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Bioenergy production from roadside grass: A case study of the feasibility of using roadside grass for biogas production in Denmark

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ABSTRACT

This paper presents a study of the feasibility of utilising roadside vegetation for biogas production in Denmark. The potential biomass yield, methane yields, and the energy balances of using roadside grass for biogas production was investigated based on spatial analysis. The results show that the potential annual yield of biomass obtainable from roadside verges varies widely depending on the local conditions. The net energy gain (NEG) from harvest, collection, transport, storage and digestion of roadside vegetation was estimated to range from 60,126–121,476 GJ, corresponding to 1.5–3.0% of the present national energy production based on biogas. The estimated values for the energy return on invested energy (EROEI) was found to range from 2.17 to 2.88. The measured contents of heavy metals in the roadside vegetation was seen not to exceed the legislative levels for what can be applied as fertilizer on agricultural land, neither does it reach levels considered as inhibitory for the anaerobic fermentation process. From a practical point of view, few challenges were identified related to the acquisition and processing of the roadside vegetation. Considering the positive net energy gains, further energy investments for management of these challenges can be made. Despite the somewhat low EROEI values, the use of this resource could however result in other positive externalities, such as improved biodiversity of the verges and recycling of nutrients.

1. Introduction

Research into alternative biomass sources (and production areas) which could mitigate environmental and economic issues related to conventional energy crops, while sustaining and improving bioenergy production has been increasingly investigated. A potential source which could meet this goal but has only been sparsely examined in the literature is vegetation from roadside verges. Roadside verges currently represent unutilised areas (with regard to food production), which could provide a beneficial feedstock for use in biogas systems.

Investigations and reports on the use of vegetation sourced from roadside verges were found to be quite limited, with roadside biomass research mainly concentrated on its use to monitor and evaluate heavy metals and organic pollutants emanating from road transport (Ho and Tai 1988; Garcia and Millán, 1998). However a few European reports and papers on this topic were identified having quite different views and conclusions related to the possibilities of utilising roadside vegetation for bioenergy production. Pick et al. (2012) concluded that the utilisation of roadside grass in biogas plants in Schwäbisch Hall County, Germany, was unfavourable due to the potential content of pollutants and waste in the roadside vegetation. Furthermore, the authors argue that the costs, associated with the biomass harvest and collection, were unfeasible. Durling and Jacobsen (2000) conducted a study in Sweden assessing the energy consumption and the costs per tonne of roadside grass when used for anaerobic digestion, composting, or combustion. The results show that anaerobic digestion and combustion of the roadside vegetation gives a positive net energy production, indicating that the utilisation is feasible from an energetic point of view. The "Living Highways Project" (Delafield, 2006) conducted trials harvesting roadside vegetation with a specialised harvesting machine in the region of Powys, Wales. The harvest machinery was evaluated to work effectively and no concerns related to waste in the harvested grass were reported. Based on the results for the harvest yields in this study, Salter et al. (2007) set up a model to determine the energy efficiency and surplus energy yield of using roadside vegetation as feedstock for biogas production in the UK. The results from this study are promising, indicating that the

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biogas quantity produced from roadside vegetation (harvested in a radius of 20 and 45 km from a biogas plant) is sufficient to cover the energy demand for harvesting, transport and biogas production processes. A common finding from most of the previous studies related to roadside biomass extraction and use was that the harvest and collection of roadside vegetation created positive impacts in the flora and fauna of the roadsides. This finding is further supported in the literature, where increases in the species richness of the roadsides have been documented when the grass cuttings are removed after harvest (Noordijk et al., 2009; Parr and Way, 1988).

The motivation behind this study stems from a recent change in the overall legislative frame conditions for the Danish bioenergy sector. Under the new conditions, the Danish biogas sector is subject to legislation that limits the quantity of purposely grown energy crops that can be used in biogas plants to 25% (weight based, % of total biomass digested) by 2017 with further reduction to 12% by 2020 (The Danish Energy Agency, 2012). At the same time the national energy policy aims to increase the share of energy produced from renewable resources in Denmark to 35% by 2020. It is therefore expected that the demand for alternative biomass will increase; hence the use of non-purposely grown energy crops and the possibilities of roadside grass use for energy production becomes increasingly relevant. No studies on the feasibility of using roadside vegetation for biogas production in Denmark was identified by the authors in the literature, despite the fact that such alternative substrates will be needed if the biogas sector is to expand as according to the national energy policy.

The aim of this paper was to evaluate potential energy yields obtainable and if it is energetically feasible to use roadside grass for biogas production in Denmark. In addition, the following questions of concern related to the biomass use were also investigated:

- What are the obtainable grass yields from the roadsides in Denmark?
- What is the methane yield using this feedstock?
- Does the roadside grass contain concentrations of harmful substances that could potentially inhibit the fermentation process or are above the legislative levels for application as fertilizer on agricultural land?
- What is the size of roadside verges that can be harvested adjacent to existing biogas plants and what corresponding yields of biomass can potentially be obtained?
- What supply challenges can be encountered with the acquisition and use of the roadside grass compared to the current management strategy?

2. Methods

The methods applied in this study consist of field and laboratory experiments, spatial analysis, and literature review.

For characterisation of the roadside grass, laboratory experiments (presented in Section 2.1) were conducted in order to assess the potential achievable yields of grass, the methane yields, and the content of harmful substances in the roadside grass. Section 2.2 presents the methods applied in the spatial analysis. The analysis was performed to the roads in Denmark available and to estimate their length. Furthermore, the distances for the roadside grass transportation were evaluated by assessing locations of existing biogas plants. Based on literature studies, the potential harvestable width of the roadside verges was assessed and three different scenarios were developed for estimating the potential area of roadside verges that can be harvested. Based on this, the total biomass and methane yields were estimated using results from laboratory experiments. Section 2.3 presents the approach used for estimating the energy potential of roadside grass in biogas production. The values for the energy requirements were based on findings from the literature, while the potential obtainable energy yields were estimated using results of the obtainable methane yields.

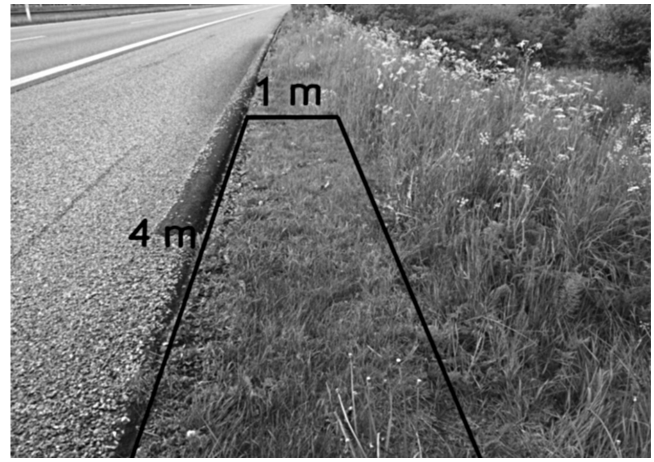

Fig. 1. A pictorial representation of the roadside grass harvesting strategy (spring harvest).

2.1. Characterisation of roadside vegetation in Denmark

A characterisation of roadside vegetation was conducted in order to estimate the potential obtainable biomass yields, methane yields and the potential content of harmful substances. Roadside vegetation harvested in Denmark was applied for this characterisation. The method and materials used for collection of the vegetation is explained in Section 2.1.1. The content of total solids and total volatile solids were analysed as in Section 2.1.2. For assessing the theoretical methane yields, the content of carbon, hydrogen, nitrogen and sulphur was applied (Sections 2.1.3 and 2.1.4). The content of harmful substances were analysed according to the method outlined in Sections 2.1.5 and 2.1.6.

2.1.1. Collection of roadside grass samples

For this study, roadside grass was collected during two sampling periods; May 2012 and in October 2012. Stripes of approximately 1 m width and 4 m length were harvested in both periods (dictated by the current management strategy for the spring season) in order to have a comparable basis (shown in Fig. 1).

The samples were collected from nine locations in Southern Denmark for both sampling periods to facilitate representative samples from a highway, a main road and a minor road. The grass was cut approximately 5 cm from the soil. Grass samples from each location were packed and transported in plastic bags, weighed and stored in a freezer at −18 °C until further analysis were conducted.

2.1.2. Total solids and volatile total solids

From each sample bag, 4 representative samples were extracted after mixing the grass thoroughly. All 36 samples were cut to sizes of ≈0.5–3.0 cm, transferred into porcelain cups, weighed and the total solids (TS) and volatile total solids (VS) contents determined using the standard methods described in APHA (2005).

2.1.3. Sample preparation for further analysis

As preparation for the subsequent experiments on the biomass heavy metals and elemental composition, three representative samples were extracted, and dried for 24 h in porcelain cups at 105 °C. The dried samples were then homogenised in an agate mortar and transferred to plastic containers where they were stored until further analysis were conducted

2.1.4. Carbon, hydrogen, nitrogen and sulphur

The content of carbon, hydrogen, nitrogen and sulphur were analysed with an elemental analyser (Perkin Elmer, Series II CHNS/O Analyzer 2400). 2 replicates were made for each sample.

2.1.5. Mercury

Approximately 1 g dried and homogenised grass from each batch was transferred to autoclave bottles, 20 ml of 7 M HNO_3 was added and autoclaved for 1 h at 90 °C. After cooling to room temperature, the bottle contents were filtered, transferred to 50 ml flasks and diluted with demineralised water to the 50 ml mark. The samples (3 replicates of each) were analysed for mercury using atomic absorption spectroscopy (AAS) combined with cold-vapour atomisation (S Series AA Spectrometer, Thermo Electron Corporation; VP 100 Vapour System, Thermo Scientific).

2.1.6. Other heavy metals, phosphorous and sodium

Accurately weighed quantities (0.4–0.8 g) of each sample were transferred to autoclave bottles where 20 ml of 7 M HNO_3 was added. The bottles were heated for 30 min at 120 °C (200 kPa). After cooling to room temperature the samples were transferred to 100 ml volumetric flasks and diluted with distilled water to the mark. The samples were then filtered and the heavy metal contents analysed with inductively coupled plasma spectrometry (Perkin Elmer, Optima 3000 DV).

2.1.7. Comparison of results

The obtained results regarding the characteristics of roadside grass harvested in southern Denmark was compared to available results for other countries found in the literature (Delafield, 2006; Kern et al., 2009; Salter et al., 2007, Werner, 2010). The results for the comparison are presented in Section 3.1.

2.2. Potential total biomass yields from roadside grass in Denmark

For estimating the total biomass yields obtainable from roadside grass in Denmark, the total length of roadsides and the potential harvestable area was assessed as explained in Sections 2.2.1 and 2.2.2. Using the results obtained from the characterisation of the roadside vegetation it was possible to estimate the total yields as explained in Section 2.2.3.

2.2.1. Assessment of the spatial distribution and length of roadsides in Denmark

Due to lack of previous geo-database assessment, a spatial analysis was carried out to assess the distribution and concentration of roadsides in Denmark. ESRI ArcMap 10.2.1® software was applied for data extraction and analysis. All dataset were projected to the coordinate system ETRS89 UTM zone 32N.

A roadmap dataset from OpenStreet Map platform © (2013)" provided information for this study about the location of the roads in Denmark, their classification and length. By using the "Select by Attributes" tool, road classes expected to be subject to the current management system[2] of roadside verges were selected for further analysis.

Land cover GIS dataset from CORINE (Coordination of Information on the Environment) programme 2006 (Aarhus University 2013) provided information about the distribution and location of different land cover classes in Denmark. The land cover dataset were used to identify roads expected to have no, or limited amounts of grass in the verges, such as roads located in urban and industrial areas. Land cover classes corresponding to urban and industrial use[3] were selected and a deleted from the dataset. The revised dataset was then applied as a "clip feature" for the roadmap dataset, leaving only roads outside urban and industrial areas in the output layer.

GIS datasets from the Ministry of Food, Agriculture and Fisheries of Denmark (2012) provided information about the number and location of centralised and farm scale biogas plants in Denmark. Roads on islands without biogas facilities, without bridge connection to the mainland were identified by visual inspection and deleted manually from the dataset, as it is not considered relevant to transport the harvested grass via ferries. Finally, the lengths of the remaining roads were re-calculated.

For further analysis the roads were classified into five new classes; motorways, main roads, minor roads, links (assess and exit roads) and unclassified roads[4] and the total length for each class was summarised. As the character of the roads defined as unclassified is uncertain it cannot be assumed that all of them have verges containing grass. Some could be pathways, service areas, private roads etc., while others could be similar to roads categorised as main or minor roads. It was assumed that only 50% of the unclassified roads have harvestable verges, hence only this share of the unclassified road network was further included in this study.

2.2.2. Potential harvestable area of roadside verges in Denmark – assumptions for possible scenarios

The potential area that can be utilised for biomass generation depends on the harvestable width of the roadsides. In compliance with the current management strategy, a 1 m wide stripe can be harvested in the spring. In the autumn season the full width of the roadsides and ditches could be harvested. Local conditions such as the occurrence of woody vegetation, bicycle paths, and sloping ditches could however complicate an extensive assessment of the practical harvestable width, as illustrated in Fig. 2.

The technological parameters, such as the width of the mowing unit and its flexibility will furthermore impact the width of the verge that can be harvested. To assess the potential harvestable area, three scenarios for the possible harvestable verge widths according to road class and time of harvest were examined: a conservative, an optimistic and a practical scenario (presented in Table 1). In the conservative and optimistic scenarios, the spring harvest was assessed using the current management strategy which applies a fixed strip of 1 m for harvest. The harvestable width of the verges in the autumn differs between the scenarios (see Table 1) according to the national guidelines for constructions of new roads (The Danish Road Directorate, 2013). The harvestable widths in conservative scenario are based on the recommended widths for verges built directly adjacent to the roads (the outer verge) (The Danish Road Directorate, 2004). The optimistic scenario is based on the guidelines for the width of the area adjacent to the road (i.e. safety zone) which depends on the horizontal radius of the road and the allowed speed level[5] (The Danish Road Directorate, 2012). However, the presence of crash barriers or other objects (such as trees and bushes) in the safety zone are expected to limit the harvestable width of the verges, as they are obstacles for the grass moving equipment. It is therefore assumed that only fifty

[2] Road classes selected: "motorway", "primary", "primary_link", "road", "secondary", "secondary_link", "tertiary", "tertiary_link", "trunk", "trunk_link" and "unclassified".

[3] CORINE land cover-codes: 111 (continuous urban fabric), 112 (discontinuous urban fabric), 121 (industrial or commercial units), 123 (port areas), 141 (green urban areas).

[4] Categorisation and attribute codes: Motorways ("motorway"), Main roads ("trunk", "primary", "secondary",), Minor roads ("tertiary", "residential", and "road"), Links ("motorway link", "trunk link", "primary link", "secondary link", "tertiary link"), Unclassified ("unclassified").

[5] Assumptions for the horizontal radius and speed level for the road classes used

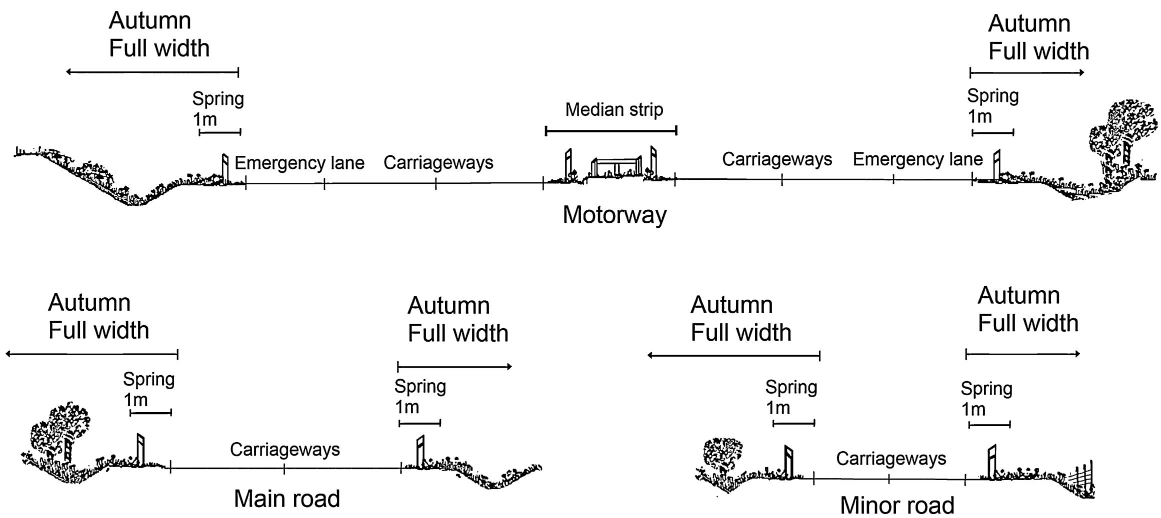

Fig. 2. Illustration on how the potential harvestable width of the three different roadside types can be impacted by the local conditions.

Table 1
The scenarios for the widths of the roadsides verges that can be harvested.

	Conservative Scenario				Optimistic Scenario				Practical Scenario			
	Spring		Autumn		Spring		Autumn		Spring		Autumn	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Motorways	1	1	1.5	1	1	1	4.75	1	1.3	1.3	1.3	1.3
Access and exit ramps	1	1	1.5	1.5	1	1	2.75	2.75	1.3	1.3	1.3	1.3
Main road	1	1	1.5	1.5	1	1	3	3	1.3	1.3	1.3	1.3
Minor roads	1	1	1.2	1.2	1	1	2.5	2.5	1.3	1.3	1.3	1.3
Unclassified	1	1	1.2	1.2	1	1	2.5	2.5	1.3	1.3	1.3	1.3

per cent of the width of the safety zone can be considered as harvestable areas. The width of the median strip adjacent to highways (as illustrated in Fig. 2) is the same as the constraint applied for the harvestable width of the verge on left side of highways. The harvestable width for left sides of highways was therefore put at a value of 1 m in all scenarios examined.

The harvestable widths in the practical scenario were put at a constant value of 1.3 m regardless of the road type or season. This width corresponds to the width of commonly used mowing units, and therefore the scenario reflects the harvestable area from a technological point of view.

2.2.3. *Total potential biomass yields in Denmark*

In order to estimate the total yields of roadside grass in Denmark, the corresponding total area of harvestable verges were estimated by multiplying the total length of each road class, with the corresponding scenario specific harvestable widths (Table 1). The scenario specific harvestable areas estimated for each road class where then multiplied with the results for the average annual yield of total solids and total volatile solids obtained per hectare (presented in Table 3, Section 3.1.1) in order to get the total potential biomass yield.

It is assumed that the harvested biomass is stored as silage before digesting it. The ensiling process cannot be assumed to be 100% efficient as some of the biomass is expected to be lost under the conservation process. The silage process was assumed to be 75% efficient, thus 25% of the biomass lost and was not included for further estimation of the gross methane yield (Livestock Knowledge Transfer Management Team, 2001).

2.3. *Energy potentials*

The annual net energy gain (NEG) and the energy return on energy invested (EROEI) (Hall et al., 2009; Arodudu et al., 2013) were estimated for the potential roadside grass use in Danish biogas production plants. The annual net energy gain (NEG) was calculated in GJ.

$$\text{NEG} = \text{output energy} - \text{input energy}$$

$$\text{EROEI} = \frac{\text{output energy}}{\text{input energy}}$$

All values used for estimating the energy requirements for the practical management of acquisition and processing of roadside vegetation, were derived from the literature. The estimated energy inputs and outputs for the individual steps related to acquisition and digestion of the roadside vegetation are presented in Appendix B.

2.3.1. *Energy input*

Practical test trials to estimate the required energy input for the roadside grass acquisition had not been previously documented for Denmark. The assumptions for the energy requirements used here were adapted from studies conducted in Sweden (Durling and Jacobsen, 2000). These values are listed in Appendix A. In order to estimate the required energy input for utilising roadside grass in biogas production, the processes were divided into the sub steps:

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to determine the width of the safety zone and thereby the harvestable width of the verges in the optimistic scenario (The Danish Road Directorate, 2012):
–Highway (horizontal radius ≥ 1000; speed level = 100–130 km/h).
–Access and exit ramps (horizontal radius ≥ 100; speed level = 50–70 km/h).
–Main roads (horizontal radius ≥ 1000; speed level = 70–100 km/h).
–Minor roads (horizontal radius ≥ 1000; speed level = 60–80 km/h).

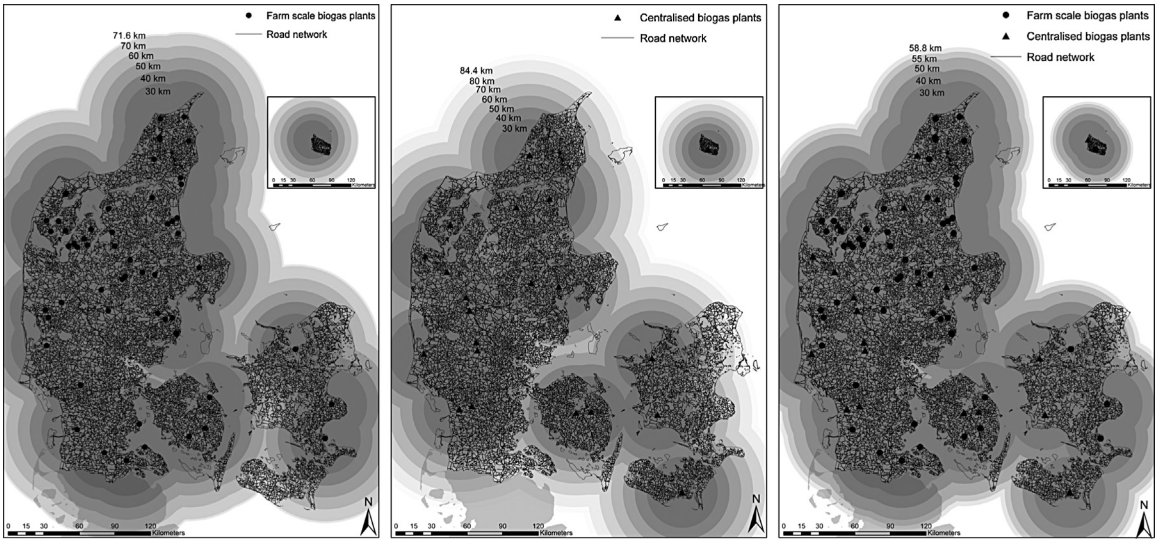

Fig. 3. Buffer analysis assessing the radii of the buffers needed around the biogas plants in order to fully cover the road network.

- Harvesting and collection in containers
- Loading of containers containing grass on trucks
- Transport of the containers to a biogas facility
- Offloading of the containers from the truck and emptying its content
- Storage in silage tubes at the biogas plant

The energy requirements for the construction of biomass acquisition machinery and maintenance of the biogas facilities are lifetime investments which would impact the long term energy balance. However, as the scope of this study is limited to estimate the annual energy balance using roadside grass, these energy investments were considered to be beyond the boundaries of this assessment.

2.3.1.1. Harvest and collection in containers. The energy demands for biomass harvesting and collection were estimated based on the total driving distance covered by the harvest area. The distance driven was calculated as the total length of the road network multiplied by two (2), as both sides of the roads are to be harvested. For scenarios with the harvestable width larger than that of the applied mowing unit (i.e. 1.3 m), an increase in the total driven distance was reached due to the additional moving steps required.

2.3.1.2. Loading of containers with grass to truck. The energy consumed for loading the full containers to a truck was estimated by considering the number of full containers required to carry the harvested grass to a biogas plant.

2.3.1.3. Transport of containers to a biogas facility. When estimating the energy requirements for the transport process, it was assumed that a truck can transport three containers at once. The required number of transport trips to the biogas plants was calculated as the number of trucks needed to carry the weight of the potentially harvestable grass.

The transport distance to the nearest biogas plant, was assessed by conducting a GIS buffer analysis around the existing biogas plants in Denmark. The location of biogas plants was obtained from the Ministry of Food, Agriculture and Fisheries of Denmark 2012). The buffer radius around the biogas plants needed for full coverage of the road network in Denmark, were found by a stepwise increase of the radii of the buffers until all roads were covered as illustrated in Fig. 3. This was done for three cases, in order to reflect the different possibilities for the end use of the roadside grass:

I. only the farm scale biogas plants will receive the harvested grass
II. only the centralised scale biogas plants will receive the harvested grass
III. both farm scale and centralised biogas plants will receive the harvested grass

The transport distances were assumed to represent the radii of the buffers needed to cover the full road network. However, several of the biogas plants are situated close to the coast line or fjords of Denmark, and clusters of biogas plants are found in some parts of the country, while only few biogas plants are present in other parts of the country. This results in large overlaps in between the buffers, and also large coverage of marine areas. Therefore, the full buffer radii are not assumed to be equivalent to the distance between the road side and biogas plants. As an approximation for estimating the distance, the percentage of marine areas within each buffer was calculated by using the intersect tool, selecting the land coverage, and calculating the area of land coverage and the total area of the buffer. The radii for each buffer were then reduced in respect to the percentage of the buffer covered by water, and multiplied by two (2) to include the return trip. The total number of trips needed to transport the harvestable grass yields (presented in Section 3.2, Table 7) from the roadsides to a biogas plant was then divided by the respective number of biogas plants.

2.3.1.4. Unloading of containers from the truck and emptying the content. The energy demand for unloading the containers from the truck and emptying their content at the end use location was estimated based on the number of trucks to be handled.

2.3.1.5. Storage in silage tubes at the biogas plant. The energy demand for storage in silage tubes was estimated based on the total quantity of fresh grass that is stored.

2.3.2. Energy output

The energy output from utilisation of roadside grass was estimated based on the yields of methane that could potentially be obtained from the anaerobic digestion of the harvestable grass. The theoretical methane (CH_4) yields obtainable from the anaerobic digestion of the roadside grass was estimated on the basis of

Table 2
The average values for the content of total solids and total volatile solids in the roadside grass samples.

Road type	TS% (g TS/g fresh grass)		VS% (g VS/g TS)	
	May	October	May	October
Motorway	25.7	28.4	93.9	89.7
Main road	26.3	24.5	88.5	76.6
Minor road	18.7	18.6	91.7	85.3

Table 3
Seasonal yields of fresh roadside grass, total solids, and total volatile solids from the three different roadside types.

	t fresh/ha		*t* TS/ha		*t* VS/ha	
	May	October	May	October	May	October
Motorway	4.25	6.25	1.17	1.71	1.10	1.54
Main road	1.50	3.92	0.33	0.96	0.29	0.74
Minor road	4.50	5.75	0.87	1.07	0.80	0.93

the samples C, H, N and S elemental compositions (Section 2.1.4) using the estimation method put forward by Boyle (1977).

Møller and Nielsen (2008) measured the practically accessible methane yield from meadow grass digested 90 days in a mesophilic reactor, and found that 45–80% of the theoretical yield was obtained. To estimate the total practical methane yield from roadside grass in Denmark, the lower range values were decided for use (presented in Section 3.2). The total potential methane yield was then estimated by multiplying the methane yields obtainable per tonne vegetation with the results for the total obtainable biomass yields (presented in Section 3.1.1).

Before estimating the final energy output from roadside grass use, part of the potential methane production was allocated to the operation of the biogas plants (heat and electricity), and the transportation of the digested organic material. For farm scale biogas plants it was assumed that 25% of the produced methane is allocated to the operation of the plant and the transportation of the digested organic material (Birkmose, 2000), and 16% for centralised biogas plants (Birkmose, 2001). For the case where both centralised and farm scale biogas plants receives the harvested grass, an average of 20% of the energy production was assumed to be allocated for operation and transport.

3. Results and discussion

3.1. Characterisation of roadside vegetation in Denmark

3.1.1. Total solids, total volatile solids and obtainable roadside grass yields

As presented in Table 2, the average biomass total solids were estimated to be highest for grass harvested on motorways in October. The average biomass volatile solids in the dry samples collected were ≈88.5–93.9% for May, and October harvested samples ≈76.6–89.7%.

The estimated total solids content in the samples from minor roads verges for the May and October harvests were observed to be generally lower than those obtained from the motorways and main roads. The samples harvested from main roads in October showed an average of ≈76.6% volatile solids content which stands out as being considerably low compared to the other samples. No visible inorganic materials, such as waste from traffic, were observed in the grass samples. However, when collecting the samples it was observed that all the verges connected to the main roads were characterised by recent removal of build-up soil. Scraping off the upper soil layer leaves the remaining soil loose and exposed, thus it is possible that greater inorganic soil quantities were collected with the harvested biomass. This could therefore explain the observed lower organic matter content of the biomass samples.

Table 4
Average annual yield of total solids per hectare for Denmark, Wales and Germany.

Country	*t* TS/ha/year
Denmark	2.04
Wales (Delafield, 2006)	3.34
Germany (Kern et al., 2009)	5.00

The average weight of yields of fresh grass, total solids and volatile total solids per hectare were seen to vary considerably as presented in Table 3.

The highest biomass yields were seen for October. This could be expected as the vegetation has had better growth conditions in the summer period (from the first harvest in May to the second harvest in October), compared to the winter period (spanning from the autumn harvest in the year before to May in 2012).

The yields were found to be lowest for the main roads verges in both May and October. As previously discussed, it was observed that all the "main roads" sample locations were characterised by recent removal of build-up soil. When removing build-up soil, the upper soil layer including the grass and part of its root system, is scraped off, thus the growth of the grass is hampered (Bisschop-Larsen, 1995). This could explain why the yields from main roads were lower than the yields from the motorways and minor roads. There might therefore be further need to consider if continuous harvest and removal of the roadside grass could impact future biomass yields due to a potential depletion of nutrients present in soil of the verges.

The average annual yield of total solids per hectare of roadside verge in Denmark is presented in Table 4 together with results for the average annual yield of total solids per hectare found in the literature for Wales and Germany.

The yield of total solids per hectare of roadside verge for Germany and Wales were obtained from the literature and found to be 60% and 40% respectively higher than the average yields found for Denmark. The achievable yields will vary depending on time of harvest, soil conditions, weather, and the dominating vegetation of the verges. However, only few locations from the case study in the region of Southern Denmark showed yields in the range of those identified for Germany.

3.1.2. Potential methane yields

The theoretical methane yields and expected practical methane yields obtainable using roadside grass in Denmark is shown in Table 5. For comparison, the practical achievable methane yield from roadside vegetation harvested in Powys, Wales, tested at laboratory scale by Salter et al. (2007) is also presented in Table 5.

The methane yield found by Salter et al. (2007) value is in the range of the practically obtainable yields estimated for Denmark.

Table 5
The theoretical and practical achievable methane yields for roadside grass.

	Theoretical methane yield Denmark	Practical methane yield Denmark	Practical methane yield Wales (Salter et al., 2007)
m^3 CH_4/kg VS	0.49	0.22–0.39	0.27

Table 6
The concentration of potential harmful substances in the roadside grass.

Substance	Denmark	UK (Delafield, 2006)	Northern Germany (Werner, 2010)	Danish legislative	Inhibition levels for anaerobic digestion (Kouzeli-Katsiri et al., 1988)	
				Maximum	Start	Failure
mg/kg TS						
As	0	n/a	n/a	25.00	n/a	n/a
Cd	0	0.26	<0.25	0.80	n/a	$1.10 \cdot 10^4$–$4.00 \cdot 10^4$
Cr	0	2.03	2.90	100.00	$2.25 \cdot 10^4$	$1.15 \cdot 10^4$–$4.00 \cdot 10^4$
Cu	19.2	11.32	14.80	1000.00	$3.00 \cdot 10^3$–$2.00 \cdot 10^4$	$8.30 \cdot 10^3$–$4.70 \cdot 10^4$
Ni	0	2.48	1.70	30.00	$2.25 \cdot 10^4$	$1.00 \cdot 10^4$
Pb	4.1	9.85	7.10	120.00	$2.25 \cdot 10^4$	n/a
Zn	110.1	54.80	60.50	4000.00	$1.00 \cdot 10^4$–$3.20 \cdot 10^4$	$1.00 \cdot 10^4$–$3.00 \cdot 10^4$
Hg	0	0.02	<1.00	0.80	n/a	n/a

Due to practical reasons related to the management of the roadsides it cannot be expected that the verges are harvested when the vegetation can provide the highest methane yields. The grass must furthermore be expected to be of a poorer quality than grass harvested from for example agricultural areas. It is therefore not considered realistic that the values in the high end of the estimated range for the CH_4 yields for Denmark are representative of what would be obtained in practice.

3.1.3. Harmful substances

Table 6 shows the concentrations of the potential harmful substances present in the roadside grass samples, compared with concentrations measured in roadside grass in Germany and the United Kingdom. Furthermore the Danish legislative maximum concentration is presented (The Danish Ministry of the Environment, 2006), as well as the levels for possible inhibitory levels on the anaerobic digestion process (Kouzeli-Katsiri et al., 1988).

The heavy metals content in the roadside grass is of importance for two reasons; the potential inhibiting effect they could have on the anaerobic digestion process and the harmful impacts that the spreading of such non-biodegradable substances on agricultural land could cause on humans and animals if they enter the food chain. Comparing the inhibition levels for the anaerobic digestion of sewage sludge (Kouzeli-Katsiri et al., 1988), it appears that none of the heavy metals were found in concentrations which could be considered as "inhibiting" or harmful.

The standard procedure for biogas plants in Denmark is to apply the digested organic biomass materials as fertiliser on agricultural land. The application of organic materials on agricultural land is subject to the legislation on fertilisation as stated by the Danish Ministry of the Environment (2009) and the rules for waste applied on agricultural land (The Danish Ministry of the Environment, 2006). As roadside grass has not yet been applied for biogas production in Denmark, it is uncertain which legislation regarding the concentration of heavy metals it is subject to. The strictest rules regarding the content of heavy metals in the biomass is enforced if the roadside grass is classified as a waste product in accordance with the rules for waste applied on agricultural land stated by the Danish Ministry of Environment. However, an evaluation of the roadside grass metal concentrations shows that none of the values exceed these legislative values.

3.2. The potential annual harvestable area and yields of total volatile solids in Denmark

The total length of roads and verge areas harvestable annually (according to the specific scenario), and the corresponding potential achievable yields of total volatile solids of grass are presented in Table 7. The loss expected under the ensiling process of the grass is considered in the presented values for total volatile solids.

Table 7
The length of roads in Denmark, the annual total harvestable area, and the corresponding yields of total solids of grass for the three scenarios.

Scenario	Length of roads (km)	Harvestable area (Ha)	Total volatile solids (*t*)
Conservative	34,983	15,745	18,727
Optimistic		25,178	29,946
Practical		17,996	21,404

The annual yields for the total volatile solids in the optimistic scenario were found to be 37% and 29% larger than the annual yields for the conservative and practical scenarios respectively. The harvestable width of the verges strongly impacts the final biomass yields that can be achieved. Flexible harvest equipment capable of harvesting a wide area around verges and mowing around trees and road signs could improve the final yields of biomass significantly.

The estimation of the total volatile solid yield is based on the values found when harvesting in a 1 m wide stripe along the roads (as presented in Section 2.1.1). However, as discussed in Section 3.1.1, it was observed that some verges were characterised by recent removal of build-up soil, hampering the growth of the grass. No indications on the width of this removal of build-up soil has been identified, thus it is uncertain if the vegetation growing further than 1 m from the road is also influenced. In case this removal is not practiced further than 1 m from the road, higher yields could be expected for all roadside verges harvested with a width greater than a 1 m.

An additional issue rarely considered, which could impact biomass yields is the fact that the removal of grass cuttings from roadside verges implies removal of nutrients in the plant biomass. It is therefore not clear (given the current management strategy) how nutrients being taken out will be made available for the growth of roadside grasses in subsequent seasons; and if this will affect the annual yield of biomass adversely over time. However, verges adjacent to agricultural land could be subjected to nutrient flow from fertilisation on the agricultural land, but it is uncertain to what extend this happens and how much it impacts the yield.

3.3. Energy potentials

The estimated values for the total annual input energy, output energy, NEG and EROEI are presented in Table 8.

For all scenarios positive net energy gains (NEG) were observed, indicating that the energy requirements for the biomass harvest, collection, transport, and digester operation would not exceed the achievable energy outputs with roadside grass use for biogas production in Denmark. However, the NEG only corresponds to 1.5–3.0% of the present national production of energy from biogas. All estimated values for the energy return of invested energy (EROEI) were above 2, showing that the energy returns are slightly higher than what is invested in the process.

Table 8
The total annual input energy, output energy, NEG and EROEI when utilising roadside grass.

	Farm scale biogas Plants			Centralised biogas Plants			Centralised and farm scale biogas plants		
	Cons.	Optim.	Pract.	Cons.	Optim.	Pract.	Cons.	Optim.	Pract.
Input energy (GJ)	51,420	76,918	44,317	52,285	78,302	50,230	50,638	75,667	48,347
Output energy (GJ)	111,546	178,373	127,493	124,932	199,777	142792	118,983	190,264	135,992
NEG (GJ)	60,126	101,454	83,176	81,415	121,476	92,339	68,345	114,597	87,646
EROEI	2.17	2.32	2.88	2.39	2.55	2.84	2.35	2.51	2.81

The highest net energy gains were found in the optimistic scenarios. Although more energy input was needed for the acquisition process, the energy outputs were sufficient to result in positive NEG (due to the larger harvest widths and correspondingly larger biomass yields). Nevertheless, the estimated EROEI were found to be highest for the practical scenarios. This is because the total driven distance under the harvest was smaller, as it is assumed the verges can be moved in one step.

The cases where it was assumed that the harvested grass is transported to centralised biogas plants resulted in the highest values for NEG and EROEI. Although the energy input needed for transport was found to be higher than for the other cases due to the larger transport distances to a centralised biogas plants, it seems that the higher efficiency of the centralised plants compensates for this.

As the roadsides in Denmark are already mowed up to two times annually to ensure traffic safety it can be argued if the energy consumed for conducting the current management practices ought to be included in the energy balance. This argument can be viewed as a matter of what the principal aim of roadside mowing is for. Is it to facilitate traffic safety or for biomass production for energy? The energy requirements for the harvest and collection of the roadside grass on average represent 70% of the total energy input. Estimating the energy balance, considering only the additional energy requirements after the current management practices (which are done to facilitate traffic safety only) would result in considerably higher NEG and EREOI. This would favour the use of roadside grass for biogas production in the final results.

3.4. Practical challenges associated with roadside biomass use

3.4.1. Acquisition

Before roadside grass could be used for biogas production in Denmark, some changes to the current procedures for managing the roadsides will be initially required. Importantly, the grass must first be collected and transported to a storage facility or directly applied at the biogas plant. For harvest and collection in Denmark, flail-mowers are considerably the best option for mowing roadsides due to their flexibility, and the fact that the cuttings were mulched, making it possible to collect the cuttings with a suction fan. Implementation of harvest machinery with three mowing units mounted to the tractor has been used in Denmark. The equipment is capable of mowing a width of 3.8 m. With conventional machinery, the verges must be mowed several times, if biomass from more than 1.3 m width of the verges is to be obtained. Specialised harvest equipment could reduce the number of mowing times and the driven distance during harvest. The feasibility of investment in such machinery should be considered further to evaluate if it increases the energy investments, and the cost for labour and fuel. Further research into the energy consumption, when using specialised harvest equipment, is required to evaluate if a positive net energy production can be maintained.

3.4.2. Waste management

An important challenge that should be considered with the roadside grass collection is the management of waste left in the roadsides. Although the samples collected in this study were observed not to contain significant inorganic wastes quantities (e.g. plastics and metal cans), the presence of such contaminant in the collected grass can be foreseen to be an unavoidable problem with biomass collection and use. The most widespread technology in Danish biogas plants is liquid digestion, thus the removal of inorganic wastes which could be present in the roadside verges must be considered, as they can cause operational problems during the anaerobic digestion process. Operations to effectively separate the undesirable inorganics from the biomass must therefore be effected prior to the biomass use. The current Danish solution to the problem of inorganic wastes left in the roadsides is to collect the waste manually several times every year, which is a very costly process. Inorganic wastes should be collected manually just before the roadside grass harvesting, to prevent co-collection of grasses with inorganic wastes (e.g. plastics and metals) by the suction fan of the flail-mower on the one hand, while also avoiding the spending of extra investments on the separation of inorganics from grasses downstream the process chain (before using the grasses for fermentation) on the other hand.

Although no specific separation technologies or their costs were identified or assessed by this study, systems used to separate household waste could hold a promising potential, either separated solely at each plant or mixed with household waste at a waste facility plant.

3.4.3. Anaerobic digestion of roadside grass

Nizami and Murphy (2010) reviewed different technologies for the application of grass silage in anaerobic digestion and found that both solid-state (dry) and liquid (wet) fermentation was feasible. Liquid fermentation in continuously stirred tank reactors is the most widespread technology for biogas production in Denmark. However, the application of grass for liquid fermentation is reported to cause some operation problems. Using a suction fan for collection of the roadside grass forms a risk that the grass is contaminated with soil, such sediments must therefore be regularly removed from the digester. Furthermore it has been reported that grass tends to float in the surface of the digester (Prochnow et al., 2009; Thamsiriroj and Murphy, 2010). This could potentially increase the energy consumption for the stirring process. The stirring equipment can also be subject for operation failures if long grass particles get stuck around it (Prochnow et al., 2009). The same problems can be encountered in cases where inorganic waste present in the biomass is not separated before being fed in into the digester. When working with grass feedstocks with high dry matter, pumping difficulties into the digester might also be encountered using conventional equipment. Mixing the grass with manure before application or tipping it into the digester with a loader could however solve these issues.

The content of lignin in grasses from permanent grassland and natural areas has been reported to increase with the age of the plants (Shiralipour and Smith, 1984); therefore, grass harvested in the autumn can be expected to contain higher lignin content than grass harvested in the spring. Pre-treatment methods should therefore be considered to obtain the optimum CH_4 yields. Several different technologies for pre-treatment of lignocellulosic biomasses have been described by Hendriks and Zeeman (2009) (e.g. steam pre-treatment, liquid hot water pre-treatment, lime pre-treatment, and ammonia bases pre-treatment). If the roadside grass is used only as a supplementary co-feedstock, it should be kept in mind to keep the costs and level of sophistication as low as possible. Communition of the grass size is however, a simple but efficient pre-treatment method that is recommended for roadside grasses, because the reduction of the grass particle size will increase the surface area available for the anaerobic digestion process.

4. Conclusion

The study results showed that net energy gains can be achieved using grass harvested from roadsides for biogas production. The energy return on invested energy was above 2 for all investigated scenarios, thus utilisation of roadside grass in biogas production in Denmark could be feasible from an energetic point of view. Some practical challenges related to the processes of acquisition and anaerobic digestion, were however identified. This include management of inorganic waste in the harvested grass, removal of sediments from the digester, operational failures due to long grass particles getting stuck in the digester stirring equipment, and pre-treatment of grasses with high lignin content. In order to manage these challenges, further energy investments in the acquisition and processing stages might be necessary. It should be stressed that utilisation of this resource could result in other positive externalities, such as improved biodiversity of the verges and recycling of nutrients. Recycling of the biogas digestate for agricultural use could further improve the energy potential, if included in the calculation for NEG and EROEI. This would make it an even more attractive option for biogas production.

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Appendix A.

A.1. Assumptions for estimating the net energy gain (NEG) and the energy return of invested energy (ERIOE) if utilising roadside vegetation for biogas production

The applied values originated from a study where the energy demand for harvest was estimated with a 125 hp tractor (Valtra Valmet 8150), mounted with a 1.3 m wide mowing unit, that collects the grass cuttings (Herder Grenadier MBK 135 S) (Durling and Jacobsen, 2000). The cuttings were transported via a hydraulic suction fan into a container placed on a hook lift mounted to the tractor. The average speed of the harvest process was 2.7 km/h. Full containers were reloaded to a truck (Scania 124, from year 1998, 420 hp) that can transport three containers at a time. The truck transported the roadside grass to the biogas plant where it is tilted off the containers. Energy requirements for the ensiling process was estimated based the assumption that the roadside grass is stored in a silage tube via a tractor driven silage packer (Table A1).

Table A1
Assumptions for estimating the energy balance.

Assumptions	
Diesel consumption for harvest and collection	15 l/h
Speed for harvest and collection	2.7 km/h
Diesel consumption per loading of container	1.5 l
Quantity of grass per container	3741 kg
Diesel consumption for transport	0.42 l/km
Diesel consumption for reloading and emptying 3 containers	15 l
Diesel consumption for ensiling in tube via a tractor driven silage packer	15.0 l/h
Capacity for ensiling system	30 t/h
Energy content in diesel oil	41.8 MJ/l
Energy content in methane	0.0361 GJ/nm^3

Appendix B.

The individual energy inputs and outputs for each step of the acquisition and digestion process in GJ are presented in Table B1.

Table B1
Energy inputs and outputs (GJ).

Case for end use	Scenario	Transport	Harvest and collection	Loading of containers to truck	Unloading and emptying	Storage	Operation and transport of digestate	Produced energy
Farm scale biogas Plants	Conservative	8617	36,464	1135	3782	1422	37,182	148,728
	Optimistic	13,779	53,002	1815	6049	2274	59,458	237,830
	Practically	4924	32,147	1297	4323	1625	42,498	169,991
Centralised biogas Plants	Conservative	9482	36,464	1135	3782	1422	23,797	148,728
	Optimistic	15,163	53,002	1815	6049	2274	38,053	237,830
	Practically	10,838	32,147	1297	4323	1625	27,198	169,991
Centralised and farm scale biogas plants	Conservative	7834	36,464	1135	3782	1422	29,746	148,728
	Optimistic	12,528	53,002	1815	6049	2274	47,566	237,830
	Practically	8954	32,147	1297	4323	1625	33,998	169,991

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