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Assessment of biomethane production from maritime common reed

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A B S T R A C T

Several ongoing projects are harvesting maritime biomass from the Baltic Sea for eutrophication mitigation and utilisation of the recovered biomass. Some of this biomass comprises common reed (*Phragmites australis*), one of the most widespread vascular plants on Earth. Reed utilisation from eutrophied coastal areas needs to be evaluated. Therefore, a system analysis was performed of reed harvesting for biofuel and biofertiliser production. The specific objectives of the analysis were to: investigate the methane yield associated with anaerobic co-digestion of reed; make a primary energy assessment of the system; quantify Greenhouse Gas (GHG) savings when a fossil reference system is replaced; and estimate the nutrient recycling potential of the system. The results from energy and GHG calculations are highly dependent on conditions such as system boundaries, system design, allocation methods and selected indicators. Therefore a pilot project taking place in Kalmar County, Sweden, was used as a case study system. Laboratory experiments using continuously stirred tank reactor digesters indicated an increased methane yield of about 220 m^3 CH$_4$/t volatile solids from co-digestion of reed. The energy balance for the case study system was positive, with energy requirements amounting to about 40% of the energy content in the biomethane produced and with the non-renewable energy input comprising about 50% of the total energy requirements of the system. The net energy value proved to be equivalent to about 40 L of petrol/t reed wet weight. The potential to save GHG emissions compared with a fossil reference system was considerable (about 80%). Furthermore an estimated 60% of the nitrogen and almost all the phosphorus in the biomass could be re-circulated to arable land as biofertiliser. Considering the combined benefits from all factors investigated in this study, harvesting of common reed from coastal zones has the potential to be beneficial, assuming an appropriate system design, and is worthy of further investigations regarding other sustainability aspects.

1. Introduction

Many coastal areas around the world suffer from eutrophication, one such being the coastal zone of the Baltic Sea (e.g. Kautsky et al., 1986; Elmgren, 1989; Isaeus et al., 2004). In the Baltic area, numerous eutrophication mitigation projects have been initiated to reduce nutrient loads and several in the last few years have focused on harvesting maritime biomass. These initiatives primarily revolve around pilot harvesting of biomass such as macroalgae (Filipkowska et al., 2008; Risén et al., in press), cyanobacteria (Gröndahl et al., 2009), blue mussels (Lindahl et al., 2005), and common reed (Cofreen, 2011) from the Baltic Sea, with the intent of achieving eutrophication mitigation while simultaneously utilising the recovered biomass for biofuel, chicken feed, agar production or building material. In addition, the Swedish Environmental Protection Agency recently listed harvest of maritime biomass as a potential mitigation strategy eligible for reimbursement in a future national trading system in emissions certificates (Swedish EPA, 2010).

Common reed (*Phragmites australis*, hereafter referred to as reed) is one of the most widespread vascular plants on Earth and is one of the dominant plants in European land-water ecotones (Huhta, 2007). In addition, reed occurrence is correlated to high nitrogen loads. As a consequence, the abundance of reed within the Baltic Sea coastal zone has increased in a historical perspective (Huhta, 2007) due to eutrophication (Kautsky et al., 1986; Elmgren, 1989). A very rough estimate of the total reed stand in Sweden suggests that it amounts to about 100 000 ha containing about 1 kg

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Abbreviations

AD	Anaerobic Digestion
CHP	Combined heat and power
CSTR	Continuously Stirred Tank Reactor
DM	Dry Matter [%]
dwt	Dry weight
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
IOR	Input to Output Ratio
NEV	Net energy value [MJ/t wwt]
NREV	Net renewable energy value [MJ/t wwt]
NRIR	Net renewable input ratio
VS	Volatile Solids [% of DM]
wwt	wet weight

reed dry matter/m^2 (Granéli, 1984). Finnish reed stands have been estimated to cover about 30 000 ha and the Baltic countries, for example Estonia, also report reed stands covering large areas (Cofreen, 2011).

One of the potential uses for the recovered biomass is anaerobic digestion (AD) for biogas production. Due to the increased demand for sustainable and renewable energy sources the use of this process has increased drastically in recent years, in some cases by up to 25% annually (Buffiere et al., 2008). Biogas is commonly used as fuel for combined heat and power production. In addition, upgrading of biogas to biomethane is taking place in parts of northern Europe to enable its use as a vehicle fuel (Hjort-Gregersen et al., 2011).

Despite these potential benefits (eutrophication mitigation, utilisation of the recovered biomass) and the many ongoing projects, there has been a lack of critical evaluation of the usage of maritime biomass such as reed as a substrate for biomethane production (Komulainen et al., 2008). Previous studies have assessed land-based biomass and focused solely on energy or greenhouse gas (GHG) balances. Few have performed an integrated assessment of energy, GHG and nutrient flow performance of biomethane production systems (Hansson and Fredriksson, 2004; Berglund and Börjesson, 2006; Börjesson and Berglund, 2006). Reed harvesting for multiple purposes needs to be evaluated. Therefore, the overall aim of this study was to perform a systems analysis of reed harvesting for biofuel production and to increase nutrient recycling from the Baltic Sea coastal zone onto farmland. Specific objectives were to:

- Investigate the methane yield associated with anaerobic co-digestion of reed
- Make a primary energy assessment of the system
- Quantify GHG savings when a fossil reference system is replaced
- Estimate the nutrient recycling potential of the system

The method of analysis used in the study was a case study. As the energy balance of AD systems can vary considerably, it is preferable to utilise site- and system-specific data (Berglund, 2006). For this reason, most of the data used in the study were taken from a Baltic Sea pilot project taking place in Kalmar County, Sweden. Reed is being harvested from the Baltic Sea coastal zone within this pilot project, and the site-specific data were used here to make an assessment of the ongoing pilot project.

2. Methods and system description

2.1. Case study area

A pilot project where reed is harvested from the Baltic Sea coastal zone has been initiated by the Regional Council in Kalmar County on the Swedish east coast (Isaksson, 2011). The county, indicated in Fig. 1, has an 1181 km long coastline (excluding the island of Öland) (Stålnacke and Hedenklint, 2011) and has about 233 000 inhabitants. In all of Kalmar County (Fig. 1) the area of reed stands is roughly estimated at about 530 ha (excluding the island of Öland) (Berglund, 2010). As part of the pilot project, about 5 ha of reed beds were harvested in Kalmar municipality during summer 2011, which generated approximately 74 t wet weight (wwt) of reed. The total reed bed within the municipality has been roughly estimated at about 180 ha (Berglund, 2010). Thus the harvesting represents less than 3% of the total natural resource potential within the municipality.

2.2. System description and system boundaries

The case study system, described in Fig. 2, includes harvesting of reed along the coastal stretch within the case study area, ensiling and transportation to a local biogas plant for anaerobic co-digestion with other substrates. AD is followed by upgrading of the biogas produced to biomethane, and transportation and spreading of the digestate as biofertiliser on nearby farmland. The end products, as displayed in Fig. 2, are biomethane and biofertiliser. System design, system boundaries and allocation within this study were designed to portray the pilot project taking place in Kalmar County.

The system boundaries encompassed not only direct energy input but in addition the energy embodied in the production of ensiling material and the production of the electricity and fuels used. Energy inputs into production of buildings and necessary physical infrastructure were not included in the analysis. Final pressurisation of the gas at the tank station and the end use of the biomethane as vehicle fuel were also excluded from the analysis, since the aim was to evaluate biomethane production from reed, not to compare the final use of the biomethane with other vehicle fuels.

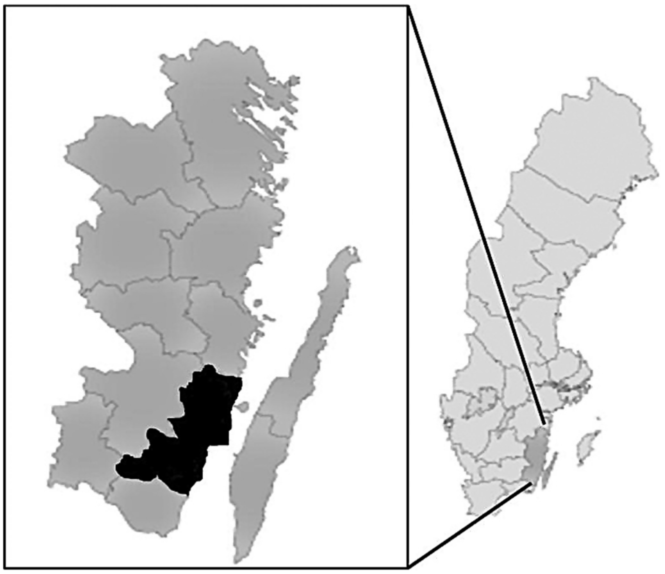

Fig. 1. Map of Sweden with an insert on Kalmar County, with Kalmar municipality in black.

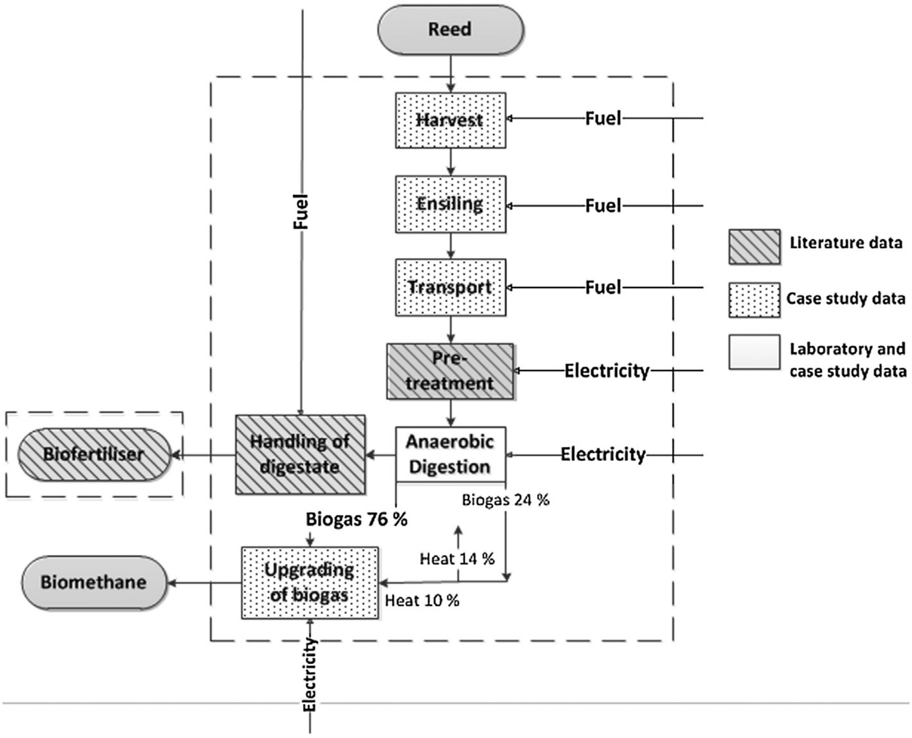

Fig. 2. System description. Energy inputs are indicated by arrows into the system. Outputs are indicated by arrows out from the system. Rectangles symbolise process steps and shading indicates the source of the data.

The functional unit used in the study was 1 t wwt of reed. The density of reed dry matter (DM) was determined, and the average weight of the round bales was 0.44 t/m^3. This density was assumed during harvesting and ensiling. Due to the low DM content in the substrate mixture, it was also assumed that 1 t wwt of harvested reed gave 1 m^3 of substrate after mixing with wetter substrate fractions. Finally, it was assumed that 1 m^3 of substrate corresponded to 0.8 m^3 of digestate, based on laboratory experiments indicating that 20% of mass is lost during AD due to formation of CH_4 and CO_2 and water evaporation (Appendix A).

2.3. Calculation and data of energy input

All data and parameters used for the energy calculations are listed in Appendix B. The source of the data (case study-specific, laboratory experiments or the literature) is indicated in Fig. 2. Primary energy conversion factors are displayed in Table 1.

2.3.1. Harvesting and ensiling

The reed was harvested with an amphibian utensil carrier, Truxor DM 4700B, fitted with a cutting shovel that can cut and gather reed both in water and on land. After the shovel was filled the reed was transported to a nearby field, where it was laid out in strings. A round bale press was then used to ensile the reed.

Table 1
Primary energy conversion factors.

Primary energy conversion factors	Value	Unit	Data source
Petrol	35.64	[MJ/L]	Swedish EPA (2009)
Diesel	39.6	[MJ/L]	Swedish EPA (2009)
Electricity (Swedish energy mix)	7.56	[MJ/kWh]	Swedish EPA (2009); Uppenberg et al. (2011)
Heat	4.68	[MJ/kWh]	Swedish EPA (2009); Uppenberg et al. (2011)
Natural gas (98.5% CH_4)	39	[MJ/m^3]	Swedish EPA (2009)
Plastics	45.5	[MJ/kg]	Hansson and Fredriksson (2004)

The energy inputs for cutting, transportation and packaging into round bales were calculated based on data from actual pilot trials at five different locations within the case study area, with the same individual performing the harvesting (Isaksson, 2011). During the pilot trials about one-third of the harvesting time was spent on actively cutting the reed, while movement and repositioning were other time-consuming activities (Isaksson, 2011). Primary energy input calculations were based on fuel consumption of the harvesting machine and the round bale press, as well as energy requirements during the production of ensiling material.

2.3.2. Transportation

The harvested and ensiled reed within the pilot project was transported with a tractor to a collecting depot at an average distance of 10 km from the harvesting point before being transported by lorry (10 km) to the biogas plant. An empty return trip was included in all transportation calculations. Fuel consumption during transportation and unloading within the biogas plant facilities was not considered in this study, since it was considered to represent small primary energy inputs in comparison with harvesting and other transportation.

2.3.3. Pre-treatment

It was assumed that the reed was pre-treated using a diesel-driven chopping machine that fragmented the biomass, based on Hansson and Fredriksson (2004). This assumption was not based on case-specific data, since the harvested and ensiled reed within the pilot project is not pre-treated or digested, as indicated in Fig. 2.

2.3.4. Biogas plant operations and biogas upgrading

Data on heat and electricity requirements for biogas plant operations and biogas upgrading were taken from a local large-scale biogas plant within the case study area, from which conditions for methane yield experiments were also designed (see Section 2.4). At the biogas plant, heat is internally generated in biogas-fired boilers from a fraction of the biogas produced. Heat requirements are based on the amount of biogas combusted in the boilers that supplies heat to the digester and upgrading process, respectively. In this study, it was assumed that heat and electricity demand [MJ/m^3] substrate did not change when fractions of reed were added to the substrate mixture and that the heat and electricity demand for upgrading, per 1 m^3 of biogas, remained unaffected. All gas volumes presented corresponds to normal cubic meters of gas (Nm^3), defined at 1 atm pressure and 0 °C (STP).

The biogas plant co-digests a mixture of different substrates that mainly originate from agriculture (see Fig. 3). The substrate mixture is stored in a mixing tank and before entering the digester it is sanitised at 70 °C for 1 h. Excess heat from sanitisation is returned to the incoming substrate mixture. The digester operates at a process temperature of 52 °C, which is in the thermophilic temperature range, and has a hydraulic retention time (HRT) of 24 days. The digestate is stored in a sealed tank before being transported from the biogas plant. The amount of fuel consumed during transportation and spreading of the digestate on farmland was assumed from Berglund and Börjesson (2006), as no such measurements have been performed in the case study. There is no heat recovery from the digestate, but since the storage tank is sealed, it works as a post-digestion vessel from which biogas is collected. Electricity requirements for plant operation mainly refer to pumping of liquids (substrate mixture, digestate and water in heat exchange systems) and mixing. Methane losses during plant operations and storage of digestate at the plant were assumed to be negligible, based on measurements at the case study biogas plant.

At the biogas plant, chemical absorption technology is utilised for upgrading of biogas to biomethane, by removing CO_2 and other impurities such as H_2S. An activated carbon filter is used to remove H_2S and CO_2 is absorbed in an amine-based solvent and later stripped when the temperature of the solvent is increased. Losses of CH_4 during upgrading were set at 0.2% of the biomethane produced as determined in the plant. Heat for the amine-based solvent is supplied by a biogas-fired boiler and the system operates without any external heat recovery installed. The biomethane is pressurised to approximately 5 bars before leaving the upgrading unit.

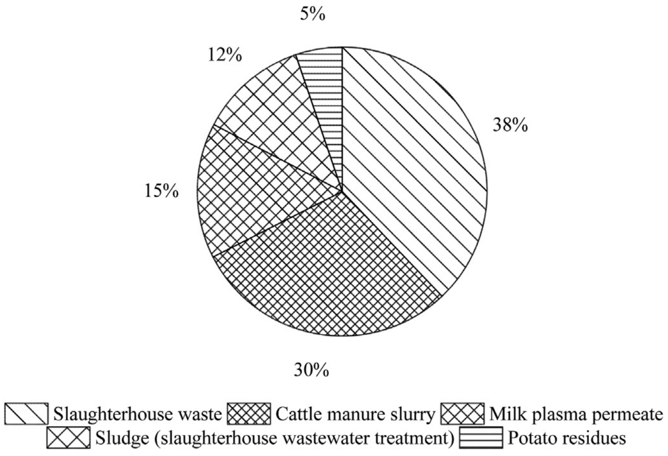

Fig. 3. Substrate mixture at the large-scale biogas plant studied.

2.3.5. Digestate utilisation

The digestate from AD is used as biofertiliser and the system therefore replaces production of artificial fertilisers. However, the total input energy was not allocated between the two end products (biomethane and biofertiliser), as previous studies have concluded that allocation between end products should be avoided when possible since the choice of allocation method has a large impact on the energy balance (Khatiwada and Silveira, 2009; Börjesson and Tufvesson, 2011). Instead, the energy not used in artificial fertiliser production due to replacement with biofertiliser was included in the energy balance, indicated as E_{subst} in Table 2, and indicated by a dotted square in Fig. 2.

2.4. Methane yield and reed composition

The reed used for methane yield experiments was harvested during August 2010, ensiled for 6 months and cut to approximately 12 mm length before being loaded into the experimental digester together with the substrate mixture. During the growth season the composition of reed varies, resulting in changes in both nutrient content and degradability of the harvested reed. This study focused on summer-harvested reed.

As a basis for the energy output calculations, digestion experiments were carried out using two laboratory-scale continuously stirred tank reactors (CSTR) anaerobic digesters. The experiments were based on the notion that the harvested and ensiled reed would be co-digested with other substrate fractions at the biogas plant within the case study area and the conditions applied in the methane yield experiments simulated conditions at that large-scale biogas plant. Both CSTR digesters, with 30 L active reactor volume, ran at an operating temperature of 52 °C and 24 days HRT. At start-up, both reactors were inoculated with fresh digester material from the biogas plant. The experiments with reed addition ran 4 times the HRT and energy output data from co-digestion of reed were calculated based on increased methane yield from addition of reed to the substrate mixture. The experimental setup and calculations are further described in Appendix A.

2.5. GHG calculations and data

The GHG emissions were calculated based on quantified primary energy inputs (Fig. 2) and included emissions of N_2O, CH_4 and fossil CO_2 during the production of energy carriers and their final use in the system as well as emissions avoided when the system replaces production of artificial fertilisers. Data on vehicle fuel consumption and emissions from production of energy used within the system are presented in Appendices B and C.

2.6. Calculations of nutrient net flows

The composition of reed at the five different harvesting locations was analysed on separate occasions during the summer harvesting season in 2011 (Table 6). The composition of fresh reed was used as basis for nutrient flow estimates. In contrast to energy flows, estimates of nutrient losses were not based on the pilot project. Instead, nitrogen and phosphorus losses during ensiling, storage, AD, spreading of the digestate and finally losses due to leakage from farmland were estimated as mass-percent based on literature values (Table 8).

2.7. Energy assessment

In order to assess the energy balance of the system, a number of indicators were applied. These indicators evaluated different aspects of the energy performance of the system, as described in

Table 2
Description of energy indicators used in the study.

Indicator	Acronym	Equation	Measure criteria	Previous use
Input–output ratio	IOR	$\text{IOR} = (E_{\text{tot in}} - E_{\text{subst}})/E_{\text{tot out}}$	Energy efficiency of a system IOR ratio < 1 positive	(Berglund and Börjesson, 2006; Börjesson et al., 2010; Pöschl et al., 2010)
Net energy value	NEV	$\text{NEV} = E_{\text{tot out}} + E_{\text{subst}} - E_{\text{tot in}}$	Net energy output from the system NEV > 0 positive	(Hansson and Fredriksson, 2004; Varadharajan et al., 2008)
Net renewable energy value	NREV	$\text{NREV} = E_{\text{tot out}} + E_{\text{subst}} - E_{\text{Nrin}}$	Amount of avoided non-renewable energy usage NREV>0 positive	(Graboski, 2002; von Blottnitz and Curran, 2007; Varadharajan et al., 2008)
Non-renewable input ratio	NRIR[a]	$\text{NRIR} = E_{\text{Nrin}}/E_{\text{tot in}} \cdot 100$	Percentage of total energy input of non-renewable origin	Not previously used
Energy renewability efficiency	ERenEF	$\text{ERenEF} = (E_{\text{tot out}} - E_{\text{nrin}})/E_{\text{tot out}} \cdot 100$	Renewability efficiency	(Malca and Freire, 2006)

[a] Heating of the plant with biogas was considered as an external energy input in NRIR in order to assess all energy utilised.

Table 2. In Table 2, $E_{\text{tot in}}$ [MJ/t wwt] is the total amount of primary energy utilised for 1 t of reed, and $E_{\text{tot out}}$ [MJ/t wwt] is the energy produced from biomethane from 1 t of harvested reed. Furthermore, as described earlier, E_{subst} [MJ/t wwt] is the energy savings when digested sludge originating from 1 t of reed replaces artificial fertiliser on arable farmland and $E_{\text{nr in}}$ [MJ/t wwt] is the non-renewable primary energy input.

2.8. GHG savings

The amount of GHG emissions that can be avoided when the biomethane produced replaces non-renewable fuel were calculated using Equation (1) (European Parliament and the Council of the European Union, 2009; Khatiwada and Silveira, 2011). Avoided emissions, $A_{\%}$ [%], include savings when artificial fertiliser is replaced with digestate and were calculated from total emissions of carbon dioxide equivalents from the process per 1 MJ produced, $m_{\text{tot CO}_2\text{ eq}}$ [g $\text{CO}_{2\text{ eq}}$/MJ], and the amount of carbon dioxide equivalents that would be emitted from the fossil reference system per 1 MJ, $m_{\text{tot CO}_2\text{ eq ref}}$ [g $\text{CO}_{2\text{ eq}}$/MJ]:

$$A_{\%} = \left(m_{\text{tot CO}_2\text{ eq ref}} - m_{\text{tot CO}_2\text{ eq}}\right) \Big/ m_{\text{tot CO}_2\text{ eq ref}} \cdot 100 \tag{1}$$

In this study, we chose to compare GHG emissions as the percentage of carbon dioxide equivalents per 1 MJ fuel produced that is saved in comparison with a fossil reference system. This functional unit is suitable, as described by Börjesson et al. (2010).

2.9. Nutrient net flows

The indicator nutrient net flow (NNF), displayed in Equation (2), was used in order to assess the potential of the system to re-circulate nutrients from the eutrophied coastal zone onto farmland. The indicator shows the percentage of the harvested content of the nutrients, i (nitrogen and phosphorus), in reed that can be used as fertiliser on farmland. The equation expresses the amount of nutrients available as fertiliser on farmland after expected losses have been subtracted, $m_{\text{i land}}$ [t wwt], as a percentage of the total amount of nutrients harvested, $m_{\text{i tot}}$ [t wwt].

$$\text{NNF}_{\text{i}} = m_{\text{i land}}/m_{\text{i tot}} \cdot 100 \tag{2}$$

3. Results and discussion

3.1. Energy input

The energy requirement for each process step in relation to the total energy input is displayed in Fig. 4. As can be seen from the diagram, the process that has the largest energy requirement is the upgrading of the biogas, followed by the energy demand for heat and electricity in AD. Thus, the dominant input energy carriers are biogas for heating and electricity. The third most substantial input is vehicle fuel for harvesting events. Process steps that require less than 10% of the total energy input are ensiling, transportation, pre-treatment and digestate handling.

Tables 3 and 4 show the energy inputs into each system step for the case study, along with data for other systems found in the literature. For the sake of comparison with literature values, the input data are shown as MJ/t dwt, MJ/m^3 substrate and MJ/m^3 biogas, even though the basis for all calculations was 1 t wwt of harvested reed, as mentioned earlier. As can be seen in Table 3, the energy used in harvesting was large in the case study in comparison

Table 3
Primary energy inputs to harvesting, ensiling, pre-treatment, transportation and spreading of digestate. n.a. – not available. Calculated from a DM content of 10% in the digestate.

Process step	Reed		Straw		
	This study	Hansson and Fredriksson (2004)	Pöschl et al. (2010)	Berglund and Börjesson (2006)	Börjesson and Berglund (2006)
Harvesting [MJ/t dwt]	560	n.a.	n.a.	280[a]	230[b]
Ensiling [MJ/t dwt]	330	75	140[c]	n.a.	n.a.
Transportation tractor [MJ/(km·t dwt)]	8.5	4.4	6.9	n.a	n.a
Transportation lorry [MJ/(km·t dwt)]	13	n.a.	n.a.	3.5[d]	3.5[d]
Transportation digestate [MJ/(km·t dwt)]	4	n.a.	2.5	n.a.	n.a.
Pre-treatment [MJ/t dwt]	150	150	n.a.	n.a.	33
Spreading of digestate [MJ/t dwt digestate]	150	400	202	170	250

[a] Straw recovery and transport from field to storage.
[b] Diesel consumption by machinery + manufacture of transport machinery.
[c] Fuel consumption during baling operations.
[d] Calculated from 2.0 MJ/t wwt with an DM content of 82%.

Table 4
Primary energy input in biogas plant operation and biogas upgrading. n.a. – not available. Calculated from a DM content of 10% in the digestate.

Process step	This study	Berglund and Börjesson (2006)	Beil (2009)
Biogas plant heat [MJ/m^3 substrate]	285[a]	110[b]	n.a.
Biogas plant electricity [MJ/m^3 substrate]	150	66	n.a.
Biogas upgrading heat [MJ/m^3 biogas][c]	4 (765[d])	n.a.	2.1
Biogas upgrading electricity [MJ/m^3 biogas]	0.8 (140[d])	n.a.	0.9

[a] Large-scale biogas plant (CSTR, thermophilic process temperature).
[b] Large-scale biogas plant (CSTR, mesophilic process temperature).
[c] Chemical (amine) absorption.
[d] [MJ/m^3 substrate], based on the biogas production from 1 t wwt of reed (1 t wwt = 1 m^3 substrate).

with previous studies. Aspects contributing to this larger energy demand were the focus on reed growing in diversified coastal areas, whereas Berglund and Börjesson (2006) and Börjesson and Berglund (2006) studied agricultural residues cultivated in arable fields, which allow harvesting to be optimised. Furthermore, Hansson and Fredriksson (2004) calculated reed harvesting efficiency based on literature values, whereas in the present case study we used data from field experiments, which can be expected to be more realistic.

As shown in Table 4, the heat requirements at the large-scale biogas plant studied here were more than twice those reported by Berglund and Börjesson (2006). This result was expected due to two factors. Firstly, the plant operate at a higher process temperature (thermophilic compared with mesophilic in previous studies), which doubles the heating demand (Zupančič and Roš, 2003). Secondly, there is no heat recovery from the outgoing digestate at the studied plant. In addition, the heat demand for upgrading is high in comparison with previous literature values for chemical amine absorption presented by Beil (2009). This can be explained by the unutilised external heat recovery potential.

Data on energy input found in the literature are associated with high uncertainty when applied to case-specific processes (Berglund, 2006). Tables 3 and 4 show the large range in available literature values due to different designs and efficiencies of systems, as well variations in system boundaries and allocation methods between studies. This further emphasises the importance of using process- and site-specific data on energy input, as was the case in this study.

3.2. Energy yield and reed composition

Table 6 shows the reed composition during summer in the case study area. Although reed is not a particularly nutrient-rich substrate, it has a low N/P ratio in comparison with the other substrates co-digested in the large-scale biogas plant studied here. The reed can therefore add value by decreasing the high N/P ratio of the digestate.

Table 5
Average reactor loading, methane production and volatile solids (VS) removal during last 21 days of reactor operations. Standard deviation (SD).

	Substrate mixture +19% reed (±SD)	Substrate mixture without reed (±SD)
Organic loading rate [kg VS/(d·m^3)]	3.4 ± 0.1	2.9 ± 0.1
Methane production [m^3 CH_4/d]	0.0393 ± 0.0005	0.0357 ± 0.0017
VS removal [%]	54 ± 2	56 ± 2

Table 6
Mean composition of five reed samples taken at different locations in Kalmar County. Standard deviation (SD).

	Samples	
	Used in experiments	Sampled from field Mean value ± SD
Dry matter [%]	42	45 ± 10
Volatile solids [% of DM]	91	94 ± 1
Total Kjeldahl nitrogen [% of DM]	1.1	1.5 ± 0.4
Phosphorus [% of DM]	0.2	0.14 ± 0.05
Potassium [% of DM]	1.3	1.2 ± 0.3

The results from the laboratory experiments indicated an increased methane yield of about 220 m^3 CH_4/t VS when reed is co-digested with the substrate mixture (Table 5). The methane yield generally depends on reed composition, possible pre-treatment, plant design and process parameters, e.g. time of harvest, mechanical or thermal pre-treatment, process temperature and HRT. Information on the methane yield of reed is limited to a few studies and differences in experimental setup make it difficult to compare results between studies. However, Jagadabhi et al. (2011) reported a methane yield of 220–260 m^3 CH_4/t VS from AD of reed in laboratory-scale batch reactors.

3.3. Energy assessment

Based on the indicators presented in Table 7, we can conclude that the energy balance for the system assessed is positive. In particular, the input–output ratio (IOR) indicates that the energy requirements amount to about 40% of the energy content in the biomethane produced. Net energy production (NEV) per 1 t wwt of reed roughly corresponds to 38 L of petrol. To put these figures in perspective, if the total reed stand within Kalmar municipality (180 ha) were to be harvested, the net energy produced in the form of biomethane would represent less than 1% of the total annual energy utilisation of the municipality's transport sector (consumption of mostly petrol and diesel) corresponding to an annual fuel consumption of about 100–150 cars (Statistics Sweden, 2011). Furthermore, the net renewable energy value (NREV) indicates that about 44 L of net petrol equivalents per tonne of harvested reed could be replaced with renewable energy flows.

The net renewable input ratio (NRIR) indicates that about half the total input is of renewable origin and thus not included in NREV. The non-renewable energy input ratio could be decreased; case study stakeholders report that the availability of cost-competitive renewable sources to electricity and vehicle fuel are the main limiting factor for the reduction of non-renewable energy input. Furthermore, the energy renewability efficiency (ERenEF) indicates that about 70% of the total output is obtained from renewable resources. As a comparison, Malca and Freire (2006) estimated the ERenEF for petrol production (−20%). Even though this study had different system boundaries, the comparison

Table 7
Input output ratio (IOR), net energy value (NEV), net renewable energy value (NREV), net renewable input ratio (NRIR) and energy renewability efficiency (ERenEF) for the case study system. Criteria for indicators are shown in brackets.

IOR (<1)	NEV [MJ/t wwt] (>0)	NREV [MJ/t wwt] (>0)	NRIR [%]	ERenEF [%]
0.39	1.644	1.891	53%	68%

Table 8
Percentage loss of total nitrogen and phosphorus during the different process steps.

Process	Loss of N_{tot} [% of DM]	Loss of P_{tot} [% of DM]
Harvest	–	–
Ensiling	10%[a]	–
AD	–[a]	–[a]
Storage of sludge	1%[a]	–
Spreading of digestate	15%[a]	–
Nutrient losses from farmland	10%[b]	1% [b]
Total	36%	1%

[a] From Hansson and Fredriksson (2004).

[b] Based on average nutrient losses from arable land in the area (Johnsson et al., 2008).

indicates much better renewability efficiency of the studied system than for petrol production.

The different indicators used (Table 2) reflect different energy inputs for the system, thus emphasising the importance of choosing indicators that address the intended aspect of the energy performance. NREV is closely linked to another indicator, sometimes referred to as the energy yield ratio (EYR), where the energy content in the biofuels produced is divided by fossil energy input. EYR is used in order to assess how "sensible" a particular product of a system is (e.g. von Blottnitz and Curran, 2007). We suggest that indicators which only consider non-renewable energy input should not be the only assessment tool of a system in this context, since the amount of non-renewable input is primarily dependent on regional or local supply of renewable energy sources of energy carriers and is not process-specific. Thus, process design should not be assessed based on non-renewable energy use solely, but also on overall energy performance of the system.

Different studies have differences in system design, system boundaries and methodological approaches as well as differences in allocation methods. Therefore, results are difficult to compare between studies. This is a general weakness of the method of analysis and a future standardisation of the method would facilitate comparisons between assessments, cases and substrates. This study was designed to describe the case study of the ongoing pilot project taking place in Kalmar municipality. As an example of how allocation methods affect results, Berglund and Börjesson (2006) concluded that different allocation methods of input energy between co-digested substrates with different DM content could alter energy input by 75% for a substrate with high DM content. Here, we assumed that substrates with high DM content are mixed with fractions with lower DM content until an appropriate DM content of the mix is achieved, and thus no allocation was made of water between the substrates. If we instead allocated water to the reed from substrates with higher water content, this would result in a significantly poorer energy performance for the reed. However, we argue that this allocation method is not realistic, since it is highly inefficient from an energy perspective to dilute high DM content substrates with water. Instead, one of the benefits of co-digestion is that substrate fractions are mixed based on their DM content until a suitable mixture is achieved.

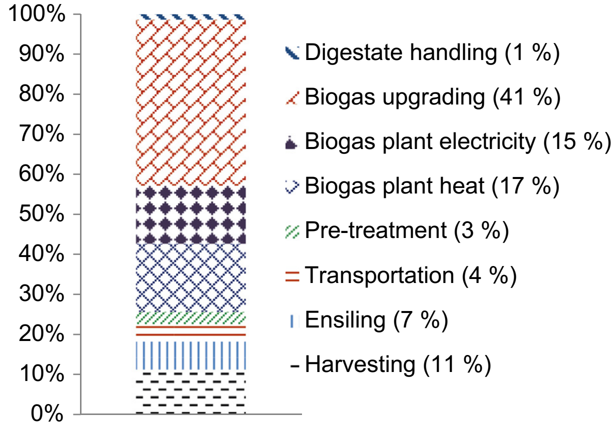

Fig. 4. Fractions of total energy input to harvesting, ensiling, transportation, pre-treatment, biogas plant heat, biogas plant electricity, biogas upgrading and digestate handling.

In this system, heat is produced from some of the biogas formed (Fig. 1). However, biogas is an energy carrier that can be upgraded to vehicle fuel and should preferably not be utilised as low quality energy in the form of heat, as commonly practiced (see e.g Ahamed et al., 2011; Szargut et al., 1988 for a definition of energy quality). A more sustainable system from an energy quality perspective would utilise heat from a less valuable energy carrier, such as district heating, and instead produce biomethane from all of the biogas formed. This aspect was not evaluated with the indicators assessed in this study. Despite this, we believe that the chosen indicators give sufficient information regarding the energy performance of the system, since the aim of this study was to assess a pilot case of reed harvesting and not to compare different system designs of biomethane production systems.

A central weakness of commonly used indicators not often discussed in the literature is that many of them are sensitive to system design. The indicator IOR is for example sensitive to assumptions concerning whether energy inputs are internally recirculated energy flows or added from an external resource. In this study, the heat input into AD and upgrading was assumed to be internally generated from a fraction of the biogas produced and the energy requirements were therefore subtracted from the total output in IOR calculations. If the process were to use the same amount of heat from an external source, the IOR would increase to about 0.6. This is a considerable difference, emphasising the importance of investigating how selection of allocation methods, system design and indicators contributes to the overall results of a study, as was done here.

3.4. GHG savings

The potential to avoid GHG emissions when a fossil reference system is replaced is considerable ($A_{\%}$, about 80%). Avoided emissions are closely linked to the quantified energy flows of the system and thus sensitive to for example system boundaries, system design and process design. The European Union has stated that renewable energy systems should reduce GHG emissions by at least 35% (50% reduction from 2017), when replacing fossil energy systems, in order to be sustainable from a GHG balance perspective (The Swedish Government, 2009). The system assessed here meets this demand with a wide margin, and could therefore be seen as sustainable from a GHG emissions perspective.

Börjesson et al. (2010) concluded that the GHG savings when biogas is produced from household waste, industrial waste, manure or sugar beets are on average 77–90% for Swedish conditions. Furthermore, The Swedish Government (2009) reported that GHG savings of about 73–86% are common for biogas production systems. The present study did not use the same system boundaries and allocation principles as previous studies, but nevertheless provide an indication that our reduction potential is of the same order of magnitude as that of other biogas production systems.

3.5. Nutrient net flows

Nutrient net flow indicators (Equation (2)) showed that about 60% of nitrogen and almost all phosphorus can be utilised as fertiliser on farmland. The recycling capacity of the system for phosphorus can therefore be seen as considerable and satisfactory. In addition, Table 8 shows estimates of nutrient losses as percentage mass for each process step. The largest loss of nitrogen occurred during spreading of digestate. The nutrient losses during ensiling, spreading and leakage back to the coastal zone may be reduced by preventive measures, such as timing of spreading and completely anaerobic ensiling. However, it is difficult to avoid these losses entirely and for both nitrogen and phosphorus, similar losses may be expected from similar biomethane production systems based on ensiled biomass.

The reed harvested (74 t) from the 5 ha pilot project area within Kalmar municipality would theoretically be sufficient to supply 3 ha of farmland (assuming N:P requirement of 110:20) with nitrogen and 2 ha of farmland with phosphorus on an annual basis, based on the values presented in Tables 6 and 8. Thus, reed harvesting on municipality scale may very well be a suitable technique for recycling nutrients from the eutrophied coastal zone back to farmland. Although the estimates presented in Table 8 are based on literature values and are not specific for the case study system, their magnitude gives important indications regarding the nutrient recycling capacity of the system.

If the entire estimated reed stand in Kalmar County (530 ha) were to be harvested, this would result in a maximum nutrient net recycling of about 34 t nitrogen and 5 t phosphorus. This corresponds to about 1% of annual nitrogen losses and 19% of the annual phosphorus losses from farmland within the county as reported by Johnsson et al. (2008). Consequently, if a large fraction of the total reed stand were to be summer harvested, the associated recycling of phosphorus has the potential to affect the total phosphorus load from the county to the Baltic Sea coastal zone.

3.6. System analysis

There are multiple aims with reed harvesting from coastal zones. This study therefore investigated whether key ambitions are being met in the pilot project studied. The criteria were: net energy production, considerable GHG savings and good nutrient recycling capacity. The energy performance of the system was assessed here with a number of indicators. When biomethane production potential from reed is compared with fuel consumption of the transport sector within Kalmar municipality, it is evident that reed harvesting cannot provide any considerable amounts of biofuel to the municipality. Nevertheless, there is a positive energy balance in the system and the system has the potential to replace fossil energy usage with flows of renewable energy.

The potential for considerable GHG savings is a proven benefit of the system. The biofertiliser produced can add value to the co-digested mixture by decreasing the N/P ratio and the system effectively removes nutrients from the eutrophied coastal zone and uses them on farmland. The results indicate that phosphorus recycling to farmland has the potential to reduce phosphorus loads from Kalmar County to the Baltic Sea coastal zone. Kalmar municipality is participating in national and Baltic-wide attempts to combat eutrophication, as are most municipalities within the coastal zone context. Therefore this eutrophication mitigation potential is an essential aspect.

However, it is important to note that this study forms part of a larger sustainability assessment and a number of aspects regarding the sustainability of the system remain to be investigated; e.g. socio-economic aspects of the process. In addition, reliable estimates of total reed stands and the harvesting potential of these stands on regional, national and Baltic-wide scales are lacking.

It is essential to determine the impact of reed harvesting on the ecosystem before large-scale harvesting regimes are established in the Baltic Sea coastal zone. Reed beds are important habitats, contributing to biodiversity, and Huhta (2007) claims that poorly managed reed harvesting can damage local ecosystems and therefore have a negative environmental impact. Harvesting technique, time of harvest and local growth conditions may affect re-growth of the reed and it is essential that the rhizome system of the reed plants is not removed or damaged during harvesting. These aspects are not further addressed within the boundaries of this study and should be the subject of future studies.

4. Conclusions

Small scale continuously stirred tank reactor experiments indicated that common reed has the potential to be a suitable substrate for biogas production, with increased methane yield of about 220 m^3 CH_4/t VS from co-digestion of reed. The energy input requirements to the entire harvest to product system correspond to about 40% of the energy content in the biomethane produced. However, if the total reed stands in Kalmar municipality were to be harvested it would be able to support less than 1% of the municipality's transport sector with fuel on an annual basis. Thus, biofuel production should not be seen as the primary driving force for the studied system. However, results indicate that the system is defensible from an energy perspective.

This study indicates a possible GHG emissions saving of about 80% in comparison with a fossil reference system. Furthermore, nutrients are also removed from the eutrophied coastal zone through reed harvesting. In Kalmar municipality, 1 ha of reed can supply about 0.7 ha of farmland with nitrogen and about 0.5 ha of farmland with phosphorus on an annual basis, which is a substantial benefit for the municipality.

For the pilot project studied, the system analysis indicated that the key ambitions are being met. These include a positive energy balance, a considerable GHG reduction and potential to recycle nutrients. The results provide an indication to stakeholders in similar coastal zone initiatives that there are potential benefits with reed harvesting in eutrophied coastal areas, assuming an appropriate system design. Therefore, we suggest that the system is worthy of further assessment regarding other sustainability aspects, such as natural resource potential, socio-economic impact and impact on the ecosystem.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2013.03.030.

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