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Is it beneficial to use biogas in the Danish transport sector? – An environmental-economic analysis

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ABSTRACT

Denmark is ambitious in the green transition of its transport sector. The biogas has potentials to substitute diesel as the vehicle fuel. In this paper, we examine the whole chain of biogas utilisation (biomass supply, biogas production and distribution, and fuel substitution) from both environmental and economic perspectives. We find that with low/high biomass supply potentials, the saved greenhouse gas emissions range from 0.89 to 1.66 million tons/2.19 to 4.27 million tons CO_2e (carbon dioxide equivalent). The soil carbon stock could increase 52310/124770 tons with low/high biomass supply potentials (measured as remaining carbon in soil in 100 years after application of digestate into soil). The biogas plant owners can obtain a return of investment ranging from 10.78% to 13.62% depending on biomass supply potentials and biogas production technologies. The farmers can save up to 717.93 and 1382.1 million DKK (Danish krone) by substituting mineral P (phosphorus) and N (nitrogen) fertilisers with low biomass supply potential and 1.74 and 3.44 billion DKK with high biomass supply potential. Finally, the vehicle users have incentives to use biogas because of its cost advantage. However, there are also some potential barriers and uncertainties in achieving the green transition, e.g. initial investment for CO_2 conversion equipment and diesel-vehicle users' sunk costs, which could require suitable policy supports. We suggest that using biogas in heavy-duty vehicles could be an effective way to reduce carbon emissions in the transport sector.

1. Introduction

Nowadays we face two important challenges: energy or resource scarcity, and climate change (Clastres, 2011; Cong, 2013). Although new sources of fossil fuels are occasionally discovered worldwide, they will be still depleted in the future due to the non-renewable essence (Shafiee and Topal, 2009). The combustion of fossil fuel is one main source of greenhouse gas (GHG) emissions which are responsible for the global warming and climate change (Davis and Caldeira, 2010). In contrast, renewable energy, such as bioenergy, may be naturally replenished (Cong and Shen, 2014). Upon sustainable management of biomass resources, bioenergy production systems may perform with low or near-zero carbon emission from the full life-cycle perspective (Niero et al., 2014; Seghetta et al., 2016b; Thomsen et al., 2017). Therefore, bioenergy production may be both resource and climate compatible. Bioenergy can substitute fossil energy in many ways, one of which is as the motor fuels (Farrell et al., 2006). One promising type of biofuel is biogas, which can be produced from organic biowaste, e.g. manure, sludge, green biomass, industrial and household waste, based on the anaerobic digestion process using the second generation biofuel technologies (Lastella et al., 2002). Biogas produced from organic waste and plant residues does not necessarily conflict with agricultural land for food production like the first generation technologies (Sims et al., 2010).

To limit the rise in global average temperature to 2 °C and improve the portfolio of energy supply, the European Union has set a "20-20-20" target by 2020 for reducing GHG emissions by 20% from the 1990 levels; supply 20% of EU energy from renewables; and increasing energy efficiency by 20% (Böhringer et al., 2009). The EU Renewable Energy Directive set Denmark a goal of at least 10% of the transport energy consumption to be based on renewable energy by 2020 (Danish Energy Agency, 2015). In accordance, the Danish government set a plan for Green Growth in 2009 stating that up to 50% of livestock manure in Denmark must be used for

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Nomenclature

As	Arsenic
AT	Articulated truck
BS	Biogas settings
Cd	Cadmium
CH_4	Methane
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Cr	Chromium
Cu	Copper
DKK	Danish krone
DM	Dry matters
GHG	Greenhouse gas
H	High
HDV	Heavy duty vehicle
Hg	Mercury
ICCT	The international Council on Clean Transportation
kWh	Kilowatt-hour
L	Low
LNG	Liquefied natural gas
N	Nitrogen
Ni	Nickel
Nm^3	Normal cubic meter
P	Phosphorus
Pb	Lead
PJ	Petajoule
RS	Reference scenario
TS	Total solid
TT	Truck-trailer
VS	Volatile solid
WtW	Well-to-wheel
Zn	Zinc

energy production (mainly biogas) by 2020 (Foged, 2012; Thomsen et al., 2017). There is also a policy objective that the Danish transport sector needs to be 100% CO_2 neutral in 2050, yet this sector is currently far behind the target compared to other sectors (Mathiesen et al., 2015).

Currently the Danish transport sector is highly dependent on fossil fuels (which occupied 95% of total transport energy consumption in 2014) while vehicles powered by biofuel and electric grow slowly (Table A1) (Jørgensen, 2014). As a promising vehicle fuel, biogas can be upgraded and distributed using natural-gas networks. Denmark has great potentials for biogas production from different organic biomass sources. The current biogas production is around 4 Petajoule (PJ) whereas the estimated potential can reach 40 PJ and perhaps up to 85 PJ if including all available organic resources (Energistyrelsen, 2014). Road transport uses about 160 PJ, of which heavy duty vehicles (HDVs) consume approximately 90 PJ and cannot be easily substituted by, e.g., electric vehicles.

In sum, there are political, administrative and commercial interests for the development and use of biogas in the transport sector and therefore there is the need to investigate the environmental and economic effects of using the biogas from different stakeholders' perspectives. Numerous studies have been carried out on evaluation of biogas utilisation from technical, economic and environmental perspectives (Johansson, 1996; Murphy et al., 2004; Patterson et al., 2011). First, biogas utilisation in transportation is dependent on technical development, e.g. utilisation efficiency of biogas affects its competitiveness (Murphy and Power, 2009). Second, the utilisation process is affected by numerous economic factors, e.g. production cost of biogas and prices of fossil fuels can jointly affect the profitability of biogas utilisation (Murphy and McCarthy, 2005). Third, biogas utilisation is also motivated by its environmental benefits. As such, GHG emission reduction from biogas utilisation could be consistent with public interests and compensated by the government, which is an important factor to keep the biogas system competitive (Lantz et al., 2007). However, the studies about biogas utilisation in the transportation sector are still relatively rare (Patterson et al., 2011; Uusitalo et al., 2013). It is not clear whether (or in which way) the biogas utilisation in the transport sector is beneficial. Furthermore, the answer to this question will be dependent on the intertwined factors above and also the perspectives, i.e. from the perspective of private sectors or the whole society. The private sectors could care more about the profitability, while ignoring the potential environmental externalities. In contrast, for the whole society the economic and environmental effects are both important.

The aim of this study is to compare costs and benefits of biogas utilisation in the Danish transport sector with the current fossil fuel option from perspectives of private sectors (i.e. biogas plants), farmers, vehicle users and the whole society. There are some specific questions to be addressed: 1) how large is the potential for GHG reduction when using biogas as the vehicle fuel; 2) how does the profitability of biogas plants vary given different energy production technologies; 3) is biogas competitive in current Danish market compared with fossil fuel (diesel)?

The paper is structured as follows: In Section 2, we present input data and analysis methods along the whole value chain and future scenario settings. In section 3, we present results in terms of environmental and economic effects from different stakeholders' perspectives. In section 4 we discuss implications of biogas utilisation to Danish energy policy and potential uncertainties in promoting biogas utilisation and section 5 concludes.

2. Materials and methods

In this study, we perform the environmental-economic analysis (Cong and Termansen, 2016) along the entire value chain from production to utilisation of biogas in the transport sector (Biogas settings, BS), where the reference scenario (RS) uses diesel in the transport sector. In the BS, the value chain includes biomass supply, biogas production, upgrade and distribution, and biogas use for vehicles. The value chain analysis of RS includes the economic analysis of diesel use (market price) and its direct and indirect emissions. The research framework is visualized in Fig. 1.

The outcome of the assessment is dependent on the total amount and structure of biomass supply, the biogas production technologies, the inputs and outputs of biogas plants and substitution with diesel currently used in HDVs.

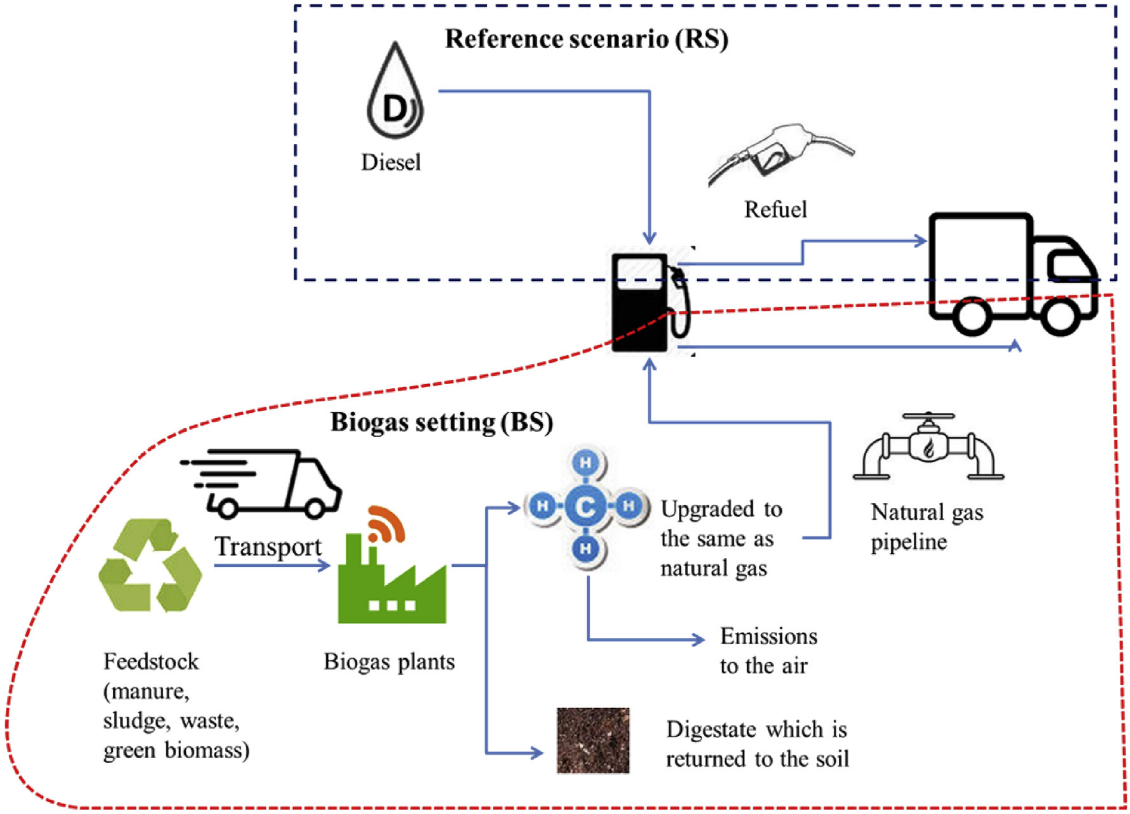

Fig. 1. The reference and biogas scenarios.

2.1. Biomass supply

We set 2035[1] as the year of scenarios. The biomass supply potential in 2035 is estimated according to the preconditions and methodological setup of the +10 Million Tonnes Study (Gylling et al., 2013; Jensen et al., 2017). The baseline setting is business as usual, which means that there will be no major changes in the cropping systems. The two alternative settings are 1) biomass-optimised setting which implies several changes in cropping systems and harvesting methods to maximize biomass production; 2) environment-optimised setting which includes not only changes in the biomass optimised setting but also modifications to enlarge environmental benefits (e.g. reduction of nutrient losses, improvement of soil carbon, enhanced biodiversity and reduced pesticide use). The methodology for the agricultural part of the settings (including assumptions and calculation basis) is described in detail in Gylling et al. (2013) and an online note (Kristensen and Jørgensen, 2012). We set up the biomass supply scenarios based on the biomass resources quantified in the environmental-optimised setting (Jensen et al., 2017).

To reduce the complexity we set two levels for biomass supply: the low (L) and high (H) levels. The low level assumes that 50% of potential manure, 20% of potential green biomass, 40% of potential industrial and household waste and 62% of potential sludge are used for biogas production. The high level assumes that 100% of potential manure, 60% of green biomass, 80% of potential industrial and household waste and sludge are used for biogas production (Birkmose et al., 2015). The biomass supply in dry matters (DM) in two levels are provided in Figure A1 and Table A2.

[1] The +10 Million Tonnes Study chose 2020 as the scenario year. In a recent study, Jensen et al. found the implementation process in the +10 Million Tonnes Study was delayed and would not be achieved until 2035.

2.2. Biogas production

The biogas plants usually use green biomass, manure, industrial and household wastes, and sludge as feedstock (the second-generation technology). Two types of plants are considered in our study: 1) manure-based where the plants take 75% of feedstock as manure and the remaining as green biomass; 2) sludge-based where there are not any formal limits about the feedstock mixture. The mixture of feedstock is co-digested through the anaerobic process to produce biogas.

In addition to the CH_4 production, the biogas plant also produce residues (digestate) and CH_4 emissions (leakage) during the production process. The digestate (containing N, P but also micro-pollutants such as heavy metals) are applied to soil substituting mineral fertilisers (Seghetta et al., 2016a). An overview of inputs and outputs of biogas plants are provided in Figure A2.

There are three settings for the biogas plant technologies (Birkmose et al., 2013):

1) Business-as-usual. The biogas is upgraded to biomethane by conventional methods. Process heat is produced by biogas and therefore less methane output. Data from the most recenty installed biogas plants is used.
2) Optimised plant. Retention is prolonged and losses from biomass in the whole biogas production process are reduced to a minimum to give higher outputs. Process heat is supplied by heat pumps running on renewable energy and cooling down the digested biomass.

Table 1
Scenarios setting.

Biomass supply potential	Biogas production technology	Biogas scenarios
Low biomass supply	State of the art	Scenario 1
	Optimised plant	Scenario 2
	Optimised plant with CO_2 conversion technology	Scenario 3
High biomass supply	State of the art	Scenario 4
	Optimised plant	Scenario 5
	Optimised plant with CO_2 conversion technology	Scenario 6

3) Optimised plant with the CO_2 conversion technology. The biogas with the current technology and optimised setting includes 65% methane (CH_4) and 35% carbon dioxide (CO_2). Using the carbon dioxide conversion technology ($4H_2+CO_2$->CH_4+2H_2O), the biogas output can have higher methane content (90% CH_4 and 10% CO_2). The optimised plant converts the CO_2 in the biogas to CH_4 using surplus electricity from wind energy.

Finally, the biogas from all three technologies will be upgraded to the same standard as natural gas (>95% CH_4) and substitute diesel for transportation using the natural gas network (pipelines). The unit methane outputs from different types of biomass in the plants with three conversion technologies are provided in Figure A3. According to biomass supply potentials and biogas production technologies, six biogas scenarios are included in the following analysis (Table 1).

2.3. Substitution with diesel in the transportation

The fuel consumption of the road transport sector is about 158 PJ in 2013 and will decrease towards 2035 (145 PJ) as a combination of improved fuel efficiency and increase in km travelled (Nielsen et al., 2015a; Winther, 2015). The potential biogas production is estimated to be less than the predicted demand, which requires considerations of how biogas should be used in the road transport sector (instead of power generation or other utilizations) to maximize renewable energy substitution and environmental benefits.

The upgraded biogas is predominantly used to substitute diesel use for HDVs, which are hardly replaced by other alternatives, e.g. electric vehicles. The HDVs mainly include rigid trucks, truck-trailers (TT), articulated trucks (AT) and buses which are further divided according to their weight categories and emission levels corresponding to EU emission standards (EMEP/EEA, 2013). In practice, the rigid trucks and buses are usually substituted by CNG (Compressed Natural Gas) driven vehicles, whereas the replacement of TT/AT trucks is mainly made with LNG (Liquefied Natural Gas) trucks.

According to Winther and Jensen (2016) and ICCT (2015)'s estimations. We assume that a 10% lower fuel economy for both CNG and LNG vehicles compared with the diesel vehicles in calculation (i.e. an extra 10% energy is needed for gas-driven vehicles for an identical distance).

2.4. Environmental effects analysis

Regarding the environmental effects, we consider the (net) greenhouse gas emissions as difference between saved GHG emissions due to fuel substitution and methane emissions during production, distribution and use of biogas, soil carbon stock obtained by using digestate as biofertilizer (Thomsen et al., 2017), the amounts of bioavailable phosphorus and nitrogen in the digestate and the externalities associated to heavy metals (Pizzol et al., 2015).

Starting from the average methane outputs (Figure A3), we calculate the methane production from each different type of biomass in the plants with three production technologies and the low and high biomass supply potentials (Table A3). We calculate methane emissions for each of the ingestate biomass for the biogas plant according to equation (1):

$$CH_4E_{i,s,j,k} = DM_{i,s} \times VS_i \times MP_{i,j} \times EF_k \tag{1}$$

where $CH_4E_{i,s,j,k}$ is the methane emissions (m^2 CH_4) from biomass (i) in the supply level (s) with the production technology (j) and plant type (k); $DM_{i,s}$ is the amount (dry matter) of biomass i in supply level (s) (i.e. low or high supply potential); VS_i is the percentage of volatile solid of dry matter content in biomass i; $MP_{i,j}$ is the average methane conversion potential in biomass i with technology j (Figure A3) expressed as m^3 CH_4/kgVS. Values for $DM_{i,s}$, VS_i and $MP_{i,j}$ are provided in Table A2 (Jensen et al., 2017). Finally, EF_k represents the methane emission factor for type k (manure-based and sludge-based) biogas plants (Nielsen et al., 2015b).

The amount of digestate with low and high biomass supply potentials for the manure and sludge-based biogas plants are derived by multiplying the ingestate biomass with the ratio between the dry matter contents in digestate versus ingestate, $DM_{digestate}/DM_{ingestate}$, at manure and sludge-based plants which are equal to 0.33 and 0.67 (Table A4) (Thomsen et al., 2017).

The concentrations of heavy metals (including Zn (Zinc), Cu (Copper), Ni (Nickel), Hg (Mercury), Pb (Plumbum), Cd (Cadmium), As (Arsenic) and Cr (Chromium)), P, N, in digestate from manure and sludge-based plants are calculated according to equation (2):

$$Con_{digestate,l} = \left(\sum_i DM_{ingestate,i} \times Con_{ingestate,i,l}\right) \Big/ \times \sum_i DM_{digestate,i} \tag{2}$$

where $Con_{digestate,l}$ is the concentration of heavy meatal (l) in the digestate measured in units of mg/kg DM; $DM_{ingestate,i}$ ($DM_{digestate,i}$) is the dry matter of biomass type (i) in ingestate (digestate); $Con_{ingestate,i,l}$ is the concentration of heavy metal l in the ingestate i (DM) measured in units of mg/kg. DM. Concerning the heavy metals relative to manure, the parameter has been calibrated as an average of cattle and pig related manure (solid and liquid) (Thomsen, 2016). Data are provided in Table A5.

Lastly, for soil carbon stock, we assume that the carbon content of digestate is 50%. All digestate is applied to soil as biofertilisers and after 100 years, while 10% of the carbon content in the biofertilisers will remain in the top soil (the remainings being gradually mineralized and emitted to air) (Seghetta et al., 2016b).

[2] Five farm biogas plants include: Lynggaard, Madsen Biogenergi, Grøngas, Combigas and Holbæk; nine common biogas plants include: Ribe, Linkogas, Lemvig, Thorsø, Hashøj, Blaabjerg, Vegger, Biokraft and Maabjerg.

2.5. Economic effects analysis

In the economic analysis, we consider four types of stakeholders: biogas plant owners, farmers, vehicle users, and society because of their various objectives.

2.5.1. Biogas plant owners

There are often significant technical differences between Danish biogas plants, including the difference between farm and common plants, size, plant design and input structure. We mainly refer to a survey of 14 representative existing biogas plants in Denmark including nine common biogas plants and five farm biogas plants[2] (Figure A4) (Hjort-Gregersen, 2015). Common plants are usually larger and have higher production capacities than farm plants. Therefore, we use the averages of common plants and farm plants in the following analysis.

The profit before tax is an important indicator for the plant owners, which is equal to the difference between revenue and cost. The costs of biogas plant (*c*) include both the fixed and variable costs. The fixed cost (*fc*) includes the depreciation cost (*dc*), interest cost (*ic*), labor cost (*lc*), operation and other cost (*otc*). The variable cost (*vc*) includes the feedstock cost (*fsc*), transportation cost (*tc*), process heat cost (phc), electricity cost (ec), hydrogen cost (hc), digestate process cost (*dpc*). Therefore, the total cost can be calculated as:

$$c = fc + vc \\ = (dc + ic + lc + otc) + (fsc + tc + phc + ec + hc + dpc) \qquad (3)$$

We use the investment cost (*invc*) divided by the lifetime (*t*) to get the depreciation cost (*dc*) (Straight-line Depreciation Method) as below:

$$dc = invc/t \qquad (4)$$

The investment cost is calculated by multiplying the total biomass processed (*tbp*) with the unit investment cost (*uic*). The investment cost is about 1250 DKK/ton dry matter processing capacity with a depreciation rate of 6.7% (the average lifetime is 15 years). The yearly installment is calculated as below (Chandrasekar and Kandpal, 2004):

$$ic = invc \times r \times (1+r)^t \Big/ \left((1+r)^t - 1\right) \qquad (5)$$

We assumed that the biogas plants have the average investment of 5 million DKK and hire employees which are equivalent to 2 full-time jobs. So the labor cost is calculated as:

$$lc = invc/5,000,000 \times 2 \times aw \qquad (6)$$

where *aw* is the average wage for the full-time employee. *otc* in equation (3) is the other cost including the operation, maintenance, miscellaneous expense, administrative expense, insurance, storage and etc.

The feedstock cost is calculated to capture costs related to feedstock collection, sorting and purchase. The transportation costs consider the average transportation distance, trucks' average capacities, drivers wage and trucks' purchase, usage and maintenance costs. The process heat usually comes from different sources. Most plants utilise heat from their own motor-generator sets and the net heat consumption (where we deduct the heat produced by the plants) is about 62 kWh/ton (in dry weight, dw) of feedstock.

The electricity is used to pump and mix biomass for cleaning and transport of biogas, ventilation, lighting, etc. The optimised plants needs roughly double the electricity consumption because of the prolonged retention time compared with the state-of-art plants. In the state of the art technology, the process electricity is about 0.25 kWh/Nm^3 CH_4. In the optimised technology, because the plants typically have longer residence time which also increases the need for stirring, we assume that the process energy is 0.5 kWh/Nm^3 CH_4.

The optimised plants with CO_2 conversion technology needs extra hydrogen and energy inputs for increased methane production. The conversion cost is obtained by multiplying the unit cost for CO_2 conversion (*Uccc*) with extra CH4 production through conversion.

A complete list of variables used in the analysis can be seen in Table A6. The main price and physical input information can be found in Tables A7. The revenue is from sales of upgraded methane (CH_4), which is calculated as the product of methane price (P_m) and methane output (O_m) (see Section 2.2).

2.5.2. Farmers

The benefits are saved P (W_{Pfert}) and N (W_{Nfert}) fertilisers because of spreading digestate with P (S_{Pfert}) and N (S_{Nfert}) to soil. The substitution ratio (*Su*) is set as 1 kg P from digestate could substitute 0.75kg mineral P fertilizer ($Su_{Pdigestate,mineral}$); 1 kg N from the digestate could substitute 0.9 kg mineral N fertilizer ($Su_{Ndigestate,mineral}$).

$$W_{Pfert} = S_{Pfert} \times Su_{Pdigestate,mineral} \qquad (7)$$

$$W_{Nfert} = S_{Nfert} \times Su_{Ndigestate,mineral} \qquad (8)$$

We calculated farmers' benefits as the products of fertilisers' prices (Table A8) and their saved amounts, i.e. W_{Pfert} and W_{Nfert}.

2.5.3. The society

The environmental costs arise from increased heavy metal concentration in digestate compared with mineral fertilizer measured per mass units content of P. We choose cadmium as a representative because its shadow price is known (Table A8) (Pizzol et al., 2015). The increased cadmium (ΔCd) is:

$$\Delta Cd = C_{cd,Pfert} \times W_{Pfert} - C_{cd,slu} \times W_{slu,d} - C_{cd,man} \times W_{man,d} \qquad (9)$$

$$W_{Pfert} = S_{Pfert} \times Su_{Pfert,d} \\ = \left(C_{p,slu} \times W_{slu,d} + C_{p,man} \times W_{man,d}\right) \times Su_{Pdigestate,mineral} \qquad (10)$$

where $C_{cd,Pfert}$ is the proportion of cadmium in P mineral fertilizer; $C_{cd,slu}$ is the proportion of cadmium in digestate of sludge-based plants; $C_{cd,man}$ is the proportion of cadmium in digestate of manure-based plants; $W_{slu,d}$ is the amount of digestate from sludge-based plants; $W_{man,d}$ is the amount of digestate from manure-based plants; $C_{p,slu}$ is the proportion of P fertilizer in the digestate of sludge-based plants; $C_{p,man}$ is the proportion of P fertilizer in the digestate of manure-based plants;

Regarding environmental benefits, there are saved GHG emissions because of 1) carbon sequestration in the soil, which can be calculated as multiplying the carbon sequestration in 100 years (see section 2.5) with 44/12 (the ratio of CO_2 to C); and 2) using biogas to substitute diesel while considering the methane emissions during production and use, which can be calculated as the difference between (both direct and indirect) emission of diesel substituted by biogas and the methane emissions during biogas production, distribution and vehicle use (see section 2.4).

2.5.4. The vehicle users

We compare fuel consumption (*FC*) of biogas and diesel based on the their respective heat value (*HV*) (Table A9) and utilisation efficiency (see section 2.3), as shown in equation (11):

$$FC_{diesel} \times 1.1 \times HV_{diesel} = FC_{CH4} \times HV_{CH4} \tag{11}$$

We find that one ton of diesel (1201.92L) can be substituted by 1.00688 tons of CH4 (= 1409.632Nm^3 (Normal cubic meter)).

3. Results

3.1. Environmental effect analysis

3.1.1. Greenhouse gas emissions

3.1.1.1. Methane emissions from biogas plant. Methane emissions from biogas production could range from 29.31 to 53.06 million m^3 with the low biomass supply potential, of which the methane emissions from manure-based plants occupy about 91.5%. With the high biomass supply potential, the methane emissions from biogas production could be 2.4 times higher than the low supply potential (ranging from 70.68 to 127.91 million m^3), where 98,2% of the emissions are from manure-based plants (Fig. 2).

For the manure-based biogas plants, it can be seen that emissions are mainly from manure, grain and rape substituted with grass, and straw from grain and rape. In general, the biomass supply potentials have larger effects on the source structure of emissions than the biogas plants' technologies. With the high biomass supply potential, the manure's relative contribution for methane emissions (e.g. 31.58% in Scenario 4) is less than the low supply potential (40.91% in Scenario 1). Instead, the contributions of all types green biomass are enhanced with high biomass supply potential compared with the low supply potential. When the biogas plants are optimised and the retention time is prolonged, the relative contributions of straw (both from grain and rape, and grass seed production), grass and road verge cutting become larger, while the manure, catch crop and grass (to substitute rape and grain)'s contributions become less (Figure A5).

For the sludge-based biogas plants, it can be seen that emissions are mainly from sludge, mixed organic household waste, and biodegradable waste. Similarly, the biomass supply potentials have larger effects on the source structure of emissions than the biogas plants' technologies. With the high biomass supply potential, the sludge's relative contribution for methane emissions (e.g. 35.2% in Scenario 4) is less than with the low supply potential (45.63% in Scenario 1). Instead, the contributions of all types of waste are enhanced with high biomass supply potential compared with the low supply potential. When the biogas plants are optimised and the retention time is prolonged, the relative contributions of biodegradable kitchen waste, biodegradable waste, organic household waste and sludge become larger, while the grease and oil mixture from oil, edible oil and fat, mixed organic household waste's contributions become less (Figure A6). We find that for both types of biogas plants, the CO_2 conversion technology primarily affects the total emissions instead of affecting the source structure of emissions.

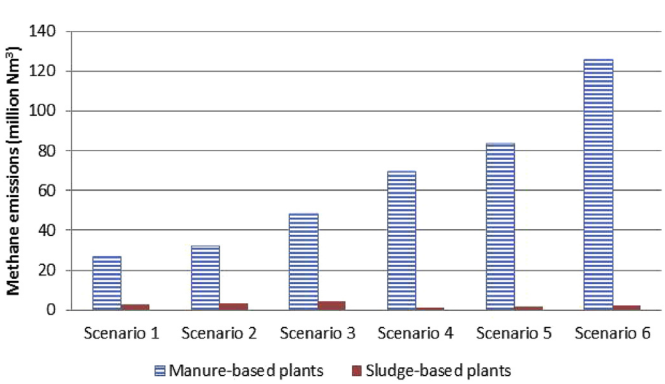

Fig. 2. Methane emissions from manure-based and sludge-based biogas plants.

3.1.1.2. Methane emissions from fuel stations and vehicles. With the low leakage case, the methane emissions from exhaust, engine loss and fuel stations range from 1.96 to 3.55 million Nm^3 CH_4 (low biomass supply potential) and from 4.93 to 8.92 million Nm^3 CH_4 (high biomass supply potential). The engine loss contributes the most (56.82%) in the methane emissions, followed by fuel stations loss (42.75%). Methane in the exhaust is relatively small (0.43%). In contrast, for the high leakage case, methane emissions from exhaust, engine loss and fuel stations are range from 8.44 to 15.27 million Nm^3 CH_4 (low biomass supply potential) and from 21.2 to 38.37 million Nm^3 CH_4 (high biomass supply potential). The engine loss still contributes the most (61.79%) in the methane emissions, followed by fuel stations loss (23.24%). Methane in the exhaust has a more significant contribution (14.96%) compared with the low leakage case (Fig. 3).

Regarding the saved GHG emissions, we find that with the low biomass supply potential, the saved GHG emissions range from 0.89 to 1.66 millions of tons (ca 1.6–3.1% of Denmark net GHG emissions in 2012). For the high biomass supply potential, the saved GHG emissions are even higher, ranging from 2.19 to 4.27 millions of tons, which is equivalent to 4.1%–8.04% of Denmark net GHG emissions in 2012 (Fig. 4).

3.1.2. Soil carbon stock

With low biomass supply potentials (Scenarios 1–3), the total carbon returned to the soil in 100 years can reach 52310 tons, 84.11% of which is from manure-based biogas plants. While for high biomass supply potentials (Scenarios 4–6), the total carbon returned to the soil in 100 years can reach 124770 tons.

From the perspective of source structure of soil carbon stock, it can be observed that for the low biomass supply potentials, the carbon stock is primarily contributed from animal manure (45.71%), followed by the straw from grain and rape (21.35%) and grain substituted with grass (16.78%) in the manure-based biogas plants. The remaining green biomass (straw from grass seed production, rape substituted with grass, permanent grass, weed and road verge cutting) only contribute 16.17% of the carbon stock from the biogas plants.

The high biomass supply potentials shows that the relative contribution of animal manure decreases compared to the low supply potentials. This loss is distributed among each of the green biomass. The straw from grain and rape is shown to have the largest increase in the contribution, followed by grain substituted with grass, rape substituted with grass and straw from grass seed production. Overall, the other green biomass increases by 0.84%.

For the sludge-based biogas plants, the low biomass supply potentials show that the carbon stock is primarily from the sludge (63.82%), followed by mixed organic household waste (22.35%) and biodegradable waste (10.72%). The remaining waste only contributes to 3.1% of the carbon stock from the biogas plants.

For the high biomass supply potentials, the relative contribution of sludge decreases by 10.51% compared to the low potentials, with this loss shared between the other wastes. The mixed organic household waste gets the largest increase in the contribution, followed by biodegradable waste. The other waste increases by 0.9% in total (Fig. 5).

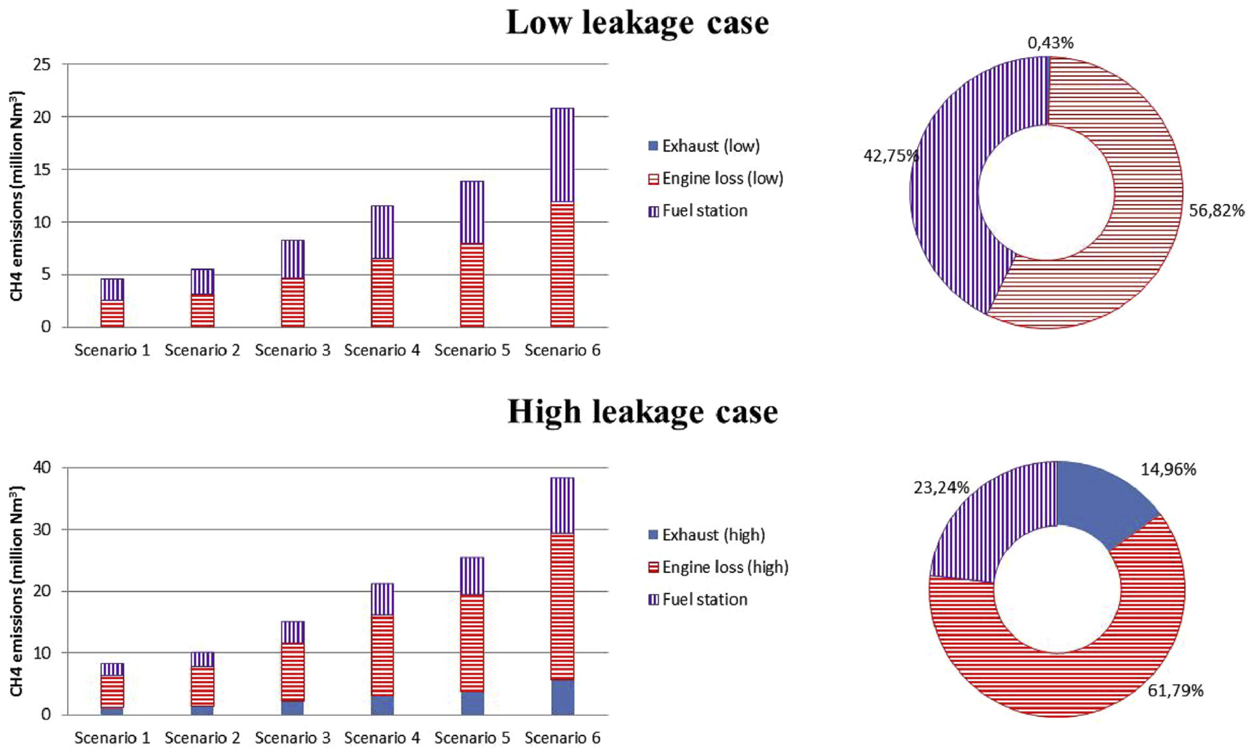

Fig. 3. Methane emissions from fuel stations and vehicle use.

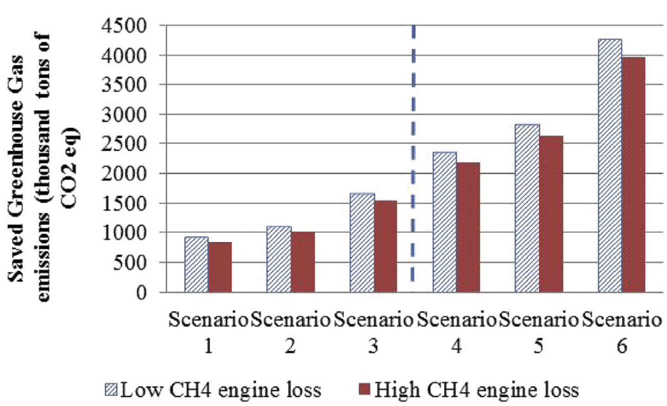

Fig. 4. Saved GHG emission in six scenarios considering both the low and high levels of CH_4 engine loss.

3.1.3. The heavy metal effects and saved mineral fertiliser

In general, there are more zinc (Zn) and copper (Cu) residues than other heavy metals in digestates of biogas plants. In (Scenarios 1–3), the total residues of zinc and copper can reach 1066.75 and 625.75 tons respectively. While in Scenarios 4–6, the total residues of zinc and copper can increase by 135.3% and 139.5%, and reach 2509.99 and 1498.94 tons respectively.

In contrast, the residues of nickel (Ni), mercury (Hg), plumbum (Pb), cadmium (Cd), arsenic (As) and chromium (Cr) are relatively low. In scenarios 1–3, the residues of Ni are the highest (23.46 ton), followed by Pb (22.11 ton), Cr (8.89 ton), As (3.85 ton), Cd (1.27 ton) and Hg (0.29 ton). Compared with scenarios 1–3, the residues of As, Cr and Ni increase larger (146.26% on average) than Hg, Pb and Cd (90.99% on average) in Scenarios 4–6 (Fig. 6).

Because digestates are used to feed back to the soil to substitute chemical fertilisers, it would be more useful to compare the differences of heavy metal outputs between the digestates and chemical fertilisers. Due to lack of data, we only compared cadmium as an example. With the low biomass potential, the total phosphorus reaches 59,827.31 ton, of which 75% can be used as P fertilizer. The equivalent P chemical fertilizer includes 0.98 ton cadmium on average. So using the digestate to substitute P fertilizer has an extra Cd output (ca. 0.29 ton). The extra Cd output is about 0.39 ton for the high biomass supply potentials.

3.2. Economic effects analysis

3.2.1. Biogas plant owners

We start from the profitability analysis. In all the scenarios, the biogas plants all show positive profitability. With the low biomass supply potential, the average profit is 571.46 million DKK (range from 475.44 to 717.68 million) while the average rate of return is 11.98% (range from 10.93% to 13.10%). With the high biomass supply potential, the average profit is 1.45 billion DKK (range from 1.24 to 1.78 billion) while the average rate of return is 12.21% (range from 10.78% to 13.62%).

With both biomass supply potentials, the absolute profits of optimised plants with CO_2 conversion technology are the highest followed by optimised plants and then the state-of-art plants. However, regarding to the relative profitability (rate of return), there is an opposite trend, i.e. state-of-art plants have the highest rate of return, followed by the optimised plants and then the optimised plants with CO_2 conversion technology (Fig. 7). The potential reasons are the relative increases in investment for three types of plants surpass the increases in profits.

We further investigate cost structures of biogas plants in different scenarios. It can be seen when the plants are optimised, the maintenance and other costs have the greatest increase followed by electricity and labor costs (Figure A7). When the optimised plants are equipped with CO_2 conversion technology, the

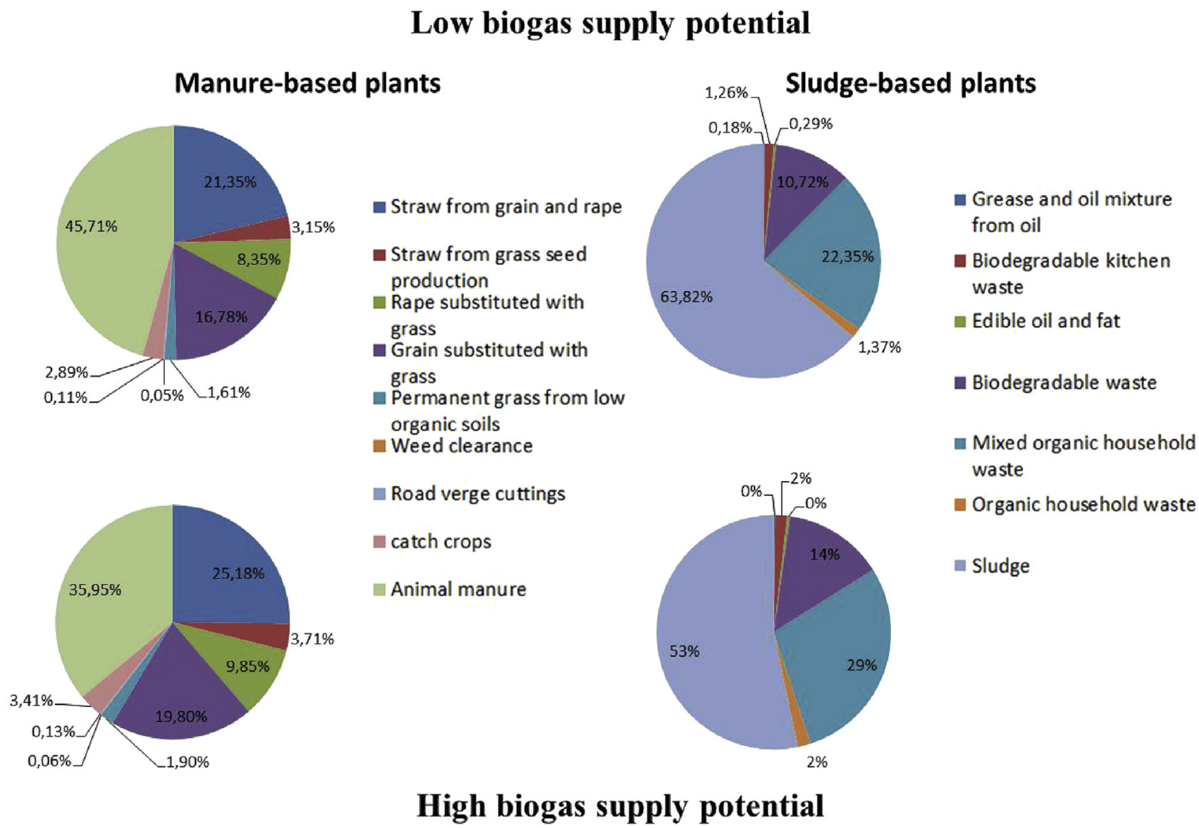

Fig. 5. Source structure of soil carbon stock for manure- and sludge-based plants.

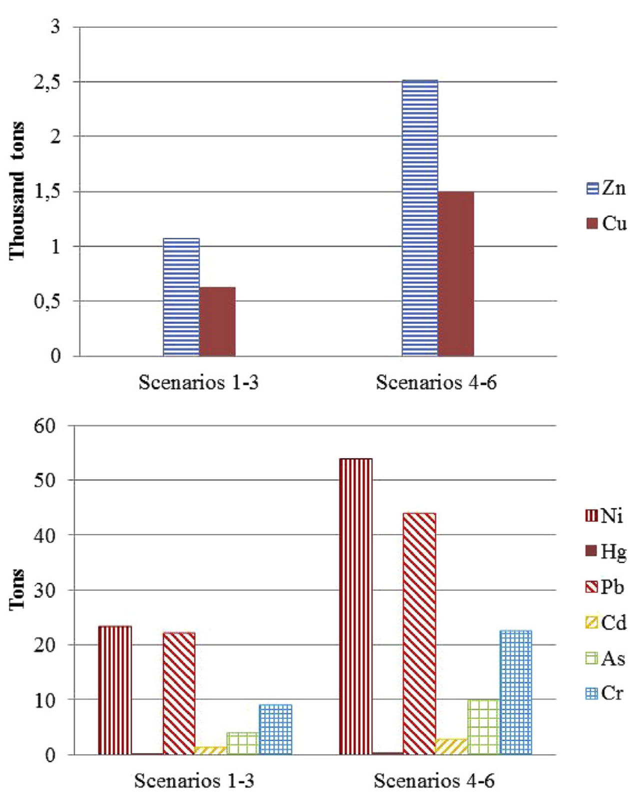

Fig. 6. The outputs of heavy metals with low (Scenarios 1–3) and high (Scenarios 4–6) biomass supply potentials.

maintenance and other costs still increased the most followed by hydrogen and labor costs. The investment costs, which affect both maintenance and other costs, and depreciation costs, become influential when the plants are upgraded.

3.2.2. *Farmers*

With low biomass supply potentials, the farmers can save up to 717.93 and 1382.1 million DKK for P and N fertilisers respectively. With high biomass supply potentials, the farmers can save even more, e.g. 1.74 and 3.44 billion DKK for P and N fertilizer respectively.

3.2.3. *The society*

For society, the environmental benefits (or costs) are in different scales. The cadmium cost are relatively small, e.g. 706,720 and 979,780 DKK in low and high biomass supply settings. In contrast, the Carbon stock benefit could be very significant, e.g. 22.22 and 52.99 million DKK in low and high biomass supply settings.

Regarding to environmental benefits of saved GreenHouse Gas (GHG) emissions, we find that with the low biomass supply potential, the benefits range from 89.16 to 174.45 million DKK (ca 0.27–0.54‰ of Denmark GDP in 2012). With the high biomass supply potential, the saved GHG emissions are even higher (range from 229.65 to 448.49 million DKK), which is equivalent to 0.71–1.38‰ of Denmark GDP in 2012.

3.2.4. *The vehicle users*

For one ton diesel (or CH4 equivalent), the diesel vehicle uses need to pay 10,396.61 DKK while the CH_4 vehicle users need to pay 8246.35 DKK. If we do not explicitly consider the cost difference of diesel engine and gas engine, the CH_4 is competitive in the market compared with diesel.

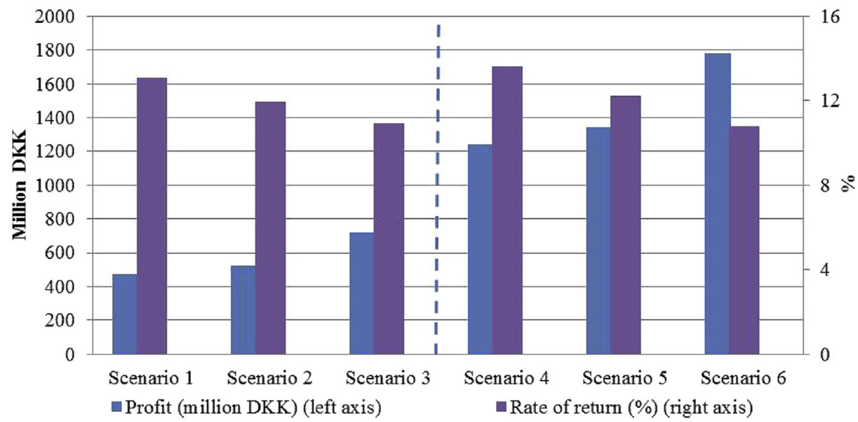

Fig. 7. Profits and rates of return of biogas plants in the six scenarios.

4. Discussion

4.1. GHG reduction potentials and its role in Danish climate policy

Denmark has an ambitious climate policy which requires that the transportation sector should be CO_2 neutral in 2050 (Mathiesen et al., 2015). According to the latest Danish energy statistics, the observed CO_2e emissions from transport reached 14.49 million tonnes (Danish Energy Agency, 2016b), corresponding to 207.89 PJ energy consumption. According to the predications of Danish Energy Agency (2016a), Denmark's gross energy consumption ranged from 590 PJ to 653 PJ depending on different energy systems. If the proportion of transport in the gross energy consumption (27.68%) and the carbon intensity in the transport (69.7 k tonnes CO_2/PJ) remain unchanged, CO_2 emissions from the transport sector will range from 11.38 to 12.6 million tonnes. Taking the average prediction of CO_2 emissions (11.99 millions), the carbon reduction for the low biomass supply potential could occupy 7.46%–13.84% of the gross emissions from transport. For the high biomass supply potential, the carbon reduction could range from 18.27% to 35.61%. In addition to the CO_2 reduction from substituting diesel with biogas, using the digestates as fertilisers can also reduce mineral fertilizer production and therefore the GHG emissions during the production process. Using digestates can also enhance the carbon sequestration in soils, which is proven as successful practices in many countries (Horschig et al., 2016; Morero et al., 2015; Patrizio et al., 2015). In sum, using biogas as a vehicle fuel could be an important way for the transport sector to be CO_2 neutral and help Denmark reach climate policy targets.

4.2. Biogas plants' trade-off among different energy conversion technologies

In our analysis, the biogas plants have three choices about the energy conversion technologies: current technology, optimised technology where retention is prolonged and loss is minimized and optimization technology with CO_2 conversion. Although with increased CH_4 outputs, the options of optimised technology and optimised technology with CO_2 conversion could not as attractive as the current technology for the investors. The optimised technology and optimised technology with CO_2 conversion imply extra processing and investment costs. For example, the return of investment are 13.1% (current technology), 11.9% (optimised technology) and 10.9% (optimised technology with CO_2 conversion) with the low biomass supply potential. Investors are most likely to prefer a high return of investment and light investment. However, from the perspectives of the government and society, the plants with optimised technology and optimised technology with CO_2 conversion might be more beneficial because of benefits of energy security and greenhouse gas emission reduction. Therefore, there is a gap between the market- and social efficient solutions. To fill this gap, suitable policy instruments are needed. An investment subsidy might be a potential option for partly covering high investment cost of CO_2 conversion equipments (Cong and Brady, 2012; Klaassen et al., 2005). Another option could be subsidies for extra CH_4 outputs from optimization and CO_2 conversion.

4.3. Vehicle users' fuel choices

For vehicle users, CH_4 seems an economic choice compared with diesel. However, there are still uncertainties in vehicle users' choices. One of them is the sunk cost. A sunk cost is a cost that has already incurred and thus cannot be recovered. Although the vehicle users can sell their used vehicles in the second-hand market, they still lose some residue values. At least in the short term, the current diesel vehicle users need to make a trade-off between the sunk cost and the saved cost for fuel use, because purchase and maintenance costs for gas driven vehicles are usually higher than diesel driven vehicles (Danish Energy Agency, 2014).

Another uncertainty could be from the fuel storage and infrastructure available for CH_4 delivery and distribution. CH_4 must be stored in high pressure cylinders (3000 psi to 3600 psi for CNG) or cryogenic cylinders (−260F to −200F for LNG), which requires using more on-vehicle spaces than diesel tanks. The fuel stations available for CH_4 in Denmark are limited because of higher technical requirements for CH_4 than diesel.

4.4. The technical solution for the extra cadmium effects

Although we show that there are economic and environmental benefits for substituting diesel with (upgraded) biogas in the transport sector, we cannot neglect the potential negative environmental effects of extra heavy metal (e.g. cadmium) from using residues (from biogas plants) to substitute mineral fertilisers. However, there are potential technical solutions for removal of cadmium, e.g. using orange residues (Pérez-Marín et al., 2007), marine green algae (Ghoneim et al., 2014) or post treatment of digestate by oxidative hydrolytic destruction (OHD) (Thomsen, 2016). It could be beneficial if the biogas plants in this study are integrated with these solutions.

5. Conclusion

Denmark has an ambitious climate policy, where biogas could be an important option for the transport sector's green transition. In this study, we examine the whole chain from biomass supply potentials, biogas production technologies, input/outputs of biogas plants and substitutions with diesel and chemical fertilisers from both economic and environmental perspectives. We further consider benefits for four types of stakeholders: biogas plant owners, farmers, the society and vehicle users.

We find that the greatest reductions of GHG emissions can be achieved if biomass supply potential is high and the plants use the optimised technology with CO_2 conversion (about 4.27 millions of tons CO_2), which could be equal to one third of the transport sector emission reduction objective in 2035. In addition, there is also soil carbon stock effects by using residues from biogas plants as fertilisers. The biogas plant owners can earn profits through producing methane. The farmers can save costs of buying mineral fertilizer inputs. Society can achieve positive environmental benefits through reducing fossil fuel use. The vehicle users could choose the methane because of its cost advantage.

However, there could be also some potential barriers/uncertainties in using biogas to substitute diesel, e.g. investors' preferences for conventional technologies; vehicle users choice. Considering sunk costs, it may be not economic for users with low usage of vehicles to choose gas-driven vehicles compared with diesel-driven vehicles (Cabral and Ross, 2008). There could also be some negative environmental externalities (e.g. from heavy metal) because of using the residues as fertilisers. The government may need to consider some policy instruments, e.g. subsidising the investment of biogas plants with new technologies, or subsidising vehicle users' purchase for gas driven vehicles. The Danish tax system should also be adapted to give more tax advantages for vehicles driven by biogas (Lantz et al., 2007). The biogas plants could be integrated with other relevant industries to reduce negative environmental externalities.

In sum, the utilisation of biogas in transport sector seems to be reasonable and expands the opportunities to use biomass. The use of biogas, and also biomass, is expected to further grow in the future which enables Denmark to develop a climate-resilient and bio-based circular economy. Goals towards energy self-sufficiency and zero fossil fuel use are leading use of biogas into this direction. It is noteworthy that in this analysis our research scope is in Denmark. However, it would be interesting to investigate opportunities and barriers of international trade of biogas in the EU and world in the future (Junginger et al., 2011).

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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.2017.07.183.

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