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CO_2 emission saving by small-scale manure digestion

Report N^0:	**INN 13.001**
Version :	**2**
Status:	**Public**
Date:	**September 2013**
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Library data report:
CO_2 emission saving by small-scale manure digestion
A study performed within the framework of the Climate KIC project, Biogas, energizing the countryside
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INN 13.001 v2
Deventer, CCS B.V., 2013

Distribution of publications of CCS B.V. by:

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CCS B.V. Energie-advies

Acknowledgements:
The development of the technology described in this report is supported by:

Province of Overijssel

TKI Gas

EIT Climate KIC

SUMMARY

A consortium is developing a biogas upgrading plant for small-scale digestion. To partially fund this development a Climate KIC project proposal was written for the project called “Biogas, Energizing the Countryside” ([De Vries et al., 2012]). In this project proposal a table was presented showing the CO_2 savings due to the use of a small-scale cow manure digester. The project reviewer put forward a number of questions with regard to the source of the values and the method used in calculating the CO_2-emissions in the project proposal. Additionally a sensitivity analysis was asked.

These questions were addressed, and the method was refined by a more detailed CO_2-savings calculation, following the [EC, 2009] standard for emission savings due to the use of biofuels. [EC, 2009] was explained and summarised. It was concluded that [EC, 2009] does not have a specific term to incorporate the evaded greenhouse gas emissions due to reduced open manure storage time. This study shows that this term is very important and of the same order of magnitude as the actual savings by replacing the fossil fuel! Additionally this study shows that the assumed engine efficiency for the renewable fuel is of the utmost importance; it should be obliged to include engine efficiency in the calculation of the effects of the use of the biofuel on greenhouse gas emissions.The factors from [EC, 2009] were calculated for small-scale digester, with an input of 5000 ton of cow manure and 550 ton of co-product.

The CO_2-saving for manure storage has been re-evaluated in this study, and has been calculated as 34.5 kg CO_2 eq/ton manure (with methane to CO2 conversion factor of 23, in order to follow [EC, 2009]; this value equals 31.5 kg/ton for the more common IPCC value of 21). For 5000 ton/year of manure the emission savings from the manure storage alone accounts for 173 ton CO_2 eq/year. New stables should be constructed without pit storage in animal confinements in order to reduce this methane emission even more. Note that this value is valid for the cold climate of the Netherlands (average annual temperature of 10°C); the value is very sensitive to average annual temperature, and the emission saving for warmer climates is hence significantly higher.

Additional emissions are mainly caused by electricity use and to a lesser extent methane slip, as the heat demand is fulfilled by using some of the produced gas. The difference in the specific CO_2 emission from electricity production between different EU member states, is quite big, which can lead to differences in the emission savings, as discussed in the sensitivity analysis of Chapter 6.

The initial calculation as presented in [De Vries et al., 2012] is in good agreement with the more precise calculation presented in this report. In this report the approach of [EC, 2009] was followed. The reduction of the greenhouse gases for the replacement of diesel by CNG have been calculated as: 339 ton CO_2 eq/year.

The saved greenhouse gas emissions from manure to green gas in the grid have been calculated as 313 and 435 ton CO_2 eq/year.

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1 INTRODUCTION

A consortium is developing a biogas upgrading plant for small-scale digestion. To partially fund this development a Climate KIC project proposal was written for the project called “Biogas, Energizing the Countryside” ([De Vries et al., 2012]). In this project proposal a table was presented showing the CO_2 savings due to the use of a small-scale cow manure digester. The project reviewer put forward a number of questions with regard to the source of the values and the method used in calculating the CO_2-emissions in the project proposal. Additionally a sensitivity analysis was asked.

This report addresses these questions, and refines the used method by a more detailed CO_2-savings calculation, following the [EC, 2009] standard for emission savings due to the use of biofuels.

In chapter 2 a short description is given of greenhouse gas emissions and its effects. In chapter 3 the method of [EC, 2009] will be discussed. In chapter 4 the yearly CO_2-savings for three different uses of biogas will be presented, being green gas to the grid, compressed green gas for transportation (sometimes called driving on biomethane or biogas, both names are slightly misleading) and the conventional conversion in a combined heat and power plant. The CO_2 saving in accordance to [EC, 2009] is determined for the compressed green gas in Chapter 5, and a sensitivity analysis is performed in Chapter 6. A short comparison is made between the previous values from [De Vries et al., 2012] and the present study in Chapter 7. Subsequently conclusions are drawn.

2 Effects and emission of Greenhouse Gasses

Global warming is the rise of the average temperature of the Earth, which is caused by the increased insulative capacity of the Earth's atmosphere. The gases that create this effect are called greenhouse gases, or GHG's, of which CO_2 is probably the most well-known. To understand the impact of greenhouse gases on global warming a brief description is needed about the Earth's greenhouse effect.

2.1 The basic principles of the greenhouse effect

The spectrum of the radiation of a black body, like the sun and the earth, depends, according to Planck's Law, on the temperature of the body. For this reason solar radiation is mostly UV and visible light, whereas the earth's radiation is mainly infra-red. The Earth's atmosphere is mainly transparent for solar radiation. Only a part of the solar radiation is absorbed and scattered by oxygen, ozone and by the Raleigh effect. The radiation from the Earth is adsorbed mainly by the Earth's atmosphere. The absorbed heat by the atmosphere is re-emitted in all directions, thereby warming the surface of the Earth and the lower atmosphere and increases the average temperature on Earth [Pachauri, 2007]. In Figure 2.1 a schematic representation of the greenhouse effect is shown.

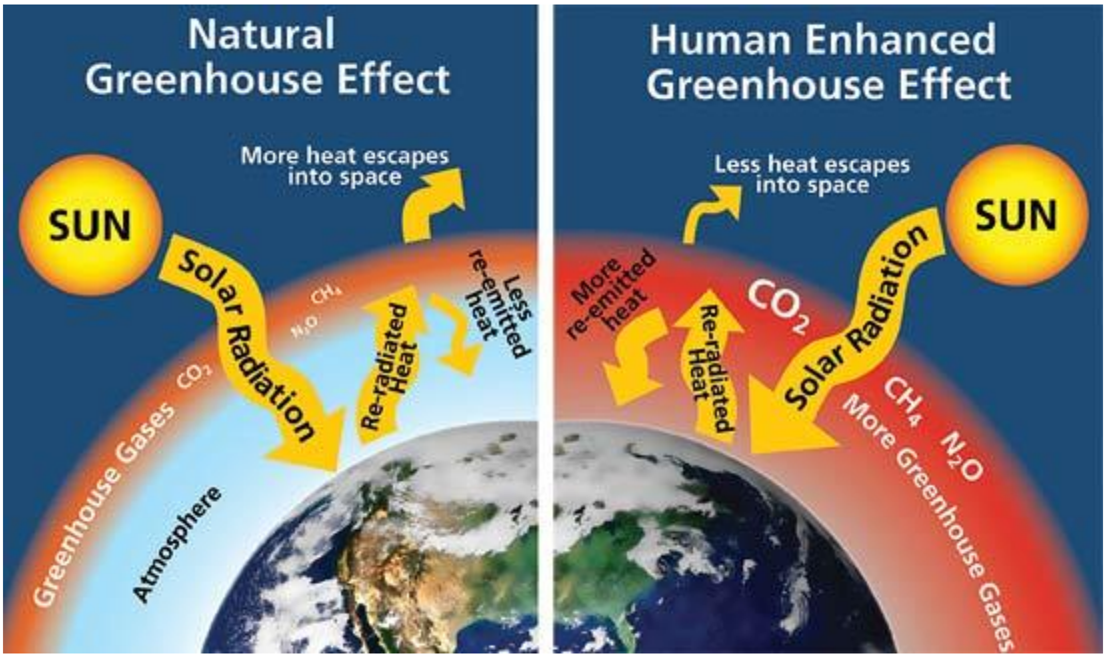


Figure 2.1: Schematic representation greenhouse effect [Elder, 2012]

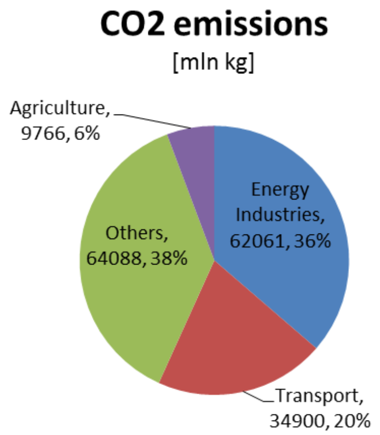
2.2 The most important greenhouse gasses

The IPCC, Intergovernmental Panel on Climate Change, indicates three gases as the main influential greenhouse gases, namely; Carbon dioxide (CO_2), Nitrous oxide (N_2O) and methane (CH_4). [Solomon et al, 2007]. Another well known, and the most abundant, greenhouse gas is H_2O. Due to the abundance of water in the earth's atmosphere, it contributes most to its insulating properties. [Hansen, 2008].

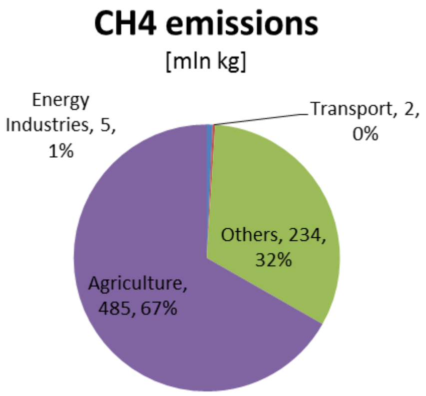
The common unit to express the impact, or potency, of the different greenhouse gases is CO_2-equivalent. This equivalent is the amount of CO_2 needed to have the same impact. According to the UNFCCC rules CH_4 is 21 times as potent as CO_2 and N_2O as many as 310 times.

2.3 Greenhouse gas emissions in the Netherlands

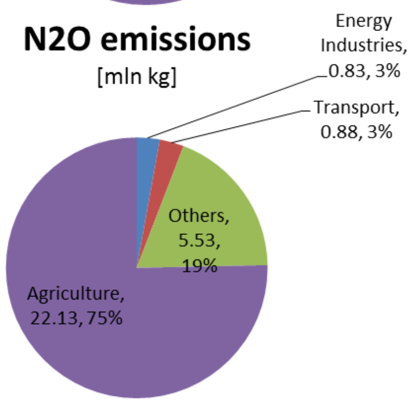
To understand the impact of these greenhouse gases on the environment it is needed to look into the total emission of these three substances; the real impact depends on the emitted quantities. The Netherlands is used as an example.



CO_2 is a greenhouse gas that is emitted in the largest quantities, mainly by the combustion of fuel. The main emitters of CO_2 are the energy and transport sector, which can be explained by the amounts of fuel consumed by these sectors. The share of agriculture CO_2 emission is about 5%.



The total emission of CH_4 in the Netherlands is, with “just” 727 million kg, a lot less than the emission of CO_2. The CH_4 is emitted mainly by gastro-digestion in livestock and to a lesser extent by cold digestion in manure storages. [Kuikman et al, 2005]
Due to the fact that CH_4 has 21 times the impact of CO_2 on the environment the agricultural emission is equivalent to an emission of 10200 million kg of CO_2.



The absolute emission of N_2O is negligible compared to the quantities of CO_2 and CH_4 emitted, with 29.37 million kg. But, as indicated in section 2.2, N_2O is 310 times more potent than CO_2, therefore the agricultural emission of N_2O is equivalent to the emission of 7080 million kg CO_2.

In the agricultural sector N_2O is emitted from several sources as an intermediate product of denitrification [Kuikman et al, 2005].

Figure 2.2: GHG-Emissions in the Netherlands based on Inventory 2011 Submission 2013 v1.3 [Agency NL, 2013]

The total CO_2 equivalent emission is given in Figure 2.3.

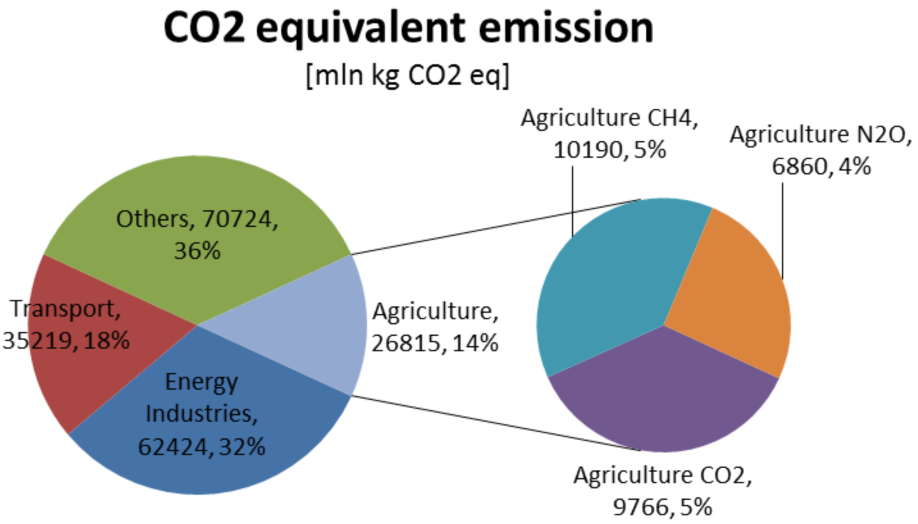


Figure 2.3 CO_2 equivalent emission of the Netherlands in 2011 and the different contributions of agriculture

Three gasses are identified as the main contributors to the greenhouse effect; CO_2, CH_4 and N_2O. Agriculture is the largest single source of CH_4 and N_2O. CH_4 is mainly emitted by cattle and cattle manure.
CH_4 and N_2O are effecting the greenhouse effect strongly, respectively 21 and 310 times more than CO_2. Agriculture itself attributes to 14% of the total CO_2 equivalent emissions. Methane emission is the largest contributor, closely followed by CO_2 and N_2O.

3 CALCULATION RULES ACCORDING TO EU FUELS DIRECTIVE 2009

3.1 EXPLANATION AND DISCUSSION OF THE CALCULATION PROCEDURE

The calculation procedure of the European Commission [EC, 2009], which is repeated in APPENDIX 1, contains quite a number of separate units, that can be implemented easily enough but obfuscate the reasoning behind the calculation procedure. By grouping some of the terms a more easily readable overview can be given.
The CO_2 equivalent emission by use of a biofuel is given in formula 2.1.

$$E = e_{CO2balancebiomass} + e_{biomassproduction} + e_{fuelproduction} + e_{transport\&storage} - e_{avoidedemissions} - e_{CCS} \quad (3.1)$$

The variables are explained below:
E is the CO_2 equivalent emission expressed per MJ of biofuel (in gCO_{2eq}/MJ).
$e_{CO2balancebiomass}$ is the influence of the biomass on the atmosphere, i.e. the balance of uptake of CO_2 from the air during growth and release of CO_2 in use and production, which will be explained in more detail in section 3.2.
$e_{biomassproduction}$ is equal to e_{ec} from [EC, 2009] (see also APPENDIX 1), which are the greenhouse gas emissions from cultivation and harvesting of the biomass. This includes for example the CO_2 emissions of machinery required for harvesting the biomass and cultivating the land. It also includes the direct and indirect greenhouse gas emissions from fertilizers and its production.
$e_{fuelproduction}$ is equal to e_p from [EC, 2009], which are the greenhouse gases emitted during the production of the biofuel. These are for example greenhouse gas emissions due to the consumption of external utilities, like electricity, fossil fuels, or chemicals, but also the greenhouse gas emissions due to process waste streams, if any. Note that CO_2 from biological origin is not incorporated in this term, as it already has been accounted for in $e_{CO2balancebiomass}$. This clarification was not presented in [EC, 2009], but the same assumption is present in [EC, 2009].
$e_{transport\&storage}$ is equal to e_{td} from [EC, 2009], which are the emissions from the transport, distribution and storage of raw materials, intermediate products, waste streams and end products.
$e_{avoidedemissions}$ includes all greenhouse gas emissions, that are avoided, except for the replacement of the fossil fuel that the biofuel itself replaces, as the latter is the outcome of the calculation. I.e. emissions that did not occur, because fossil fuels are replaced by a co-product of the fuel production plant, or greenhouse gases that were not emitted due to a change in handling of the raw materials. This includes the factors e_{ee} (the avoided emission of electricity production, if a surplus of electricity from the fuel production plant is delivered to the grid) and e_{ccr} (the avoided emission by using CO_2 from biological origin instead of CO_2 from fossil origin), see [EC, 2009] or APPENDIX 1 for an exact definition. It also includes other emissions not clearly identified within the framework of [EC, 2009]. In this study the most notable effect will be the avoided emission of methane from the manure storage, due to the reduction of storage time of unprocessed manure.

$$e_{avoidedemissions} = e_{ee} + e_{ccr} + e_{otheravoided} \quad (3.2)$$

e_{ccs} is equal to e_{ccs} of [EC, 2009], which is the CO_2 that is captured and sequestrated in the conventional way when talking about carbon capture and storage. From the formulation of the greenhouse gas emissions of the biofuel, it becomes clear that this excludes sequestration of carbon in biomass, like in for example a greenhouse.

Within this report first the yearly CO_2-equivalent emissions will be determined.
The relation of the yearly emission reduction and the factor E is given by (3.3). The emission reduction factors will then be calculated, using (3.4).

$$E = \frac{\dot{C}_{biofuel}}{\dot{m}_{fuel} \times LHV_{fuel} \times Gramtometricton \times \left(\frac{\eta_{renewable}}{\eta_{fossil}}\right)} \quad (3.3)$$

Where
E is the CO_2 equivalent emission expressed per MJ of biofuel (in gCO_{2eq}/MJ), with $\dot{C}$ the yearly CO_2 equivalent emission (in ton CO_{2eq}/year), $\dot{m}$ the yearly fuel production in kg/year, LHV_{fuel} the lower heating value of the fuel (MJ/kg), Gramtometricton the conversion factor to convert gCO_{2eq} into ton CO_{2eq}, i.e. $1 \cdot 10^{-6}$ and $\eta_{renewable}$ and η_{fossil} the engine efficiency for renewable and reference fossil fuel respectively. This definition deviates from [EC, 2009]. In [EC, 2009] a correction for engine efficiency is optional, (see point 3 of [EC, 2009], repeated in APPENDIX 1), whereas this should be obliged, especially since the optionality will lead to an overestimation of the greenhouse gas savings for renewable fuels with a lower engine efficiency than their fossil counterparts.

Similar to equation (3.3) equation (3.4) can be written:

$$e_x = \frac{\dot{C}_x}{\dot{m}_{fuel} \times LHV_{fuel} \times Gramtometricton \times \left(\frac{\eta_{renewable}}{\eta_{fossil}}\right)} \quad (3.4)$$

With e_x the greenhouse gas equivalent emission contribution of subscript x, (all terms as defined in [EC, 2009] and equation (3.1)), and $\dot{C}_x$ the yearly greenhouse gas equivalent emission contribution of subscript x. Other variables are explained above.

The total yearly emission of greenhouse gases due to the use of biofuel produced is given in equation (3.5), and the yearly CO_2 saving is given in equation (3.6).

$$\dot{C}_{biofuel} = \dot{C}_{CO2balancebiomass} + \dot{C}_{biomassproduction} + \dot{C}_{fuelproduction} + \dot{C}_{transport\&storage} - \dot{C}_{avoidedemissions} - \dot{C}_{CCS} \quad (3.5)$$

$$\dot{C}_{saving} = \dot{C}_{conventional} - \dot{C}_{biofuel} \quad (3.6)$$

3.2 Carbon balance biomass

Carbon is a structural element for all biomass. For plants, the majority of this carbon is stemming from CO_2 in the air. A small part is stemming from carbon stored in the ground. After the plants' life the plant is slowly decomposed. The majority of the plant ending up as CO_2 in the air again, whereas some carbon will end up in the soil.
Note that biomass that is consumed by animals or humans will also end up as CO_2. Either when using the energy of the food to live and breathe (and hence expulse CO_2), or at the end of the lifetime of the animal or human. The only difference is the pathway. This is why the use of biomass is sometimes referred to as short-cycle CO_2, as opposed to fossil fuels, which are referred to as long-cycle CO_2.

As CO_2 is converted into carbon-containing compounds in biomass, biomass can therefore be considered as a temporary CO_2-sink. A change in the amount of biomass on the land, will hence lead to a change in CO_2-concentrations in the atmosphere. This is why urbanisation has a negative impact on the CO_2-concentrations in the atmosphere.

We can express this in the form of an equation, where the yearly CO_2 release is given by the difference between release and uptake.

$$\dot{C}_{CO2balancebiomass} = \dot{C}_{CO2toairbm} - \dot{C}_{CO2fromairbm} \quad (3.7)$$

The uptake of CO_2 is related to the biomass growth. It is important however to realise that CO_2 from the atmosphere is not the only source of carbon. Carbon from the ground and fertilizers also add to the carbon content of the plant. Therefore a carbon balance can be made of the plant growth.

$$\dot{C}_{Cbiomassgrowth} = \dot{C}_{CO2fromairbm} \times \left(\frac{M_C}{M_{CO2}}\right) + \dot{C}_{Cfromsoil} + \dot{C}_{Cfertilizertobm} \quad (3.8)$$

With M_C the molar mass of carbon, and M_{CO2} the molar mass of carbon dioxide in kg/mole.

The yearly CO_2 release is related to the use of the biomass. It assumes that the "harvested" biomass is totally decomposed into CO_2, except for the part of the biomass that adds to the carbon content of the soil. For the production of biofuel, this includes the CO_2-emissions from biomass during biofuel production and biofuel use. Therefore an additional term to incorporate the emissions of use of fuel, like e_u in [EC, 2009], is redundant, and should by definition be zero. This also shows that a term including CO_2-emissions from biomass during biofuel production is not required.

$$\dot{C}_{CO2toairbm} = \left(\dot{C}_{Cbiomassuse} - \dot{C}_{Ctosoil}\right) \times \left(\frac{M_{CO2}}{M_C}\right) \quad (3.9)$$

If we assume that biomass growth equals biomass use, we can obtain an equation for the added amount of CO_2.

$$\dot{C}_{CO2balancebiomass} = \left(\dot{C}_{CO2fromairbm} \times \left(\frac{M_c}{M_{CO2}}\right) + \dot{C}_{Cfromsoil} + \dot{C}_{Cfertilizertobm} - \dot{C}_{Ctosoil}\right) \times \left(\frac{M_{CO2}}{M_C}\right) - \dot{C}_{CO2fromairbm} \quad (3.10)$$

$$\dot{C}_{CO2balancebiomass} = \left(\dot{C}_{Cfromsoil} + \dot{C}_{Cfertilizertobm} - \dot{C}_{Ctosoil}\right) \times \left(\frac{M_{CO2}}{M_C}\right) \quad (3.11)$$

If we assume that the carbon content in the fertilizer is of biological origin, we can say that the use of the carbon content of the fertilizer on the atmosphere is zero.

$$\dot{C}_{CO2balancebiomass} = \left(-\Delta\dot{C}_{Csoil}\right) \times \left(\frac{M_{CO2}}{M_C}\right) \quad (3.12)$$

Under these assumptions we can say that the influence of the biomass growth is only influenced by the change in carbon content of the soil.

However, biomass growth does not necessarily equal biomass production. Especially because biomass growth is not necessarily constant for every year. Think of the CO_2 uptake of trees for example. A small one year old tree may take up less CO_2 than a five year old tree, and a very old tree is known to take up less CO_2 than a fast-growing tree. Therefore it makes more sense to evaluate the CO_2-uptake and release over the period of the project, and calculate an average. Additionally the previous consideration did not take into account that the land used to produced biomass, is not bare, i.e. without any vegetation. At the same time, at the end of the project the land may still contain biomass. This allows for a consideration based on initial and end situation, i.e.

$$\dot{C}_{CO2balancebiomass} = -\frac{\left(C_{Cbiomassend} - C_{Cbiomass0} + C_{Csoilend} - C_{Csoil0}\right) \times \left(\frac{M_{CO2}}{M_C}\right)}{t_{project}} \quad (3.13)$$

$$\dot{C}_{CO2balancebiomass} = -\frac{\left(\Delta C_{Cbiomass} + \Delta C_{Csoil}\right) \times \left(\frac{M_{CO2}}{M_C}\right)}{t_{project}} \quad (3.14)$$

We can express this as:

$$\dot{C}_{CO2balancebiomass} = \frac{-(CS_A - CS_R) \times A_{land} \times \frac{M_{CO2}}{M_C}}{t_{project}} \times Gramtometricton \quad (3.15)$$

With CS_A and CS_R the reference and actual mass of carbon stored in vegetation and soil per unit area of land. Note that in [EC, 2009] they are formulated rather loosely, in terms of its units, and in terms of the moment of the "actual" value. This actual value should be the value at the end of the project. The units should be in g of carbon per m^2 of land if the area of land is defined as m^2.

And we can bring this in correspondence with the notation in [EC, 2009].

$$e_{CO2balancebiomass} = \frac{(CS_R - CS_A) \times \frac{M_{CO2}}{M_C} \times A_{land}}{\dot{m}_{fuel} \times LHV_{fuel} \times t_{project}} \quad (3.16)$$

In [EC, 2009] a project period of 20 years was selected, and a productivity of fuel per area of land was introduced. Note that this term equals the term e_l for land use change, with the exception of the bonus for use of contaminated land that was introduced in [EC, 2009]. Note that although this term is called land-use change in [EC, 2009], it will also account for non-renewable biomass projects, i.e. projects, where the initial biomass vegetation is not restored after a 20 year period, or where the soil is depleted.

3.3 SUMMARY

From the discussion of the calculation method of [EC, 2009] in section 3.1 it can be concluded that the definition of [EC, 2009] does not allow for logical incorporation of other avoided emissions due to the use of biomass, most notably anaerobic reactions, that should be incorporated. Additionally from the discussion in section 3.2 it can be concluded that the direct CO_2-emissions due to use of the biofuel (e_u from [EC, 2009]) and CO_2-emissions from the biomass released in the production process should by definition be set to zero. Note that the CO_2 bonus for the growth of biomass on polluted land is a political choice, and not a factor that is directly related to the CO_2-emissions of growing or producing biofuel. [EC, 2009] leaves room for a more positive greenhouse gas savings calculation by not obliging a correction for reduced engine efficiency when using the renewable fuel.

In this report first the yearly emission savings will be calculated. Subsequently the emission factors will be determined based on the fuel production. Note that the yearly emission savings for other types of bioenergy can also be calculated using equations (3.5) and (3.6).

4 CALCULATION OF THE YEARLY CO_2 REDUCTION FOR BIOENERGY PRODUCTION

4.1 EMISSION FACTORS OF FOSSIL REFERENCE CASES

To calculate the CO_2-equivalent emission of the fuel production, reference emission factors for the geographical location of the plant are required. In this calculation the reference factors for the Dutch situation are used, as shown in Table 4.1. The emission factor of the Netherlands is only slightly higher than the EU average. In the sensitivity analysis the specific emission is varied.

The value for diesel is stemming from [EC, 2009]. It is commented in a literature review on the LCA's of petrol and diesel by [Eriksson and Ahlgren, 2013], that this factor is in fact rather low for the emissions of the use of diesel. They found values between 82 and 99 g CO_2-eq/MJ for diesel. They only found one value lower than the 83.8 g/MJ as used by [EC, 2009]. This means that the emission savings as calculated in this report are rather conservative. Note that the value of the Climate KIC proposal from [De Vries et al., 2012] was well within this range, and only slightly higher than the value of [EC, 2009].

Table 4.1 Emission factors of references and fossil fuel

	Emission factor	Source
Electricity to grid (NL)	433 g/kWh	[EEA, 2013]
Losses in grid (NL)	4.38 %	[Te Buck et al., 2010]
Electricity from grid	453 g/kWh	Calculation result
Natural gas from grid (NL)	1795 g/Nm^3	[Te Buck et al., 2010]
Diesel	83.8 g/MJ	[EC, 2009]

Three different cases will be distinguished:

1. Production of green gas to replace natural gas from the grid (at 8 bara)
2. Production of CNG to replace diesel
3. Production of electricity and heat with a CHP

The third case is used as a reference case for the other two cases. All cases are based on small-scale digestion at a scale of 5000 ton/year of manure with 500 ton/year wheat yeast concentrate as co-substrate. Digester data is constant for all the cases.

The emission factors from [EC, 2009] are used, to be in accordance with this directive throughout. Note that these values differ slightly from the values that the IPCC presents [Solomon et al, 2007], and were used in the previous calculation, that the consortium presented [De Vries et al., 2012].

Table 4.2 Factors relating emissions to CO_2-equivalent emissions

	Emission factor [ton CO_{2eq} emission/ton emission]	Source
CH_4	23	[EC, 2009]
N_2O	296	[EC, 2009]
CO_2	1	[EC, 2009]

Within this chapter the yearly carbon dioxide due to the creation of the biofuel will be calculated, using all the factors from Chapter 3.

4.2 BIOMASS PRODUCTION AND LAND USE CHANGE

Manure is a waste product, that is created irrespective of its use as a biofuel. It also has no (direct) effect on land use change, as it is not grown. It may have an indirect effect, as it reduces the amount of carbon per nutrient, and thereby reduce the carbon content of the fertilizer.

The co-substrate for co-digestion can be specially grown, when for example energy maize is used as the co-substrate. However, we opt to use a waste stream of food production. Therefore the yearly production of carbon dioxide due to biomass production and the yearly production of carbon dioxide due to land use change can be set to zero.

4.3 FUEL AND ENERGY PRODUCTION

4.3.1 GENERAL DESCRIPTION OF THE DIFFERENT CASES

The defined case is for a small-scale digester with a feed of 5000 ton/year cow manure and 550 ton/year wheat yeast concentrate. Using the Anaerobic Digestion Profit Calculator (ADPC) that has been developed within the IEE project, BioEnergy Farm, a biogas yield of 29 Nm^3/h can be calculated with a methane content of 56.23%. At this small scale it is not reasonable to have two conversion technologies. This automatically means that the factor e_{ee} (avoided emission due to additional electricity production) is zero. This also means that the required electricity is not generated on-site and is taken from the grid for the gas upgrading cases, i.e. the gas grid quality and CNG case. For the CHP case the electricity consumption of the digester is covered by the generated electricity by the engine. The heat required for the digester is covered by the heat from the CHP for the CHP case. For the gas upgrading cases the heat demand for both digester and gas upgrading plant is covered by burning some of the produced gas in a boiler.

For the digester a manure bag type digester has been selected. This type of digester is cheaper in investment, but has a larger heat loss, compared to other type of digesters. Electricity consumption is comparable to other digesters. This means that the presented estimates are a conservative estimate in terms of the greenhouse gas savings.

The heat consumption is based on data from a digester producer [Bijman, 2011] for 18 Nm3/hr biogas and subsequently scaled linearly to a scale of 29 Nm^3/hr. The electricity consumption is based on the data of [Bijman, 2011] of the electricity consuming equipment and CCS experience with regards to the operational hours of this equipment. Most notably the mixer, that requires a large power, but is not constantly mixing. This is subsequently scaled to a scale of 29 Nm3/hr.

Table 4.3 Energy consumption digester

Electricity consumption	27 945	kWh/year
Heat consumption	242 668	kWh/year

Note that in correspondence with [EC, 2009] the emissions due to the production of the (materials of the) biogas plant are ignored.

4.3.2 CASE GAS GRID QUALITY

The gas grid case is calculated to feed the gas into the gas grid at 8 bar(a).
The electricity use of upgrading up to gas grid quality is made up of three almost equal parts

- Biogas blower and circulation pumps
- Compression up to 8 bar
- Nitrogen generator

The electricity use of the nitrogen generator are based on manufacturers data. Compression up to 8 bar is based on a calculation, assuming polytropic efficiency of 80% (corresponding with an isentropic efficiency of 75%) and 95% efficiency of the electric drive, power electronics, etc. The biogas blower and circulation pump data is based on the design of the biogas upgrading plant.

For the gas grid quality case compression up to 8 bara is included. This compressor is not strictly necessary if the gas is delivered to the mbar grid. In this planning phase a nitrogen generator is added to condition the Wobbe-index, i.e. lower it. It is assumed that the gas is upgraded to 3% CO_2 and is subsequently diluted to contain up to 8% of nitrogen. Recently the restrictions with regard to CO_2-content in gas for the low-pressure network in The Netherlands have been relaxed, and up to 10% CO_2 is allowed. This means that the electricity consumption could turn out to be lower (as less nitrogen needs to be added). Additionally less heat will be required to regenerate the washing fluid. Ignored in this calculation is the electricity consumption of the fans of the air cooling. However, this influence is expected to be within the bandwidth of the sensitivity analysis of Chapter 6.

Heat is necessary to release CO_2 that is absorbed in the fluid. However not all heat that is consumed in this process is lost. A large part of the heat is exchanged within the process, thereby leaving a small temperature difference that needs to be overcome in the stripper column. Part of the heat that is released cannot be used within the upgrading system, but is of sufficient temperature to be used within the digester. This integration will result in a higher amount of green gas that can be fed into the grid.

Table 4.4 Energy consumption gas upgrading and compression 8 bara case

Electricity consumption gas upgrading up to 8 bara	63 093	kWh/year
Heat consumption	212 164	kWh/year
Heat usable within digester	114 723	kWh/year

Methane slip gives an additional contribution to the greenhouse gas emissions from production of the biofuel. We assume 0.5% of methane slip due to losses from the digester and incidents. One of the focus points of the biogas upgrading plant is a limited methane loss to the environment. Methane hardly dissolves in the washing liquid, and therefore the methane slip from the biogas upgrading plant is only 0.06%, based on literature for similar compositions [Bauer et al., 2013]. Therefore a total methane slip of 0.56% is assumed that accounts for a yearly CO_2-equivalent emission of 19 metric ton/year CO_2-equivalent emission.

The final composition of the washing liquid is still unknown, as it is an important parameter to optimise, in terms of costs and performance. Therefore the CO_2-equivalent emission of its production is still unknown. However given the small amount of washing liquid that will actually be consumed, related to the large amount of fossil fuels that are saved, it seems fair to ignore this term at this point. At a later stage within the Climate-KIC project the provider of the chemicals will be contacted to see if the required data is available.

Table 4.5 and Table 4.6 show the total consumption, and yearly CO_2-equivalent emission during production of gas grid quality gas at 8 bara from digestion of manure.

Table 4.5 Overview data case gas grid 8 bara

Total electricity consumption	91 038	kWh/year
Total heat consumption	340 109	kWh/year
Methane slip	0.56	% of methane in raw biogas

Table 4.6 Overview yearly CO_2 emission due to production gas grid qualtiy gas (8bara)

Electricity	41	Metric ton CO_2-equivalent/year
Heat consumption[1]	0	Metric ton CO_2-equivalent/year
Methane slip	18	Metric ton CO_2-equivalent/year
Total production	60	Metric ton CO_2-equivalent/year

4.3.3 Case CNG

The case of CNG has also three main energy users, but the energy use of the nitrogen generator is no longer necessary, as the CNG vehicles are more flexible to fuel quality changes, because of the different gas composition throughout Europe. In its place comes the compression energy to compress the gas to fill the fuel tank. Here a scenario is assumed where the gas is first compressed to 250 bara in a buffer. This gas is subsequently used to fill a tank at 200 bara.The compression energy is based on data from the manufacturer BRC fuelmaker. Model type FMQ 8 P36 is used.

Table 4.7 Energy consumption gas upgrading to fuel quality

Electricity consumption gas upgrading up to CNG	77 555	kWh/year
Heat consumption	212 164	kWh/year
Heat usable within digester	114 723	kWh/year

Methane slip gives an additional contribution to the greenhouse gas emissions from production of the biofuel. We assume 0.5% of methane slip due to losses from the digester and incidents. One of the focus points of the biogas upgrading plant is a limited methane loss to the environment. Methane hardly dissolves in the washing liquid, and therefore the methane slip from the biogas upgrading plant is only 0.06%, based on literature for similar compositions [Bauer et al., 2013]. Additionally we assume another 0.5% of methane slip from the process of filling the tank and combustion in the engine. A total methane slip of 1.06% is assumed that accounts for a yearly CO_2-equivalent emission of 35 metric ton/year CO_2-equivalent emission.

The final composition of the washing liquid is still unknown, as it is an important parameter to optimise, in terms of costs and performance. Therefore the CO_2-equivalent emission of its production is still unknown. However given the small amount of washing liquid that will actually be consumed, related to the large amount of fossil fuels that are saved, it seems fair to ignore this term at this point. At a later stage within the Climate-KIC project the provider of the chemicals will be contacted to see if the required data is available.

[1] The yearly CO_2-emission due to heat consumption is zero, because the produced gas will be used to produce the required heat, thereby reducing the net gas production

Table 4.8 and Table 4.9 show the total consumption, and yearly CO_2-equivalent emission during production of CNG in the tank from digestion of manure. Methane emissions from driving have been accounted for.

Table 4.8 Overview data case CNG

Total electricity consumption	105 500	kWh/year
Total heat consumption	340 109	kWh/year
Methane slip	1.06	% of methane in raw biogas

Table 4.9 Overview yearly CO_2 emission due to production CNG

Electricity	48	Metric ton CO_2-equivalent/year
Heat consumption[2]	0	Metric ton CO_2-equivalent/year
Methane slip	35	Metric ton CO_2-equivalent/year
Total production	83	Metric ton CO_2-equivalent/year

4.3.4 Case CHP

In the case of the CHP the CHP provides both the heat and electricity for the digester, and no additional energy is consumed. Therefore the only additional greenhouse gas emission is limited to the methane losses.

CHP's are known to have a relatively high amount of unburned methane in its exhaust gas. We assume a 0.5% of the yearly methane production in the form of methane slip from the digester (or due to an incident) and 0.5% of the yearly methane production due to methane slip through the engine [van Dijk, 2012]. We therefore assume a yearly methane slip of 1%. This equates to 33 metric ton/year CO_2-equivalent emission, due to methane slip.

Table 4.10 and Table 4.11 show the total consumption, and yearly CO_2-equivalent emission of combined heat and power production from digestion of manure.

Table 4.10 Overview data case CHP

Total electricity consumption	27 945	kWh/year
Total heat consumption	242 668	kWh/year
Methane slip	1.00	% of methane in raw biogas

Table 4.11 Overview yearly CO_2 emission CHP

Electricity	0	Metric ton CO_2-equivalent/year
Heat consumption	0	Metric ton CO_2-equivalent/year
Methane slip	33	Metric ton CO_2-equivalent/year
Total production	33	Metric ton CO_2-equivalent/year

[2] The yearly CO_2-emission due to heat consumption is zero, because the produced gas will be used to produce the required heat, thereby reducing the net gas production

4.4 TRANSPORT AND DISTRIBUTION

The emissions by transport and distribution are a discussion point. The European Commission defined reference values, that include the emission from transport and distribution of manure to the digester and distribution of CNG. This value will be too high for a case where the digestion takes place at the farm and where CNG will be used at the farm. In this case the only emission (except for leakages) will be the transport of the co-substrate for digestion.

The emission due to the transport of co-substrate is 6.1 metric ton CO_2/year for 150 km of transport. This factor is taken from SimaPro 7.3 [Ligthart, 2012], [Pré Sustainability, 2013]. When this is converted into the emission factor per MJ of fuel, this will be compared with the value of [EC, 2009].

4.5 AVOIDED EMISSIONS

4.5.1 AVOIDED EMISSIONS FROM MANURE STORAGE

The main avoided emission due to small-scale digestion is the emission from methane and nitrous oxide from the storage of manure.

Anaerobic digestion of manure is a naturally occurring process in manure, mainly taking place in liquid manure. Solid manure is more prone to aerobic break-down, due to its more porous structure. The produced methane from this anaerobic digestion is released into the environment. The main emissions are methane and to a lesser extent N_2O emissions. With digestion these emissions are significantly reduced because of the hermetical storage of manure after digestion and the very short storage times of “raw” manure.

The methane emissions from manure storage are given by the IPCC in 2006 as:

$$EF_{CH4} = VS \times B_{VS} \times MCF \times \rho_{methane} \quad (3.1)$$

With EF_{CH4} the emission factor in kg CH_4/kg manure, VS the fraction volatile solids in kg volatile solids/kg manure, B_{VS} the maximum theoretical methane emission in m^3 CH_4/kg VS, MCF the methane conversion factor (as a fraction) and $\rho_{methane}$ the density of methane (0.67 kg/m^3). [IPCC, 2006] comes up with temperature dependant emission factors for storage. For an average temperature of 10°C (annual average of the Netherlands) and pit storage in animal confinements (the most common form of manure storage for dairy cattle within the Netherlands) a MCF of 0.17 is defined for storage longer than 1 month, and 0.03 for manure storage shorter than 1 month. Note that the emission from storage longer than 1 month is very temperature dependant. It increases to 0.27 at 15°C. If it is a bit warmer than outside (which is likely), this has a big influence on methane emissions, see Figure 4.1. The evaded emissions could therefore be seen as a minimum.

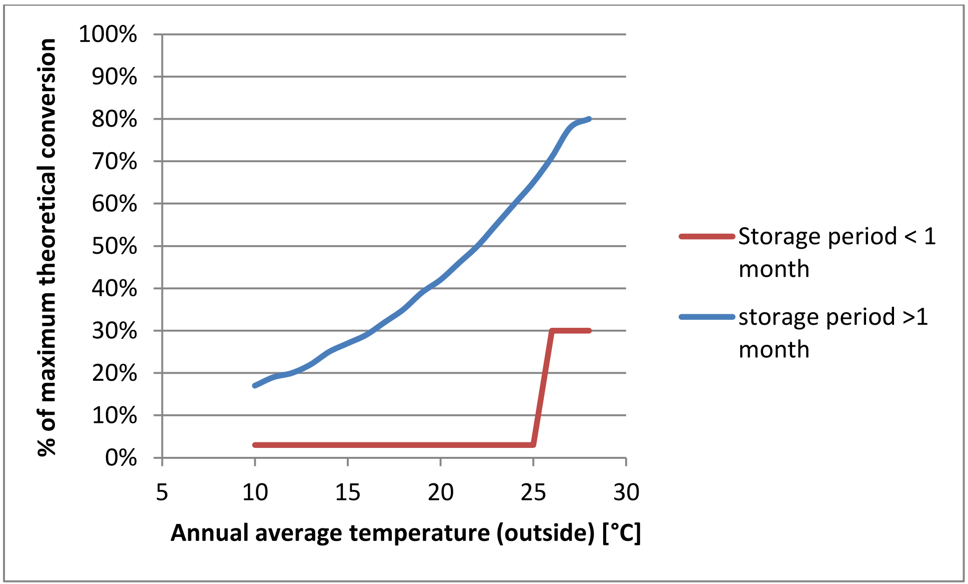


Figure 4.1 Dependance of maximum methane conversion (MCF) in a pit in animal confinements on annual temperature, based on data from [IPCC, 2006]

The Netherlands uses a country specific approach where methane emission is linked to the organic matter instead of volatile solids:

$$EF_{CH4} = OS \times B_{OS} \times MCF \times \rho_{methane} \qquad (3.2)$$

With EF_{CH4} the emission factor in kg CH_4/kg manure, OS the fraction organic matter in kg organic matter/kg manure, B_{OS} the maximum theoretical methane emission in m^3 CH_4/kg OS, MCF the methane conversion factor (as a fraction) and $\rho_{methane}$ the density of methane (0.67kg/m^3) [Ministerie van Infrastructuur en Milieu, 2013a] en [Ministerie van Infrastructuur en Milieu 2013b][3]. The value of OS is 0.064 kg/kg and B_{OS} is 0.25 Nm^3 CH_4/kg OS. The value of MCF is 0.17 for manure in the stable [Ministerie van Infrastructuur en Milieu 2013b].

In the Netherlands methane emissions from manure management account for about 1% of the total greenhouse gas emissions [Ministerie van Infrastructuur en Milieu, 2013b].

The emission from nitrous oxide (N_2O), is expressed as:

$$EF_{N2O} = N_{content} \times EF_N \times M_{N2O}/(2 \times M_N) \qquad (3.3)$$

With EF_{N2O} the emission in kg N_2O/kg manure, $N_{content}$ the amount of nitrogen in manure in kg N/kg manure, and EF_N the mass fraction kg "N_2O-N"/kg N. The mass N_2O-N is the mass of nitrogen stored in the form of N_2O. As 2 molecules of N are stored in 1 molecule of N_2O, the conversion factor of kg N_2O-N to kg N_2O equals $M_{N2O}/(2*M_N)$. A $N_{content}$ of 4,6 kg per ton seems to be used in the calculations.

A value of 0.001 is used for EF_N [Ministerie van Infrastructuur en Milieu, 2013c]. [IPCC, 2006] recommends a value of 0.002, but indicates a large uncertainty with regard to the actual value.

In this study [Ministerie van Infrastructuur en Milieu, 2013b] and [Ministerie van Infrastructuur en Milieu, 2013c] are followed. A sensitivity analysis is provided in chapter 6.

[3] In fact the NIR protocol 12-029 2013 for methane emissions from manure [Ministerie van Infrastructuur en Milieu, 2013a] and the National Inventory Report [Ministerie van Infrastructuur en Milieu, 2013b] do not seem to be in agreement. From the National Inventory Report and CFR 2013 it seems that the protocol has not been updated appropriately. Therefore [Ministerie van Infrastructuur en Milieu 2013b], which additionally is in agreement with [IPCC, 2006] is followed. Dutch government has been contacted to clarify this.

Based on the above presented data it is possible to calculate the emissions from manure storage in a pit in animal confinements.

Table 4.12 Emission from manure storage (pit storage in animal confinements, 10°C)

		CH_4 (kg/ton)	N_2O (kg/ton)	CO_{2eq} (kg/ton)*
Cow manure	<1 month	0.32	0.0072	9.5
	>1 month	1.82	0.0072	44.1

* The conversion factors from [EC, 2009] have been used, see APPENDIX 1.

For existing stables, the cow manure will still enter into the pit prior to entering the digester. Additionally the pit will not be entirely empty. Therefore it seems reasonable to assume that the reduction in methane emissions from digestion in existing stables is limited to the difference in emission between a storage period longer than 1 month and a storage period shorter than 1 month. This means that the evaded emissions are 34.5 kg/ton manure.

For 5000 ton/year the evaded emission equals 173 ton CO_2-equivalent per year. Note, that the immediate use of manure in the digester is not only beneficial for the emission of greenhouse gases, but also from the point of view of the produced amount of biogas and the amount of heat necessary to heat the digester. A good design for a digester should therefore already start in the stable. New stables should preferably not be equipped with a manure pit in the animal confinements. This way a higher reduction of methane emissions from manure storage can be obtained.

Note that as the value of evaded emissions refer to the relatively cold Dutch climate, larger emission reductions can be obtained in warmer, i.e. more southern European countries.

4.5.2 AVOIDED EMISSIONS FROM THE USE OF DIGESTATE

A lower methane emission is expected when digestate is applied as fertilizer instead of manure, due to its lower content of organic matter and volatile solids. However, research findings are inconclusive [Hoeksma et al., 2012]. Additionally it is postulated that the lower organic matter content in digestate reduces the biological demand of breakdown of manure, and hence reduces the formation of N_2O. However, here too evidence is still inconclusive [Hoeksma et al., 2012].

The Danish greenhouse gas inventory takes these effects into account. Although it is plausible that the emissions from the application of digestate are lower, convincing evidence is missing.

Reduced greenhouse gas emissions due to the use of digestate for fertilizing the land instead of manure have therefore not been taken into account.

4.5.3 AVOIDED EMISSIONS DUE TO COGENERATION OF ELECTRICITY DURING FUEL PRODUCTION

As already argued in section 4.3.1, the additional saving due to electricity production is zero for this small scale.

4.5.4 AVOIDED FOSSIL FUEL USE FOR CO_2

It is possible to use the CO_2 from the gas upgrading plant (and also the biogas CHP) for other purposes, most notably CO_2 fertilisation in greenhouses. This way some fossil fuel emission could be avoided, provided that the CO_2 would be made for this purpose only. Although this is theoretically possible, we don’t expect a large scale application. Furthermore a large share of the used CO_2 is a by-product from other chemical processes, like the production of ammonia or urea.

4.6 Captured and stored CO2

There is no capture and storage of CO_2 foreseen. Therefore we can set the yearly CO_2 saving due to carbon capture and storage to zero.

4.7 Total yearly saved CO2-equivalent emissions

4.7.1 Biogas production

The yearly biogas production has been calculated using the Anaerobic Digestion Profit Calculator, that has been developed by CCS in the framework of IEE project, BioEnergy Farm. For more information on the calculation procedure, please refer to [Van der Werf, 2011]

The digester is fed with 5000 ton/year of manure and 550 ton/year wheat yeast concentrate. It is calculated that 29 Nm3/hr of biogas is produced with 56.23% of methane. This corresponds with 16.3 Nm3/hr of pure methane.

4.7.2 Case gas-grid quality

In order to calculate the yearly savings first it should be calculated how much green gas is produced, and subsequently how much of the gas after upgrading is used to heat the gas upgrade installation and digester. A boiler efficiency of 85% is assumed. Heat integration is in accordance to section 4.3.2.

Table 4.13 Gas production

Gross gas production	1 418 655	kWh/year
Heat consumption	340 109	kWh/year
Gas used to heat digester	400 128	kWh/year
Net gas production	1 010 583	kWh/year
Net gas production (Dutch equivalent)	114 948	Nm3/year

Table 4.14 shows the yearly CO_2-savings due to green gas into the grid from biogas from digestion. The components that have been discussed in previous sections and have a value of zero are omitted from this overview, as they do not add more information, and make this overview longer than strictly required.

Table 4.14 Yearly CO_2-savings due to green gas in the gas grid

Total evaded CO_2 emissions	**379**	Metric ton CO_2-equivalent/year
Evaded emissions natural gas	206	Metric ton CO_2-equivalent/year
Evaded from manure storage	173	Metric ton CO_2-equivalent/year
Total additional emissions	**66**	Metric ton CO_2-equivalent/year
CO_2-influence biomass	0	Metric ton CO_2-equivalent/year
Emissions from transport	6	Metric ton CO_2-equivalent/year
Methane slip from production	18	Metric ton CO_2-equivalent/year
CO_2 emissions from production	41	Metric ton CO_2-equivalent/year
Total yearly CO_2-savings	**313**	Metric ton CO_2-equivalent/year

4.7.3 Case CNG

In order to calculate the savings by CNG production first the amount of replaced fossil fuel should be determined. CNG can replace both petrol and diesel. Petrol replacement is more common in cars; diesel replacement is more common in buses and heavy duty vehicles. As diesel engines are more fuel efficient than petrol engines, the choice of the reference fossil fuel will also determine how CNG compares in terms of fuel efficiency. Moreover, the fuel efficiency of CNG will depend on the engine concept (stoichiometric combustion or lean burn engine, the latter being more efficient) and whether CNG is the only fuel driving the engine or a dual-fuel system is used.

A dual-fuel engine is an engine that uses two fuels at the same time, in this case natural gas and diesel, in contrast to a bi-fuel engine that can use two fuels, but generally not at the same time. The most common example is natural gas and petrol. The dual-fuel engine is an adapted compression ignition engine (i.e. diesel engine). In this engine type the fuel mixture auto-ignites, in the so-called pre-mixed combustion, followed by the main combustion. The natural gas can only replace the main combustion. The pre-mixed combustion needs to be diesel. However, as the main combustion accounts for the majority of fuel combusted, up to 90% of the amount of diesel can be replaced by natural gas. This type of engine can run on diesel, and a diesel-natural gas mixture, but never on natural gas alone. Advantages of this type of engine are superior fuel efficiency over spark-ignited engines, and reduced dependency on availability of natural gas. Additionally one can always fall back to the diesel characteristic of the engine, by reducing the amount of natural gas that is mixed with the diesel. In a dual-fuel engine this is all automatically controlled by the ECU.

The discussion above show that it is not easy to put a single number on the amount of fossil fuel that can be replaced by a kg of CNG. Therefore this will be used as one of the variables in the sensitivity analysis of chapter 6.

For small-scale digestion on a farm, the first step would be to replace the diesel use of a tractor by CNG. Conversion systems to retrofit tractors to dual-fuel systems are already on the market, a.o. [Rap, 2013], [Steyr, 2013a]. Tractor producers are announcing their first dual-fuel tractors [Valtra, 2013]. Steyr announced the first all CNG tractor for 2015 [Steyr, 2013b].

For farm equipment the effect of using CNG on fuel consumption has not yet been studied into detail. This has been done for buses and trucks. For buses the impact is studied in a field study by [Pelkmans et al]. They found that a diesel bus used 75.5% less fuel (expressed in energy) than a CNG bus with similar performance. For dual-fuel engines such data is not widely available, but in non-scientific literature it is commented that the energy consumption on diesel, or diesel and natural gas mixture is similar.

We will compare the efficiency of a diesel engine with an all-CNG engine, based on the study of [Pelkmans et al.], i.e. a CNG engine has an efficiency of 75.5% of a diesel engine, i.e. a CNG engine needs about a third more energy than a diesel engine. This is a more conservative approach than the equal efficiency for dual-fuel engines compared to diesel engines as assumed in [De Vries et al., 2013]. Table 4.15 shows the amount of CNG produced in energy terms, and the amount of diesel replaced.

Table 4.15 CNG production and diesel replacement

Gross CNG production	1 418 655	kWh/year
Heat consumption	340 109	kWh/year
Gas used to heat digester	400 128	kWh/year
Net CNG production	1 010 583	kWh/year
Diesel replacement	846 606	kWh/year
Diesel replacement	84 661	l/year

Table 4.16 shows the yearly CO_2-savings by the replacement of a diesel engine by a CNG engine. Bear in mind, that this is a conservative assumption, as a comparison between a gasoline engine and CNG engine, or diesel engine and dual-fuel (diesel and CNG) engine will show efficiencies of gas engines much closer to their counterparts fueled by conventional fossil fuels.

Table 4.16 Yearly CO_2-savings due to diesel replacement by CNG

Total evaded CO_2 emissions	**428**	Metric ton CO_2-equivalent/year
Evaded emissions natural gas	255	Metric ton CO_2-equivalent/year
Evaded from manure storage	173	Metric ton CO_2-equivalent/year
Total additional emissions	**89**	Metric ton CO_2-equivalent/year
CO_2-influence biomass	0	Metric ton CO_2-equivalent/year
Emissions from transport	6	Metric ton CO_2-equivalent/year
Methane slip production and use	35	Metric ton CO_2-equivalent/year
CO_2 emissions from production	48	Metric ton CO_2-equivalent/year
Total yearly CO_2-savings	**339**	Metric ton CO_2-equivalent/year

4.7.4 Case CHP

In order to calculate the yearly savings the net and gross production of renewable energy and heat should be determined. Subsequently the yearly savings can be determined by using the emission factors from Table 4.1 and the additional emissions from the digestion of manure, based on the previous sections of this chapter.

An electrical efficiency of 30% is assumed and a total system efficiency of 85%.

Table 4.17 Net and gross heat and electricity production CHP

Gross electricity production	425 597	kWh/year
Net electricity production	397 652	kWh/year
Gross heat production	780 260	kWh/year
Net heat production	537 592	kWh/year

For the actual savings it is necessary to assume how much of the produced heat is used. Additionally it is required to calculate how much gas is replaced with this heat. We assume that 100% of the net produced heat replaces heat that is produced by a natural gas boiler with an efficiency of 85%. Table 4.18 shows the yearly CO_2-savings due to a CHP powered on biogas from digestion. The components that have been discussed in previous sections and have a value of zero are omitted from this overview, as they do not add more information.

Table 4.18 Yearly CO_2-savings due to CHP application (average grid emissions used, not fossil replacement)

Total evaded CO_2 emissions	**474**	Metric ton CO_2-equivalent/year
Evaded for electricity	172	Metric ton CO_2-equivalent/year
Evaded for heat	129	Metric ton CO_2-equivalent/year
Evaded from manure storage	173	Metric ton CO_2-equivalent/year
Total additional emissions	**39**	Metric ton CO_2-equivalent/year
CO_2-influence biomass	0	Metric ton CO_2-equivalent/year
Emissions from transport	6	Metric ton CO_2-equivalent/year
Methane slip from production	33	Metric ton CO_2-equivalent/year
CO_2 emissions from production	0	Metric ton CO_2-equivalent/year
Total yearly CO_2-savings	**435**	Metric ton CO_2-equivalent/year

5 EMISSION FACTORS AND EMISSION SAVINGS

5.1 THE EMISSION FACTORS IN ACCORDANCE WITH [EC, 2009]

Based on the replaced fuel and the yearly CO_2-emissions and savings due to the production of CNG derived in Chapter 4, the emission factors of [EC, 2009] can be determined. [EC, 2009] leaves room for neglecting a reduced engine efficiency in comparison to the fossil fuel. We list the emission factors with a reference in MJ renewable fuel and MJ replaced fossil fuel, i.e. diesel, with the efficiency as reported in section 4.7.3.

Calculated values for this study are compared with values reported in [EC, 2009] in Table 5.1

Table 5.1 Emission factors small-scale digestion and biogas upgrading to CNG

	[EC, 2009]	This study Reference Green Gas	This study Reference Diesel	
E	**13**	**-32.5**	**-43.0**	**g CO2eq/MJ**
e_{ec}	0	0	0	g CO2eq/MJ
e_l	0	0	0	g CO2eq/MJ
e_p	8	32	42	g CO2eq/MJ
e_{td}	5	2.4	3	g CO2eq/MJ
e_u	0	0	0	g CO2eq/MJ
e_{sca}	0	0	0	g CO2eq/MJ
e_{ccs}	0	0	0	g CO2eq/MJ
e_{ccr}	0	0	0	g CO2eq/MJ
e_{ee}	0	0	0	g CO2eq/MJ
$e_{otheravoided}$	0	67	89	g CO2eq/MJ

When comparing the values of this study and [EC, 2009] a few things are obvious. They are the large difference in $e_{p,}$ $e_{otheravoided}$ and as a result E. The low value for e_p from [EC, 2009] can almost only be explained if (part of) the electricity consumption is covered by a CHP that is matched on heat demand and is running on biogas. The produced electricity is then considered to have zero CO_2-emission. Note that this set-up leads to a lower fuel production. As mentioned in section 4.3.1, it is not economically feasible to invest in both the upgrading plant and a CHP for small-scale digestion.

Another striking difference is the term “other avoided emissions”. This is caused by the reduction of methane emissions from the manure storage. [EC, 2009] did not account for them, but as can be seen from Table 5.1, they have a significant contribution on the emission of greenhouse gases.

The difference between the reference natural gas and reference diesel is caused by the difference in engine efficiency. It clearly shows the importance of this efficiency, and also the drawback of expressing the CO_2-reduction as a unit of the energy content of the replaced fuel. From Table 5.1 it can be concluded that producing a replacement for diesel leads to a lower CO_2-emission than the replacement of methane, while in fact the emitted amount of CO_2 is exactly the same.

5.2 FUEL SAVINGS

Fuel savings is defined by [EC, 2009] as

$$SAVINGS = \frac{E_F - E_B}{E_F} \quad (5.1)$$

This means that the fuel savings compared to a fossil diesel case is 151%. That is, the saving is larger than just the evaded emissions by using the diesel fuel. This is true, because the fact that the open storage time is reduced, gives a large additional bonus in CO_2-emissions. When calculating the savings in comparison to CNG the savings are 139%. This is lower than diesel, because more fuel is replaced (in MJ).

6 SENSITIVITY ANALYSIS

6.1 INTRODUCTION

In the previous chapters the yearly greenhouse gas emission savings and relative energy savings have been calculated. In this chapter it will be investigated how sensitive these results are. The values that are used in the sensitivity analysis are shown in Table 6.1. The results are discussed in the separate sections. As Table 6.1 shows the deviation is assumed to be 20% for all variables, except for the methane slip. That is, because the methane slip is one of the more uncertain values in the calculations presented in this report, and therefore a deviation of 100% is used.

Table 6.1. Values changed in sensitivity analysis

	Deviation
Biogas production	+/- 20%
Saved greenhouse gas emissions from manure storage	+/- 100%
Efficiency engine compared to fossil fuel	+/- 20%
Heat consumption	+/- 20%
Electricity consumption	+/- 20%
Methane slip	+/- 100%
Specific CO_2 emission of electricity	+/- 100%

6.2 SENSITIVITY TO BIOGAS PRODUCTION

A sensitivity analysis to biogas production has been performed, as the actual biogas production accomplished may vary from the biogas production projected, as this will depend on design choices, most notably retention time in the digester.

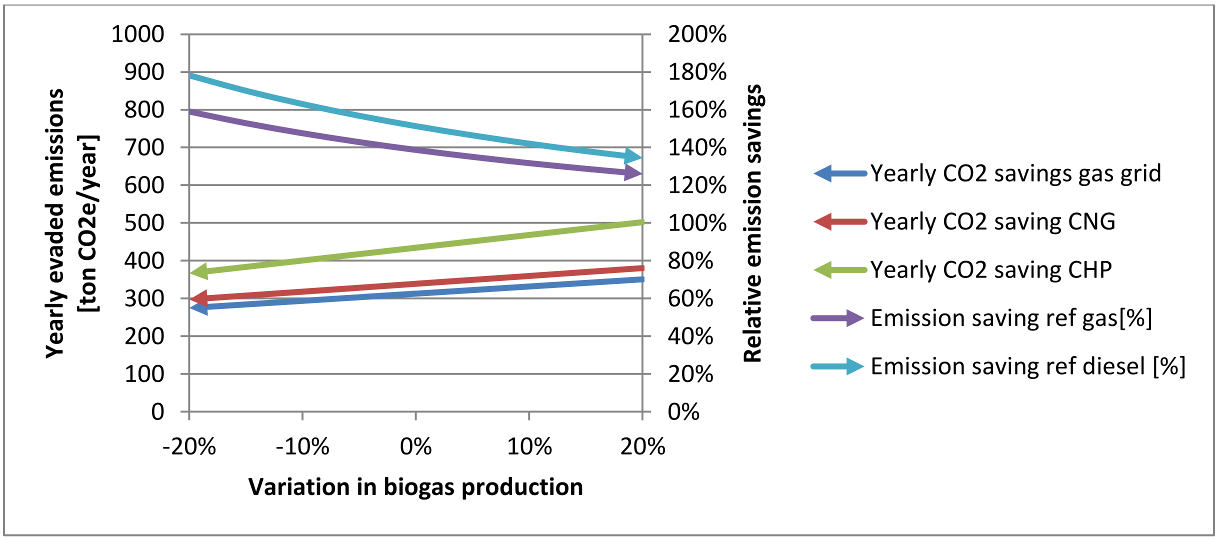


Figure 6.1 Sensitivity of yearly evaded emission (left) and fuel savings (right) to biogas production

A 20% reduction in biogas production leads to a reduction in yearly CO_2 emissions of about 12-16%. The reduction of greenhouse gas emissions by the manure storage is independent of the biogas production, and hence the total reduction in greenhouse gas emissions is lower than the 20% of the reduction in biogas production. Relative emission saving, as expressed in [EC, 2009], see APPENDIX 1, increases with decreasing biogas production. This is caused by the fact that the fuel production decreased by 20% while the CO_2-production less, therefore the relative savings increased.

6.3 Sensitivity to saved greenhouse gas emissions in manure storage

As indicated in section 4.5.1 the amount of greenhouse gases saved from manure storage is highly sensitive to the storage temperature, and hence geographic location; an increase in 5°C in storage temperature already results in an increase in evaded methane of close to 100%. Additionally the type of storage plays a very large role, an uncovered anaerobic lagoon for example, has a methane emission that is 4,5 times higher than storage in animal confinements at the same climatic conditions. Therefore a variation of 100% is used in emissions from manure storage. This clearly shows the importance of the actual emissions from manure storage and the importance of closed manure storage. It also shows the importance of including evaded emissions from manure storage in the calculation of the effect of digestion on greenhouse gasses.

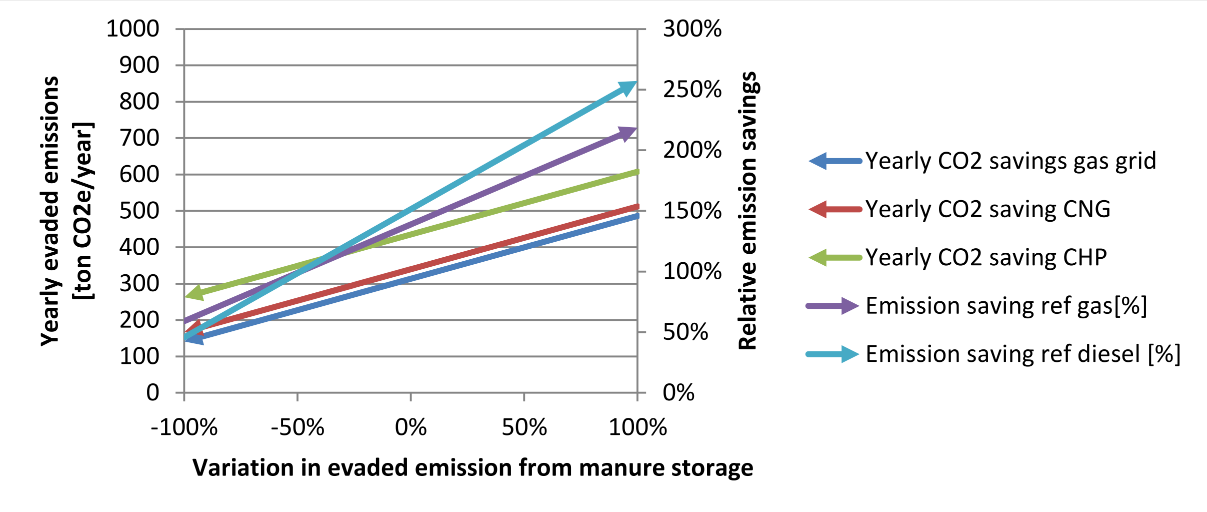


Figure 6.2 Sensitivity of yearly evaded emission (left) and fuel savings (right) to variation in evaded emissions from manure storage

6.4 Sensitivity to engine efficiency compared to fossil fuel

The engine efficiency of diesel versus CNG fuel has been changed by 75.5% +/- 20%. It clearly shows the importance of proper boundary definitions for the expected fuel savings.

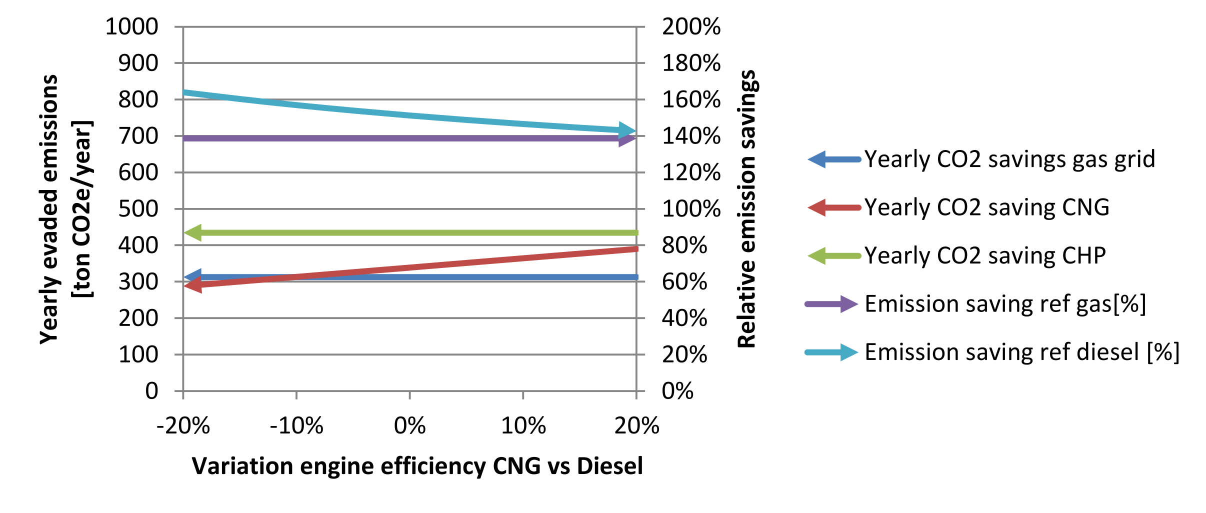


Figure 6.3 Sensitivity of yearly evaded emission (left) and fuel savings (right) to variation in engine efficiency CNG vs Diesel

6.5 Sensitivity to heat consumption

Some of the energy contained in the biogas is used to heat the digester, and upgrading installation. For a profitable exploitation a good heat integration is required, an estimate of this integration is made in this calculation. The digester that is used in this calculation has a rather high heat consumption, therefore a reduction in heat demand is also possible. A 20% variation in heat demand shows a rather limited effect on the yearly evaded emissions.

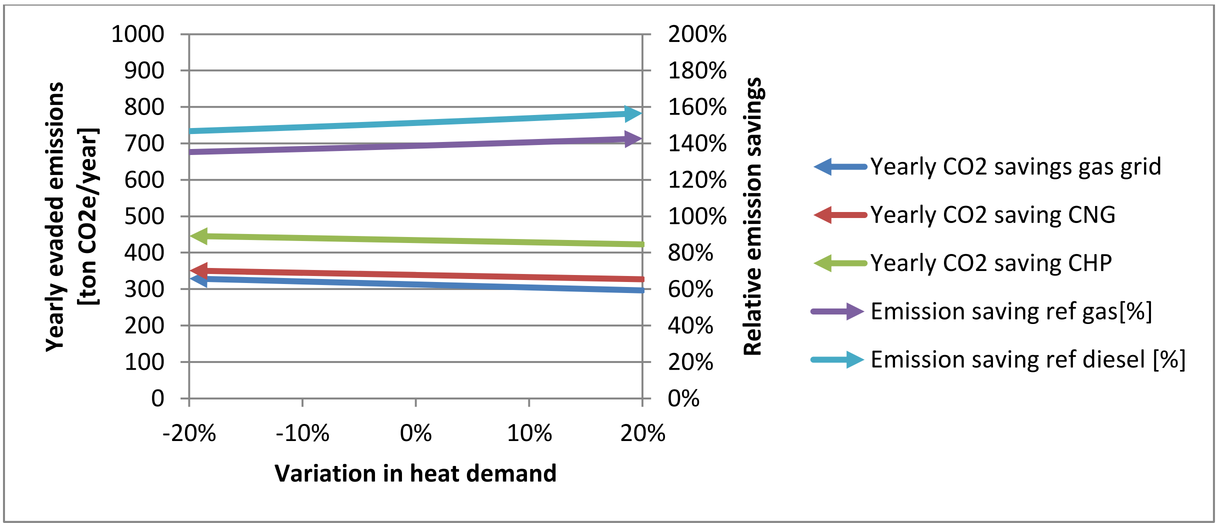


Figure 6.4 Sensitivity of yearly evaded emission (left) and fuel savings (right) to variation in heat demand of digester and upgrading

6.6 Sensitivity to electricity consumption

The electricity consumption of the digester and upgrading and CNG installation has been estimated. The actual value may vary from this estimation. The influence on the evaded CO_2-emissions is limited however.

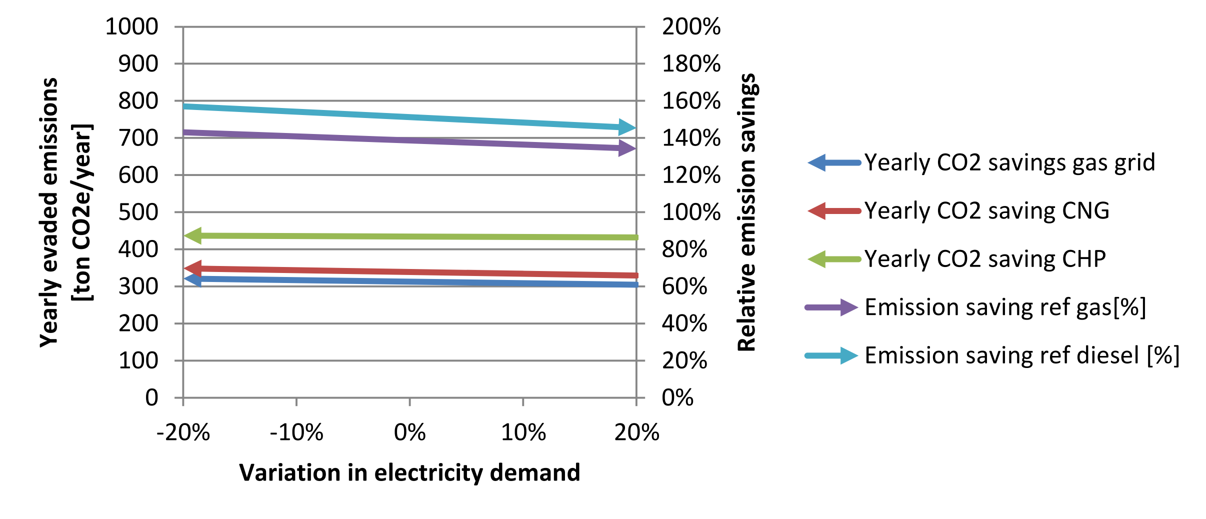


Figure 6.5 Sensitivity of yearly evaded emission (left) and fuel savings (right) to variation in electricity demand of digester, upgrading and CNG compression

6.7 Sensitivity to methane slip

The methane slip is estimated between 0.56% for gas upgrading up to 1 and 1.06% for CHP and CNG respectively. The biggest uncertainty are the emissions that are leaking from the digester, and are released by incidents. Figure 6.6 shows the importance of a good estimation of the methane slip on the CO_2-effect.

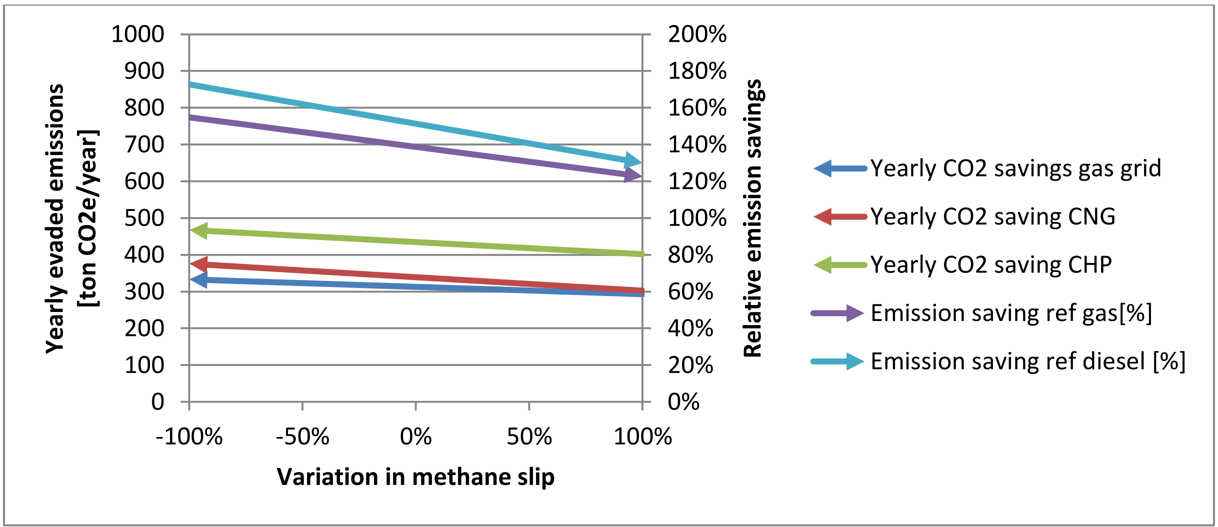


Figure 6.6 Sensitivity of yearly evaded emission (left) and fuel savings (right) to variation in methane slip

6.8 Sensitivity to specific CO_2-emission electricity production

Between the different European countries a big difference exists in the CO_2-emission of power in the grid. The EEA reports for 2009 a value of 4.5 kg CO_2/MWh for Norway and 990 kg CO_2/MWh for Estonia. The specific emission of the Netherlands is with 433 kg CO_2/MWh rather in the middle, and close to the EU average of 396 kg CO_2/MWh [EEA, 2013]. This large spread has a very profound influence on the evaded emissions. The gas grid and CNG cases profit from a lower grid emissions, whereas the CHP case suffers from lower grid emissions, as the emission of the emission that is replaced is much lower.

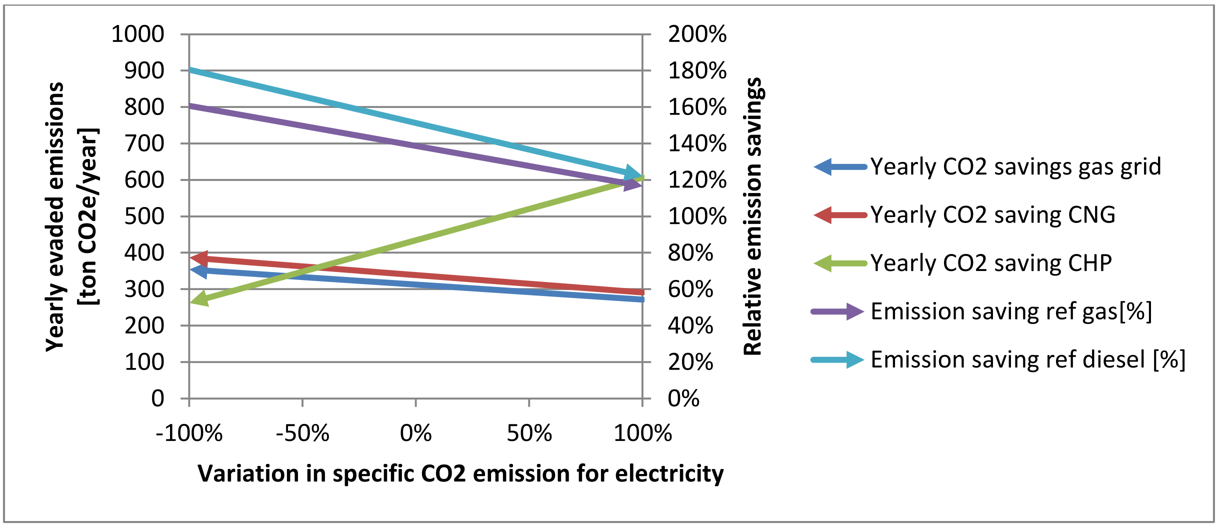


Figure 6.7 Sensitivity of yearly evaded emission (left) and fuel savings (right) to variation in specific CO_2-emission of electricity from the grid.

6.9 Summary of the results of the sensitivity analysis

A sensitivity analysis has been performed on the most important parameters. The CO_2-saving is highly sensitive to the geographic location of the installation. For the green gas cases this is because of the strong temperature dependence of methane emissions from manure storage, that can be evaded by digestion. Note that as The Netherlands is located in a cold region, it is more likely that the emissions from manure storage for the EU as a whole have been underestimated than overestimated! The CHP case is also sensitive to geographical location, because of the difference in national specific CO_2 emissions of electricity in the grid. Note that generally, the replaced fossil electricity is used, as an indicator, of the benefits of a CHP. This will Additionally the methane slip has a big influence.

An overview of the sensitivity of the different cases to the variation to certain parameters is given in Table 6.2. It can be concluded that uncertainties in heat consumption and electricity consumption have a rather limited effect on the evaded CO_2-emissions.

Table 6.2 Overview of sensitivity of evaded CO_2 from high sensitivity to low sensitivity

	Deviation	Change in yearly evaded CO_2 emissions		
		Gas grid	CNG	CHP
Saved greenhouse gas emissions from manure storage	100%	55%	51%	40%
Specific CO_2 emission of electricity	100%	-13%	-14%	40%
Biogas production	20%	12%	12%	16%
Efficiency engine compared to fossil fuel	20%	0%	15%	0%
Methane slip	100%	-6%	-11%	-8%
Heat consumption	20%	-5%	-4%	-3%
Electricity consumption	20%	-3%	-3%	-1%

7 Comparison to [De Vries et al., 2012]

In the project proposal for Climate KIC, a CO_2-savings calculation was presented in the form of Table 7.1.

Table 7.1 CO_2-reduction according to [De Vries et al., 2012]

Variable	Number	Unit	Calculation
Direct emission reduction			
(1) Livestock quantity	200	Cows	
(2) Average manure production	25	tonnes/yr/cow	
(3) Total manure available	5000	tonnes/yr	(1) * (2)
(4) Standard emission reduction factor (ERF) for anaerobic digestion of dairy cattle manure instead of volatilization into the open air (Netherlands)	34	kg CO_2 eq./ton manure	
(5) Direct emission reduction	170,000	kg CO_2 eq./yr	(3) * (4)
Indirect emission reduction			
(6) Typical biogas yield of cattle manure	22	Nm^3 biogas/ton manure	
(7) Estimated total biogas production	110,000	Nm^3/yr	(3) * (6)
(8) Assumed methane content of raw biogas	55	%	
(9) Lower heating value of methane	35.8	MJ/Nm^3	
(10) Gross energy yield	2166	GJ/yr	(7) * (8) * (9)
(11) Parasitic load of digester, needed for powering the upgrading and digestion processes	27	%	
(12) Net energy yield	1581	GJ/yr	(10) * (11)
(13) Lower heating value of regular diesel	35.7	MJ/l	
(14) Ordinary diesel replaced	44,289	l/yr	(12) / (13)
(15) Emission factor of diesel	85.8	kg CO_2/GJ	
(16) Emission avoided	135,659	kg CO_2/yr	(12) * (15)
Total emission reduction	**305**	**tonnes CO_2/yr**	(5) + (16)

The project reviewer asked to clarify this calculation.

The CO_2-saving for manure storage was derived from a factor that was used in The Netherlands as the official value by the Dutch government for project proposals. This factor has been re-evaluated in this underlying study, using 2013 data, and has been calculated as 34.5 kg CO_2 eq/ton manure (with methane to CO2 conversion factor of 23, in order to follow [EC, 2009]; this value equals 31.5 kg/ton for the more common IPCC value of 21). Methane slip should be incorporated separately. The influence of climate on this value was stressed. For warmer climate, the emission saving will be significantly larger. As the business case is based on actual manure output and not the number of cows, the direct emission reduction is almost equal with 173 ton/year.

The calculation of the indirect emission reduction has been changed. A clear distinction was made between emission reduction (i.e. diesel replacement) and additional emissions (a.o. electricity consumption, that was mentioned under parasitic load of the digester).

Additionally the calculation was brought into accordance with the business-case of Annex 5 of the proposal, in terms of biomass input, as a little bit of co-product is necessary for a realistic business case. This way the amount of biogas increased from 22 to 29 Nm^3/hr, and as a result the emission saving increased as well. Without this correction the new calculation would have resulted in about 294 ton/year. The initial calculation was in good agreement with this new, more precise calculation.

8 CONCLUSIONS

Good agreement with [De Vries et al., 2012]
The initial calculation as presented in [De Vries et al., 2012] is in good agreement with the more precise calculation presented in this report. In this report the approach of [EC, 2009] was followed. The reduction of the greenhouse gases for the replacement of diesel by CNG have been calculated as: 339 ton CO_2 eq/year.

The saved greenhouse gas emissions from manure to green gas in the grid and combined power and heat have been calculated as 313 and 435 ton CO_2 eq/year respectively.

Emissions from manure storage are important
The emission reduction from manure storage due to the use of digestion is very important, and the method of [EC, 2009] does not incorporate this effect. This factor in its turn is heavily dependent on outside temperature and hence geographic location. The calculation performed in this report is conservative, as the cool climate of The Netherlands is used to calculate the emission from the manure storage. The CO_2-saving for manure storage has been re-evaluated in this study, and has been calculated as 34.5 kg CO_2 eq/ton manure (with methane to CO2 conversion factor of 23, in order to follow [EC, 2009]; this value equals 31.5 kg/ton for the more common IPCC value of 21). For 5000 ton/year of manure the emission savings from the manure storage alone accounts for 173 ton CO_2 eq/year. New stables should be constructed without pit storage in animal confinements in order to reduce this methane emission even more. Methane slip from the digester and postprocessing (either upgrading or biogas engine) are important factors in the emissions during production.

Comments on [EC, 2009]
The savings of the manure storage are in the same order of magnitude as the savings by replacing the diesel fuel. Expressing the CO_2 savings in a percentage or g CO_2/MJ is therefore inconvenient, as savings larger than 100% have been calculated, and a decrease in biogas production from manure, leads to a higher amount of saved CO_2/MJ, as the saved emission from the manure storage has to be spread over more MJ of replaced fuel. Therefore the emissions should be expressed in reduced ton CO_2 per year.

This study shows that the default values as used in [EC, 2009] are not valid for small-scale digestion, as significantly larger emissions from production have been calculated. On the other hand evaded emissions from manure storage were not included. The actual CO_2-reduction is strongly dependent on engine efficiency of the CNG engine, and the fossil fuel with which it is compared. [EC, 2009] should be updated to oblige inclusion of the engine efficiency in its method.

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APPENDIX

APPENDIX 1. CALCULATION RULES ACCORDING TO EU FUELS DIRECTIVE 2009

This appendix displays the rules to calculate the greenhouse gas emission saving according to DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL [EC, 2009], which is quoted below:

"

1. *Greenhouse gas emissions from the production and use of transport fuels, biofuels and bioliquids shall be calculated as:*
   $E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}$,
   Where E = total emissions from the use of the fuel;
   e_{ec} = *emissions from the extraction or cultivation of raw materials;*
   e_l = *annualised emissions from carbon stock changes by land-use change;*
   e_p = *emissions from processing;*
   e_{td} = *emissions from transport and distribution;*
   e_u = *emissions from fuel in use;*
   e_{sca} = *emission saving from soil carbon accumulation via improved agricultural management;*
   e_{ccs} = *emission saving from carbon capture and geological storage;*
   e_{ccr} = *emission saving from carbon capture and replacement; and*
   e_{ee} = *emission saving from excess electricity from cogeneration;*
   Emissions from the manufacture of machinery and equipment shall not be taken into account.

2. *Greenhouse gas emissions from fuels, E, shall be expressed in terms of grams of* CO_2 *equivalent per MJ of fuel,* gCO_{2eq}/MJ.

3. *By derogation from point 2, for transport fuels, values calculated in terms of* gCO_{2eq}/MJ *may be adjusted to take into account differences between fuels in useful work done, expressed in terms of km/MJ. Such adjustments shall be made only where evidence of the differences in useful work done is provided.*

4. *Greenhouse gas emission saving from biofuels and bioliquids shall be calculated as:*
   $$SAVING = \frac{E_F - E_B}{E_F}$$
   Where E_B = *total emissions from the biofuel or bioliquid; and*
   E_F = *total emissions from the fossil fuel comparator.*

5. *The greenhouse gases taken into account for the purposes of point 1 shall be* CO_2, N_2O *and* CH_4. *For the purpose of calculating* CO_2 *equivalence, those gases shall be valued as follows:*

   CO_2: 1
   N_2O: 296
   CH_4: 23

6. *Emissions from the extraction or cultivation of raw materials,* e_{ec}, *shall include emission from the extraction or cultivation process itself: from the collection of raw materials; from waste and leakages; and from the production of chemicals or products*

used in extraction or cultivation. Capture of CO_2 in the cultivation of raw materials shall be excluded. Certified reduction of greenhouse gas emissions from flaring at oil production sites anywhere in the world shall be deducted. Estimates of emissions from cultivation may be derived from the use of averages calculated for smaller geographical areas that those used in the calculation of the default values, as an alternative to using actual values.

7. *Annualised emission from carbon stock changes caused by land-use change, e_l, shall be calculated by dividing total emissions equally over 20 years. For the calculation of those emissions the following rule shall be applied:*

$$e_l = (CS_R - CS_A) \times 3.664 \times \frac{1}{20} \times \frac{1}{P} - e_B$$ [4]

Where:

e_l = annualised greenhouse gas emissions from carbon stock change due to land-use change (measured as mass of CO_2 equivalent per unit biofuel energy)

CS_R = the carbon stock per unit area associated with the reference land use (measured as mass of carbon per unit area, including both soil and vegetation). The reference land use shall be the land use in January 2008 or 20 years before the raw material was obtained, whichever was the later;

CS_A = the carbon stock per unit area associated with the actual land use (measures as mass of carbon per unit area, including both soil and vegetation). In cases where the carbon stock accumulates over more than one year, the value attributed to CS_A shall be estimated stock per unit area after 20 years or when the crop reaches maturity, whichever the earlier;

P = the productivity of the crop (measured as biofuel or bioliquid energy per unit area per year); and

e_B = bonus of 29 gCO_{2eq}/MJ biofuel or bioliquid if biomass is obtained from restored degraded land under the conditions provided in point 8.

8. *The bonus of 29 g CO_{2eq}/MJ shall be attributed if evidence is provided that the land:*
   a) was not in use for agriculture or any other activity in January 2008; and
   b) falls into one of the following categories:
   i) severely degraded land, including such land that was formerly in agricultural use;
   ii) heavily contaminated land.

   The bonus of 29 g CO_{2eq}/MJ shall apply for a period up to 10 years from the date of conversion of the land to agricultural use, provided that a steady increase in carbon stocks as well as a sizable reduction in erosion phenomena for land falling under (i) are ensured and that soil contamination for land falling under (ii) is reduced.

9. *The categories referred to in point 8(b) are defined as follows:*
   a) 'severely degraded land' means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded;
   b) 'heavily contaminated land' means land that is unfit for the cultivation of food and feed due to soil contamination.
   Such land shall include land that has been the subject of a Commission decision in accordance with the fourth sub-paragraph of Article 18(4).

[4] The quotient obtained by dividing the molecular weight of CO_2 (44.010 g/mol) by the molecular weight of carbon (12.011 g/mol) is equal to 3.664

10. *The Commission shall adopt, by 31 December 2009, guidelines for the calculation of land carbon stocks drawing on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories – Volume 4. The Commission guidelines shall serve as the basis for the calculation of land carbon stocks for the purposes of this Directive.*

11. *Emission from processing, e_p shall include emissions from the processing itself: from waste and leakages; and from the production of chemicals or products used in processing.*

    In accounting for the consumption of electricity not produced within the fuel production plant, the greenhouse gas emission intensity of the production and distribution of that electricity shall be assumed to be equal to the average emission intensity of the production and distribution of electricity in a defined region. By derogation from this rule, producers may use an average value for an individual electricity production plant for electricity produced by that plant, if that plant is not connected to the electricity grid.

12. *Emissions from transport and distribution, e_{td}, shall include emission from the transport and storage of raw and semi-finished materials and from the storage and distribution of finished materials. Emissions from transport and distribution to be taken into account under point 6 shall not be covered by this point.*

13. *Emission from the fuel in use, e_u, shall be taken to be zero for biofuels and bioliquids.*

14. *Emission saving from carbon capture and geological storage e_{ccs}, that have not been accounted for in e_p, shall be limited to emissions avoided through the capture and sequestration of emitted CO_2 directly related to the extraction, transport, processing and distribution of fuel.*

15. *Emission saving from carbon capture and replacement, e_{ccr}, shall be limited to emissions avoided through the capture of CO_2 of which the carbon originates from biomass and which is used to replace fossil-derived CO_2 used in commercial products and services.*

16. *Emission saving from excess electricity from cogeneration, e_{ee}, shall be taken into account in relation to the excess of electricity produced by fuel production systems that use cogeneration except where the fuel used for the cogeneration is a co-product other than an agricultural crop residue. In accounting for that excess electricity, the size of the cogeneration unit shall be assumed to be the minimum necessary for the cogeneration unit to supply the heat that is needed to produce the fuel. The greenhouse gas emission saving associated with that excess electricity shall be taken to be equal to the amount of greenhouse gas that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit.*

17. *Where a fuel production process produces, in combination, the fuel for which emissions are being calculated and one or more other products (co-products), greenhouse gas emissions shall be divided between the fuel or its intermediate product and the ci-products in proportion to their energy content (determined by lower heating value in the case of co-products other than electricity).*

18. *For the purposes of the calculation referred to in point 17, the emissions to be divided shall be e_{ec}+e_l+those fractions of e_p, e_{td} and e_{ee} that take place up to and including the process step at which a co-product is produced. If any allocation to co-products has*

taken place at an earlier process step in the life-cycle, the fraction of those emissions assigned in the last such process step to the intermediate fuel product shall be used for this purpose instead of the total of those emissions.

In the case of biofuels and bioliquids, all co-products, including electricity that does not fall under the scope of point 16, shall be taken into account for the purposes of that calculation, except for agricultural crop residues, including straw, bagasse, husks, cobs and nut shells. Co-products that have a negative energy content shall be considered to have an energy content of zero for the purpose of the calculation.

Wastes, agricultural crop residues, including straw, bagasse, husks, cobs and nut shells, and residues form processing, including crude glycerine (glycerine that is not refined), shall be considered to have zero life-cycle greenhouse gas emission up to the process of collection of those materials.

In the case of fuels produced in refineries, the unit of analysis for the purposes of the calculation referred to in point 17 shall be the refinery.

19. For biofuels, for the purposes of the calculation referred to in point 3, the fossil fuel comparator E_F shall be the latest available actual average emissions from the fossil part of petrol and diesel consumed in the Community as reported under Directive 98/70/EC. If no such data are available, the value used shall be 83.8 g CO_{2eq}/MJ.
For bioliquids used for electricity production, for the purposes of the calculation referred to in point 4, the fossil fuel comparator E_F shall be 91 g CO_{2eq}/MJ.

For bioliquids used of heat production, for the purposes of the calculation referred to in point 4, the fossil fuel comparator E_F shall be 77 g CO_{2eq}/MJ.

For bioliquids used for cogeneration, for the purposes of the calculation referred to in point 4, the fossil fuel comparator E_F shall be 85 gCO_{2eq}/MJ."