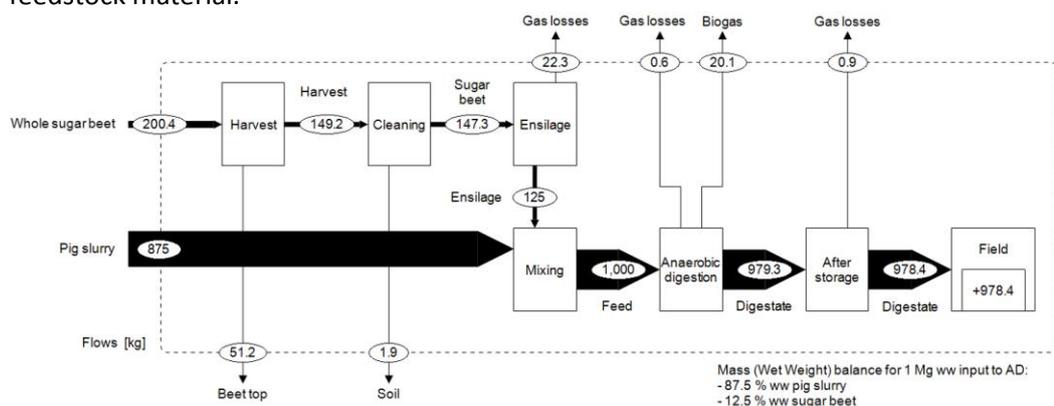


Figure 2 – Mass (kg, wet weight) balance of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-12.5, i.e. a mix of PS (87.5% ww) and SB (12.5% ww).

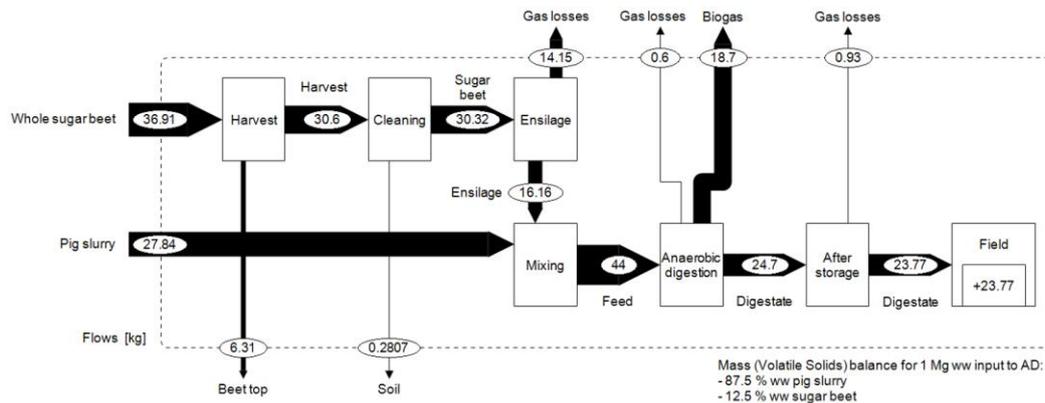


Figure 3 – VS (kg) balances of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-12.5, i.e. a mix of PS (87.5% ww) and SB (12.5% ww).

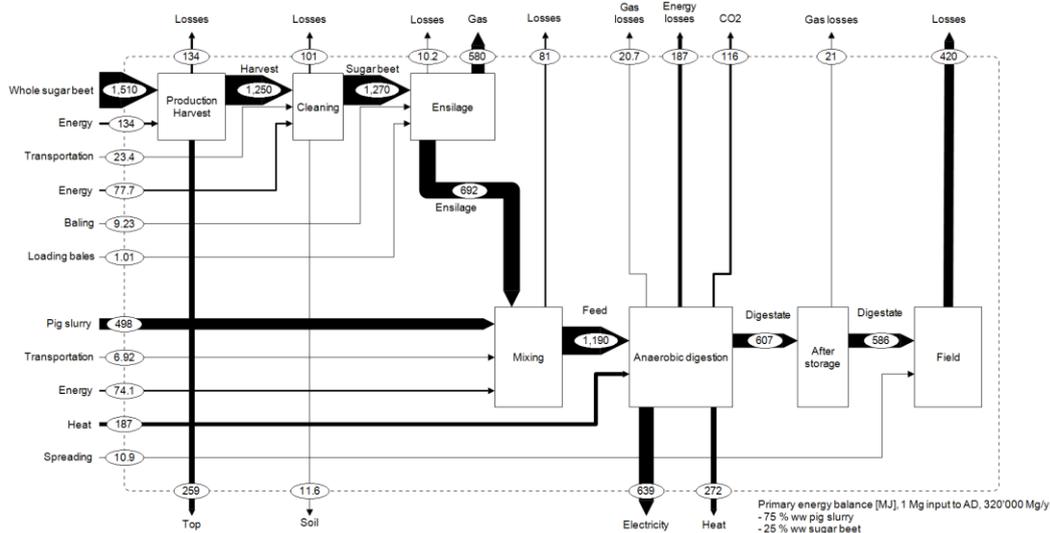


Figure 4 – Energy balance (MJ of primary energy) of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-25, i.e. a mix of PS (75% ww) and SB (25% ww), while the size of the plant is 320,000 Mg/y.

VS degradation throughout the whole biogas chain is in the order of 45% to 68% (Table 3) of VS input into the system, whereas VS degradation within the digestion process is in the order of 43 to 56%. This figure is in line with what was reported by Møller et al. [18] for cattle manure (i.e. 21–44%) and pig manure (i.e. 47–78%), while it is lower than findings for other substrates (e.g. 53–80 in Marañón et al. [63], Gebrezgabher et al. [37], Schievano et al. [64], Delzeit & Kellner [41]). The results in Table 3 show that, with a fixed HRT, the addition of SB as a co-substrate decreases CH₄ yield (as percent of the BMP), while the overall VS degradation increases slightly. This is due to the fact that SB contains a larger amount of slowly degradable VS, which in turn possibly requires longer HRT to reach high yields. In general, a significant share of the VS in the digestate is non-degradable in anaerobic conditions (i.e. 21% for PSSB-0, 17% for PSSB-12.5, 28% for PSSB-25).

Table 3 – Overview of key parameters for the modelling of biogas production.

Parameter	Unit	PSSB-0	PSSB-12.5	PSSB-25
CH ₄ yield	m ³ /Mg _{ww} input	9.10	12.3	18.0
CH ₄ yield	m ³ /Mg _{vs} input	296	343	369
CH ₄ yield	% of BMP	96.6	82.2	87.6
CH ₄ concentration	% in biogas	57.2	57.1	57.2
VS degradation – system	% VS input to the system	44.8	66.4	67.6
VS degradation – digester	% VS input to the digester	43.5	55.6	51.2
VS _{ND} in digestate	% of total VS	20.6	29.4	27.8

3.2. GHG balance

Our findings show that increasing the share of SB in the feedstock mix results in a significant decrease in N₂O emissions from land application (Table 4). This is due to the fact that adding SB to the mix enhances both the C content and the C:N ratio of the digestate, thereby increasing CO₂ production and decreasing the formation of N₂O per unit of VS added (see supporting information, section 2.2).

An overview of GHG emissions from the analysed system is presented in Table 5, according to individual sub-processes in the biogas chain. We found that fugitive emissions of gases from the digestion process, and the storage and application on land of digestate, represent a significant contribution to the overall GHG balance (i.e. between 33 and 44% of direct emissions). Because of a lack of data, some of these estimations may, however, be associated with significant uncertainty. For example, in the present study we assumed fugitive emissions from digestion in the order of 3.1% of the produced biogas; however, other studies indicate that such a value may be subject to significant variability. For example, fugitive emissions in the order of 0.3-2.6% were estimated by Liebetrau et al. [65] for 10 agricultural biogas plants in Germany, and 2.1-4.4% were estimated by Yoshida et al. [66] for a biogas plant treating wastewater treatment plant sludge in Denmark. However, it is generally not well-clarified whether the age/technology of the biogas plant, as well as the feedstock material, has an influence on these emissions. The operation of the digester (i.e. pumping, heating, etc.) also makes some significant contribution to the overall GHG balance, in the order of 16 kg CO₂eq/Mg of feedstock. The use of SB as a co-substrate also significantly influences overall GHG emissions, in that it makes a significant contribution to direct emissions, albeit this is completely counterbalanced by increased biogas production. Energy production (i.e. electricity and heat) from biogas is the most important element in the GHG balance, as it may offset energy production somewhere else in the system (i.e. the results in Table 5 are displayed as negative contributions). In this context, the choice of the alternative source of energy production (herein coal, see table S6 in supporting information) may have a significant influence on the results.

The results in Table 5 show that, regardless of the size of the plant and the subsequent distance driven, transportation does not make significant contribution to direct GHG emissions. This represents a substantial inconsistency compared with results regarding bioenergy production based solely on energy crops, where transportation did matter, as driven distances were much longer (e.g. Boldrin & Astrup), while highlighting the importance of both using biomass residues and carefully selecting the location of the biogas plant to ensure the availability of locally (short distance) produced biomasses.

Table 4 – Emissions of N₂O from applying different digestates on land (NH₃ loss 10%, soil water potential -0.015 MPa).

Treatment	N ₂ O [g N ₂ O/kg _{vs,applied}]	N ₂ O from NH ₃ loss [g N ₂ O/kg _{vs,applied}]	Total N ₂ O [g N ₂ O/kg _{vs,applied}]
PSSB-0	0.66	0.17	0.83
PSSB-12.5	0.59	0.12	0.71
PSSB-25	0.45	0.06	0.50

Table 5 – Overview of GHG emissions [kg CO₂eq/Mg input] throughout the biogas production chain.

Stage	Process	GHG emissions [kg CO ₂ eq/Mg input]		
		PSSB-0	PSSB-12.5	PSSB-25
SB production	SB production		11.3	22.5
SB transportation	110,000 Mg/y		0.68	1.37
	320,000 Mg/y		1.04	2.08
	500,000 Mg/y		1.12	2.25
PS transportation	110,000 Mg/y	0.59	0.52	0.44
	320,000 Mg/y	0.82	0.72	0.61
	500,000 Mg/y	1.01	0.89	0.76
SB pre-treatment and storage	Washing		4.15	8.31
	Baling		0.71	1.42
	Loading bales		0.05	0.09
Anaerobic digestion	Milling + pumping	7.9	7.9	7.9
	Heat to digester	8.7	8.7	8.7
	Electricity production	-34.4	-46.7	-68.3
	Heat production	-9.9	-13.4	-19.6
	Biogas fugitive losses	5.6	7.6	11.2
Digestate storage	Gas losses	5.9	8.0	11.4
Application on land of digestate	Spreading	1.2	1.2	1.1
	N ₂ O in field	4.0	3.7	4.0

3.3. Economic analysis

We estimated total income (TI) for the biogas plant in the range 17.3-24.9 €/Mg of input into the biogas plant (Supporting Information, Table S33). Gas subsidies have a significant influence on income (Figure 5 and Figure S8), while market revenue for energy products is less pronounced. Without subsidies, the TNI of biogas production would be negative, thus confirming previous findings (e.g. Gebrezgabher et al. [37], Delzeit & Kellner [41], Mafakheri & Nasiri [34]). This highlights the importance of future support policies for the sustainability of biogas production in Denmark. Our findings show positive signs of economies of scale, whereas the composition of the feedstock has an even greater effect on the results, as increasing the utilisation of SB significantly enhances biogas production, albeit not enough to outweigh increased costs related to the SB.

We estimated total costs (TCs) for the biogas production chain in the range 15.8-26.5 €/Mg of input into the biogas plant (supporting information, Table S35). Costs, to a high degree, are connected to the feedstock supply, as the price of manure is closely linked to an agreement with farmers, whereby manure is returned in a treated form as digestate; feedstock costs are considered here only as SB costs and account for 0-39% of the costs, depending on the share of SB utilised (see Figure S9 for details). This figure is in the lower range compared with previous findings by Schievano et al. [44] for maize (i.e. 40-62%), rye (i.e. 54-67%), triticale (i.e. 34-48%) and sorghum (i.e. 49-62%) cultivated in a Mediterranean climate. Particularly in the PSSB-0 cases, the positive scale effect on capital costs (C_{capex}) becomes clear, while operational costs (C_{opex}) dampen the economy of scale effect. The TC is significantly influenced by both the feedstock mix and the scale of the plant. In fact, the SB is so costly that it becomes the most important cost factor in the PSSB-25 cases. Moreover, the utilisation of SB also has an influence on the costs of transportation (which can add up to 20% of TC), as longer distances need to be covered to guarantee the supply of SB for biogas production. The scale of the plant also influences transportation and C_{capex} costs, as an increase in plant size requires a larger supply of feedstock with a subsequent increase in driven distance, which varies in the range 5.5-10.3 km for PS and

0-70.4 km for SB (supporting information, Table S15), depending on the plant size. These figures, however, depend strongly on local farming types (e.g. animal, plant), thereby suggesting that decision making should be based on regional considerations. We estimated costs for transportation in the range 1.1-4.1 €/Mg, with lower figures associated with small-scale plants not making use of SB. These values are in line with what is reported by, for example, Walla & Schneeberger [35]. Capital costs (C_{capex}) are estimated in the range of 3.1-5.2 €/Mg (supporting information, Table S36), with lower figures referring to large-scale plants. We estimated operation costs (C_{opex}) in the range 3.3-4.3 €/Mg (Table S36). The size of the plant has rather a small influence on the C_{opex} , while C_{opex} does increase when introducing SB to the feedstock, as additional manpower is needed for handling SB (additional details in supporting information).

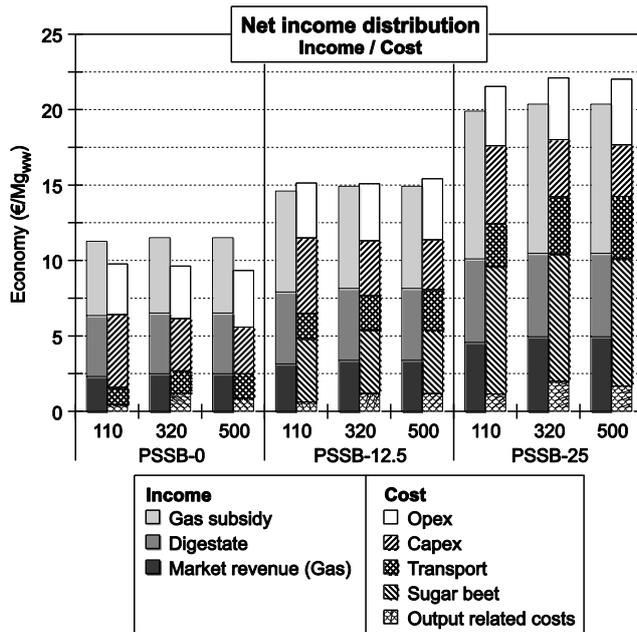


Figure 5 – Distribution of total income (TI) and total costs (TC) per Mg of input to the biogas plant.

An overview of total net income (TNI) is shown in Table 6. Based on existing subsidies, price assumptions for inputs and outputs and the production technology (biogas yield), the only viable input composition is a feedstock containing 0% of SB (i.e. PSSB-0). In this case the largest plant is the most profitable. Scenarios including SB utilisation as a feedstock (i.e. PSSB-12.5 and PSSB-25) result in negative TNI, as costs are greater than income, due to the fact that increasing costs related to SB input are not counterbalanced by increased biogas production and any associated revenue. Conversely, for the entirely PS-based case (i.e. PSSB-0), the result is positive, meaning that incomes exceed costs. The size of the plant does influence the TNI to some extent, in particular because of the costs associated with transportation (i.e. the larger the plant, the greater the distance) and investment (i.e. the larger the plant, the smaller the investment per unit input). The results presented in Table 6 differ from what was estimated by Delzeit and Kellner [41], as our figures indicate that large-scale facilities have a fundamental potential for better profitability compared with small-scale facilities. For those cases with SB, the benefits of increasing scale are not clear, as we find that the TNI per unit of input is almost neutral in relation to scale.

Table 6 – Overview of total net income (TNI) [€/Mg] for the biogas chain, according to plant size and input mixture.

Treatment	Unit	Plant capacity (1,000 Mg)		
		110	320	500
PSSB-0	€/Mg	1.52	1.88	2.18
PSSB-12.5	€/Mg	-0.54	-0.17	-0.50
PSSB-25	€/Mg	-1.64	-1.74	-1.66

3.4. Comparison

Results for energy balance, GHG emissions and TNI are presented comparatively in Figure 6, in which it is evident that utilising SB is a major factor influencing the results of the energy, GHG and economic analyses. However, a univocal conclusion cannot be drawn, because while the energy and GHG analyses may suggest that the utilisation of SB as a feedstock into the biogas plant may prove beneficial, the economic analysis indicates that this may be too costly in the long run. As previously described, the only viable input composition is a feedstock containing 0% of SB (i.e. PSSB-0), whereas increasing utilization of SB results in negative TNI.

The scale of the plant has little influence on the energy and GHG balances, as also indicated in previous studies (e.g. Stephenson et al. [68]); the scale, however, significantly affects net income, while if the biogas plant is operated using solely PS as a substrate, a large-scale plant may be preferable. If an SB co-substrate is employed, it becomes less clear what is preferable. A similar conclusion was reached by Walla & Schneeberger's [35] study of biogas production in Austria using maize silage as feedstock.

With respect to the results in Figure 6, we found that the most critical assumptions and main uncertainties are related to the price of SB (relative to manure) and biogas yield in the AD plant. The price of SB is about 4.5 times higher than the PS one. In general terms, production costs for energy crops must be reduced to make biogas production profitable [35,37,44]. The increased biogas yield obtained when using SB as a substrate results in better energy and GHG balances, but it does not compensate for increased costs, due to the larger input costs of SB. Biogas yield is indeed a very critical factor for profitability. To reverse negative results for the TNI in Figure 6, a further increase in gas yield (i.e. 5% for PSSB-12.5 and 13% for PSSB-25) is needed, thus suggesting that further optimisation of the process is required. The profitability of large-scale facilities seems more affected by biogas yield, as increased biogas generation would allow counterbalancing the costs for longer transportation journeys. In general, improving biogas yield may play an important role in relation to the profitability of biogas production [34,41,67].

Our results (Figure 6) seem to indicate that the low-to-no use of additional co-substrate is preferable for the profitability of biogas production. However, while TNI on a unitary basis (per Mg input of m³ biogas produced) is better, the overall production of biogas is significantly lower, meaning that achieving renewable energy targets would be more difficult. The TNI results are quite sensitive to biogas yield, SB price and transport distances, and thus small deviations could make adding SB a more profitable undertaking. With respect to the economy of scale, medium- to large-scale plants are probably most favourable. This would, however, require significant planning, where many factors (e.g. type and density of farms) would be taken into account and contextualised to local/regional conditions. Planning should make use of dynamic models to be used for optimisation purposes, taking into consideration a number of uncertainties, which could be a key aspect in decision making. Alternative scenarios to be investigated could include a price/value comparison between upgraded biogas to natural gas quality compared to the actual value of biogas used in local CHPs. In fact, biogas injected into the natural gas grid can be used for more diverse purposes and at more valuable times, thanks to storage advantages. In such a scenario, larger biogas plants may have an advantage in connection with the relatively high investment costs involved in upgrading facilities.

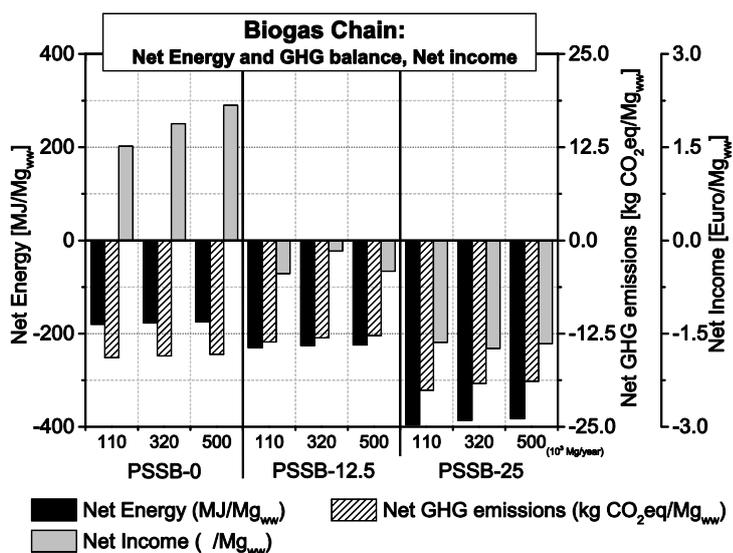


Figure 6 – Comparative overview of net energy balance (MJ/Mg), net GHG balance (kg CO₂eq/Mg), and Net Income (€/Mg) per Mg ww of input to the biogas plant.

4. Conclusions

We carried out an integrated assessment of the biogas production chain based on the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). The assessment was based on detailed mass, energy and GHG balances, coupled with an evaluation of economic profitability. The influence of feedstock composition was studied using three different feedstocks (i.e. with 0% SB, 12.5%, and 25%). The assessment included three sizes (i.e. 110,000 Mg of biomass per year, 320,000 Mg/year and 500,000 Mg/year) of biogas plant to investigate economies of scale. The study was based ostensibly on experimental data and/or data collected specifically and referring to the Danish context.

We found that increasing the share of SB in the feedstock mix has a beneficial impact on energy and GHG balances. This improvement in energy balances is due mostly to increased biogas and energy production, whereas the transportation of feedstock plays a minor role (regardless of the size of the plant). Utilisation of SB was beneficial for the GHG balance, mainly because of reduced N₂O emissions after applying digestate to land. The results showed that fugitive emissions of CH₄ from the biogas plant may make a significant contribution to overall GHG emissions. The profitability of biogas, on the contrary, was negatively affected by the introduction of SB as a co-substrate, as the increase in income from selling biogas was less than the increase in costs associated with buying SB and the transporting it. The subsidy level was established as a key aspect in biogas profitability.

The size of the biogas plant does not significantly influence the energy and GHG balances, as the performance of the conversion process has little to do with scale. Conversely, though, size is important with regards to economic analysis, as an increase in size is associated with reduced capital costs, which are outweighed by SB-related costs in the PSSB-12.5 and PSSB-25 cases, in particular because of the transportation distances involved.

The results indicate overall that utilising energy crops as a co-substrate, while preferable from an energy and GHG balance point of view, is not profitable from an economic point of view. In this respect, we identified the price of SB and biogas yield as the most sensitive parameters for the results.

5. Acknowledgments

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