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Ville Uusitalo

POTENTIAL FOR GREENHOUSE GAS EMISSION REDUCTIONS BY USING BIOMETHANE AS A ROAD TRANSPORTATION FUEL

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Supervisor Professor Risto Soukka
LUT Energy - Environmental Technology
Faculty of Technology
Lappeenranta University of Technology
Finland

Reviewers Senior Researcher, Ph.D. Alessio Boldrin
Department of Environmental Engineering
Technical University of Denmark
Denmark

Senior scientist, Ph.D. Laura Sokka
VTT Technical Research Centre of Finland
Finland

Opponent Post-Doctoral Reseacher, Ph.D. Briana Niblick
Department of Life Cycle Engineering (GaBi)
Fraunhofer Institute for Building Physics (IBP)
University of Stuttgart
Germany

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Abstract

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The aim of this thesis is to study whether the use of biomethane as a transportation fuel is reasonable from climate change perspective. In order to identify potentials and challenges for the reduction of greenhouse gas (GHG) emissions, this dissertation focuses on GHG emission comparisons, on feasibility studies and on the effects of various calculation methodologies. The GHG emissions calculations are carried out by using life cycle assessment (LCA) methodologies. The aim of these LCA studies is to figure out the key parameters affecting the GHG emission saving potential of biomethane production and use and to give recommendations related to methodological choices. The feasibility studies are also carried out from the life cycle perspective by dividing the biomethane production chain for various operators along the life cycle of biomethane in order to recognize economic bottlenecks.

Biomethane use in the transportation sector leads to GHG emission reductions compared to fossil transportation fuels in most cases. In addition, electricity and heat production from landfill gas, biogas or biomethane leads to GHG reductions as well. Electricity production for electric vehicles is also a potential route to direct biogas or biomethane energy to transportation sector. However, various factors along the life cycle of biomethane affect the GHG reduction potentials. Furthermore, the methodological selections have significant effects on the results. From economic perspective, there are factors related to different operators along the life cycle of biomethane, which are not encouraging biomethane use in the transportation sector.

To minimize the greenhouse gas emissions from the life cycle of biomethane, waste feedstock should be preferred. In addition, energy consumption, methane leakages, digestate utilization and the current use of feedstock or biogas are also key factors. To increase the use of biomethane in the transportation sector, political steering is needed to improve the feasibility for the operators. From methodological perspective, it is important to recognize the aim of the life cycle assessment study. The life cycle assessment studies can be divided into two categories: 1.) To produce average GHG information of biomethane to evaluate the acceptability of biomethane use compared to fossil transportation fuels. 2.) To produce GHG information of biomethane related to actual decision-making situations. This helps to figure out the actual GHG emission changes in cases when feedstock, biogas or biomethane are already in other use. For example directing biogas from electricity production to transportation use does not necessarily lead to additional GHG emission reductions. The use of biomethane seems to have a lot of potential for the reduction of greenhouse gas emissions as a transportation fuel. However, there are various aspects related to production processes, to the current use of feedstock or biogas and to the feasibility that have to be taken into account.

Keywords: biogas, biomethane, life cycle assessment, LCA, greenhouse gas emissions, limiting factors, energy production, feasibility
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For the most part, this work was written in IC train nro 1 coach 2 seat 65.

Ville Uusitalo
October 2014
Lappeenranta, Finland

Contents

List of publications

This dissertation is based on the following original publications, which will be referred to in the text by Roman numerals I–VI. The rights have been granted by publishers to include the publications in dissertation.

I. Uusitalo, V., Havukainen, J., Kapustina, V., Soukka, R., Horttanainen, M. (2014). Greenhouse Gas Emissions of Biomethane for Transport: Uncertainties and Allocation methods. *Energy & Fuel*, 28(3), pp. 1901–1910.

II. Uusitalo, V., Havukainen, J., Manninen, K., Hohn, J., Lehtonen, E., Soukka, R., Horttanainen, M., Rasi, S. (2014). Carbon Footprint of Selected Biomass to Biomethane Production Chains and GHG Reduction Potentials in Transportation Use in Helsinki Region. *Renewable Energy*, 66, pp. 90–98.

III. Uusitalo, V., Soukka, R., Horttanainen, M., Niskanen, A., Havukainen, J. (2013). Economics and Greenhouse Gas Balance of Biogas Use Systems in the Finnish Transportation Sector. *Renewable Energy*, 51, pp. 132–140.

IV. Uusitalo, V., Havukainen, J., Soukka, R., Väisänen, S., Havukainen, M., Luoranen, M. Creating Systematic Approach for Recognizing Limiting Factors for Growth of Biomethane in Transportation Sector Based on Case Finland. *Submitted*

V. Niskanen, A., Värri, H., Havukainen, J., Uusitalo, V., Horttanainen, M. (2013). Enhancing landfill gas recovery. *Journal of Cleaner Production*, 55, pp. 67–71.

Author's contribution

The author of the thesis is the corresponding author in Publications I–IV. The author planned the articles and calculation models with the supervisor and co-authors. The author conducted the major part of the experimental work and analyzed the results. The author made the first drafts of the publications which were then completed in co-operation with the supervisor and co-authors.

In Publications I and Publication II, Jouni Havukainen had the main role in the modeling of pretreatment and digestion processes. In Publication V, the author participated in the development of the calculation model for landfill gas injection into the natural gas grid and in data collection.

Nomenclature

Latin alphabet

c_p	specific heat capasity	$J\ kgK^{-1}$
E	total emissions	$gCO_{2eq}\ MJ^{-1}$
e	emissions/emission savings	$gCO_{2eq}\ MJ^{-1}$
I	investment	€
p	pressure	Pa
P	power	W
q_m	mass flow	$kg\ s^{-1}$
S_e	yearly expenses	€ a^{-1}
S_i	yearly incomes	€ a^{-1}
T	temperature	K

Greek alphabet

η	efficiency	-
η	polytrophic efficiency	-

Subscripts

B	biofuel or bioliquid
ccs	carbon capture and geological storage
ccr	carbon capture and replacement
e	expenses
ec	extraction or cultivation of raw materials
ee	excess electricity from cogeneration
F	fossil fuel comparator
i	incomes
l	annualized carbon stock changes caused by land-use change
max	maximum
min	minimum
p	processing
real	realistic
sca	soil carbon accumulation via improved agricultural practices
td	transport and distribution
tot	total
u	the fuel in use
1	first stage
2	second stage

Abbreviations

AGR	agricultural biomass

aLCA	attributional life cycle assessment
aMDEA	activated methyldiethanolamine
AW	amine wash
BAT	best available technology
BW	biowaste
$CaCO_3$	calcium carbonate
CBG	compressed biogas
CH_4	methane
CHP	combined heat and power
cLCA	consequential life cycle assessment
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
FIN	Finland
H_2S	hydrogen sulphide
HC	hydrocarbons
Hki	Helsinki
HVO	hydrotreated vegetable oil
IPCC	Intergovernmental Panel on Climate Change
LDV	light duty vehicle
ec-a	economic based allocation
el	electricity
en-a	energy based allocation
EU	European Union
EC	European Community
F	fair
FAME	fatty acid methyl ester
G	good
GHG	greenhouse gas
ISO	International Organization for Standardization
LBG	liquid biogas
LCA	life cycle assessment
LFG	landfill gas
LNG	liquid natural gas
LPG	petroleum gas
LUC	land use change
MB	membrane
MS	membrane separation
mth	month
N	nitrogen
N_2O	nitrous oxide
NG	natural gas
NGV	natural gas vehicle
no-a	no allocation

NO_X	nitrous oxides
OPEC	Organization of the Petroleum Exporting Countries
OECD	Organization for Economic Co-operation and Development
P	phosphorous
P	poor
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
PSA	pressure swing adsorption
scen	scenario
SNG	synthetic natural gas
SO_2	sulfur dioxide
TS	total solids
UC	University of California
UK	United Kingdom
USA	United States of America
upg	upgrading
V	very good
VOC	volatile organic compound
VS	volatile solids
WS	water scrubber
WWT	waste water treatment
WWTP	waste water treatment plant
WWTPS	waste water treatment plant sludge

1 Introduction

1.1 Background and research environment

One of the greatest global environmental challenges is the climate change and global warming due to increasing greenhouse gas (GHG) emissions. Carbon dioxide is the most important greenhouse gas, and it is released mainly from the use of fossil based energy. (World Resource Institute 2009, IPCC 2007) Population growth will probably increase the energy demand worldwide, which may lead to even faster growth in fossil energy consumption and in GHG emissions (EIA 2013A).

Approximately 15% of global GHG emissions are released from the transportation sector, and the share is expected to grow during the forthcoming decades (World Resource Institute 2009, IPCC 2007). The two major options to reduce GHG emissions from the transportation sector are to cut down the total energy consumption or to increase the share of energy sources with lower GHG emissions (EPA 2012). There are several different options to affect these two main options as can be seen in Figure 1.

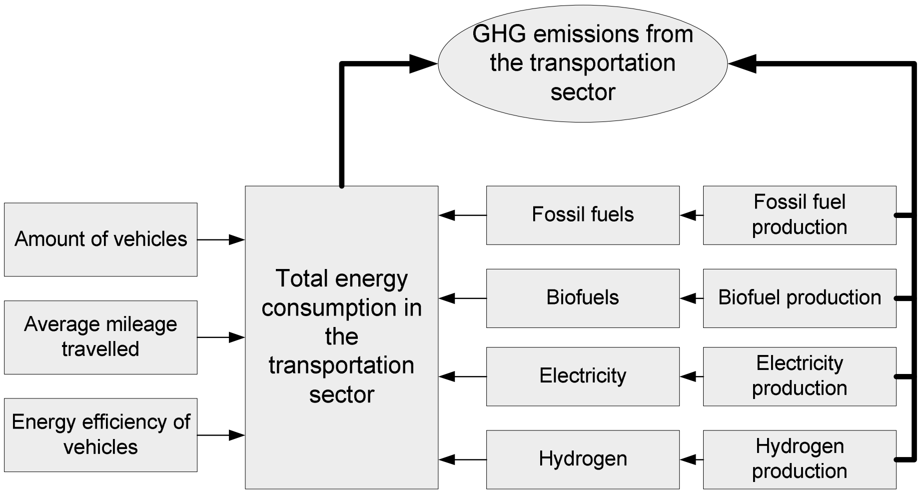

Figure 1: Factors affecting the total GHG emissions from the transportation sector. (EPA 2012, Ogden & Anderson 2011).

Cutting down consumption can be done by decreasing the total amount of vehicles, by decreasing the travel mileages per vehicle, or by improving energy efficiency in vehicles (EPA 2012). These actions would lead to a lower total energy demand in the transportation sector, and therefore, also to lower GHG emissions. Another option would be to affect the GHG emissions related to transportation energy production and use.

It is not likely that the total amount of vehicles will decrease worldwide during the forthcoming decades due to high growth rates in the number of vehicles in developing countries. Vehicle amounts per 1000 inhabitants are quite stable in developed countries, but the growth is rapid in developing countries such as Mexico, Brazil, and China. (The World Bank 2012, World Energy Council 2013B). The international Transport Forum predicts that the amount of passanger cars will increase between 2000 and 2050 by 30–40% in the OECD countries and by a factor of 5–6.5 outside the OECD region (International Transport Forum 2011). OECD 2011 predicts that the amount of cars will double between 2008 and 2035, and that the majority of the growth will happen in developing countries. (OECD 2011)

The average driving distance of vehicles is a complicated factor. Increasing transportation fuel prices may decrease the travelled mileages in some countries. Annual mileages travelled have decreased or stayed approximately at the same level for example in Finland and in the USA (Kumpulainen; U.S. Department of Transportation, 2011). Estimating average mileages travelled in developing countries is more complex due to lack of specific information. For example in China, the average mileages travelled have been traditionally longer than in developed countries. This is likely due to the lower amount of vehicles and the different ownership characteristics of passenger car owners. (Huo et al., 2007)

The improvement in vehicle efficiencies will likely help to decrease the energy consumption, but how notable the effect will be is difficult to predict (Ogden & Anderson, 2011). Vehicle efficiencies can be improved for example by developing advanced vehicle technologies, by using lighter materials or by reducing aerodynamic resistance of vehicles by better shape design (EPA 2012). The development of average fuel consumption has been slowly decreasing despite that average vehicle masses have been increasing (Bovag-rai, 2008). OECD 2011 predicts that average global car fuel consumption will decrease annually by 1.7% between 2008 and 2035 (OECD 2011).

Despite the fact that vehicle technology is slowly improving, the total energy consumption in the transportation sector is estimated to grow in the near future especially in developing countries (IPCC 2007; International Transport Forum, 2011). Therefore, to reduce GHG emissions from the transportation sector, attention should also be paid on fuel and energy sources and GHG emissions related to their production and use.

In addition to or instead of reducing total energy consumption, shifting to energy sources with low GHG emissions from production and use is another main option to reduce GHG emissions from the transportation sector. The majority of energy in the transportation sector is produced using fossil petrol and diesel. Instead of these fossil fuels, other fossil fuels with lower GHG emissions such as natural gas (NG), propane or butane can be used as compressed or liquid gas. (Motiva, 2012) Natural gas use as a vehicle fuel leads to greenhouse gas reductions, which are approximately 6–20% lower than from petrol use (U.S. Department of Transportation; U.S. Department of Energy, 2013B; Gasum Oy). However, there are also studies that show that when only tailpipe GHG emissions are studied, they can be higher or at the same level from NG vehicles than from diesel vehicles (Technical Research Centre of Finland, 2014; Kokki, 2006). On the other hand, when comparing emissions from the whole life cycle perspective, GHG emissions from NG are lower than from petrol or diesel use (U.S. Department of Energy, 2013B).

In addition to traditional combustion engines, transportation sector can be fuelled by electricity or hydrogen (EPA 2012). According to Ogden and Anderson (2011), electric cars and hydrogen vehicles will be a part of the green transportation sector, and it is likely that all the options are needed to receive high share of renewable based energy in transportation sector. Electric cars are solely breaking into markets, and several big car manufacturers have started their manufacturing (Hybridcars). The emissions from electric cars are related to electricity production because electric cars have no tailpipe emissions. If the electricity is renewable, the GHG reductions are obvious compared to fossil fuels. As well as electric cars, hydrogen cars have also penetrated the markets (Hybridcars). Analogous to electric cars, the emissions of hydrogen cars are related to hydrogen production, as they do not have direct emissions. Hydrogen production GHG emissions are highly dependent on the energy consumed in hydrogen production (U.S. Department of Transportation).

On the other hand, the development of electric cars is technically limited by the storage capacity of battery technology. This problem is bigger in heavy-duty vehicles where the needed battery may even exceed the cargo weight. (Daimler Trucks North America LLC, 2010) In addition, commercialization of long-range electrical vehicles requires 220V home charging stations, and utilities will need to provide the appropriate incentives to consumers to charge during less expensive off-peak hours. (Ogden & Anderson, 2011) The technical challenges that are limiting the use of hydrogen fuel are the further need for proton exchange membrane fuel cell cost and durability, hydrogen storage in vehicles and technologies for zero carbon hydrogen production. Increased hydrogen utilization will demand a wider spread hydrogen infrastructure. The problem is to distribute hydrogen with costs low enough to disperse users. For wider spread hydrogen use, it is likely that technology-specific policies will be needed to support the hydrogen transition. (Ogden & Anderson, 2011)

Biofuels can be produced from renewable feedstock, and it is assumed that the utilization of biofuels will lead to GHG emission reductions compared to fossil fuels. Ogden and Anderson (2011) predict that in the future 10–25% of transportation fuels could be biofuels depending on feedstock productivity and vehicle consumption improvements. A 20% prediction for biofuels in 2050 is presented also by Kahn Ribeiro et al. (2007). In addition to GHG emissions, other driving forces for the increased use of biofuels are improved self-sufficiency, supply security improvements and economic aspects (Ogden & Anderson, 2011; Finnish Petroleum Federation). Globally the most widely produced biofuels are biodiesel and ethanol. Figure 2 presents the share of different transportation fuels and modes.

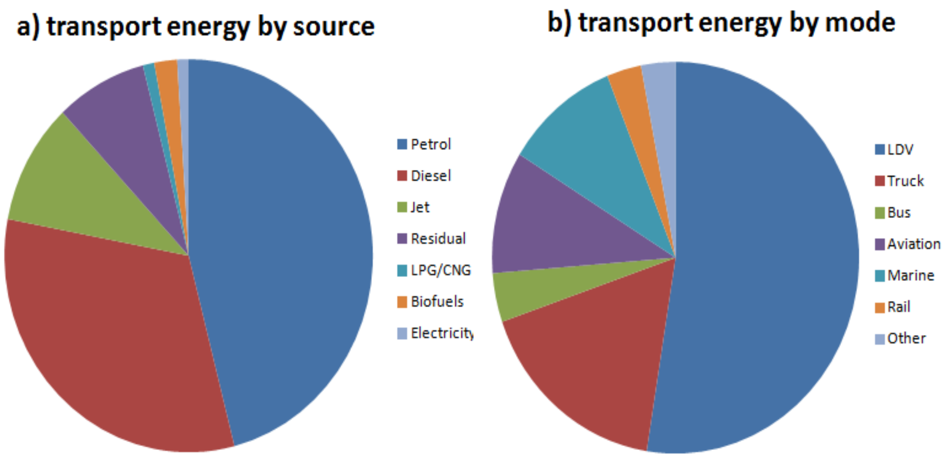

Figure 2: Global transport energy by source and by mode. (World Energy Council 2011).

As can be seen in Figure 2, the share of biofuels in the total fuel consumption in the transportation sector is marginal compared to fossil fuels. There are several challenges which are limiting the growth of biofuels. Technically, the large scale production from biomass to fuels is still a challenge with some of the feedstock and fuels. Some fuels, for example ethanol, may require dedicated storage and transportation systems or they may have limitations in use in the existing vehicles. Fuel share limitation in the existing vehicles is called "blend-wall" and is approximately 10% for ethanol in petrol cars and 5–7% for biodiesel in diesel cars (U.S. Department of Energy, 2013A, Neste Oil). The production is also limited by the amount of feedstock available. The increased production of feedstock may lead to increased use of arable land, fertilizers and water. Therefore, the environmental impact of using the resources has to be weighed against the benefits from producing biofuels. The increased production may also impact on food and feed production and on land use change (LUC). (Ogden & Anderson, 2011) Land use issues are one of the major problems from GHG emissions, social aspects and biodiversity perspectives with cultivated biomass based biofuels (Khanna & Crago, 2011; European Commission, 2012). In addition to GHG emissions, attention should be paid also to other pollutants such as particulate matter and NO_x emissions, which may cause for example different kinds of health problems (Salonen & Pennanen, 2006).

Table 1 compares the characteristics of various transportation biofuels.

Table 1: The main characteristics of various transportation biofuels. (Neste Oil, Nikander, 2008; Nigam & Singh, 2011; Cascone, 2008; Latvala, 2009; Antares group incorporates, 2009; Brown, 2008; Wigg, 2011; U.S. Department of Energy, 2013A)

	Ethanol		**Butanol**	**Biodiesel (Fame)**	**Renewable diesel (HVO)**	**Biomethane**
type of feedstock	sugar and starch	lignocellulosic	sugar and starch	oil	oil	organic material
raw materials (examples)*	sugar and starch plants, wastes	lignocellulosic biomasses and plants	sugar and starch plants	oil plants, waste oils and fats	oil plants, waste oils and fats	biowastes, sludge, manure cultivated biomasses, landfill gas
production	fermentation, enzyme conversion, gasification + syngas fermentation	hydrolysis, fermentation, thermal conversion	fermentation, enzyme conversion, gasification	transesterification, gasification + Fischer Tropsch catalysis	hydrotreatment	anaerobic digestion, thermo-chemical conversion
co-products	cellulosic parts of plants	parts of plants	cellulosic parts of plants	parts of plants (kernels etcs.) glycerine	parts of plants (kernels etcs.), bio-gasoline, propane,	digestate
distribution	separate distribution system	separate distribution system	distribution systems for petrol or separate system	separate distribution system	distribution systems for diesel or separate systems	distribution systems for NG or separate systems
vehicles	petrol cars, flexi-fuel cars	petrol cars, flexi-fuel cars	petrol cars, flexi-fuel cars	diesel cars	diesel cars	gas-operated cars
blend-wall**	10% (80%)	10% (80%)	16–100%	5–7%	100%	100%
state of technology	commercial	under development	commercial, not widely used	commercial	commercial	commercial
disadvantages of fuel	corrosive, absorbs water, low energy content	corrosive, absorbs water, low energy content	poisonous, bad smell	may cause problems in engines, does not preserve long times, cold-flow properties	-	
advantages of fuel	-	-	high energy content, less evaporative	biodegradable, non-toxic	good storability, good cold weather performance	-
GHG emissions reduction according to Directive 2009/28/EC (no LUC)	16–71%	-	-	19–88%	26–68% (hydrotreated vegetable oil)	73–86% (biogas)
other emissions	increased NOx and acetaldehyde emission and decreased CO, particulate matter and benzene emissions	increased NOx and acetaldehyde emission and decreased CO, particulate matter and benzene emissions	decreased CO emissions and increased NOx emissions	increased NOx emissions	decreased particulate matter, NOx, CO and HC emissions	low particulate matter and NO_x emissions

* For gasification and thermal conversion processes the range of raw materials is wider.
** Value for flexi-fuel vehicles in parentheses

Despite the fact that biomass based energy is usually seen as a good option compared to fossil alternatives, there are also various sustainability challenges related to the biomass use. The sustainability challenges can be divided into environmental, social and economic challenges. According to Rockström et al. (2009), from the environmental sustainability perspective, global limits have been exceeded in the climate change, biodiversity loss and nitrogen cycles. According to the European Commission (2014), direct or indirect land use change, soil fertility loss, soil compaction, biodiversity loss, other soil and water impacts are the major sustainability challenges related to agricultural biomass production. According to Searchinger et al. (2009), biomass cannot be regarded as carbon neutral due to the GHG emissions related to land use change and tail pipe emissions. Bioenergy production may compete for available agricultural land against food production needed for growing global population. This may lead to direct or indirect land use change when new land areas are cleared for cultivation of food or bioenergy feedstock. Land use change leads to soil and above ground carbon stock changes. The use degraded or poor agricultural lands may lead to an increase in carbon stock change, which may even result in negative GHG emissions. (European commission, 2014; Uusitalo & al., 2014) Increased agricultural production demands more fertilizers, which lead to unsustainable nutrient cycles. Nutrient runoff may lead to eutrophication in water systems. Modifying natural environments to one-sided fields may lead to biodiversity loss. In order to recognize the challenges related to biodiversity, the studies are complicated, and different biodiversity indexes may lead to different conclusions related to biodiversity hotspots. (Orme et al., 2005; Conservation international, 2004). Another sustainability challenge is related to water use. Water stress index can be used to evaluate water availability in certain geographical locations. Biomass production may require water use for example in irrigation, and this may compete for limited water resources against other water use. In addition, the standard ISO 14046.2 instructs to evaluate both quantitative and qualitative water use. Socioeconomic sustainability challenges are directed to local people at all life cycle stages. The challenges may be related for instance to healthy issues, land ownership and food production replacement. On the other hand, there are also possibilities for example to job creation. (Havukainen et al., 2013) There are various methodological challenges related to biomass sustainability assessment. LCA can give answers to some information demands, but also other sustainability assessment methods are needed.

One of the biofuels with a relatively high production potential is biomethane. Biogas is produced from biodegradable materials by anaerobic digestion and can be further upgraded to biomethane. Common feedstock for biogas production by anaerobic digestion are organic materials such as biowaste, waste water treatment plant (WWTP) sludge and biomasses from agriculture, for example dedicated energy crops and manure. In addition to biogas from digestions processes, also landfill gas is relatively similar to biogas. According to Finnveden et al. (2005), biogas production from biowaste is a better option than composting, incineration or land filling from the GHG emissions perspective. Using waste materials, problems related to direct land use change can be avoided.

Biomethane can be used in gas-operated vehicles developed for NG or for electricity and heat production. In addition, biogas can also be used in energy production without upgrading (only rough purification is needed). On the other hand, biogas use in heat production has decreased because of competing low-cost biofuels such as straw and wood chips (Lantz et al., 2007). CHP production of biogas or biomethane is hampered due to lack of heat sinks (Lantz et al., 2007). Distribution of biomethane can be done via existing natural gas grids or by separate pipelines, and the technology is commercial. (Rasi, 2009; Poeschl et al., 2010) An example of biogas and biomethane production and utilization options is presented in Figure 3.

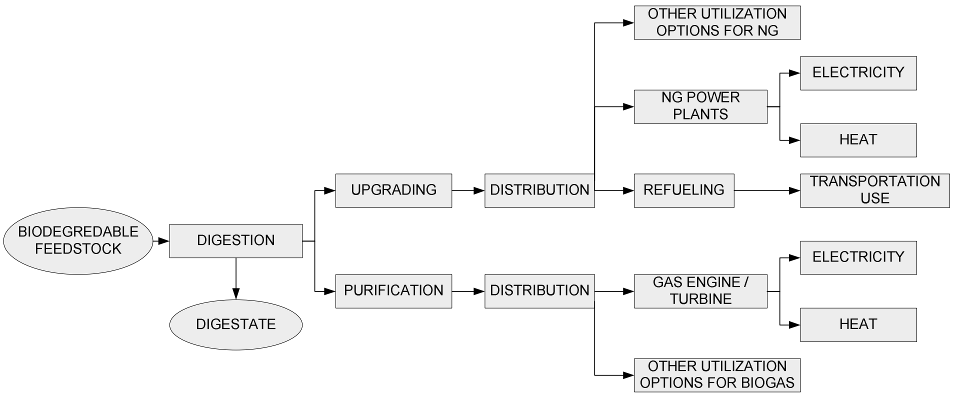

Figure 3: Biogas and biomethane production and utilization options.

Biomethane can also be produced from a variety of organic materials by gasification processes (Naik et al., 2010). In gasification, biomass is turned to syngas that consists mainly of CO, H_2, CH_4, CO_2 components and in smaller amounts of components such as H_2O, H_2S, SO_2 and NO_x (Naik et al., 2010; Pöyry Finland Oy, 2013). Syngas production by gasification is a commercial process that has been used for example in Fischer-Tropsch diesel production (Naik et al., 2010). To produce biomethane or bio-SNG (synthetic natural gas), syngas has to be purified and methanate. In the methanation process, CO and H_2 are converted to CH_4. After methanation, the methane content of the gas is up to 95%. (Pöyry Finland Oy, 2013) Another option to produce biomethane is its use as storage for renewable electricity. In the process, renewable electricity can be used in electrolysis to convert H_2O to H_2. Then H_2 can be methanated with CO_2 to CH_4. An advantage of this method is that it can be used to store cheap renewable energy during the peak production hours for example of wind power. Another advantage is that it offers a way to utilize CO_2 from carbon capture processes. (Specht et al., 2009)

The European Union has set a 20-20-20 goal for increasing the use of renewable energy by 20% of the total energy consumption, reducing greenhouse gases by 20%, and increasing energy efficiency by 20% by the year 2020. There is also a specific goal for transportation fuels. In the year 2020, 10% of energy used in the transportation sector should be renewable. (Directive, 2009/28/EC; Ministry of employment and the economy, 2008) There are also several other goals in various countries aiming to reduce GHG emissions from energy and transportation sector, for example the Californian low carbon fuel standard (Californian low carbon fuel standard). This has led to challenges for decision makers to decide whether biogas should be used for transportation purposes or for electricity and heat production purposes. Because biogas is produced from various materials and biogas or biomethane can be used in various applications policies, support mechanisms and legislations are variable and complex (Lantz et al., 2007). In Finland, a feed-in tariff was implemented to support electricity and heat production from biogas. However, the tariff does not support the transportation use of biomethane. (Ministry of employment and the economy, 2009)

The potential of biomethane use in the transportation sector can be justified by its applicability for various transportation types. Figure 4 presents various transportation types hierarchically based on the amount of available alternative energy options.

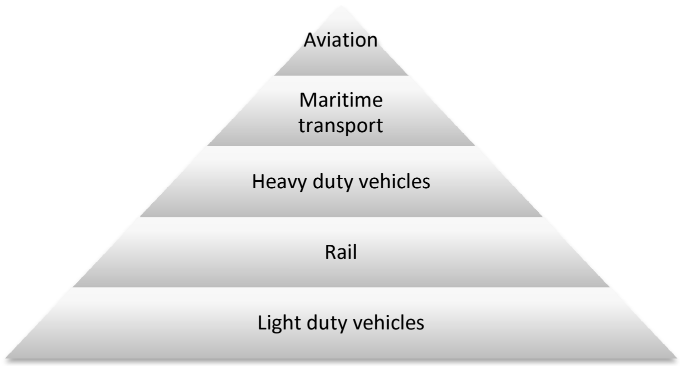

Figure 4: Energy need for transportation types presented hierarchically (Ministry of transport and communications, 2013)

Aviation fuels can only be replaced by biokerosene. Therefore, it is the most difficult transportation type for alternative fuels. Maritime transport is the second most difficult transportation type. Maritime transport could be fuelled by replacing fossil oils by bio-oils or by biomethane (as liquid biogas). Heavy-duty vehicles can use biomethane, biodiesel or renewable diesel to replace fossil diesel fuels. Lightest heavy-duty vehicles can also use ethanol fuels. Rail transportation can be carried out by biofuels for fossil diesel replacement or by biomethane. In addition, electricity is an important option for rail transportation. For aviation and maritime transportation, electricity is not a solution as they are limited by the available battery technology. Heavy-duty vehicles can use electricity only in special cases for busses in city transportation. Light-duty vehicles are the easiest transportation type from the alternative fuel options perspective. For light-duty vehicles, ethanol, biodiesel, renewable diesel, biomethane and electricity are all potential options. Hybrid technologies are also easier for light-duty vehicles. (Ministry of transport and communications, 2013) Because biomethane is a suitable fuel for all the other transportation types excluding aviation, its use for transportation purposes should probably be favoured.

According to various previous studies, biomethane use in the transportation sector leads to GHG emission reductions compared to fossil fuels (Pertl et al., 2010; Jury et al., 2010; Tuomisto & Helenius, 2008; Börjesson & Berglund, 2006). There are also previous studies that demonstrate that energy production from biogas leads aswell to GHG emissions reductions compared to alternative energy systems. (Börjesson & Berglund, 2007; Boulamanti et al., 2013). When fuel choices are made, it is important to recognize changes also in other effects, such as ecology, air pollutants and eutrophication, so that the decisions that are aiming to reduce some environmental effects are not at the same time increasing other unwanted effects. Hartmann (2006) studied ecological effects from biogas production. According to his studies, most of the ecological effects related to the biogas production chain are related to the agricultural production system. Agricultural processes produce the majority of the effects in the impact categories respiratory problems by inorganic emissions and acidification/eutrophication. (Hartmann, 2006) This is because nitrogen emissions are related to nitrogen fertilizer use. However, biogas systems have normally remarkable benefits in the form of indirect effects such as reduced eutrophication and acidification compared to conventional agricultural practices (Lantz et al., 2007).

Despite the fact that transportation biomethane seems to lead to GHG emission reductions, and is a cheaper fuel than fossil petrol and diesel, its use is still at a low level. The factors that are limiting the use of biomethane in the transportation sector are not yet known well enough, and they should be studied more systematically. Lantz et al. (2007) found out that economic aspects have a high influence in the profitability of biogas systems, but they did not carry out feasibility calculations for different operators along the life cycle of biomethane. To study the biomethane chain from different operators' perspective would be important in recognizing the economic bottlenecks.

There are also uncertainties related to the climate change performance of biomethane. Comparing the results from the previous studies is confusing because the range of the selections related to various factors along the life cycle and of methodological assumptions is huge and sometimes not well justified. In addition, it is not known in which cases the transportation use of biomethane is preferable compared to the energy production option, and what are the most important factors in these comparisons. Additional option could also be to produce electricity from biogas and use it in electric vehicles, but the option has not been previously studied. From life cycle assessment methodological perspective, the variation of the used methods in previous studies is wide. Some studies have concentrated on life cycle emissions from biomethane production like Börjesson & Berglund (2006), Pertl et al. (2010) and Tuomisto &

Helenius (2008). Other studies like Börjesson & Berglund (2007) have on the other hand concentrated on larger system scale studies where other utilization options for biogas and feedstock are studied. Different studies demand the use of different LCA methodologies, and therefore, it would be important to know when the different methods should be used.

There are various production related factors, such as feedstock selected, methane leakages and upgrading technology utilized and methodological aspects, that affect the total GHG emission reduction potential of biomethane (Börjesson & Berglund, 2007; Pertl et al., 2010; Poeschl et al., 2012). For example, Börjesson & Berglund (2006) did not include N_2O emissions from digestate spreading, Pertl et al. (2010) concentrated only on comparing upgrading systems and Tuomisto and Helenius (2008) concentrated only on agricultural biomass feedstock. It is also uncertain whether digestate can be regarded as a co-product or waste, which has led to a situation where different studies do different assumptions related to digestate use and calculation (allocation) methods related to digestate. For example, Pertl et al. (2010) excluded the GHG emissions related to the digestate use in their study, which underestimates the GHG emissions related to biomethane use. Additional GHG emission reductions can also be gained when mineral fertilizers are replaced by digestate. These factors and methodologies along the life cycle of biomethane have not been studied systematically previously.

1.2 Research problem and objectives

The aim of this dissertation is to study biomethane use in the transportation sector. The first goal is to study the advantages from the climate change perspective when biomethane is used as a transportation fuel. In this dissertation, the significance of various life cycle steps in the transportation biomethane chain GHG emissions are studied as well as the different life cycle assessment calculation methods. The aim is also to give recommendations for the use of different LCA methodologies. The second goal is to study which factors are limiting the use of biomethane as a transportation fuel from the economic perspective and how these limitations could be overcome. Feasibility studies are also carried out from the life cycle perspective by dividing the biomethane production chain for different operators.

The following research questions were formulated:

- How to maximize the benefits from the climate change point of view when biomethane is utilized for transportation purposes?
- What kind of further instruction can be given for calculation methodologies if applied for different use purposes of biomethane from the climate change point of view?
- What are the factors which are limiting the utilization of biomethane in the transportation sector from the economic perspective and how could these barriers be overcome?

1.3 Scope of the study

This dissertation consists of five research publications (four published and one submitted manuscript). All of the publications are using the life cycle assessment approach. Publication I and Publication II were carried out to study GHG emissions from biomethane production and use in the transportation sector. Publication III compares biomethane use in the transportation sector to electricity produced from biogas or biomethane use in electric vehicles from GHG and feasibility perspectives. Publication V compares GHG emissions from various landfill gas utilization options. Publication IV concentrates on estimating which factors are limiting the biomethane use in the transportation sector. The research is caried out using life-cycle assessment (LCA) methodology. Calculations are caried out by using Microsoft Office Excel 2007.

Publication I studies GHG emissions from biomethane production and use in the transportation sector. Biowaste and dedicated energy crops (timothy and clover) are used as feedstock in the study. Attention is paid to the determination of the key factors which are affecting GHG emissions of biomethane production and use in the transportation sector. In the sensitivity analysis, various factors along the life cycle of biomethane are varied in order to figure out the uncertainties derived from the assumptions and the initial data. The impacts on the results caused by alternative allocation methods for digestate are also compared from the methodological perspective.

Publication II compares GHG emissions from various biogas utilization options. The compared options are biomethane use in the transportation sector and various electricity and heat production options from biogas or biomethane. In this publication, a wider scale approach is used in addition to the allocation methodologies to give information about real decision making situations. Alternative feedstock utilization is also included in the publication.

Publication III compares GHG emissions when biomethane is used in gas-operated vehicles to a situation when the electricity produced by biogas is used in electric vehicles. In addition, feasibility comparison of the different options is carried out. The goal of the feasibility study is also to estimate the economic effects on gas-operated vehicles due to the implementation of the feed-in tariff for electricity produced by biogas in Finland.

Publication IV studies different factors that may limit the amount of gas-operated vehicles in Finland. The goal is to create a systematic approach method to estimate the most important limiting factors for biomethane use in the transportation sector. The study concentrates on estimating the theoretical biomethane potential in Finland, the development of distribution systems compared to the systems in other countries, technologies of gas-operated vehicles and the economical feasibility of biomethane production and utilization from different operators’ perspectives. In addition, the option to use reductions from external costs by using biomethane in the transportation sector is evaluated. These savings could be used to support biomethane utilization.

Publication V increases the scope of the dissertation to landfill gas. In this study, GHG emissions from landfill gas utilization in electricity and heat production are compared to landfill gas utilization in asphalt production and in district heating and to landfill gas upgrading and injection into natural gas grid and electricity and heat production.

As a conclusion, this dissertation will be carried out by studying GHG emissions and economic aspects of biomethane use in the transportation sector compared to various other utilization options. Economic aspects are studied by estimating the feasibility for different operators in biomethane production and utilization chain and by comparing different biogas utilization options. Table 2 presents some of the key issues and their inclusion in the publications.

Table 2: Publication contributions

	I	II	III	IV	V
GHG LCA studies					
Land use change	X				
Feedstock production and collection	X	X			
Landfill gas					X
Biogas production	X	X			
Upgrading	X	X	X		X
Distribution	X	X	X		X
Transportation use	X	X	X		
CHP		X	X		X
Electric vehicles			X		
Other environmental effects					
Local pollutants			X	X	
Land use change	X				
Nutrient cycles related to digestate	X	X			
Economics and limiting factors					
Contribution to self-sufficiency				X	
Biomethane potentials				X	
Technological limitations				X	
Infrastructure limitations				X	
External costs				X	
Feasibility			X	X	
Feed-in tariff			X	X	
Methodological aspects	X	X	X	X	

The work is mainly carried out from the Finnish or North European operational environment perspective. Political aspects are concentrating on the EU policy. However, all of the studies can be modified for different countries by changing the country-specific information used in the studies. The country-specific information is mainly related to GHG emissions from average energy production. In addition, climate conditions may change the operational parameters for example of the digestion process.

On the other hand applicability of methodological recommendations is not limited by geographical location.

This dissertation focuses on GHG emissions. Effects on other sustainability aspects such as biodiversity, water use and social sustainability are not included in this study. Biomethane production from thermo-chemical processes is also excluded. There are also some other novel production methods for biomethane, such as using biomethane as a storage for renewable electricity. There are also some preliminary studies which suggest biogas or landfill gas utilization for hydrogen production. This option is also excluded from this study.

From the LCA point of view, the most important processes in biomethane production and distribution chain are taken into account except the distribution as liquid biogas (LBG). This method is not widely used in biomethane distribution in Finland, and we lack reliable data concerning LBG production. Figure 5 presents the biomethane production and utilization chain from the LCA GHG perspective and the covering of the studied field by the publications of this dissertation. In this study, the transportation use of biomethane means road transportation use in passenger cars, busses and heavy vehicles. Other transportation options, such as marine transportation, are not included in this study.

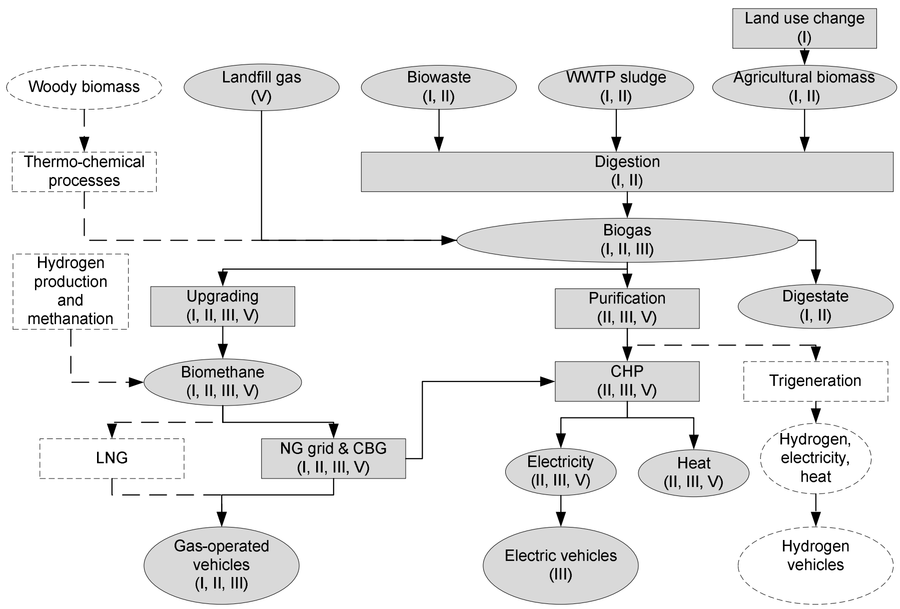

Figure 5: System boundaries in the GHG LCA studies of this dissertation. Grey process steps are included in this dissertation, and the Roman numerals present the publications in which they are included.

1.4 Brief overview of the chapters and structure of thesis work.

This thesis is based on five individual publications. Four of the publications have already been published in scientific journals. All publications are presented at the end of the thesis. The thesis consists of six chapters.

Chapter 1. Introduction presents the background of the thesis, the research questions and a short description of the working methods and the limitations of the thesis.

Chapter 2. Chapter 2 gives an overview of recent and most important research related to biomethane use as a transportation fuel. It starts with a description of various technologies and factors along the life cycle of transportation biomethane production and use. Then, the GHG emissions related to transportation biomethane are presented based on the literature. The last part concentrates on an overview of potential limiting factors for biomethane use in the transportation sector. This section is divided into potentials and contribution to self-sufficiency, economic aspects, technological aspects and political aspects.

Chapter 3. Materials and methods give overall information about the methods and data sources used in this thesis. The basic theory and rules to calculate GHG emission effects of biofules are presented according to Directive 2009/28/EC, ISO 14040 and ISO 14044 standards and Greenhouse Gas Protocol (2011). GHG emissions calculation models used in different publications are presented in their own sections. In addition, methods to create economic and potential calculation models are also presented.

Chapter 4. Results present the results of the thesis.

Chapter 5. Discussion gives information about the impacts of the results and makes comparisons to previous studies. It also answers the research questions defined in the introduction chapter. In addition, this chapter discusses limitations, the impacts of the research, future research questions and the value of the research.

Chapter 6. Conclusions chapter concludes the thesis and gives recommendations arising from the work.

2 Biomethane production and use in the transportation sector

This chapter presents the previous studies and findings related to biogas and biomethane use. It is divided into five sections. The first section presents the transportation biomethane path way and detailed information related to various unit processes. This section concentrates especially on upgrading, distribution and biomethane use in the transportation sector and gives an overview of information that is applied in case studies. The second section presents the previous studies and results related to GHG emissions from biomethane use in the transportation sector. The third section presents research related to factors that may limit or hinder the utilization of biomethane in the transportation sector.

2.1 Production technology description

2.1.1 Feedstock

Biogas can be produced from a variety of organic feedstock by anaerobic digestion processes. Digestion process can be developed for a single feedstock or for a combination of several feedstock. Examples of feedstock and feedstock methane productivities are presented in Table 3.

Table 3: Feedstock methane productivity (Gustafsson & Stoor, 2008; Rasi et al., 2012; Kahiluoto et al., 2011)

Feedstock	Methane productivity Nm^3 / $t_{wet\ feedstock}$
Sludge	10–42 (WWTP), 42 (wood industry), 14-42 (pulp and paper industry)
Biowaste	22–127
Waste	60–119 (fish), 238-351 (bakery), 18-35 (milk whey), 325 (sweets)
Fat/Animal waste	288–641 (fat), 60–230 (slaughtering)
Vegetable waste	6–97
Manure	5–58 (pig), 3-51 (cattle), 48 (horse)
Grass	60 (timothy-clover), 74-119 (silage), 57-91 (fallow), 48 (clover)
Reed	55–103
Vegetable tops	6–29
Straw	52–178 (cereals), 35-207 (rape)

In addition, landfill gas is relatively similar to biogas from anaerobic digestion. Landfill gas is produced naturally in anaerobic conditions in landfills from deposited organic wastes. Landfill gas has usually a lower methane content and higher nitrogen content than biogas. In addition, some trace compounds such as hydrogen sulfide (H_2S) are more abundant in LFG. (Rasi et al., 2007) The amount of landfill gas is likely to decrease in the future as more strict legislation will decrease organic material deposited into landfills. (Ministry of the Environment 2013).

2.1.2 Land use change, cultivation, feedstock collection and transportation

Land use change (LUC) may result in increased GHG emissions because of modifications in soil carbon stock. If dedicated energy crops are used as feedstock for biofuels, there are various options pertinent to land use change. First, feedstock from set-aside fields, from buffer strips of water systems, or from landscaping and similar areas can sometimes be regarded as waste, thus not leading to land use change. Second, if feedstock production takes place on fields already used in silage production, there are no significant additional GHG emissions from the land use change because the carbon stock level does not change in relation to the previous use. Third, if forests are logged and converted into fields, there will indeed be a change in carbon stock resulting in increased GHG emissions. Fourth, indirect LUC is also a possible consideration if feedstock cultivation on agricultural lands leads to LUC somewhere else. (Khanna & Crago, 2011; European Commission, 2012; Müller-Wenk & Brandão, 2010; Kahiluoto & Kuisma, 2010) The options 1 and 2 seem to be the most relevant to Northern Europe. This is because biogas plants are using feedstock regarded as waste, and if dedicated energy crop is cultivated, it is done on the existing fields as a part of the crop rotation cycle (Kahiluoto & Kuisma, 2008; Rasi et al., 2012).

From the GHG perspective, important factors related to cultivation processes are agricultural machinery use, fertilizer use and pesticides, fungicides and herbicides use. Agricultural machinery, for example tractors, are using fossil fuels. Mineral fertilizer production may consume high amounts of energy leading thus to GHG emissions. Furthermore, the utilization of nitrogen fertilizers leads to N_2O emissions from soil (BioGrace; Brandão et al., 2011).

Feedstock collection and transportation depends on feedstock. Biowaste and other waste materials are usually collected for example from households and industry using waste trucks. The collection of agricultural biomass, such as dedicated energy crops, is usually carried out using agricultural machines, but the transportation to a biogas plant can be carried out by trucks. (Rasi et al., 2012) WWTP sludge is not often transported long distances due to its high water content. Therefore, biogas plants are often built close to WWTPs, and in those cases, sludge transportation can be done by pipelines. Waste trucks, trucks and agricultural machines consume fossil fuels and pipeline transportation electricity. (Rasi et al., 2012; Latvala, 2009)

2.1.3 Digestion process

Organic raw-materials are turned into methane in an anaerobic digestion process. In the digestion process, micro-organisms are using feedstock as nutriment and turning the carbon of feedstock into methane, which can be collected from the digester. The process is adjusted by temperature and the moisture content of feedstock. In addition, non-volatile feedstock residues and unconverted organic matter remain in the digestate. Further advantages in addition to gas production in using biogas production are the improved hygiene and reduced odour of waste feedstock during the biogas production process. (Latvala, 2009) Figure 6 presents typical process chains to produce biogas from various feedstocks. Digestion facilities can be divided into three main categories: farm size digestion facilities, waste water treatment plant facilities and co-digestion facilities (Latvala, 2009; Ishikawa, 2006). Teghammar (2013) found out that also lignocellulosic feedstock can be used for feasible biogas production. The production from lignocellulosic feedstock can be improved by pre-treatment processes. (Teghammar, 2013) However, only a little research has been carried out related to biogas production from lignocellulosic feedstock except grass and other dedicated energy crops. According to the total solids (TS) content, digesters can be divided into wet (TS 20–40 %) and dry (TS 6–13 %) processes (Taavitsainen et al., 2002, Lehtomäki et al., 2007). Another way to divide digestion processes is by temperature: mesophilic degradation takes place within the temperature range of 30–38°C and thermophilic degradation within the temperature range of 55–60°C (Tchobanoglous et al., 1993). Further ways to divide digestion processes are based on the operation types, such as batch process, continuous one stage process and a continuous multi stage process. The advantages of thermophilic digestion are better hygiene of the digestate and shorter retention time. On the other hand, mesophilic digestion has lower energy consumption and better control options. (Taavitsainen et al., 2002, Ward et al., 2008)

Methane is usually the main compound in biogas. The second largest share is for carbon dioxide and the third largest share for nitrogen. There are also several other trace compounds with smaller shares. (Rasi, 2009) Digestate contains nitrogen and phosphorous and other inorganic parts from feedstock, and therefore, digestate can be utilized as a fertilizer. In some cases, digestate use as a fertilizer is limited due to the risk of bacteria or other health risks. In these cases, a hygienization unit can be used to reduce these risks. The qualities of digestate depend on the digestion process and feedstock utilized. In some cases, the wet and solid parts of digestate are separated for more efficient utilization. The liquid fraction contains most of the nitrogen and the solid fraction most of the phosphorous. Liquid and solid fractions can also be refined into more valuable products by stripping, thermal drying and pelletizing. The liquid fraction can also be used to replace raw water in the digestion plant when treating low moisture content feedstock with wet digestion method. The solid fraction can also be composted to produce an end product containing more humus.

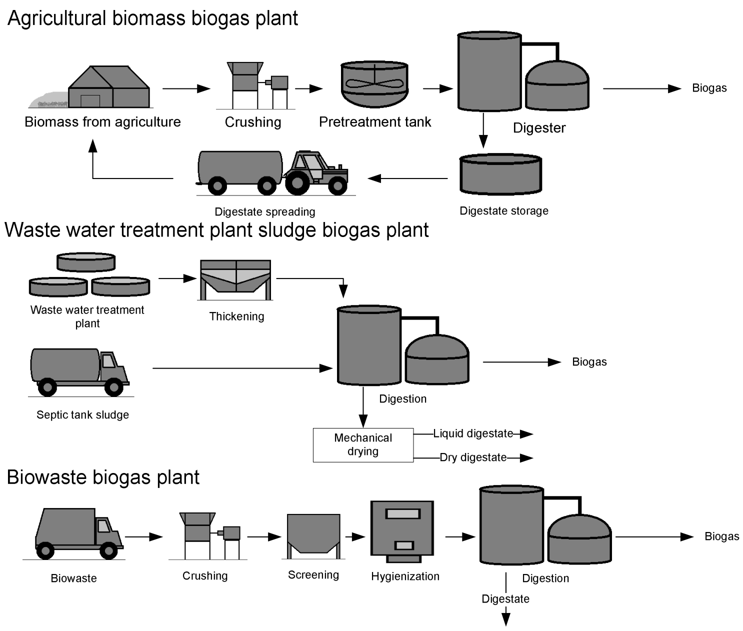

Figure 6: Example plant constructions for biogas production (Latvala 2009).

2.1.4 Upgrading process

Upgrading processes are used for increasing the methane content of biogas to meet the natural gas grid standards and recommendations. Usually carbon dioxide, nitrogen, sulfur and halogenated gas compounds are removed, and thus, the methane content increases to over 90% and the energy content of the gas increaces. The removal of H_2S is important due to its harmfulness and corrosive nature in the presence of water. There are various methods for upgrading, such as water scrubbing (WS), pressure swing adsorption (PSA), membrane technology (MB) and processes that are using other liquids than water, such as the amine wash process (AW). Different upgrading processes consume electricity, heat, water and chemicals depending on the construction of the process. There may also be methane emissions from these process steps. (Bauer et al., 2013; Rasi, 2009; Purac puregas)

Upgrading processes where gas components from the gas stream are dissolved into a solvent liquid stream are called absorption. In chemical absorption, a chemical reaction occurs between the gas and the liquid. Adsorption efficiency depends on several factors, such as pressure, temperature and liquid-gas ratio. Absorbers can be constructed by various ways. Usually, the area of contact between the liquid and gas is increased by dividing gas into small bubbles, by spreading the liquid into films or forming the liquid into small drops. A counter-current flow column is commonly used for biogas because it is simple and efficient method. Before utilization, water is usually removed from biomethane. (Bauer et al., 2013; Rasi, 2009)

Water scrubbers (WS) are based on the fact that CO_2 (and hydrogen sulfite) has a much higher solubility in water than methane. Water scrubbing removes also other harmful impurities, such as ammonia and sulfur dioxide. Water is the most common solvent in biogas upgrading. CO_2 is absorbed into water in an absorption column. The process is using high pressure: 6–10 bar. CO_2 is then released from water into a desorption column by adding air at the atmospheric pressure. Nowadays, WS processes are using water circulation to decrease water consumption. The methane slippage from WS is usually lower than from PSA (Bauer et al., 2013; Rasi, 2009). However, CO_2 and hydrogen sulfite are more soluble in organic solvents than in water. Therefore, other solvents, such as polyethene glycol and alkanol amines, are used. The upgrading process with these solvents is more efficient, but also more expensive. (Rasi, 2009)

Amine wash (AW) technology is less commonly used than PSA or WS technology. Amine wash uses a reagent that chemically binds to CO_2 molecule and removes it from the gas flow. Amines are the most common solution for this. Amines are organic compounds that contain a basic nitrogen atom. At the moment, the most widely used amine in biogas upgrading is activated methyldiethanolamine (aMDEA). In amine upgrading, CO_2 is removed from biogas in an absorber and then removed from the amine solution into a stripper. When CO_2 reacts with amines, it is transferred from the gas phase into the liquid phase. This is an exothermic reaction. The processes are usually using excess amine input compared to the CO_2 content. In the stripper column, heating is needed to remove CO_2 from the amines. AW has usually a relatively low methane slippage. (Bauer et al., 2013)

Biogas upgrading can also be done with a combination of physical and chemical capture, such as adsorption, membranes or temperature drop (Bauer et al., 2013).

Pressure swing adsorption (PSA) is a dry method, which separates gases via physical properties. Approximately 15% of the upgrading units in Sweden are using the PSA technology. PSA consists of various columns and is a continuous upgrading process. In PSA, biogas is compressed and then fed into an adsorption column. The column (bed materials) captures the CO_2, but not the CH_4 (methane flows through the column). After the column material is saturated with CO_2, the pressure is decreased and CO_2 is desorbed. During the desorption stage, in the column, there is also a certain amount of biogas, which is lost with the off-gas flow. Therefore, the methane slippage for PSA may be higher than for other devices. (Bauer et al., 2013)

Membrane separation (MB) uses membranes in separating various gas components. Biogas is directed through a membrane (a filter) that separates the components in gas. To receive high methane content with high methane recovery, selective membranes and suitable design is needed. In MB separation, membranes retain the majority of the methane while the majority of CO_2 passes through the membrane. The membranes can consist of several materials for example of polymeric hollow fibers or carbons. The membranes are continuously improved to get for instance a higher selectivity. (Bauer et al., 2013)

Cryogenic processes are not basic upgrading processes, but they can be used for several applications, such as trace compound removal, upgrading and the production of liquid biogas (LBG). Most of these processes are currently under development, and therefore, there is only a little data related to them. Cryogenic processes are based on low temperatures. The operation temperature may vary significantly. The condensation point at the atmospheric pressure is –78°C for CO_2 and –161 °C for CH_4. Cooling can be done by liquid nitrogen (expensive on a large scale) or by cooling cycle devices. (Bauer et al., 2013)

2.1.5 Biomethane distribution

There are various ways to distribute biomethane to the transportation sector and for other utilization options. The basic idea for the distribution is to use different pipelines or container/tank transportations. Containers and tanks can be transported by trucks, ships or rails. Transportation can be done either in gaseous or liquid form.

One of the distribution options is the NG grid distribution the advantage of which is the already existing NG infrastructure in various places. Various countries have different standards for biomethane for NG grid injection and vehicle use. In Switzerland, a limited amount of biogas with methane content below 50% can be added to the NG grid. For the unlimited distribution, the methane content has to be over 96%. In the Netherlands, the methane content should be 85%, in Sweden 97% and in Finland at least 95%. (Rasi, 2009; Gasum Oy) In addition to the methane content, there are also limitations and recommendations for various other factors in biomethane. However, there is a proposal to harmonize the quality limitations for biomethane in the EU. (Rasi, 2009) If the biomethane quality meets the NG grid standards, delivery can be done in the existing NG grids. In this case, biomethane is injected into the NG grid, and it can be used in different NG utilization options along the NG grid. (IEA, 2010) Because gas molecules (biomethane and fossil natural gas) are mixed during transportation, biomethane consumption and injection have to be measured in order to know how much biomethane is in the grids available for the use. The system thinking is usually similar to that of the electric grids where for example the renewable electricity input is calculator used in various utilization options. Similarly, biomethane is injected into the NG grid and used in various NG utilization options. If a NG grid is not available, distribution can be done also via separate biogas or biomethane grids, which is the most common distribution option for example in Sweden. (IEA, 2010) According to Poeschl et al. (2010), biogas upgrading to biomethane and delivery via natural gas grid is the most promising technology that could support the rapid utilization expansion. The advantages of using the NG grid for biomethane distribution are lower transmission losses, the possibility for transmission to expansive market and decentralized production. NG grids create an option for biomethane delivery if the production or consumption of biomethane is located close to natural gas grids. The wider spread the NG grid is, the easier it is to utilize the NG grid for biogas distribution. The increasing use of NG and expanding NG grids will enable wider scale biomethane production and use (Ryckebosch et al., 2011).

The biggest NG markets are in the U.S., Russia, Central Europe, China, Japan and Middle East. The main global pipeline transportations of NG are done from Canada to the USA, from Russia and Baltic Sea to Central Europe and from Central Asia to Eastern Asia. (National Energy Board, 2009) In Europe, the main pipeline connections are located in Russia, and there are also smaller connections from the North Sea and North Africa. The transit pipelines are mainly located in Central Europe and Italy. The transmission pipelines cover most parts of Europe. (GTE, 2009) According to the Gas Infrastructure Europe´s GIE road map 2050, green gas can be seen as an integral part of the NG systems in achieving a more sustainable future. This will be enabled by expanding the NG grids in Europe. (GIE, 2011) In 2009, new pipelines were being built in North Europe, mainly under water, from Russia to Germany and from Norway to Sweden. The focus of the new on land pipelines was mainly in South and East Europe. New pipeline connections were being built in France, Spain, Italy, Greece, Ireland, Turkey, Bulgaria, Romania, Hungary, Moldova, Ukraine, Russia and Belarus. In Central Europe, new pipelines were not built, but this might be due to the very extensive existing NG grid. Spain, Italy and Turkey are building undersea connections to North Africa. Turkey and other East European countries are also building new connections into the Asian direction. (GIE, 2011) Similar development can be seen also in the USA. The NG grids cover the majority parts of the USA, and according to EIA (2012B), there were almost 30 NG expansion projects going on between the years 1998–2011.

In addition to the pipeline distribution, biomethane can also be transported by trucks, rails or ships in different kinds of containers and tanks as compressed or liquefaction gas (IEA, 2010). Liquid biogas (LBG) and liquid natural gas (LNG) are stored at a temperature of approximately –160°C, and before use in gas-operated vehicles, they have to be regasified. Compressed biogas (CBG) remains in gas-form, but is compressed to a 200–300 bar pressure and put into tanks or containers for transportation. Currently, LBG and CBG are mainly used as a back-up gas. This means that they are utilized during shortages in biomethane production to ensure the gas delivery for consumers. (Bravin et al., 2010) According to Rasi et al. (2012), building a pipeline for distribution is more profitable than CBG transportation only in short distances or with high gas volumes. In addition, the global LNG transportations are growing. The number of LNG producing and consuming countries steadily continues to grow. IEA estimates high new investments on LNG infrastructure to meet the demand until 2030. According to the predictions, the global LNG trade will grow by at least 10%–15% over the next few years (Natgas). Previously, the share of LNG transportations compared to pipeline transportations was marginal. However, the share of LNG is estimated to grow. In 2020, it is estimated to be 37% of the total gas markets. (World Energy Council, 2013A) One reason for the expectedly huge growth in LNG can be the increasing production of shale gas, especially in the USA. Due to the low price and huge storages, shale gas transportations from the USA to other countries are expected to grow.

Figure 7 presents an example of the distribution of biomethane from production to refuelling station using a combination of the existing pipelines and CBG and LNG transportations.

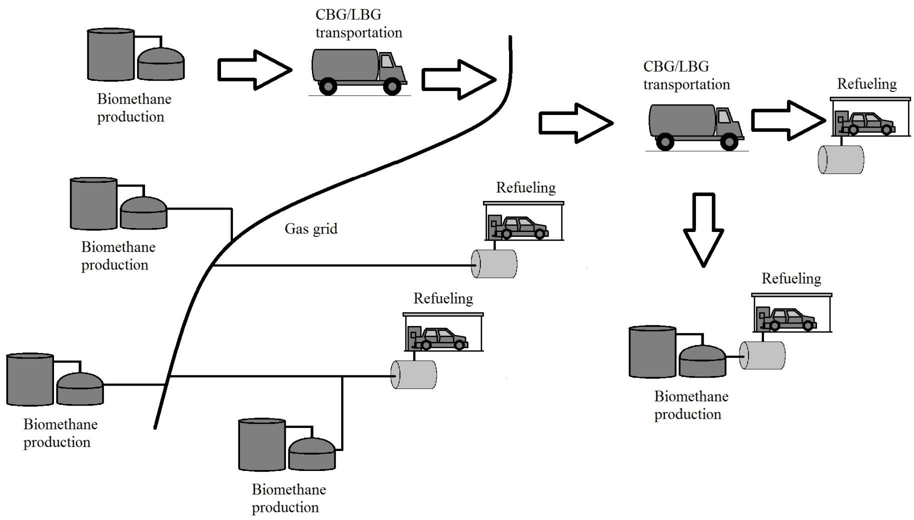

Figure 7: An example of different biomethane distribution options.

Refueling of biomethane can be done in slow or fast refueling stations depending on the refueling pressure. Public refueling stations are usually fast refueling stations, but private refueling stations can use slow refuelling technology. Fast refueling, the predominant refueling method in North Europe, takes only minutes. Slow refueling systems do not normally have gas storages, and they have only a small compressor. The refueling with slow refueling takes several hours. (Latvala, 2009; Gustafsson & Stoor,

2008) Different biomethane distribution and refueling options are presented in Figure 8 with example pressures. The pressures vary depending on the situation and technology used.

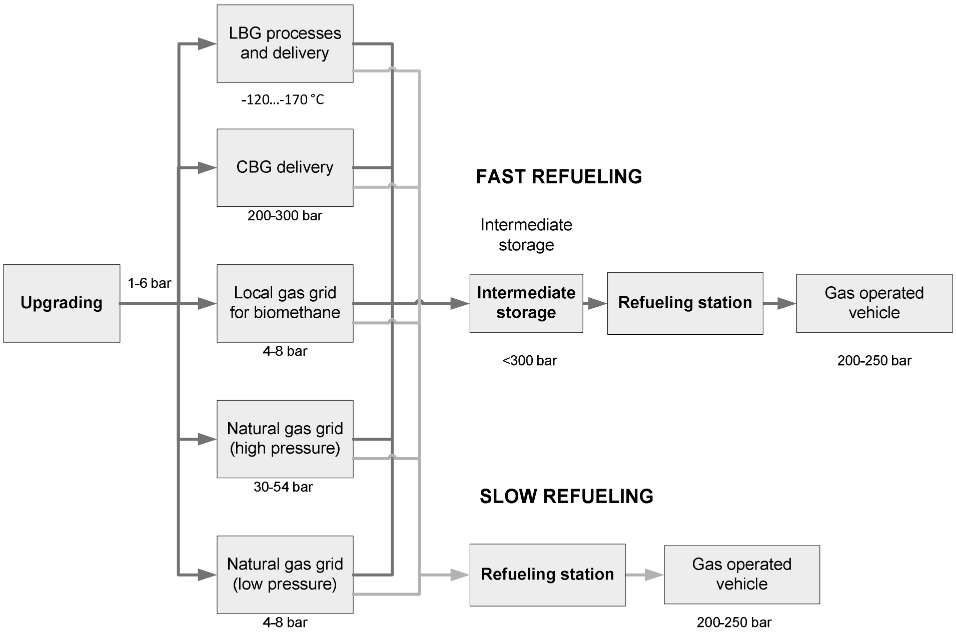

Figure 8: Biomethane distribution options to transportation purposes (Bravin, 2010; Kalmari et al., 2010; Gasum Oy).

2.1.6 Biomethane use in the transportation sector

The total amount of gas-operated vehicles in the world is approximately 18 million. The growth has been steady over the last years. From 2010 to 2011, the growth of gas-operated vehicles was 9% worldwide and 5% in Europe. The highest gas-operated vehicle amount is in Iran with approximately 3 300 000 gas-operated vehicles. In Pakistan 80% of vehicles are using gaseous fuel (mainly NG), and the share of gas-operated vehicles is highest there. (NGVA Europe, 2013) The amount of gas-operated vehicles and refuelling stations in various example countries is presented in Figure 9. The size of the circles represents the share of gas-operated vehicles of the total vehicle amount in the country.

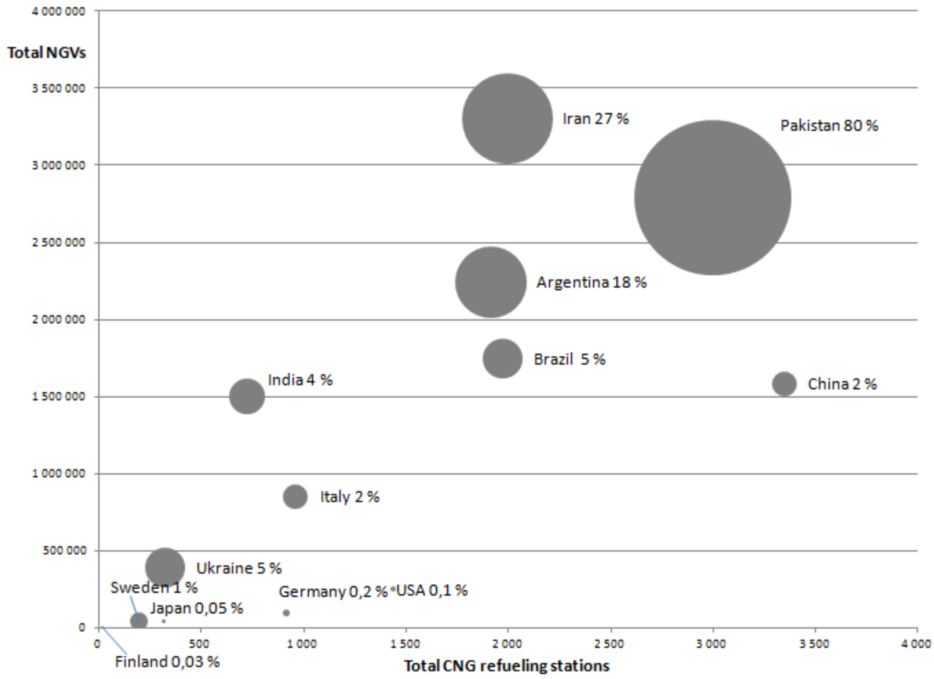

Figure 9: The amount of gas-operated vehicles and refuelling stations in different countries. The size of the circles represents the share of gas-operated vehicles of the total vehicle amount. (NGVA Europe, 2013)

The majority of the gas-operated vehicles is developed to use NG or gas with an approximately similar methane content. Gas-operated vehicles are usually so called “bi-fuel vehicles”, which are designed to use either gas or petrol. Heavier vehicles and a part of light-duty vehicles are also "single fuel" vehicles, which can only use gaseous fuel. “Bi-fuels” and “single fuels” have a little different configuration because “single fuel” vehicles are optimized to use gas, but “bi-fuel” vehicles are a compromise in the optimization between gaseous and liquid fuels. (Rasi, 2009)

Air pollutant emissions are related to the combustion of fuel in vehicle engines. Air pollutants, such as particulate matter emissions and NO_X emissions, cause for example various health problems. Reducing air pollutants is important, especially in cities, where large populations are exposed to pollutants. (Salonen & Pennanen, 2006) The Table 4 presents air pollutant changes based on literature when petrol or diesel vehicles are replaced by biomethane operated vehicles.

Table 4: Changes in air pollutants when the utilization of fossil fuels is transformed to biomethane utilization in transportation use

Pollutant	Busses diesel → biomethane	Passenger cars diesel → biomethane	Passenger cars petrol → biomethane
$PM_{2.5}$	–94%*	–99.9%*	–66%*
PM	Reduction ** Reduction *** –50...–80% ****		–15...–60% ****
SO_2	–98%*	–99%*	–98%*
NO_X (NO_X+HC)	–39%* No clear difference ** High reduction ***	–88%* High reduction **	–57%* No clear difference **
VOC	–70%*	–33%*	–79%*
CO	No clear difference ** Increase***	Increase**	No clear difference **
Noise	–50%* May be reduced **	–50%*	

*Lampinen, 2009
**IEA, 2010
***Nylund et al., 2004
****Börjesson & Berglund, 2007

As can be seen in Table 4, the main advantages of using biomethane in transportation use from air pollutants' perspective are lower particulate matter emissions, lower SO_2 emissions, lower NO_X emissions and lower VOC emissions. In addition, in some cases, also noise may be reduced. On the other hand, CO emissions seem to be increased compared to fossil fuels. Nylund et al. (2004) have done a comparison between the emissions of diesel and natural gas busses. Natural gas use in busses had many advantages compared to diesel busses. Methane is not toxic, and it is free from soot. It seems that PM levels are significantly lower with natural gas busses, but the levels of NOx are not necessarily superior to diesel. A high share of emissions with high importance on health or on the environment are lower in NG busses than in diesel busses (for example NO_2, PM mass, carcinogenic PAH, mutagenity and aldehydes). (Nylund et al., 2004) Because biomethane is approximately similar to natural gas, similar benefits are likely also when comparing biomethane use to diesel use.

2.2 GHG emission reductions by transportation biomethane utilization

Several previous studies are related to the GHG emissions of biomethane. The GHG emissions vary on a large scale depending on the feedstock used and on the technology used in the various unit processes. Table 5 presents the data related to GHG emissions from biomethane production and use according to literature.

Table 5: GHG emissions from various life cycle steps of transportation biomethane production and use according to literature.

Raw material	**Cultivation and collection** gCO2eq MJ^{-1}	**Digestion** gCO2eq MJ^{-1}	**Upgrading** gCO2eq MJ^{-1}	**Distribution and use** gCO2eq MJ^{-1}	**Total** gCO2eq MJ^{-1}	**Source**
Municipal organic waste	0	20		3	23	Directive 2009/28/EC
Wet manure	0	11		5	16	Directive 2009/28/EC
Dry manure	0	11		4	15	Directive 2009/28/EC
Landfill gas	-	-	-	-	11	Californian low carbon fuel standard
Dairy digester	-	-	-	-	14	Californian low carbon fuel standard
Organic waste	7	11	11*	0-2	30	Pertl et al., 2010
Agricultural renewable source	38–41	8–9	11*	0-2	59	Pertl et al., 2010
Energy crops (500 a time horizon)	23	10	7	5	45	Jury et al., 2010
Energy crops (100 a time horizon)	34	12	10	6	62	Jury et al., 2010
Organic Ley	12	9**	4		21–25	Tuomisto & Helenius, 2008
Biogas Ley	29	9**	4		28–32	Tuomisto & Helenius, 2008
Reed canary grass (organic)	24	5**	3		30–32	Tuomisto & Helenius, 2008
Reed canary grass (mineral)	27	5**	3		34–36	Tuomisto & Helenius, 2008
Ley crops	14	7***	7	-	27	Börjesson & Berglund, 2006
Straw	5	8***	7	-	20	Börjesson & Berglund, 2006
Sugar beet tops	5	7***	7	-	18	Börjesson & Berglund, 2006
Manure	0	8***	7	-	17	Börjesson & Berglund, 2006
Food industry waste	2	4***	7	-	12	Börjesson & Berglund, 2006
Municipal organic waste	6	6***	7	-	18	Börjesson & Berglund, 2006
Grass	21	29	20		70	Murphy et al., 2011

*With PSA and MB technologies the emissions from upgrading and distribution are higher
**GHGs from production phase can be reduced by using heat exchangers
*** Digestate transportation and spreading are included

According to the table, GHG emissions from biomethane production and use vary from 11 to 70 gCO_{2eq} $MJ^{-1}{}_{biomethane}$. GHG emissions of cultivated biomass vary from 21 to 70 gCO_{2eq} $MJ^{-1}{}_{biomethane}$, of organic wastes from 18 to 30 gCO_{2eq} $MJ^{-1}{}_{biomethane}$ and of manure from 15 to 17 gCO_{2eq} $MJ^{-1}{}_{biomethane}$. Feedstock selected for biomethane production appears to play an important role in the total overall GHG emissions: dedicated energy crops seem to lead to lower GHG emission reductions than does the utilization of waste materials due to the added environmental burden of cultivation processes (Börjesson & Berglund, 2006; Jury et al., 2010; Pertl et al., 2010). However, studies have also reached a bit differing conclusions. For example, Pertl et al. (2010) calculated relatively high, 30 gCO_{2eq} $MJ^{-1}{}_{biomethane}$, emissions for organic waste-based biomethane. GHG emissions for landfill gas seems to be lower (11 gCO_{2eq} $MJ^{-1}{}_{landfillgas}$) than those from biomethane production by digestion due to lack of digestion and digestate utilization processes.

There are also some key issues along the life cycle of biomethane, which affect the total GHG emission reduction potential. The main GHG emission sources for cultivated biomasses are cultivation, biogas plant operations and upgrading and for organic wastes and manure biogas plant operations, upgrading and distribution. According to Sinkko et al. (2010), cultivation emissions seem to be higher in Finland than in Central Europe. According to the LCA study by Jury et al. (2010), the main factors for GHG emissions are biogas yields from feedstock, agricultural practices and nitrogen utilization as fertilizer. Poeschl et al. (2012) found out that there is still potential to decrease emissions from all unit processes during the life cycle of biogas production and utilization. According to their study, ways to further reduce emissions include for example using biogas in energy production instead of NG. (Poeschl et al., 2012) Börjesson & Berglund (2006) concluded that in addition to raw material handling, electricity use in biogas production and upgrading are the main sources of emissions. According to Møller et al. (2009), the major factors for GHG emissions from biomethane production are N_2O-emissions from digestate use in soil, fugitive emissions of CH_4 and unburned CH_4. The role of N_2O and CH_4 leakages did not clearly come up in literature reviews, but it is likely that if there are high CH_4 leakages or N_2O emissions, this will have a high importance in overall emissions due to the high global warming potential of CH_4 and N_2O. Biogas yield is an important factor because it affects directly the energy amount needed in biomethane production. If biomethane productivity is low, emissions become higher per produced MJ of biomethane. According to Rehl & Müller (2011), there is variation in the GHG emissions from digestate handling processes. Composting seems to be a better option than storing in open ponds. In addition, drying and separation processes of digestate may lead to additional GHG emissions due to energy consumption. The GHG emissions from digestate handling vary from 0.06 to 0.1gCO_{2eq} $g^{-1}{}_{digestate}$ depending on the handling method. Belt drying leads to highest emissions and solar drying to lowest. (Rehl & Müller, 2011)

Ryckebosch et al. (2011) gathered information about biogas purification and upgrading systems. There are several cleaning and upgrading methods for biogas, and this process step seems to be important, especially when biogas is upgraded to biomethane for transportation purposes. Pertl et al. (2010) compared the GHG emissions when different upgrading methods were used. According to their results, electricity consumption and methane leakages were the main GHG emission sources in upgrading. Methane leakages were higher with membrane separation (MS) and with pressure swing adsorption (PSA) than with water scrubbing (WS). Electricity use was highest with MS. New amine wash (AW) technology can be used in upgrading to replace older technologies. AW has lower electricity consumption and approximately no methane emissions. However, heat consumption is higher than with other technologies. In addition, heat can be re-utilized in the digestion process after upgrading, which reduces the need of external heat in the digestion process. (Purac Puregas) Bauer et al. (2013) collected data from the suppliers related to upgrading systems. Their conclusion is that WS, PSA and MB technologies are consuming approximately 0.2–0.3 kWh Nm^{-3} electricity. However, the end pressure of the gas varies between the methods. AW, on the other hand, consumes only 0.14 kWh Nm^{-3} electricity but also 5.5 kWh Nm^{-3} heat. Methane leakages and energy consumption depend on various factors, and methane leakages can be very low if for example several MB upgrading systems are attached. According to Bauer et al. (2013), methane slippage from PSA is 1.8–2%, from WS 1%, from MB 0.5% and from AW 0.1%. These values represent modern plants and may be higher with older or malfunctioning systems. WS and PSA need tail-end solutions to decrease the methane slip further to meet stricter regulations. Tail-end solutions can be for example thermal or catalytic oxidation of the methane slip. Methane slippage with MD depends highly on the upgrading facility construction. (Bauer et al., 2013)

The energy balance of biogas systems affects GHG emissions from biomethane production due to GHG emissions related to energy production. Therefore, lower energy input compared to output would likely lead to lower GHG emissions from biomethane production if the energy production method is not changing. However, there are several options to calculate the energy balance of biogas system presented in literature. The most common ways are to calculate biogas energy produced per energy input into the system or energy input per biogas energy output. Due to high variation in systems, the results are also varying on a large scale. Berglund and Börjesson (2006) studied the energy balance of biogas systems in the Swedish operational environment. According to their study, the energy input into biogas processes is approximately 20–40% of the energy content of biogas. Tuomisto and Helenius (2008) did an approximately similar estimation: the input per output energy balance of biogas systems is 20–40 %. In their study, the biogas delivery to refueling stations and transportation use were also taken into account. According to Pölsch et al. (2010), the energy balance of biogas production and utilization systems depends on biogas yield, the utilization efficiency and the energy value of the intended fossil fuel substitution. Their results show that the energy balance of biogas system is varying between 10.5 and 64.0%. The energy output per input ratio varies in the studies from 1.8 to 13.1 depending on the system boundaries and energy flows taken into account. (Prade et al., 2012; Uellendahl et al., 2008; Gropgen, 2007; Salter & Banks, 2009) The energy input may even exceed the energy content of biogas if transportation distances for feedstock are long enough. The most energy demanding process part is the biogas plant, which consumes 40–80% of the total energy input. The energy balance is poorest in cases where feedstock handling consumes energy or when biogas yields are low or water contents of feedstock high. (Berglund & Börjesson, 2006) Biogas systems are consuming relatively high amounts of energy. On the other hand, the energy input varies on a large scale. To achieve low GHG emissions from biomethane production and use in the transportation sector, attention should be paid on the lower energy input output ratio.

The GHG emissions from biomethane production and use can be compared to GHG emissions from fossil transportation fuels. In the literature and in the previous studies, fossil reference fuels in the transportation sector have been diesel, petrol and NG. GHG emissions from these fossil fuels are also varying depending on the fossil fuel source. In Table 6, GHG emissions from biomethane production and use are compared to GHG emissions from fossil fuels, and also the GHG emission reduction potential is presented.

Table 6: GHG emission reductions by transportation biomethane compared to fossil fuels.

Raw material	GHG emissions from biomethane production	GHG emissions from replaced fuel	GHG emission reductions	Source
	gCO2eq MJ^{-1}	gCO2eq MJ^{-1}	%	
Municipal organic waste	23	83.8 (fossil fuels)	73	Directive 2009/28/EC
Wet manure	16	83.8 (fossil fuels)	81	Directive 2009/28/EC
Dry manure	15	83.8 (fossil fuels)	82	Directive 2009/28/EC
Landfill gas	11	94.7 (diesel) 95.9 (petrol)	88.1 88.2	Californian low carbon fuel standard
Dairy digester	14	94.7 (diesel) 95.9 (petrol)	85.7 85.9	Californian low carbon fuel standard
Organic waste	30	82 (NG)	63	Pertl et al., 2010
Agricultural renewable source	59	82 (NG)	28	Pertl et al., 2010
Energy crops (500 a time horizon)	45	72 (NG)	38 (30–40)	Jury et al., 2010
Energy crops (100 a time horizon)	62	72 (NG)	14 (10–20)	Jury et al., 2010
Organic Ley	21–25	80 (petrol, diesel)	68–74	Tuomisto & Helenius, 2008
Biogas Ley	28–32	80 (petrol, diesel)	60–65	Tuomisto & Helenius, 2008
Reed canary grass (organic)	30–32	80 (petrol, diesel)	60–63	Tuomisto & Helenius, 2008
Reed canary grass (mineral)	34–36	80 (petrol, diesel)	55–58	Tuomisto & Helenius, 2008
Grass	70	88.8 (diesel	22	Murphy et al., 2011

According to Table 6, the GHG emissions from fossil reference fuel vary from 72 to 95.9 gCO_{2eq} MJ^{-1} and the GHG reductions vary from 14 to 85.9%. NG comparison seems to lead to lower GHG emission reductions than petrol and diesel comparisons, depending on the GHG emission factor used for fossil fuels. Lechtenböhmer & Dienst (2008) have done calculations about the GHG emissions from the natural gas supply chain to Germany. Their conclusion is that natural gas delivery is efficient and has a low level in direct GHG emissions. On the other hand, high levels of direct gas losses from natural gas in its production, processing, transport and distribution could neutralize its low emission advantages. Therefore, it is highly important to take into account also the GHG emissions from the whole life cycle of fossil fuels and not just the tailpipe emissions.

In addition to comparing the GHG emissions from biomethane production and distribution to fossil transportation fuels, also wider scale studies can be done. In these studies, also other utilization options for feedstock and biogas and biomethane use are compared. According to Börjesson & Berglund (2007), the key factors in environmental comparisons are the raw materials utilized, energy service provided and reference system replaced. In their studies, the reference systems based on oil, NG, petrol and diesel were studied. In the reference systems, biogas feedstock was utilized traditionally for example by combustion. In addition, chemical fertilizers have to be used instead of digestate in the reference system. According to their results, biogas systems lead to GHG emission reductions compared to the reference systems. There might be indirect emissions, which can be avoided when biogas is produced. In some cases, the indirect emissions might even be higher than the direct emissions from the replaced fossil fuels. For example, when manure is digested, methane emissions can be avoided compared to the reference situation where manure is stored. Berglund (2006) found out that replacing fuel oil in district heating or petrol in light-duty vehicles by biomethane leads to an approximately 75% GHG emission reduction. According to Pertl et al. (2010), the upgraded biomethane in NG grid leads usually to GHG reductions compared to NG. With high electricity consumption and methane leakages the emissions of biomethane production and natural gas substituted were almost at the same level. On the other hand, Jury et al. (2010) studied the biogas system and injection into the NG grid with LCA methods. They found out that the contribution to the climate change is 30–40% (500a time horizon) or 10–20 % (100a) lower than the contribution of natural gas importation. Møller et al. (2009) have counted GHG emission savings when biogas is utilized in the digestion facility or when biogas is upgraded to biomethane and used in vehicles. According to their results, global warming factors range from –375 to 111 $kgCO_2eq.tonne^{-1}$wet waste. In addition to the replaced fossil fuels, mineral fertilizer substitution may have an important role from the GHG emission perspective and should be taken into account.

2.3 Limitations for increased use of biomethane in the transportation sector

The total amount of gas-operated vehicles has been growing globally during the past years (NGVA Europe, 2013). However, despite the competitive or even lower consumer price compared to other fuels and the environmental benefits, the development of gas-operated vehicle amount has been slow in Finland and also in many other countries (Åhman, 2010; Gasum Oy; NGVA Europe, 2013). There are several important factors, which may hinder the development of biomethane utilization in the transportation sector. In Finland, biomethane production is currently based mainly on organic waste materials, such as biowaste and WWTP sludge. Therefore, the potential of feedstock might be inadequate for the increased biomethane production, or the biomethane feedstock may be geographically located in different places than biomethane consumers and distribution network. There may also be technological issues related to the distribution infrastructure or to gas-operated vehicles, which limit the utilization of biomethane in the transportation sector. In addition to these factors, the main limiting factor may be economic. Political decisions are usually affecting via economic factors, for example by supports, tariffs and taxes. (Rasi et al., 2012; Lantz et al., 2007) The recognized aspects to study the limiting factors for biomethane growth in the transportation sector are presented in Figure 10.

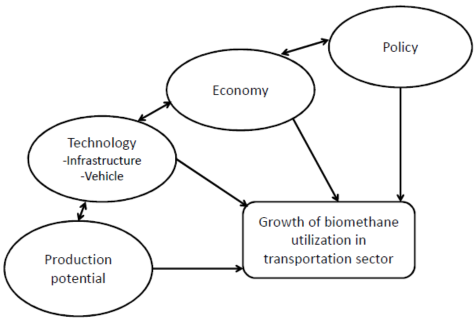

Figure 10: Various aspects that may be limiting the growth of biomethane use in the transportation sector based on literature.

2.3.1 Biomethane potentials and contribution to self-sufficiency

Biogas potentials vary depending on the geographical location and may put limitations for biomethane production. Smyth (2010) studied the biomethane potential from cultivated grass and agricultural wastes and residues in Ireland. According to her studies, by using 10% grass produced in Ireland for biomethane production, 55% of private vehicles could be fuelled by biomethane. Using agricultural wastes and residues for biomethane production, 35% of vehicles in Ireland could be fuelled. Sludge had the highest potential of agricultural wastes and residues. (Smyth, 2010) According to NREL

(2013), the USA could replace 56% of NG consumption in the transportation sector by biomethane. Seiffert et al. (2009) studied the biomethane potential in Chile to replace the imported natural gas from Argentina. According to their results, by using digestion and thermo-chemical processes, Chile could cover approximately 84% of its natural gas consumption by biomethane. Åhman (2010) studied the biomethane potential and economics in Europe. According to his results, biomethane should be considered as a large-scale future contender. Several local studies have also been carried out to clarify the biogas potential of a certain feedstock on county or city level. However, the different studies are difficult to be compared as the basic assumptions are usually very different, and therefore, the results vary considerably.

Biomethane potentials from various Finnish national studies are gathered in Figure 11 as an example. As can be seen in the figure, the biomethane potential of various areas is still unclear, and there are high differences in biomethane potentials between different areas. It is commonly known that usually the highest biomethane potentials are in areas with most intensive agriculture due to high agricultural biomass amounts (Smyth, 2010; Berglund, 2006). For some reason the strong agricultural areas in Western Finland do not arise in previous studies. Based on these studies, the total theoretical biogas potentials in the studied areas is approximately 6.5 TWh a^{-1}. The final report for the feed-in tariff for electricity produced by biogas or wind power presents the biogas potentials for Finland calculated by Pöyry Oy. According to the results, the theoretical potential for biogas production in Finland is 6.6. TWh a^{-1}. The study shows that technical biogas potential in Finland is approximately 2.8 TWh a^{-1}. The biogas utilization in Finland is currently approximately 0.5 TWh a^{-1}. (Ministry of employment and the economy, 2009) In Sweden, the approximate biogas production is 1.4 TWh a^{-1} and the potential is estimated to be ten times higher (Lantz et al., 2007). The highest biogas potential is usually in dedicated energy crops, then in manure and then in organic wastes and WWTP sludge (Lantz et al., 2007). According to Lantz et al. (2007), farmers may have limited knowledge, especially related to the use of agricultural by-products in biogas production, and the public acceptance may be against biogas plants, which may hinder biogas production.

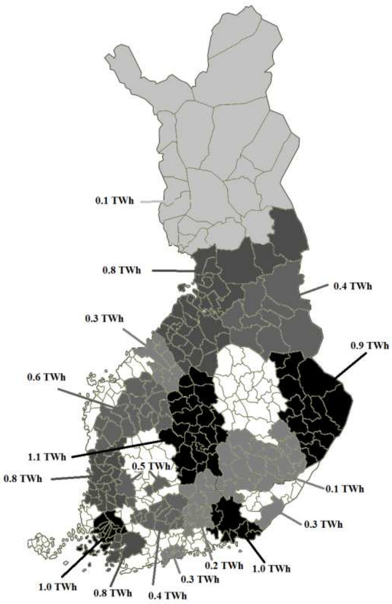

Figure 11: Biomethane potentials in Finland based on various local studies. The values are in annual biogas potentials. (Rasi et al., 2012; Kahiluoto & Kuisma, 2010; Kurki, 2008; Virkkunen, 2010; Vänttinen, 2010; Niemitalo, 2008; Laine, 2008; Kuittinen, 2006; Sankari & Imppola, 2011; Kiviluoma-Leskelä, 2010)

The increasing use of NG and increasing LNG transportations will affect the self-sufficiency of different countries. The European dependency on the imported NG was below 50% in 2010 but it is estimated to be 74% in 2030 (Bilgin, M., 2009). Locally produced biomethane and distribution to NG grid may help to reduce the dependency on imported NG. In Finland, fossil transportation fuels have been mainly based on imported oil, and several biofuels are imported or based on imported raw material, such as palm oil. Biomethane production, on the other hand, is local and based on domestic feedstock, and could therefore improve the employment and increase the self-sufficiency regionally (Seiffert et al., 2009; Latvala, 2009). Domestic production can also be more easily overseen, and environmental effects are easier to point out than for the imported biofuels.

2.3.2 Technological aspects of biomethane use

There may be some limiting factors, which can be related to the distribution network or gas-vehicle technology. For example, there are countries with a very low amount of refueling stations (for example 2 in Denmark and 4 in Estonia) and gas-operated vehicles (NGVA Europe, 2013). According to EIA 2012, the absence of widespread public refueling infrastructure may impose a serious constraint on NG vehicle purchases. Lantz et al. (2007) pointed out that the limited distribution network may be an important barrier. The vehicle technology seems to be relatively well working because gas-operated vehicles can be the main vehicle type in certain countries (NGVA Europe, 2013).

2.3.3 Economic and political aspects for biomethane production and use

The complexity of biogas and biomethane is the fact that they can be utilized both as a transportation fuel and in energy production. There are various targets to reduce GHG emissions and increase the use of transportation biofuels, but also to increase the production of renewable energy.

Patterson et al. (2011) have concluded in their studies that directing biogas to the transportation sector is economically competitive against the electricity and heat production from biogas. In addition, Patterson et al. (2011) found out that producing biogas is cheaper than producing liquid fuels. On the other hand, according to the results of Tricase & Lombardi (2009), in Italy biogas production is limited by the higher price compared to the price of fossil fuels. In some cases, competing fuels, such as ethanol, may be more inexpensive (Lantz et al., 2007). Bomb et al. (2007) compared the biofuel use in the UK and Germany from socio-political points of view. They discussed the role of the government and difficulties in putting biofuel system into action in the early years of biogas utilization. Their conclusions were that the consumers buy the cheapest fuel and the fuel emissions do not have a significant effect on the decisions. Excise duty exemptions and reductions are the key instruments to ensure the price competitive production of biofuels. According to Lantz et al. (2007), existing incentives for biogas systems can be divided into those affecting the production of biogas and those affecting the utilization of biogas. Due to the high variation of feedstock and utilization options for biogas and biomethane, the biogas systems are affected by various different incentives including energy, waste treatment, organic waste landfill deposit ban, tax on waste incineration and agricultural policies. On the other hand competing options may be made more unprofitable by using taxes such as CO_2 tax for fossil fuels, emission trade or other instruments. (Lantz et al., 2007)

There are also other instruments to increase the use of biomethane. Transport companies are usually consuming high amounts of fuels, and they are operating with relatively fixed routes. These companies can therefore operate with a relatively limited gas distribution infrastructure. In the early stage of biomethane use, co-operation with these local operators is needed. For example in Switzerland and Sweden, some cities have decided to run public transport on biomethane. This creates a good basis for biomethane producers as they have stable starting markets with a limited distribution infrastructure for biomethane. In Italy, incentives have been created with tax allowances and support for eco-investments, and the domestic car manufacturers are developing gas vehicles. Sweden grants tax reliefs, parking benefits and toll reliefs for biofuels and company vehicles using renewable energy. Other options could be to reduce tax for gas-operated vehicles provided by the employer; these passenger cars may be exempted from the congestion charge trails in Stockholm's and free parking options. There is also a demand for alternative fuels, and therefore, refueling stations have to have an option for biofuel refueling. (Rasi et al., 2012; Lantz et al., 2007)

According to Patterson et al. (2011), one of the limiting factors may be the higher purchase and maintaining costs of gas-operated vehicles. The same conclusion was also made by Lantz et al. (2007). According to their estimates, in the UK, support in this area could lead to a rapid expansion of biomethane transportation infrastructure and bring significant long-term environmental and economic advantages. In Finland, there have been problems in using gas-operated busses. The maintenance costs of gas-operated busses have been 20 000 € a^{-1} higher than those of diesel busses. In addition, gas-operated busses have operated approximately 3 000 km before a need for maintenance, but diesel busses have operated approximately 10 000 km. These factors have led to a situation where Helsingin bussiliikenne Oy is going to end using gas-operated busses in its operations. (Salomaa, 2013) According to Poeschl et al. (2010), the Renewable Energy Act and energy tax reliefs provide bases for the support of expanded biomethane utilization in Germany. According to Lantz et al. (2007), in some cases, competing treatment technologies may be more profitable, commercial fertilizers are inexpensive, energy crops not intended for biogas production may have higher profitability and partly immature market is leading to high investments.

3 Methods, materials and case descriptions

In this chapter, the methodologies used in this thesis are presented. This chapter begins with life cycle assessment methodology presentation, which is the main methodology used in this thesis. Life cycle assessment is used for GHG emissions calculations, but it is also applied in economic evaluations and in studying the limiting factor for biomethane use in the transportation sector. In addition to the LCA methodology, also the payback time and potential analysis methodologies are presented. After the methodology descriptions, data collection and quality are assessed, and they are followed by actual case example descriptions.

3.1 Life cycle assessment

Life cycle assessment is a tool or a method that can be used for assessing environmental impacts through a product life cycle. It was originally developed to help quantify various environmental pressures related to a products lifetime. (European commission, 2010) Life cycle assessment has been internationally standardized. In the early 1990s, the Society of environmental Toxicology and Chemistry working groups developed the first code of practice in LCA. It was followed by ISO 14040 series in 1997 (European commission, 2010; ISO 14040; ISO 14044) According to Cherubini et al. (2009), there is a broad agreement in the scientific community that LCA is one of the best methodologies for the evaluation of environmental burden associated with biofuel production by identifying energy and materials used as well as waste and emissions related to the environment. It also enables the recognition of options for environmental improvements. (Cherubini et al., 2009) According to the European commission (2010), there are five advantages in the use of LCA:

1. It contains a wide range of environmental problems.
2. It captures these problems in a scientific and quantitative manner.
3. It allows the environmental impact potential to be related to any defined system.
4. The entire life cycle of the studied product or process is included.
5. It equalizes different systems/options to help identify areas of improvement.

The LCA is a relative approach method, consisting of the comparison of various systems to each other (ISO 14040). There are also some limitations related to the environmental LCA (European commission, 2010). Therefore, it must be complemented with other methods depending on the case. The LCA is also developed to take into account the full sustainability assessment, which has not been possible previously. (European commission, 2010)

3.1.1 ISO 14040 and ISO 14044

The International Organization for Standardization (ISO) has published ISO 14040 and 14044 standards. ISO 14040 consists of Environmental management, Life cycle assessment and principles and framework. Its main scope is to give rules for conducting LCA studies. The standard gives instruction about scope, terminology, main characters of different methods, reporting and critical evaluation. The main characters of LCA according to ISO 14040 are presented in Figure 12.

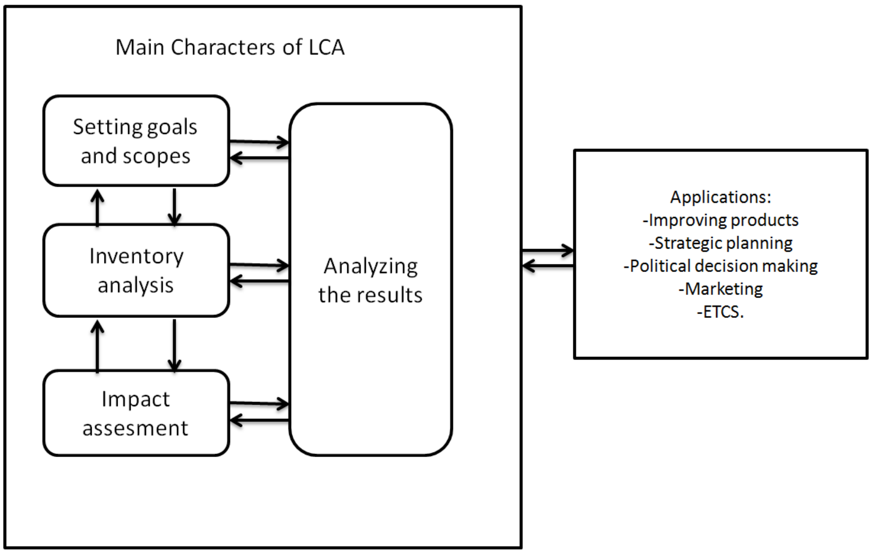

Figure 12: Main steps in conducting LCA studies according to ISO 14040.

As can be seen in Figure 12, setting goals and scopes, inventory analysis and impact assessment affect the result analyzing and vice versa because LCA is an iterative process. Therefore, all the LCA steps should be carefully evaluated to gain as good and liable results as possible. According to ISO 14040, LCA is always a relative approach, and therefore, the definition of the functional unit is important. The functional unit defines what is being studied, and the results are usually expressed based on the functional unit. After defining the functional unit, the system boundaries for the study should be set. According to ISO 14040, the following steps should be taken into consideration in setting the system boundaries:

- Acquisition of raw materials,
- Inputs and Outputs in the main manufacturing/processing sequence,
- Distribution and transportation,

- Production and use of fuels, electricity and heat,
- Use and maintenance of products,
- Disposal of process wastes and products,
- Recovery of used products,
- Manufacture of ancillary materials,
- Manufacture, maintenance and decommissioning of capital equipment and
- Additional operations, such as lighting and heating.

After the setting system boundaries, the data quality used in LCA should be evaluated to get information about the reliability of the study results.

ISO 14044 gives additional information for LCA studies. It gives guidelines for example to setting goals, inventory analysis, impact analysis, analyzing results, reporting, critical analysis and limitations. ISO 14044 presents a more detailed figure about the LCA process as can be seen in Figure 13.

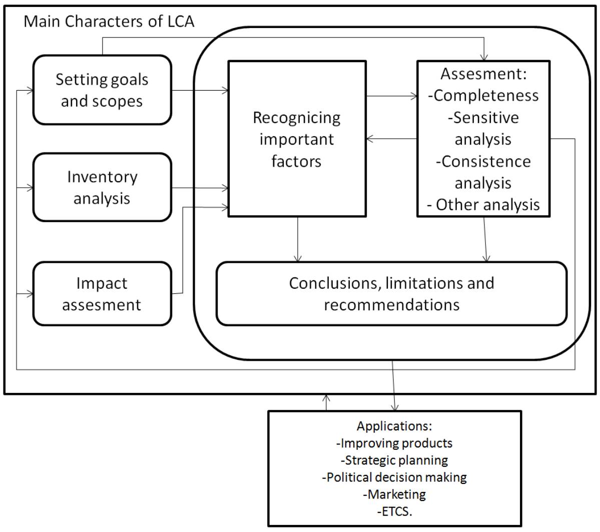

Figure 13: Main characteristics of LCA according to ISO 14044.

As can be seen inFigure 13, ISO 14044 gives instruction about the different steps which should be taken into account when conducting LCA studies. ISO standards give a framework for the LCA studies. The rules presented in the standards are applicable for various kinds of LCA studies. The rules are concentrating on handling the whole LCA process instead of detailed information. Therefore, Greenhouse Gas Protocol is also used in this thesis. Greenhouse Gas Protocol gives more detailed instructions and recommendations related to GHG emission LCA studies. Further on, Directive 2009/28/EC is also used as a basis for calculation models in this dissertation because it presents more detailed GHG emission calculation rules for biofuels.

3.1.2 Greenhouse Gas Protocol

Greenhouse Gas Protocol is an international multi-stakeholder partnership convened by the World Resources Institute and the World Business Council for Sustainable Development. It is the most widely used international accounting tool for governments and companies. The mission of the Greenhouse Gas Protocol is the development of internationally accepted GHG accounting and reporting standards and tools. Greenhouse Gas Protocol´s "Product Life Cycle Accounting and Reporting Standards" gives recommendations for LCA studies. It gives guidelines for example to boundary setting, collecting data and assessing data quality, allocation, assessing uncertainty, calculating inventory results and reporting. Figure 14 presents the process steps that should be taken into account in calculating GHG emissions. GHG emissions from biofuel use phase can be assumed to be bound back to nature via photosynthesis.

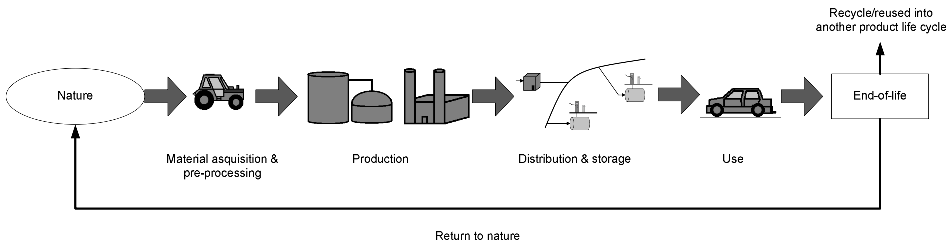

Figure 14: Product life cycle stages according to Greenhouse Gas Protocol, modified for biomethane.

According to Greenhouse Gas Protocol, the functional unit defines the unit of analysis. A well defined functional unit should consist of three general parameters, which are the magnitude of the function or service, the duration or service of the life of that function or service and the expected level of quality. (Greenhouse Gas Protocol, 2011) For boundary setting, the following parameters should be taken into account: the attributable processes in the life cycle that are directly connected to the product and its ability to perform its function, to group the attributable processes into life cycle stages and to identify the material, service and energy flows needed for each process. In addition, the illustration of the product's life cycle processes should be done with a process map. (Greenhouse Gas Protocol, 2011)

Greenhouse Gas Protocol presents also options to estimate the uncertainty of results. The protocol divides the uncertainties to three main types. The first type is the parameter uncertainty, which can be related to direct emissions data, activity data, emission factor data or global warming potential factors. The second type is the scenario uncertainty, which is related to methodological choices. The third type is model uncertainty, which is related to model limitations. (Greenhouse Gas Protocol, 2011)

3.1.3 Directive 2009/28/EC

The European Union announced the Directive 28/2009/EC to promote the production of energy from renewable sources. Article 19 in the directive gives rules to calculate the GHG impact of biofuels and bioliquids. The annexes of the directive give detailed introductions on how to calculate GHG emissions from the production of biofuels and GHG emissions savings compared to fossil fuels. According to the Directive 2009/28/EC, the total emissions from the production and use of a fuel can be calculated with the following equation.

$$E=e_{ec}+e_{l}+e_{p}+e_{td}+e_{u}-e_{sca}-e_{ccs}-e_{ccr}-e_{ee} \quad \text{(E1)}$$

E	the total emissions from the use of the fuel
e_{ec}	emissions from the extraction or cultivation of raw materials
e_{l}	annualized emissions from carbon stock changes caused by land-use change
e_{p}	emissions from processing
e_{td}	emissions from transportation and distribution
e_{u}	emissions from the fuel in use
e_{sca}	emissions savings from soil carbon accumulation via improved agricultural management
e_{ccs}	emission saving from carbon capture and geological storage
e_{ccr}	emission savings from carbon capture and replacement
e_{ee}	emission savings from excess electricity from cogeneration

The directive´s calculation method for GHG emissions and process steps taken into account in biofuel production are widely used in this thesis. Figure 15 presents the same calculation method illustrated for biomethane production and use. According to the directive, GHG emissions from biofuel use in the transportation sector (direct emissions from combustion in engines) can be assumed to be zero.

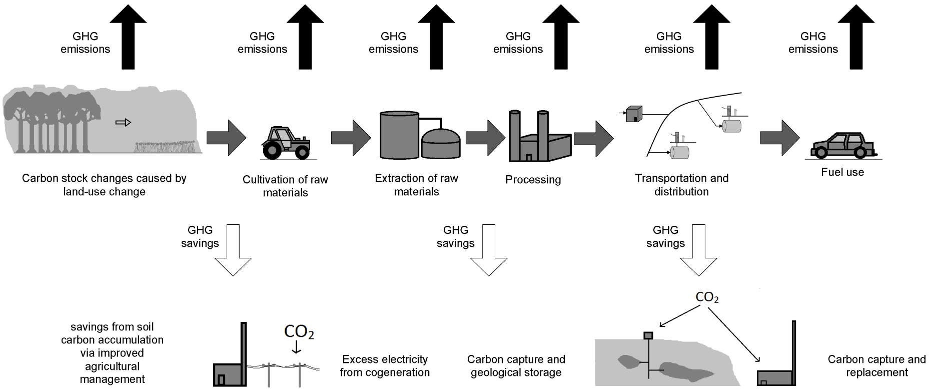

Figure 15: Different factors in calculating the total emissions of a fuel according to Directive 2009/28/EC.

In Directive 2009/28/EC, the calculated emissions from the production and use of the fuel should be compared to the value of replaced fossil fuels to calculate the GHG emission reduction. GHG emission savings can be calculated with the following equation:

$$SAVINGS=(E_F-E_B)/E_F \qquad (E2)$$

E_B the total emissions from the biofuel or bioliquid

E_F the total emissions from the fuel comparator

As s reference value for fossil fuels, 83.8 $gCO_{2eq}\ MJ^{-1}$ can be used if there is no better knowledge about the average emissions of fossil fuels in the European Community.

3.1.4 Co-product handling in LCA studies

This section presents the ways to conduct calculation in cases where in addition to the main product, also co-product or co-products are produced. These calculation methodologies are used especially when aLCA is used and the emissions from the production and use of the main products are calculated. In the biomethane case, a potential co-product is digestate, which can be used as a fertilizer to replace mineral fertilizers. According to ISO standards 14040, 14044 and Greenhouse Gas Protocol, in case there are co-products, the emissions should be divided for the main products and for the co-products. The first option is process subdivision where the common processes are divided to sub-processes. The second option is to use system expansion or substitution method, which includes the emissions that are replaced by co-products. The system expansion method is a widely used term to describe LCAs where emissions from substituted or alternative processes are modeled. To avoid misunderstandings, in this thesis the term substitution method is used when GHG emissions are calculated for biomethane and digestate and emissions, which are substituted by digestate use, are reduced from the total GHG emissions. The actual system expansion method (originally presented in ISO/TR 14049) is used when various feedstock and biogas utilization scenarios are compared. This is explained in more detail in section 3.1.5. The substitution method can be seen as a special application of the system expansion method. The third option is to use allocation procedures. In Greenhouse Gas Protocol, redefining the unit of analysis is also recommended to avoid allocation. This means changing the functional unit to cover also the co-products if possible.

In biomethane use as a transportation fuel, process subdivision or redefining the functional unit cannot be used because digestate processing is tightly bound on biogas production. Due to additional processes for biogas upgrading and distribution redefining, the functional unit is also impossible. The next section presents in more detail the substitution and allocation methods, which are the most applied methods for biomethane calculations. Table 7 presents the used co-product handling method according to the literature review of biomethane LCA studies.

Table 7: Digestate handling LCA methodologies utilized in different biomethane studies based on literature.

Source	Basic method	Notifications
Pertl et al. (2010)	Digestate and its utilization are not taken into account in calculations.	There are several utilization options for digestate, but the quality of databases is poor.
Börjesson & Berglund (2006)	Emissions from digestate utilization are included in GHG emissions for biogas.	If chemical fertilizers can be replaced by digestate, GHG emissions from digestate utilization decrease.
Jury et al. (2010)	Digestate and its utilization are not taken into account in calculations. A share of digestate is used as fertilizer in energy crop cultivation to produce feedstock for biogas process.	Digestate is assumed to be given for farmers free. If there is an economic value for the digestate, GHG emissions should be allocated according to the economic value. Another option is to use system expansion. Digestate can also be regarded as waste when emissions from digestate use in farms should be added to GHG emissions of biomethane.
Murphy et al. (2011)	Emissions from digestate utilization and spreading are included in GHG emissions for biogas.	Potential to replace chemical fertilizers with digestate is taken into account in economic calculations.
Tuomisto & Helenius (2008)	Substitution (Digestate is used to replace mineral fertilizers and GHG emission reductions are reduced from GHG emissions from biogas production).	For some of the feedstock digestate is circulated and used as a fertilizer inside the system boundaries.
Directive 2009/28/EC	Allocation based on the energy value	According to the Directive, digestate can also be regarded as waste as the processes does not aim to its production

As can be seen in the table, there are three different ways to handle the co-products from biogas or biomethane production in the literature. One is to include the GHG emissions from digestate use in the GHG emissions from biogas production. Another option is to exclude the GHG emissions related to digestate from the calculation model. The third option is to use substitution or allocation procedures.

3.1.4.1 Substitution method

According to the ISO standards and Greenhouse Gas Protocol, allocation should be avoided whenever possible. One way to avoid allocation is to expand the product system to cover the co-products and their utilization in addition to the systems that they are replacing. Weidema, B.P. (1999) sees this method as a good way to handle the co-products of renewable materials. This way the actual environmental benefits of utilizing the co-products can be studied and taken into account. Using the substitution method, the alternative option to produce co-products should be known. The basic idea for the substitution method is presented in Figure 16. In the substitution method, only average emission data is usually used, instead of modeling the whole replaced systems. The GHG emissions replaced by the co-products are reduced from the total GHG emissions of the product. In literature, the term “system expansion” is also used for the method which in this dissertation is called the substitution method. In this dissertation, the term “substitution” is used when avoided emissions are subtracted from the emissions of the main product to calculate the GHG emissions related to the main product.

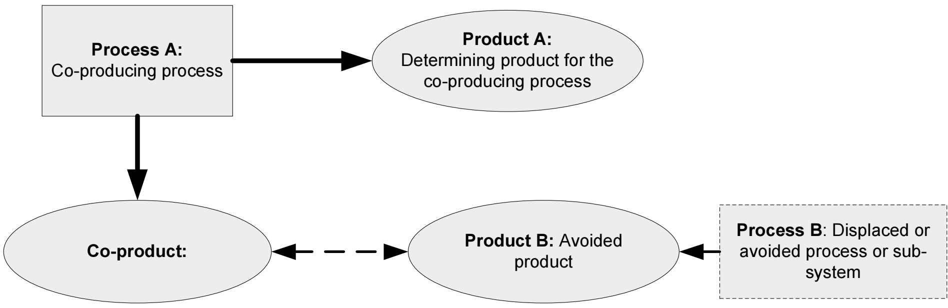

Figure 16: Substitution method (Weidema, B.P. 1999).

3.1.4.2 Allocation

If there are co-products in addition to the main product, emissions from the common processes can be allocated between the main product and co-product(s). According to ISO 14040, ISO 14044 and Greenhouse Gas Protocol, allocation should be done only if it cannot be avoided. On the other hand, according to Directive 2009/28/EC, allocation should be the primary option to take the co-products into account. A simple allocation is presented in Figure 17.

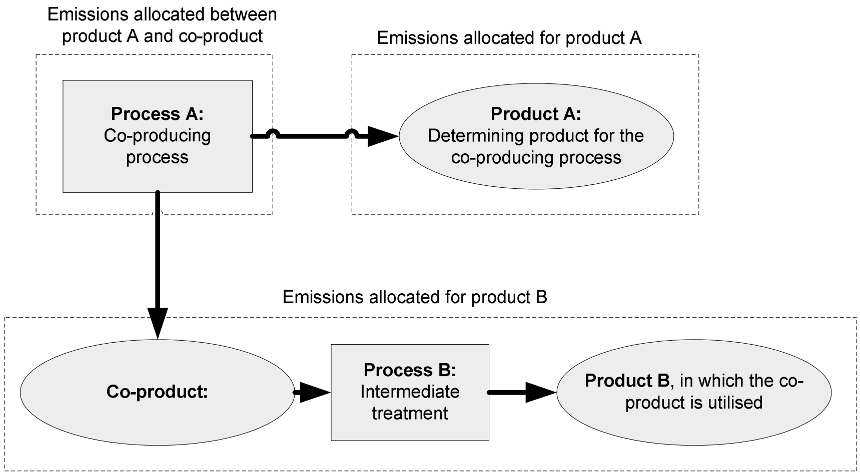

Figure 17: Basic allocation between the product and co-product

Allocation can be done by various ways, for example based on physical or economic characters of the main product and co-products. There are some different rules for the allocations between different products. According to Directive 2009/28/EC, allocation has to be done based on the energy value of different products. A side flow is regarded as a product if the processes are aiming to its production. If the process is not aiming to the production of the co-product, it cannot be regarded as a co-product and allocation cannot be done. According to ISO 14040 standard, allocations can be done according to the physical characteristics or economical values, but only for co-products, not for wastes. Objects or materials which are going to be destroyed or disposed are regarded as waste. Greenhouse Gas Protocol recommends the allocation based on physical, economical or other relationships. Physical allocation factors can be for example mass, volume, energy content, number of units, protein content of food and chemical composition. Other relations are those which cannot be measured and physical or economical allocation cannot be done. Allocations are not done for waste, which is a co-product, which does not have an economical value. Table 8 presents waste definitions and recommended allocation methods based on different instructions.

Table 8: Definition of waste and allocation methods based on different instructions.

	Directive 2009/28/EC and additional materials	ISO 14040 and ISO 14044	Greenhouse Gas Protocol
Co-product regarded as “waste” or “process residue” (no allocation)	A process residue is a substance that is not the end product(s) that a production process directly seeks to produce	A waste is an object or material which the holder is going to destroy or deposit	A co-product without economic value is considered as waste and no emissions or removals are allocated
Recommended allocation methods	Energy allocation if allocation cannot be avoided	Physical or economic allocation if allocation cannot be avoided	Physical allocation, economic allocation, other relationships if allocation cannot be avoided

3.1.5 System expansion method

The use of the term "system expansion" in this dissertation is different than its' common use in literature. According to the literature, the use of the term “system expansion” usually refers to a method, which in this thesis is called “substitution method”. In this dissertation the term "substitution method" is only used when GHG emissions are calculated for the main product and allocation is avoided by subtracting the emissions which can be avoided by co-product utilization. This division, between the two terms has been carried out in order to clearly separate the two methodological approaches that are both used in this dissertation.

In this thesis, the term “system expansion method” is utilised for wider perspective studies to compare various feedstock or biogas utilization scenarios. ISO/TR 14049 instructs to use "system expansion" in comparisons when there are options for various main products. In this method avoided emissions are not subtracted but added to alternative scenarios. For example, biogas can be used as a transportation fuel or in energy production. If biogas is used as a transportation fuel, in system expansion, energy has to be produced by other methods. As a result, system expansion presents the emissions from the whole studied system in different scenarios. Emission reduction potential can be calculated by comparing the results of different scenarios. When system expansion is used, the alternative production processes for various products has to be know. In Figure 18 a basic system expansion method in this dissertation is presented. The figure presents a situation where there is an alternative use for the current use of feedstock. The alternative process B produces an intermediate product, which has two alternative utilization options: processes C and D. In this case, emissions from the current use of feedstock can be compared to alternative uses (Scenario 1 and 2). When emissions from Scenario 1 are calculated the emissions from processes E and G have to be taken into account. These processes produce the products A and C, which are not produced from the feedstock in Scenario 1.

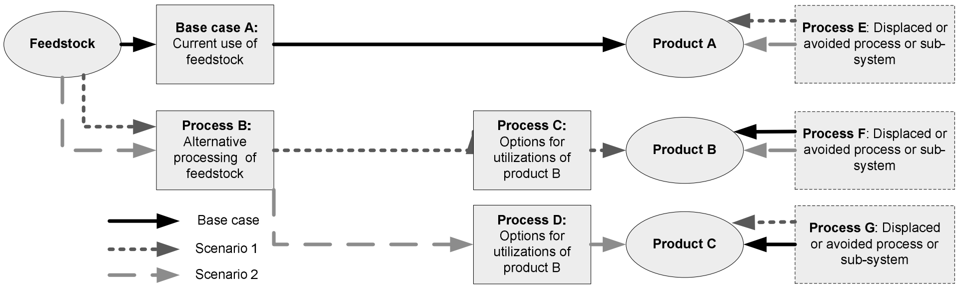

Figure 18: System expansion method in this dissertation.

3.1.6 Attributional and consequential approach

LCA studies can be divided into two main categories: attributional (aLCA) and consequential (cLCA). These two approaches have some differences, but various experts are not unanimous about the definitions. Attributional LCA concentrates on analyzing the environmental impacts through a product's life, and it commonly uses allocation methodology. Attributional LCA is not usually using a specific case but average data. The results based on aLCA are usually comparable and give overall information related to the environmental performance of products. They are also applicable for example in the marketing of the products. Consequential LCA concentrates on the environmental impact of specific cases, analyses changes and typically uses system expansion method. (Rehl et al., 2012; Väisänen, 2014; Lippke et al., 2011) It can be used for example for providing information for decisions makers. In the following figure, an example of these two approaches is presented for biomethane in the transportation use. The figure is simplified and presents an example how the differences in system boundaries between aLCA and cLCA can be divided by extreme interpretation. In this dissertation, GHG emissions related to biomethane production for transportation use are closer to aLCA, but the comparisons of various feedstock and biogas utilization options are closer to cLCA.

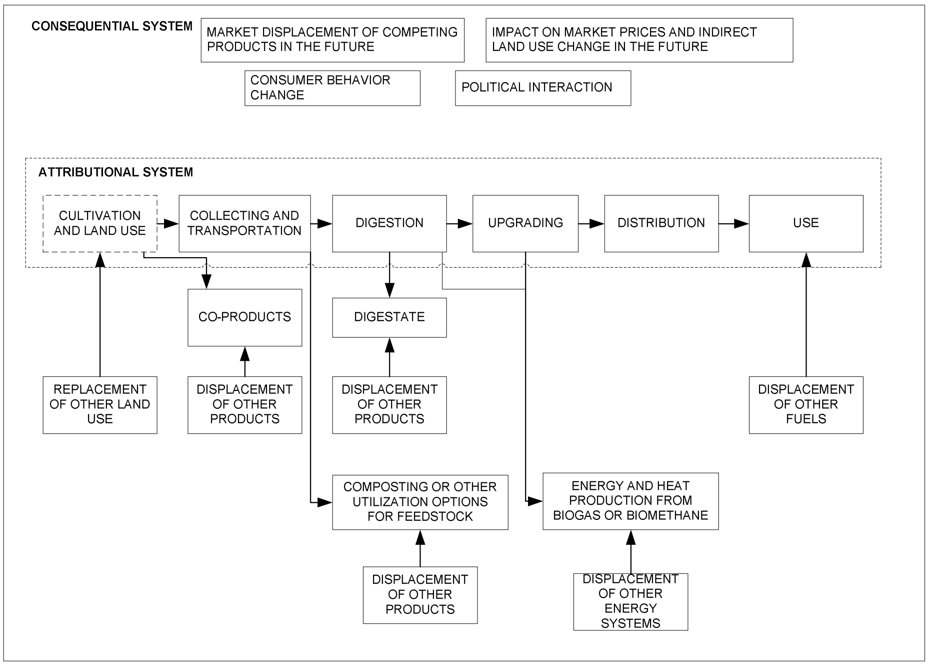

Figure 19: A simplified example of the system boundaries of the attributional allocation and system expansion consequential system approach. The figure presents the extreme interpretation of these two options. Real cases are usually somewhere between these two options (Väisänen, 2014; Rehl et al., 2012)

3.2 Feasibility and payback times

Economic comparisons are mainly carried out by using the payback time method. Payback time is the length of a period that is needed to recover the costs of investment. The shorter the payback time is, the better the investment. Payback time can be calculated simply (if the interest rate is not taken into account) by dividing the investment by annual incomes:

$$PAYBACK\ TIME = I/(S\mathrm{i} - S_e) \quad \text{(E3)}$$

I investment [€]
S_i yearly incomes [€ a^{-1}]
S_e yearly expenses [€ a^{-1}] (Haverila et al., 2005)

3.3 Biogas Potential analysis

Biogas potential can be estimated for a certain area by dividing first the area to subareas (Figure 20). The data can be collected for each subarea as detailed as possible. The feedstock for potential analysis are chosen, and the amount of each feedstock for each subarea is calculated or collected from the literature. By using the biogas productivity of various feedstock, the biogas potential for each subarea can be calculated. The total biogas potential can be calculated by combining biogas potentials of the studied subareas. This method has been used previously by Höhn et al. (2014), Rasi et al. (2012), Smyth (2010) and NREL (2013).

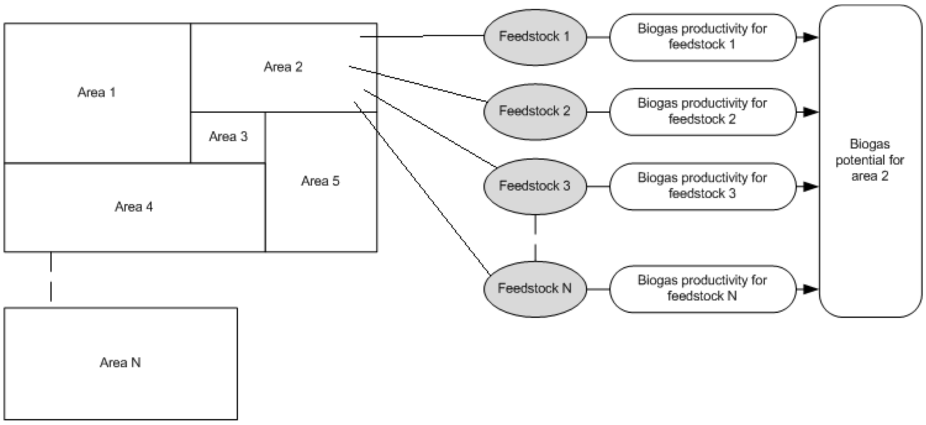

Figure 20: Biogas potential evaluation method.

3.4 Data collection and quality

To create calculation models for this thesis, initial data was collected from various data sources. For GHG emissions related to energy production and transportation use, the data has been commonly collected from various databases. Because biogas upgrading and distribution technologies are developing rapidly, more exact and up to date data has been collected from manufacturers, operators and from other experts. Economic and biomass potential data varies between different countries, and there is a lack of peer reviewed economic and biomass data concerning Finland. Therefore, the economic and biomass potential data had to be collected from national publications and from experts. Materials and Methods present all initial data and assumption but quality of main initial data sources are also analyzed in Appendix A.

3.5 GHG emission case modeling

This section presents the materials and methods related to the GHG emission models carried out in this dissertation. The first and second sections present the GHG emissions from transportation biomethane production and use. The first part of the first section is based on Publication I and the second part on Publication II. The first part concentrates on the effects of various factors along the life cycle of transportation biomethane, as well as on the effect of different allocation methods for digestate. The second part expands the research to WWTP sludge and agricultural biomass based on Publication II. The third part presents a comparison of the GHG emissions from biomethane to various fossil transportation fuels. This part is not directly from any of the publications, but combines data from Publication I and Publication II.

The second section compares various utilization options of feedstock, biogas, biomethane and landfill gas. The first part presents a comparison of biogas and biomethane utilization options based on Publication II. The second part presents a comparison of various landfill gas utilization options based on Publication V. The third part presents a comparison of biogas and biomethane based electricity use in electric vehicles compared to direct transportation use of biomethane based on Publication III.

The third section presents stydy for the limiting factors for biomethane use in the transportation sector. The first part of the section presents the theoretical biomethane potential calculation for Finland, the second and third part presents the study for technical and economic limiting factors. All of these sections are based on Publication IV. The last part of the section presents the effects of biogas electricity feed-in tariff as a political steering mechanism for biogas and biomethane use based on Publication III.

3.5.1 GHG emissions from transportation biomethane production and use

The first part presents GHG modeling for biowaste and dedicated energy crops (timothy and clover) based biomethane in the North European operational environment based on Publication I. The first part concentrates on the effect of various uncertainties along the life cycle of biomethane and on the effects of different allocation methods for digestate. The second part of the section presents GHG emission modeling for biowaste, WWTP sludge and agricultural biomass based biomethane in case Helsinki region based on Publication II, thus expanding the feedstock base of this dissertation. The third part presents a comparison of the results to GHG emissions from fossil transportation fuels.

3.5.1.1 Case biowaste and dedicated energy crops: effect of uncertainties and allocation methods for digestate

LCA methods are widely employed in similar GHG emission studies to compare various options and to evaluate the effects of certain parts of the life cycle on the entire process (Fruergaard et al., 2009; Achten et al., 2008). The functional unit in all calculations is 1 MJ of biomethane produced and distributed to the transportation sector. The modeling was carried out by calculating GHG emissions from each process step. For the factors used in the calculations, the basic assumption of a certain value is presented; thereafter, the variation of the value is presented in parentheses. The factors chosen for the sensitivity analysis are also presented in the Sensitivity analysis table in the Results section. The variation of the value is used in the sensitivity analysis to determine the significance and uncertainties related to each factor.

In this research, the North European operational environment was selected. The two types of feedstock chosen for the study are biowaste (organic waste) and dedicated energy crops (clover and timothy because they are widely used in Finland in grass production). Figure 21 presents the biomethane production chain modeled.

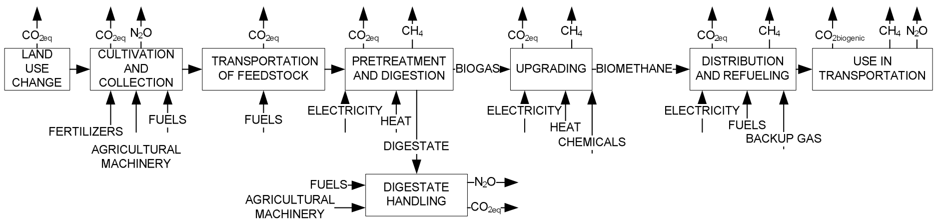

Figure 21: Biomethane production chain and flows related to various process steps (Latvala, 2009; Smyth, 2010; Tuomisto & Helenius, 2008; Börjesson & Berglund, 2006; Jury et al., 2010; Pertl et al., 2010; Murphy et al., 2011). (Publication I)

The following global warming potentials are used as carbon dioxide equivalent emissions for carbon dioxide, methane and nitrous oxide, respectively:

- 1 $gCO_{2eq}\, gCO_2^{-1}$
- 23 $gCO_{2eq}\, gCH_4^{-1}$
- 296 $gCO_{2eq}\, gN_2O^{-1}$ (Directive 2009/28/EC)

The new global warming potentials provided by IPCC are higher for methane than those used in this dissertation. The use of the 2013 values would lead to a higher importance in methane leakages from the climate change perspective.

From a methodological perspective, much variation exists in the methods used for allocating emissions from digestate handling and utilization. Emissions from digestate handling can be mainly attributed to the machinery needed for its transport and spreading and to N_2O emissions resulting from its use on fields (Murphy et al., 2011; Tuomisto & Helenius, 2008). There are four common ways of dealing with GHG emissions from digestate use in the context of studies of biomethane emissions. First, if digestate is not of economic value or the holder intends to dispose of it, it can be regarded as waste, according to the ISO 14040 standards and the Greenhouse Gas Protocol. In this case, GHG emissions from digestate utilization are added to the GHG emissions of biomethane. This method has been applied by Börjesson & Berglund (2006) and Murphy et al. (2011). Second, in other studies, GHG emissions from digestate utilization are not included for biomethane, and allocation is not done, despite the fact that the digestate is regarded as waste (Jury et al., 2010; Pertl et al., 2010). Third, if digestate is of economic value, it can no longer be regarded as waste, and thus part of the GHG emissions from the joint production of digestate and biomethane must be allocated (ISO 14040; Greenhouse Gas Protocol, 2011). Allocation may be done according to the economic value or to the instructions of Directive 2009/28/EC, based on the energy content of the products. Fourth, the substitution method is the final calculation method, and it may be employed to avoid allocation (ISO 14040; Greenhouse Gas Protocol, 2011; Tuomisto & Helenius, 2008). In this case, GHG emissions from digestate utilization are included for biomethane, but GHG emission savings incurred by replacing mineral fertilizers with digestate are subtracted from the total emissions. This dissertation studies the effects of four allocation methods applicable for digestate. The various options are presented in Figure 22, represented in Scenarios A–D.

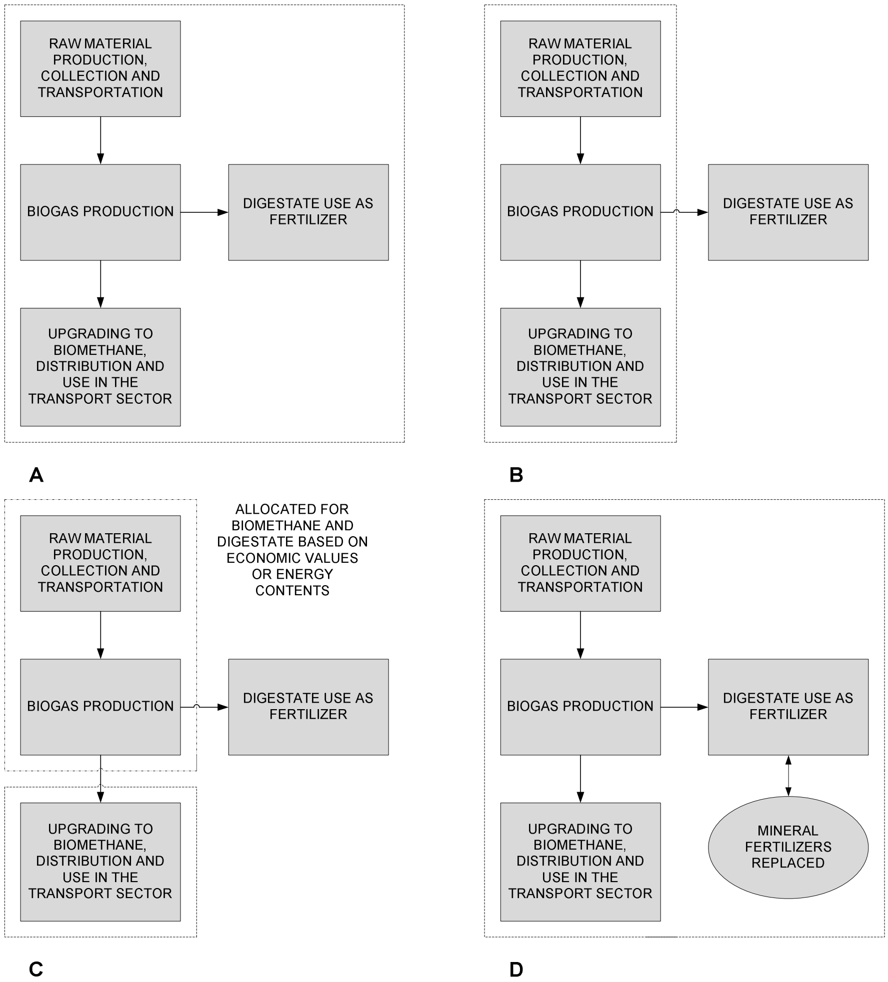

Figure 22: Various allocation methods for dealing with GHG emissions from digestate utilization. Scenario A depicts a waste assumption, whereby GHG emissions from digestate utilization are included in GHG emissions from biomethane production. Scenario B also depicts a waste assumption, but GHG emissions from digestate use are not included in GHG emissions from biomethane production. Scenario C depicts the allocation method based on economic or energy values. Scenario D depicts the substitution method for replacing mineral fertilizers. (Publication I)

When economic allocation methods are used, the economic value of the products must be defined (ISO 14040; Greenhouse Gas Protocol, 2011). The opportunity to gain an economic advantage from digestate use depends on the situation, and is still somewhat unclear. Based on the literature, the maximum price for digestate is approximately 11 $€t^{-1}_{dewatered\ digestate}$ (Kahiluoto & Kuisma, 2010). The price for biogas and biomethane also varies, but is approximately 0.5 € kg^{-1}_{biogas} and 1.5 € $kg^{-1}_{biomethane}$ (Rasi et al., 2012). For the energy allocation method, the lower heating value for digestate is assumed approximately 2.5 MJ kg^{-1}. For the substitution method, the emission factors for fertilizers are presented in the section on Cultivation.

If biowaste is used as feedstock for digestion, it can replace other waste management options such as composting. According to Finnveden et al. (2005), digestion and biomethane use as a transportation fuel is a better option than composting or landfill deposit from the global warming perspective (Finnveden et al., 2005). Replacing the composting process will lead to additional GHG emission savings with biowaste biogas. This is further studied in Publication II.

Data and assumptions

Land use change (LUC) may occur when feedstock cultivation is carried out in areas that have not been used for cultivation previously. Another option for LUC is that plant species in cultivation are changed. The basic assumption is that cultivation in Northern Europe can be done without significant LUC, so the effects of LUC are presented only in the sensitivity analysis. The worst case scenario for LUC in this dissertation is the conversion of a hectare of boreal forest into cropland, which leads to 114 tC_{eq} emissions over 119 years (the amount of time the carbon remains in the atmosphere) (Müller-Wenk & Brandão, 2010). LUC emissions are divided up to reflect two annual crops in the calculations (Rasi et al., 2012).

Cultivation processes lead to GHG emissions via the utilization of fertilizers and machinery. Feedstock productivity varies greatly depending on the geographical location. For the purposes of this dissertation, feedstock productivity (timothy and clover) is estimated to be 10 000 kg ha^{-1} (6 000 – 14 000 kg ha^{-1}) (Smyth, 2010; Rasi et al., 2012). The required amounts of fertilizer chosen for dedicated energy crops (timothy and clover) are 100 kg ha^{-1} (50–150 kg ha^{-1}) for nitrogen (N) fertilizer, 10 kg ha^{-1} (0–20 kg ha^{-1}) for phosphorus (P) fertilizer and 280 kg ha^{-1} (100–280 kg ha^{-1}) for calcium carbonate ($CaCO_3$) fertilizer (Smyth 2010). Phosphorus fertilizer use is relatively low in Europe, as nitrogen is the limiting factor for growth (Poeschl et al., 2010; Kahiluoto & Kuisma, 2010). The production of mineral fertilizers leads to GHG emissions of 5880.6 gCO_{2eq} kg_N^{-1}, 1010.7 gCO_{2eq} kg_{P2O5}^{-1} and 129.5 gCO_{2eq} kg_{CaO}^{-1} (BioGrace). In addition, the utilization of nitrogen fertilizer leads to nitrous oxide (N_2O) emissions (Brandão et al., 2011). In this research, 1% of nitrogen is estimated to react to N_2O (Brandão et al., 2011). Cultivation processes also require the use of machinery in fertilizing, harvesting, ploughing and seeding. Emissions from the use of machinery are calculated based on agricultural tractor emissions (Technical Research Centre of Finland, 2011).

Collection and transportation of feedstock related GHG emissions are calculated using transportation emission data for transportation trucks (BioGrace). Biowaste must be collected from households, public services or industry, and the collection distance is estimated to be 50 km (10–50 km) (Statistics Finland, 2010A). Dedicated energy crops collection is included in agricultural machinery and is carried out by a tractor. The transportation distance after collection for biowaste and dedicated energy crops is also approximately 50 km (10–100 km) (Statistics Finland, 2010A).

Digestion and pre-treatment process are studied as the same process step. Table 9 presents the characteristics of the feedstock used in calculations. These values are used to calculate the amount of feedstock needed to produce the functional unit of biomethane and to evaluate the effects of feedstock quality on GHG emissions.

Table 9: Characteristics of feedstock (Rasi et al. 2012).

	TS[a] %	VS[b]/TS -	CH_4 $m^3\ tVS^{-1}$	N %-TS	P %-TS
Biowaste	27 (27–66)	90 (85–90)	400 (400–450)	2	0.4
Dedicated energy crops	35 (28–35)	85 (85–90)	350 (300–350)	3.4	0.6

[a]Total solids
[b]Volatile solids

The digestion process is modeled based on anaerobic wet mesophilic digestion. The process is assumed to produce biogas with methane content of 60%. The electricity and heat demand are calculated based on the heating of the feedstock and on energy consumption during the pre-treatment and digestion processes. The electricity demand is calculated assuming 55 MJ t^{-1} (10% TS) for feedstock and 16.2 MJ $t^{-1}_{digestate}$ for dewatered digestate (Berglund & Börjesson, 2006). The marking 10% TS refers to a mixture of substrate with a 10% dry matter content. This dry matter content is obtained by recycling reject water and adding fresh water. The recycling rates, or water used, is 50% for biowaste and 100% for dedicated energy crops (the recycling rates were calculated). On the other hand, much higher energy demands are presented in the literature. Based on these assumptions, the electricity demand for biowaste is 72 MJ t^{-1} (72–230 MJ t^{-1}) (10% TS), and for dedicated energy crops, 76 MJ t^{-1} (76–230 MJ t^{-1}) (10% TS) (Berglund & Börjesson, 2006; Rasi et al., 2012). The digestion process heat demand is calculated by summing up the heat needed for heating the material for digestion and the heat losses from the reactor. Heat consumption is 59 MJ t^{-1} (59–320 MJ t^{-1}) (10% TS) for biowaste and 25 MJ t^{-1} (25–320 MJ t^{-1}) (10% TS) for dedicated energy crops. These values may be regarded as typical for new digestion plants, but especially the energy efficiencies of biogas plants vary on a large scale. (Berglund & Börjesson, 2006; Rasi et al., 2012; Pöschl et al., 2010). Various references provide low values for methane leakages from digestion (Berglund & Börjesson, 2006; Pertl et al., 2010); the maximum methane leakages in the digestion process are estimated to be 5% (Börjesson & Berglund, 2007; BioGrace).

Digestate may be used as a raw material for fertilizer production; it may be spread on fields without any additional processing (other than hygienization for biowaste based digestate), or it may be used in the composting process. The energy consumption of hygienization is taken into account in the energy demand of the digestion process. In this study, covered storages for digestate and recovery of residual methane are included to avoid methane emissions (Poeschl et al., 2012). If digestate is to be used as a fertilizer, it must satisfy the quality requirements (539/2006; Heinonen et al., 2008). For the purposes of this study, digestate is assumed to be transported by trucks to fields estimated to be located within 50 km from the digestion plant and then to be spread using agricultural tractors. It is estimated that 1% of nitrogen in the digestate results in N_2O emissions (Brandão et al., 2011). The Nitrate Directive limits the maximum amount of N that can be used for certain fields (Directive 91/676/EEC); therefore, there may not be an adequate amount of suitable fields close enough to the digester, which may in turn limit the use of digestate as a fertilizer. In these cases, additional digestate has to be for example composted. This option is studied in the sensitivity analysis. Composting does consume some electricity, but the majority of its emissions are related to N_2O emissions from N in the digestate (Rehl & Müller, 2011). It is estimated that 71 gCO_{2eq} $kg^{-1}_{feedstock}$ is emitted from a compost process (CH_3 and N_2O) and machinery use in the handling of compost products (Kahiluoto & Kuisma, 2010; Tanskanen, 2009). In addition, 1% of nitrogen in the compost product is estimated to result in N_2O emissions during the compost product utilization stage (Brandão et al., 2011). Similar compost process is used to estimate GHG emissions from biowaste composting in waste management.

Upgrading is needed for increasing the methane proportion of the produced gas by removing CO_2. There are several upgrading methods: pressure swing adsorption (PSA), water scrubbing (WS) and amine wash (AW). These methods differ in methane leakages as well as in electricity and heat consumption. Methane leakages from PSA are 4%, from WS 1.5%, and from AW 0.1% (0–0.1%) (Pertl et al., 2010; Purac Puregas; Patterson et al., 2011). The electricity use for PSA is 0.72 MJ Nm^{-3}_{rawgas}, for WS 0.97 MJ Nm^{-3}_{rawgas}, and for AW 0.36 MJ Nm^{-3}_{rawgas} (Pertl et al., 2010; Purac Puregas; Patterson et al., 2011). Additionally AW consumes 2.0 MJ Nm^{-3}_{rawgas} of heat, and 1.44 MJ Nm^{-3}_{rawgas} of heat can be recovered for the digestion process, which in turn decreases the heat consumption in digestion (Purac puregas). Heat recovery of upgrading is taken into account within the upgrading process step (so as to prevent misinterpretations). AW technology is assumed the basic selection, and emissions from PSA and WS are presented in the sensitivity analysis. After the upgrading process, the methane content of biomethane is assumed 98%.

Distribution of biomethane to consumers is also needed. Several solutions for distributing biomethane to the transportation sector are available. The natural gas grid and other suitable gas grids can be used to distribute biomethane. In gas grid distribution, biomethane is pressurized to conform to grid pressure, which, for example, is 55 bar for natural gas grid distribution in Finland, but may be lower if distribution is done via low pressure grids (Rasi et al., 2012). Electricity consumption in the compressor is 0.5 MJ m^{-3} for natural gas grid distribution (Rasi et al., 2012). If no grids are obtainable, the biomethane must be transported in liquid or compressed form by trucks, rail or ships. This dissertation examines both the natural gas grid distribution and truck transportation of compressed biomethane. For the latter, biomethane is pressurized to 250 bar, and the transported gas amount is 2000 kg per truck (Rasi et al., 2012; NSCA; Gustafsson & Stoor, 2008). The transportation distance for the compressed biomethane is assumed 100 km (50–250 km) based on the locations of refuelling stations and gas grids in North Europe. The amount of dewatered digestate is 0.07 kg MJ^{-1} (TS 30%) for biowaste and 0.134 kg MJ^{-1} (TS 30%) for dedicated energy crops.

Gas-refuelling stations are needed for biomethane distribution. The stations may be located either along the gas grids or in separate locations. For fast refuelling, the predominant refuelling method in Northern Europe, the pressure of the biomethane should be increased to 250 bar from NG grid´s pressure, and refuelling takes only minutes (Latvala 2009; Gustafsson & Stoor 2008). Electricity consumption in refuelling station compressors is 0.16 MJ m^{-3}, and in other devices, 0.04 MJ m^{-3} (Rasi et al., 2012; BioGrace). If a refuelling station is not located along the gas grid, a back-up gas system is required to ensure gas delivery during the shutdowns of bioreactors. In this research, the proportion of back-up gas is estimated to be 10% of the total distributed gas amount, but it should be borne in mind that only little information related to back-up gas use is available.

Several kinds of vehicles are developed to run on gaseous fuel. The most obvious users are buses, taxis and other vehicles operating in relatively confined areas. For example, local buses can operate with only one refuelling station. It is also possible to use biomethane in heavier vehicles, such as waste trucks (Kokki, 2006). An example passenger car in our research has an average gas consumption of 2.3 MJ km^{-1}, and an example bus has an average consumption of 21.2 MJ km^{-1} in urban driving (Rasi et al., 2012; Technical Research Centre of Finland, 2011). Vehicle emissions used in this study are 0.0011 gCH_4 km^{-1} and 0.0021 gN_2O km^{-1} for passenger cars and 1.0 gCH_4 km^{-1} and 0.032 gN_2O km^{-1} for busses (Technical Research Centre of Finland, 2011). Based on Directive 2009/28/EC, emissions from the utilization of biofuels in transportation can be excluded from the studies, and this is taken into account in the sensitivity analysis.

Emissions levels from processes consuming energy depend largely on the emissions resulting from energy production. Emissions among various energy production methods vary greatly; therefore, various emission factors must be used in calculations. In Finland, GHG emissions from average electricity production vary from 45 to 86 gCO_{2eq} MJ^{-1} (Statistics Finland, 2012C). However, GHG emissions originating from electricity production may be significantly lower if a high share of renewable energy is used. In other Nordic Countries, emissions from electricity production are lower than in Finland. For example, in Sweden, GHG emissions from average electricity production may be as low as 14 gCO_{2eq} MJ^{-1} (Schakenda & Nyland, 2008). On the other hand, if new electricity consumption occurs, new electricity production is also needed, and this new electricity may be produced by marginal electricity production methods (coal power) especially in the beginning (Voorspools & D´haeseleer, 2000). GHG emissions from marginal electricity vary from 222 to 250 gCO_{2eq} MJ^{-1} (Thyholth & Hestnes, 2008; Holttinen & Tuhkanen, 2004). Based on this information, 83 gCO_{2eq} MJ^{-1} (14–250 gCO_{2eq} MJ^{-1}) is chosen for this study to determine the effects of the utilized electricity type. The chosen value represents the GHG emissions from the average electricity production in Finland. The variation of electricity production related emissions is applicable also in many other geographical locations. Emissions from average heat production in Finland are 58 gCO_{2eq} MJ^{-1} (Statistics Finland, 2012C). The highest emissions from the heat use by energy method in Finland were 81 gCO_{2eq} MJ^{-1} during 2005–2009, which is close to the emissions from natural gas-based heat (Statistics Finland, 2012C). The lowest emissions from heat production are 4 gCO_{2eq} MJ^{-1}, occurring when heat is produced by wood chips (Rasi et al., 2012). In this research, emissions from heat production are assumed 58 gCO_2 MJ^{-1} (4–81 gCO_{2eq} MJ^{-1}).

3.5.1.2 Case biowaste, WWTP sludge and agricultural biomass in Helsinki region

This research is based on Publication II and the GHG emissions from biowaste, WWTP sludge and agricultural biomass based biomethane are calculated using Helsinki region as a case example. In the Finnish capital region, there are two digesters that are using sludge from waste water treatment plants (WWTP) as a feedstock. They have been using the produced biogas for electricity and heat production. The produced heat has been used to cover the own heat consumption of the WWTP. The electricity has been sold to the grid. However, one of the WWTPs started to sell its biogas for the NG grid delivery and transportation use instead of energy production. In addition to the WWTP digesters, there is a biowaste digester under construction. It will start using source separated biowaste from the capital region to produce biogas for the gas engines to produce electricity and heat. In addition to biowaste and WWTP sludge, there are organic agricultural masses, which could be used for biogas production.

This research is carried out by calculating the GHG emissions from different process stages of three different digesters: biowaste, WWTP sludge and agricultural biomass, which are the main feedstock for biogas production. The digestion plant for biowaste is located in the Ämmässuo landfill where the source separated biowaste is transported, the digestion plant for the WWTP sludge close to the WWTP plant and the digestion plant for agricultural biomass close to the NG grid in the area where the agricultural biomass density is the highest. (Rasi et al., 2012)

The functional unit used in this study is 1 MJ biogas produced. Process steps studied for biomethane from different feedstocks are presented in Figure 23.

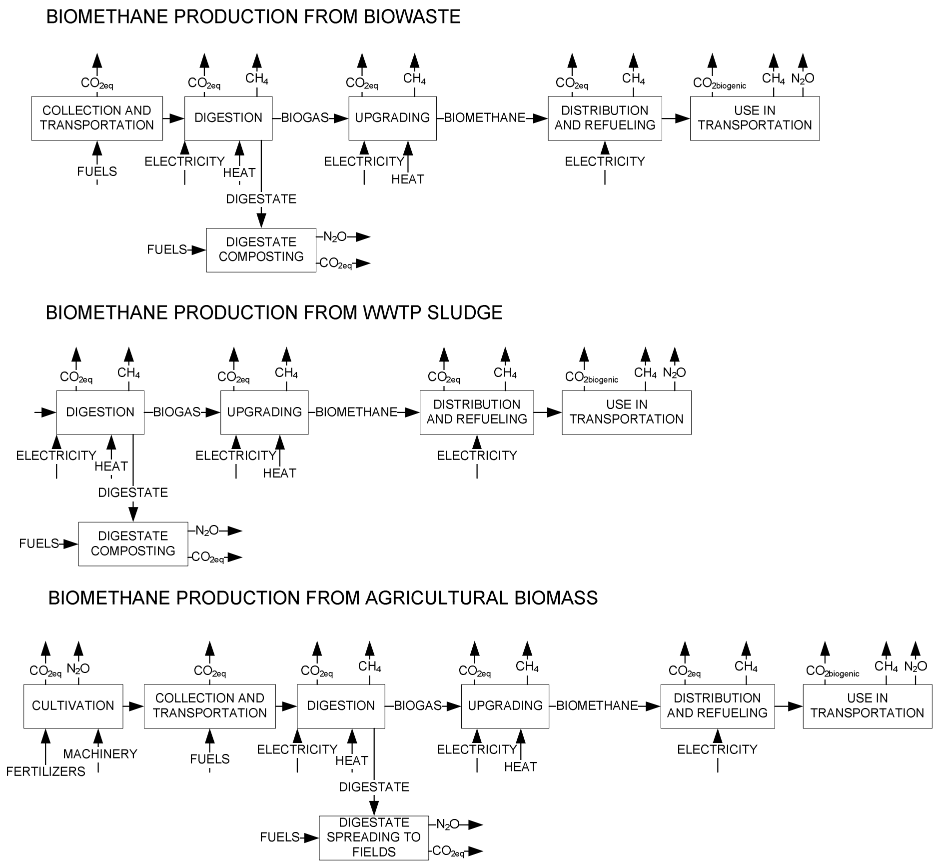

Figure 23: Process steps and GHG emissions for biomethane production from different feedstocks.

The research is basically carried out analogous to the research presented in the previous section. However, the feedstocks are different and some Helsinki region specific data is used. In the calculation model, GHG emissions related to digestate use are included in biomethane GHG emissions (waste assumption) or allocated according to energy values. The maximum heating value for digestate used is 2.5 MJ kg^{-1} (Statistics Finland, 2011).

Data and assumption

Feedstock production and transportation. The amounts of collected biowaste and WWTP sludge in 2009 in Finland's capital region are chosen for the study. The agricultural biomasses, used as raw material in the agricultural biogas plant, are manure, silage, straw of cereals, vegetable tops, greenhouse waste and potato waste. The raw materials, with the exception of silage, are considered as waste materials, and therefore, the GHG emissions from their acquisition phases are not included here. The field area that is not used for feed and food production is considered to be potentially available for energy crop production (MAVI). The biomasses and their total solids (TS) are presented in Table 10.

Table 10: Biomass amounts and their total solids used in the study. (MAVI; HSY, 2010; Tike, 2008; Sundell, 2011; EVIRA, 2009)

Mass fraction	Mass $t\ a^{-1}$	TS %
Agricultural biomass		
Manure	1 100	32
Silage	20 000	35
Straw of cereals	5 000	85
Vegetable tops	300	11
Greenhouse waste	20	12
Potato waste	20	25
Source separated biowaste	36 700	27
Sewage sludge	149 400	10

Grass is considered to be a potential energy crop. Crop rotation of grass is assumed with grain in the sequence of two seasons of grass and three seasons of grain. The yield used for the grass is 7.5 $t_{dry}\ ha^{-1}$ (Rasi et al., 2012). The emissions of silage cultivation and harvesting are based on machinery use in agricultural processes. Fertilizing is assumed to be carried out by using digestate from the digestion process as fertilizers. This is explained in more detail in the section Digestate use.

The transportation of biowaste is carried out by waste trucks. Waste trucks are collecting source separated biowaste from the households, public services and industry sector. The collected biowaste is transported to the digestion plant. The average collection and transportation distance for biowaste is 13 km $t^{-1}_{biowaste}$ and the GHG emissions from transportation are calculated by using the emission data of the Research Centre Finland (Technical Research Centre of Finland, 2012). For WWTP sludge, no transportation is needed as the digestion plant is located next to the WWTP. To the agricultural biogas plant the masses are assumed to be transported from within 10 km of the plant based on a pre-analysis. (Rasi et al., 2012) The transportation distance over which the biogas feedstock can be economically moved depends on its energy density and its transportation properties. In practise, the transportation distances for raw materials vary from 10 to 40 km (Dagnall et al., 2000; Palm, 2010). Agricultural biomass is assumed to be mostly transported by a tractor (Technical Research Centre of Finland, 2012).

Biogas production. Wet (total solids 10%) mesophilic digestion is used in biogas production. The used electricity consumption is 55 MJ t^{-1} (10% TS) for all digesters (Berglund & Börjesson, 2006), and the calculated heat consumptions are 97 MJ t^{-1} for the sewage sludge, 59 MJ t^{-1} for the biowaste, and 25 MJ t^{-1} for the agricultural biomass digesters. The heat demand includes the heating of the material and the heat losses from the reactor. The recycling rate of water is 50% in biowaste digestion, while with agricultural masses it can be as high as 100%. For WWTP sludge digester there is no water recycling because WWTP entering the process is already wet for digestion. The digestate was assumed to be mechanically dewatered by decanting centrifuge consuming 4.5 kWh t^{-1} electricity (Møller et al., 2002).

Digestate transport and use. Dewatered digestate from biowaste and sewage sludge digestion is assumed to be treated in a composting plant. The GHG emissions for composting (direct emissions and emissions related to machinery) used in this study are 71 $kg_{CO2eq}\ t^{-1}{}_{digestate}$ (Tanskanen, 2009).

The dewatered digestate from the agricultural biomass digestion is used as a fertilizer in the arable land used for the silage cultivation. It is assumed to be transported with a tractor and a trailer for a distance of 7 km. The reject water is directed back to the digester to substitute fresh water. The digestate is assumed to cause N_2O emissions of 0.203 $kg_{N2Oeq}\ t^{-1}$ feedstock when applied on the arable land (IPCC, 2006). The spreading is done by using an agricultural tractor, and the diesel consumption is 14 MJ t^{-1} for the dewatered digestate (Berglund & Börjesson, 2006). There is also additional digestate from agricultural biomass which can be sold to replace mineral fertilizers elsewhere. The share of additional digestate is approximately 24% based on the N and P contents of digestate and need in silage cultivation. The amounts of digestate and N and P contents of digestate are calculated using the data provided by Rasi et al. (2012). Emissions from mineral fertilizer production are 5881 $g_{CO2eq}\ kg_N^{-1}$ and 1011 $g_{CO2eq}\ kg_{P2O5}^{-1}$ (BioGrace).

Purification and upgrading. The upgrading process is also located close to the digestion plant because the gas amount is reduced during the upgrading, and therefore, the transportation of the upgraded gas is more profitable. In this study, AW is used as an upgrading method especially due to its low methane leakages. The methane leakage from AW is 0.1%. Its electricity use is 0.1 kWh Nm^{-3}_{rawgas} (Purac puregas). AW is also using 0.55 kWh Nm^{-3}_{rawgas} heat, and 0.4 kWh Nm^{-3}_{rawgas} of the heat can be recovered back to the digestion process, thus decreasing the heat consumption in the digestion (Purac puregas). In the Result section, the heat recovery of the upgrading is taken into account in the upgrading process to prevent misunderstandings.

Biogas distribution. In this research, only the NG grid distribution is studied because it is the only delivery method for longer distances used currently in Finland. In the NG grid delivery, biomethane is pressurized to NG grid's pressure (55 bar) and injected into the grid (Gasum Oy). Biomethane from the NG grid can be used in the existing refueling stations along the grid. Biomethane compression is estimated to consume 0.143 kWh m^{-3} electricity for NG grid´s pressure and 0.045 kWh m^{-3} electricity for the refueling pressure. (Rasi et al., 2012) In addition, other devices in the refueling station consume 0.01 kWh m^{-3} electricity (BioGrace).

Biogas and biomethane use. The example gas-operated passenger car in this research is Volkswagen Passat with an average gas-fuel consumption of 0.6 kWh km^{-1}. GHG emissions from vehicles are regarded as biogenic emissions and are not included in calculations based on the calculation rules of Directive 2009/28/EC.

GHG emissions related to energy production. GHG emissions from electricity and heat production used in the study are presented in Table 13. For the electricity consumption the average GHG emissions are used. For the heat consumption, in addition to average heat production, the effects of renewable and NG heat are also studied.

3.5.1.3 GHG emissions comparison of transportation biomethane and fossil transportation fuels

The previous sections present the ways that the life cycle GHG emissions from transportation biomethane production and use were calculated in this study. These emissions can be compared to GHG emissions from production and use of fossil transportation fuels. In Publications I and II, a standard value presented in Directive 2009/28/EC is chosen for fossil transportation fuels. However, there are various fuels that may be replaced by biomethane use, and the GHG emissions from these replaced fuels vary on a large scale according to the literature. In this dissertation, the GHG emission reduction of transportation biomethane (based on Publications I and II) has been compared to fossil petrol, diesel and NG. GHG emissions from these fossil fuels have been varied according to the literature. NG replacement is an obvious option for biomethane because both fuels can be used in gas-operated vehicles. On the other hand, if the share of biomethane increases in the transportation sector, it is likely that biomethane utilization will replace the use of fossil petrol and diesel. Petrol cars can be modified to use gaseous fuels (NG and biomethane), but the change may occur also when people are investing in new vehicles. The following table presents the variation of GHG emissions from various fossil fuels.

Table 11: GHG emissions from fossil fuels according to the literature (Directive 2009/28/EC; Californian low carbon fuel standard; Pertl et al., 2010; Jury et al., 2010; Tuomisto & Helenius, 2008; Murphy et al., 2011; Technical Research Centre of Finland, 2014; Wang-Helmreich & Lochner; Statistics Finland, 2012C)

Fuel	GHG emissions [$gCO_{2eq}\ MJ^{-1}$]
Fossil petrol	69.3–95.9
Fossil diesel	71.7–94.7
Natural gas	55–82
Fossil fuels (Directive 2009/28/EC)	83.8

Vehicles operating with different fuels have different efficiencies in turning the energy content of fuels to travelled kilometers (tank-to-wheel). According to Technical research centre of Finland (2013), the average energy consumption of a petrol passenger car is 2.5 MJ km^{-1} and 2.3 MJ km^{-1} for a diesel passenger car. Kappel and Vad Mathiesen (2013) compared gas consumption to petrol consumption. According to their comparisons and literature review, it seems that gas operated vehicles have approximately the same energy efficiency as petrol engines. There may be marginal differences, depending on whether the engine is using only gas or bi-fuel technology. In this comparison, the GHG reductions are calculated per travelled kilometers, and for that, the energy efficiency of petrol and gas-operated vehicles is estimated to be the same. In Publication I and Publication II, the functional unit is MJ biomethane produced, but in this section, the results have been modified per km travelled.

3.5.2 Comparison of biomethane, biogas and landfill gas in various utilization options

The first part presents the GHG modeling for various biogas and biomethane utilization options. In this model, Helsinki region is used as a case example, and the transportation use of biomethane is compared to various electricity and heat production options. In addition, other feedstock utilization options are also studied. The second part presents the GHG modeling for various landfill gas utilization options. In this part, biomethane from landfill gas is compared to electricity and heat production and to heat production option (heat production for asphalt production and for district heating).The third part presents a model for the comparison of biogas or biomethane based electricity use in electric vehicles and direct biomethane use in the transportation sector.

3.5.2.1 Biogas and biomethane utilization options comparison

The goal of this calculation model is to compare GHG emissions from various feedstock, biogas and biomethane utilization options to figure out where the biogas or biomethane should be used in various situations. The study is carried out by using a calculation model based on the system expansion method. By using system expansion method, the differences between various biogas and biomethane utilization options can be studied from the whole Helsinki region´s perspective. (ISO 14040; Greenhouse Gas Protocol, 2011).

Biogas or biomethane can be used for energy production with several applications. In this research, gas engine and micro gas turbine are studied for biogas. Gas engines and micro gas turbines are used to produce energy from landfill gas, and therefore, they are proven technology. Replacing NG in an already existing NG combined heat and power (CHP) plant is also studied as it is one option to utilize biomethane. Table 12 presents the electricity and heat production efficiencies of the studied energy production methods. The basic assumption is that the heat can be utilized throughout the year. However, in some cases, there is a need for heat only during the winter months. Heat utilization during only the three winter months is studied in sensitivity analysis. Feedstocks in this study are biowaste, WWTP sludge and agricultural biomass.

Table 12: Heat and electricity production efficiencies in different energy production applications.

	Electricity production efficiency	Heat production efficiency	Operational hours [h]	Source of data
Gas engine	0.4	0.4	6000	(MWM)
Micro gas turbine	0.32	0.4	6000	(Capstone 2010)
NG CHP plant	0.47	0.43	8700	(Helsingin Energia)

Using the system expansion method, GHG emissions from different scenarios can be calculated and compared to other scenarios. In all scenarios, transportation mileages, electricity, heat and compost/peat are chosen as functional units and they are produced by biogas or by alternative production methods. The system expansion calculations are carried out by comparing different scenarios which are the following:

- Scenario 1: Composting. All the feedstocks are composted. Electricity and heat are produced by average energy generation methods, and petrol is used as a fuel in the transportation sector.

- Scenario 2: Transportation use. Feedstocks are used for biogas production, and biogas is used in the transportation sector. Electricity and heat are produced by average energy generation methods, and peat is used instead of compost. Digestate is composted or used as a fertilizer.

- Scenario 3: Gas engine use. Feedstocks are used for biogas production, and biogas is used in electricity and heat production in gas engines. Additional electricity and heat are produced by average energy generation methods, petrol is used in the transportation sector, and peat is used instead of compost. Digestate is composted or used as a fertilizer.

- Scenario 4: Micro gas turbine use. Feedstocks are used for biogas production, and biogas is used in electricity and heat production in micro gas turbines. Additional electricity and heat are produced by average energy generation methods, petrol is used in the transportation sector, and peat is used instead of compost. Digestate is composted or used as a fertilizer.

- Scenario 5: NG CHP plant use. Feedstocks are used for biogas production, and biogas is used to replace NG in a NG CHP plant. Additional electricity and heat are produced by average energy generation methods, petrol is used in the transportation sector, and peat is used instead of compost. Digestate is composted or used as a fertilizer.

Figure 24 presents the process steps chosen for the system expansion method and different scenarios.

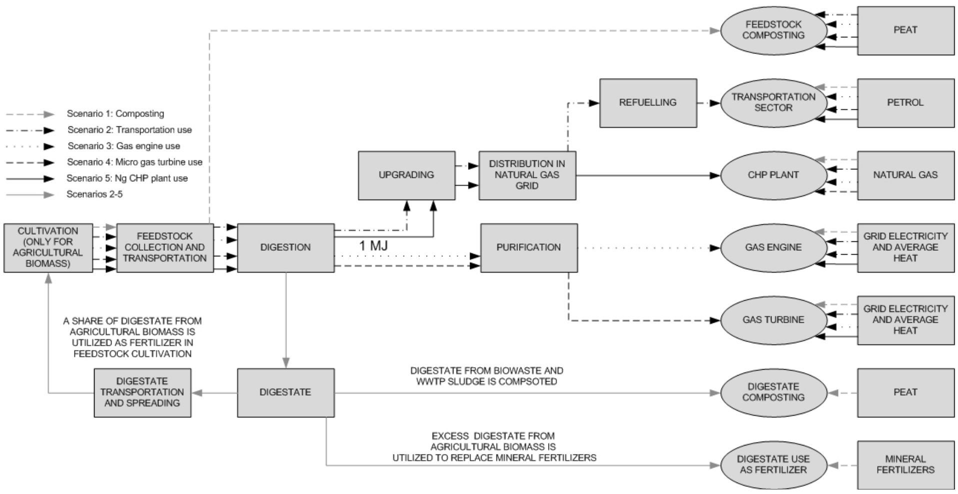

Figure 24: Total GHG emissions from biogas sector are studied using the system expansion method. Different scenarios are displayed by different arrows. (Publication II)

Data collection for the calculation models

GHG emissions of energy used in processes. GHG emissions from the energy production are varying yearly and depend on the variation in production. The method to calculate GHG emissions related to energy production (allocation between electricity and heat) has also impacts on the results. Maximum and minimum GHG emissions from electricity and heat production in Finland by energy and benefit allocation methods are presented in Table 13. The calculations are carried out by using emissions from the average electricity and heat production. When new production or electricity consumption is launched, it leads to increased energy production, and this energy may be produced by marginal methods. Over time, the structure of electricity production reacts to the changed consumption, and the consumed electricity will be closer to the average electricity. Therefore, the electricity used in processes may, in reality, be categorized as somewhere between the marginal and average electricity on a long term (Voorspools & D'haeseleer, 2000). The effects of marginal electricity, renewable heat and NG heat are studied in the sensitivity analysis. Marginal electricity in the European electricity markets is electricity produced in coal condensing power plants (Thyholt & Hestnes, 2008).

Table 13: GHG emissions from energy production (Rasi et al., 2012; Thyholt & Hestnes, 2008; Statistics Finland, 2012C).

	Average emissions chosen for calculations	Variation of average emissions	Alternative emissions used in sensitivity analysis
	g_{CO2eq} kWh^{-1}	g_{CO2eq} kWh^{-1}	g_{CO2eq} kWh^{-1}
Electricity	300	162–309	820 (marginal coal)
Heat	210	92–287	16 (renewable wood chips) 287 (NG heat)

Emissions for gas engine use are 90 g_{CH4} MWh_{biogas}^{-1} and 0.14 g_{N2O} MWh_{biogas}^{-1} and for micro gas turbine 110 mg_{CH4} m_{CH4}^{-3} and 17 mg_{N2O} m_{CH4}^{-3} (Niskanen, 2009; Nielsen et al., 2008). Emissions from NG used in a NG CHP plant are 86.2 g_{CO2} MJ_{NG}^{-1} (BioGrace). Purification needs to be done before the gas engine or gas turbine use to remove water and siloxanes from biogas. The gas engine is usually located close to the digestion plant to prevent the biogas distribution in long pipelines and to enable the utilization of the produced heat in the digestion processes. The compost is sold further to be used as soil for landscaping by replacing peat. Emissions from peat production and transportation are estimated to be 102 kg_{CO2eq} t_{peat}^{-1} maximum (Myllymaa et al., 2008). GHG emissions for petrol use in passenger cars are 169 g_{CO2eq} km^{-1} (Technical Research Centre of Finland, 2012).

3.5.2.2 Landfill gas utilization option comparison

In this study, GHG emissions from various utilization options of landfill gas (LFG) are studied. The research is published in Publication V. This calculation model expands the thesis to LFG in addition to biogas production by digestion process. Three utilization options for LFG are compared from the GHG emission perspective: combined heat and power (CHP) production, heat production for asphalt production and district heat production and LFG upgrading to biomethane.

LFG production

The calculations are based on an old (closed in 2001) and a new (opened in 2001) landfill located in Kymenlaakso region in Finland. The landfills are located next to each other.

Approximately 0.80 million $m^3\ a^{-1}$ LFG was collected in the old landfill in 2008, and the new landfill produced approximately 4.5 million $m^3\ a^{-1}$ LFG in 2010 according to a micrometeorological measurement method carried out by Finnish Meteorological Institute (Detes, 2008; Laurila, 2010). Methane concentration for the old landfill is 33% and for the new landfill 56%. (Sarlin, 2007; Laurila, 2010). In this model, the gas collection efficiency for the new landfill is set to 75% as recommended by USEPA (2008). The energy content of yearly collected LFG is thus 2 600 MWh for the old landfill and 18 700 MWh for the new landfill. The total yearly collected LFG is 21 300 MWh, which is a reference unit for each gas utilization scenario.

LFG and biogas utilization scenarios

In a base case LFG is treated by flaring. The treatment efficiency for LFG flaring is assumed 99 % (SEPA, 2002). The other studied scenarios are:

- Scenario 1: Combined heat and power (CHP) production with a gas engine.
- Scenario 2: The combination of heat generation for the asphalt production process in the summer and district heat production by a water boiler in the winter.
- Scenario 3: LFG upgrading to biomethane (corresponding to the quality of natural gas).

Scenarios 1 and 2 are chosen based on previous feasibility studies (Karttunen, 2007; Niskanen et al., 2009). Scenario 3 can be seen as an innovative option in Finland, and hence, it is included in this research. In Scenario 3 biomethane is utilized in a NG CHP plant along the NG grid. The LFG utilization options are presented in Figure 11.

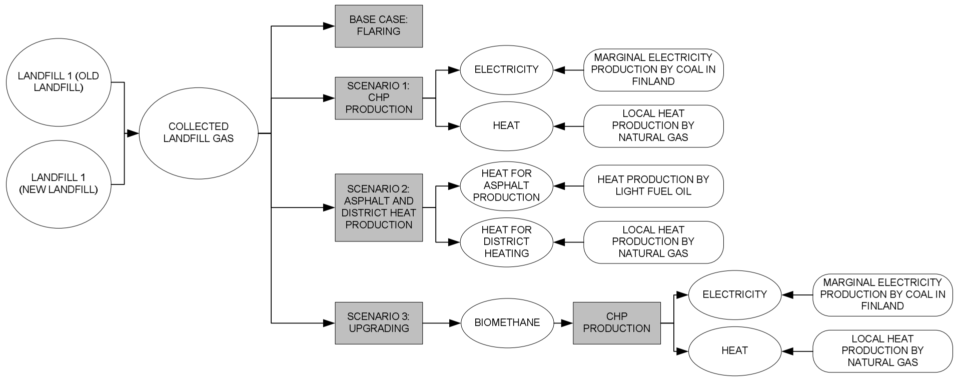

Figure 25: The LFG utilization options and replaced processes.

In every scenario, yearly utilization period is estimated to be 8000 h. In CHP production, gas engines are used. For a gas engine, the efficiency to produce electricity is 39% and heat 44% (Wong et al., 2001). The efficiency of heat production in district heating and in asphalt production is approximately 90%. The overall internal energy consumption in the upgrading process is 9.1%, including CH_4 loss, which is set to 1.5% of the total amount of collected CH_4 (Pertl et al., 2010).The lost CH_4 is not assumed to be released into the atmosphere without treatment.

LFG collection is assumed to use average electricity with GHG emissions of 207 kg MWh_e^{-1}. The upgrading process is estimated to use marginal electricity because if the utilization process is realized, it will increase the load of electricity consumption. GHG emissions from marginal electricity production are estimated to be 823 kg MWh_e^{-1}. (Dahlbo et al., 2005; Statistics Finland, 2010B) The methane oxidation efficiency in the landfill cover for the released LFG is assumed to be 10%. The GHG emission factor (GHG emissions per production, for energy production in unit: kg_{CO2eq} MWh^{-1}) and other assumptions for LFG utilization and the emissions of replaced fuels are presented in Table 14.

Table 14: Assumptions of replaced processes and emission factors.

Utilization process	Replaced process	Basis for the assumption	GHG emission factor [$kg_{CO2\text{-}eq}$ MWh^{-1}]
CHP heat production by LFG	Local heat production by NG	Current fuel for district heating	213[a]
CHP electricity production by LFG	Marginal electricity production by coal in Finland	Change in electricity generation	823[a]
District heat by LFG	Local heat production by NG	Current fuel for district heating	213[a]
Heat production in asphalt production process	Heat production by light fuel oil (specific process)	Current fuel in asphalt production process	220[b]
CHP heat production by upgraded LFG	Local heat production by NG	Current fuel for district heating	213[a]
CHP electricity production by upgrading LFG	Marginal electricity production by coal in Finland	Change in electricity generation	823[a]

[a]GHG emissions based on fuel classification of Statistics Finland (2010B) and heat and electricity production efficiencies reported by Flyktman and Helynen (2003).
[b]The heat production efficiency for NG is assumed to be 90%.

3.5.2.3 Biomethane use in the transportation sector compared to electricity produced from biogas or biomethane use in electric vehicles

This calculation model is created to compare GHG emissions from transportation use of biomethane to GHG emissions from biogas or biomethane based electricity use in electric cars. The calculation model and results are published in Publication III. The model is based on a new anaerobic digester planned to be built in Nastola, Finland. The amount of biogas produced in the bioreactor is examined in this study. The biowaste and sludge volumes fed into the bioreactor are approximately 120 000 ta^{-1}. The bioreactor will produce approximately 5.2 million m^3 of methane yearly. (Häme Regional Environment Centre, 2009). A part of the produced biogas will be used to generate power needed in the bioreactor's own processes, and only a part of the total biogas amount can be directed to further processing. A rough estimation is that the bioreactor's own energy consumption is 50% of the energy content of the biogas. Additionally, 4% of the produced biogas will be lost due to leakages, but it is turned into carbon dioxide in burners. The methane content of the biogas can vary from 45% to 75%, and it is estimated to be 55% in this study (Deublein & Steinhauser, 2008). The location of the biogas reactor is 2 000 meters from the natural gas grid, and therefore, the upgraded biogas can be delivered through the NG grid. This provides a wider range of possibilities for biomethane use in different applications.

Biogas can be upgraded into transportation fuel and used in gas-operated cars, or used to produce power for electric cars (NGVA Europe, 2013; Bekkering & Broekhuis, 2010). Power and heat can be produced in gas engines near a bioreactor or from upgraded biogas in natural gas installations, for example in large scale combined heat and power plants (CHP plants). The studied ways to utilize the energy from biogas in transportation are presented in Figure 26.

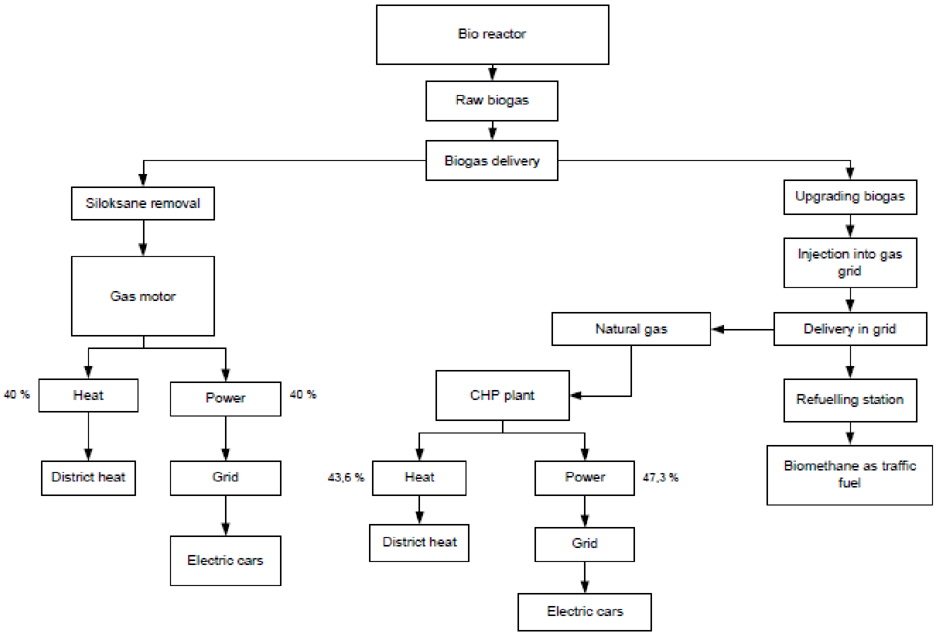

Figure 26: Different ways of using biogas as an energy source for transportation. (Publication III)

The average energy consumption figures of Finnish car distribution used in this study are 0.66 kWhkm^{-1} for diesel cars, 0.69 kWhkm^{-1} for petrol cars, 0.3 kWhkm^{-1} for electric cars and 0.5 kWhkm^{-1} for gas-operated cars (Technical Research Centre of Finland, 2011; U.S. Department of Energy, 2011; Gustafsson & Stoor, 2008). The energy consumption of electric cars is presented as electricity consumption. In electricity production from biogas or biomethane, the production efficiencies are taken into account. With these average consumption figures, the total distances driven with biomethane or with electricity produced from biogas or biomethane can be calculated. The processes needed in the different options to use biogas as an energy source for transportation are presented in Figure 27.

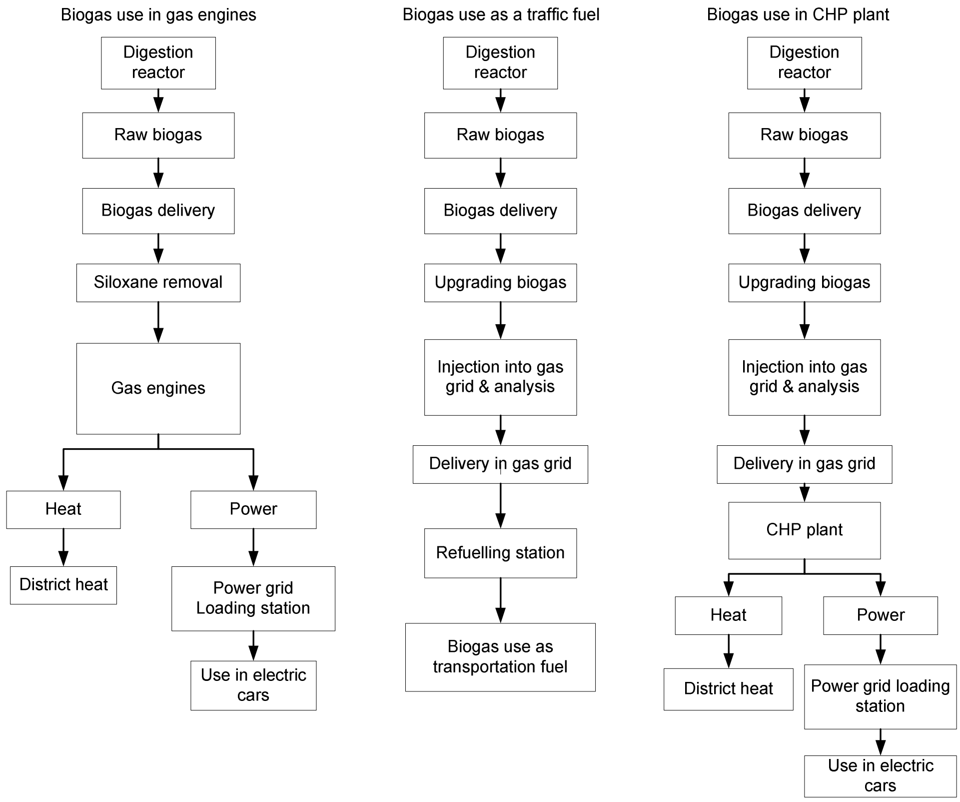

Figure 27: The processes of the different options to use biogas as an energy source for transportation. (Publication III)

Biogas use in gas engines near the bioreactor. Biogas should be pressurized and purified before it can be used in gas engines to generate electricity. Siloxanes and water are removed from the biogas, but the methane concentration is not notably increased (Lammi, 2009). Two gas engines are used to produce power and heat in the example plant in Nastola. Using two gas engines will enable more flexible usability. Annual maintenance operations are assumed to take approximately 1 000 hours. The maximum electric load can be utilized for approximately 7 760 hours a year. Heat can be utilized only during the three winter months (2 200 h per year). During downtimes, the produced biogas will be burned in a burner. It is also possible that the produced heat cannot be put to use at all, or if heat consumption increases in nearby areas, it can be used throughout the year. A connection pipeline to the local district heat grid will be needed for the heat delivery (Finnish Energy Industries, 2006). A generator and a grid connection to the electric grid are needed for the electricity delivery. In Finland, electric cars can be charged by using already existing heating posts. This is slow, and therefore, also some high-speed charging stations are needed. The efficiency of power production in gas engines is assumed 40% and that of heat production 40% (MWM). The power capacity of a gas engine is 1 200 kW, as is the heat capacity. (Lammi, 2009; MWM)

Biomethane use as a transportation fuel. Biogas needs to be pressurized and transferred to an upgrading plant to process it into a transportation fuel. At the upgrading plant, the methane concentration of the biogas will be increased to over 95% by removing carbon dioxide and sulphuric oxides. The upgrading can be carried out for example by water scrubbing or by pressure swing adsorption (Pertl et al., 2010). Feeding into the natural gas grid requires the pressurization of the biogas into the grid pressure of 54 bar (Gasum Oy). A pipeline connection and analysis centre to measure the biomethane amount are needed. According to the gas grid analogy, the gas amounts taken from the natural gas grid should be at the same level as the amounts fed into the natural gas grid. There are already refuelling stations in Finland for gas-operated cars (Gasum Oy). The capacity of the existing refuelling stations allows the delivery of the studied biomethane volumes. In this study, however, it is assumed that two new refuelling stations have to be built: one larger and one smaller.

Biogas use in natural gas CHP plant. The biogas upgrading and feed into the natural gas grid are similar to the transportation use option. The biomethane can then be used in an existing natural gas CHP plant to replace natural gas. The Helsinki Energia power plant in Vuosaari is considered here as an example plant. The total efficiency of the Vuosaari power plant is 91% (Helsingin Energia). The electrical power capacity of the plant is 630 MW and the heat capacity is 580 MW. Overall, 47.3% of the energy produced is electricity and the rest is heat (Helsingin Energia). The produced heat is used for district heating in the Helsinki metropolitan area (Helsingin Energia). The delivery system for power and heat exists already, but two high-speed charging stations are needed to direct the power to transportation use.

Evaluating the effects on the GHG balance

The GHG emissions were calculated by comparing emissions to the situation before the use of biogas or biomethane. The used method is the expanding the product system. The functional unit of this study is the annual biogas amount produced in the biogas reactor. The final scenarios are the following:

Reference situation. Petrol and diesel are used in transportation, a local heating plant in Nastola produces heat in the region near a bioreactor, and a CHP plant produces heat for the district heating grid in the Helsinki Metropolitan area and electricity for the national grid from natural gas.

Scenario 1. Power and heat are produced in gas engines near the bioreactor. Electricity will be used in electric cars to replace a part of petrol and diesel. Heat produced with biogas will replace local heating in the district heating grid near the bioreactor in Nastola. The CHP plant operates normally, as in the reference situation.

Scenario 2. All petrol and diesel are replaced with biomethane as a transportation fuel. The CHP plant and the district heat plant operate normally, as in the reference situation.

Scenario 3. A part of the petrol and diesel are replaced by electricity produced from biomethane. Natural gas will be replaced with biomethane in a CHP plant in Helsinki. Because the power is produced for transportation purposes, additional electricity has to be taken from the national grid. Electricity consumption of the scenarios is presented in Table 15.

Table 15: Electricity consumption of the scenarios.

Process step	Scenario 1 [MWh a^{-1}]	Scenario 2 [MWh a^{-1}]	Scenario 3 [MWh a^{-1}]
Biogas pressurization and delivery from bioreactor	500	500	500
Biogas purification	700	0	0
Biogas upgrading and pressurization	0	1 400	1400
Refueling	0	500	0

The actual fuel distribution of the district heating plant is not known, but we can use the average values for a Finnish district heat plant near the natural gas grid (40% natural gas, 20% biomass, 20% peat and 20% oil). The average carbon dioxide emission for such a plant would be approximately 0.214 $kg_{CO2}kWh^{-1}$ (Statistics Finland, 2012C). The average carbon dioxide emissions of electricity produced in Finland in 2006 amount to 0.280 $kg_{CO2}kWh^{-1}$ (Statistics Finland, 2012C). The carbon dioxide reduction calculation system is presented in Figure 28.

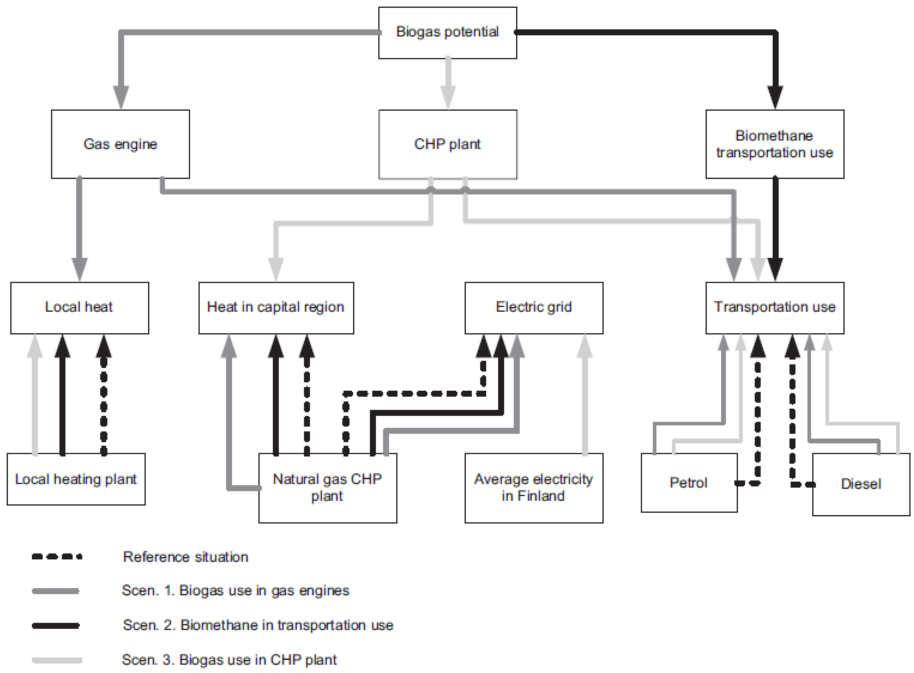

Figure 28: Energy flows in different scenarios. (Publication III)

CO_2 reductions in transportation can be calculated based on the total driving distances when using biogas or electricity produced with biogas or biomethane as an energy source for transportation. Without the use of biomethane, the same driving distance should be performed using petrol and diesel as fuel. In Finland, a bit less than 20% of passenger cars are diesel-fuelled, but a relative number of diesel cars will increase in the near future, and therefore, it is estimated that, in this study, 20% of passenger cars are diesel fuelled. (Pöllänen et al., 2006). The average carbon dioxide emissions for a car with 1.7 passengers, driving in cities 35% and on highways 65% are 181 gkm^{-1} for petrol cars and 175 gkm^{-1} for diesel cars (Technical Research Centre of Finland 2011). The electric cars are not emitting GHG emissions during their drive, and the GHG emissions from biomethane-operated cars are assumed to be zero as the CO_2 is biogenic (Pöllänen et al., 2006).

In this research, the actual biogas production processes are not included in the study because these process steps are similar for all studied options. To compare the three scenarios, it is not necessary to include biogas production steps.

3.6 Modeling and estimating limiting factors for biomethane use in the transportation sector

In this section, potential limiting factors for biomethane utilization in the transportation sector are studied. The limiting factors are studied from the life cycle perspective in Finland’s operational environment. The first step is to calculate the theoretical biomethane production potential in Finland. Then the limiting factors are studied from technological and economic perspectives. The technological study concentrates on gas-operated vehicles, and for the economic study, the biomethane production chain is divided into various operators’ perspectives. Possible reductions of the external costs, and the potentials to use these reductions to support biomethane use in the transportation sector are also studied.

3.6.1 Biomethane potential modeling case Finland

This study is carried out by calculating theoretical biomethane potentials of different areas in Finland. Biomasses that are used for other purposes such as for food production are excluded from this research. Finland is divided according to the Centre of economic development, transport and the environment, as data is available for this scale. These regions are similar to the counties in Finland with few exceptions. Aland is not included in this study, as it is not a part of the continental Finland. Figure 29 presents the locations of each studied region.

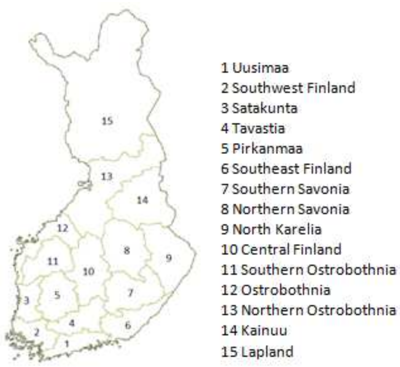

Figure 29: Finland is divided into regions presented in the map (Centre of Economic Development, Transport and the Environment, 2011).

In Finland, population is concentrated on Southern Finland while Northern and Eastern Finland are more sparsely populated. Due to the population distribution, also the highest transportation fuel need is in Southern Finland. Table 16 presents the population, area and amount of passenger cars in each region in Finland.

Table 16: Population, area and amount of passenger cars in different regions (Statistics Finland, 2012A, Finnish Transport Safety Agency, 2012).

Area	Area km^2	Population -	Amount of passenger cars -
1 Uusimaa	9 100	1 550 000	676 600
2 Southwest Finland	10 700	470 000	234 000
3 Satakunta	8 000	230 000	122 700
4 Tavastia	10 000	380 000	190 200
5 Pirkanmaa	12 400	490 000	236 700
6 Southeast Finland	10 800	320 000	167 600
7 Southern Savonia	14 000	150 000	79 200
8 Northern Savonia	16 800	250 000	120 500
9 North Karelia	17 800	170 000	85 100
10 Central Finland	16 700	270 000	133 200
11 Southern Ostrobothnia	13 400	190 000	108 600
12 Ostrobothnia	12 800	247 644	134 500
13 Northern Ostrobothnia	35 500	400 000	184 500
14 Kainuu	21 500	81 200	41 500
15 Lapland	92 700	180 000	88 500

In Finland, biogas is mainly produced from biowaste, WWTP sludge and agricultural biomasses, such as manure, potato waste and grass. (Latvala 2009)

Evaluating feedstock amounts and biomethane production potential are the first steps in the life cycle of biomethane. In order to calculate theoretical potential, the basic assumption is that biogas is not used to produce energy needed in the biogas production process. Therefore, all biogas can be upgraded to biomethane. The energy needed in the processes has to be produced by other energy options such as natural gas or wood chips. The results are compared to renewable transportation fuel targets of the European Union. In addition, the effects on Finland's transportation fuel self-sufficiency are also studied.

In Finland, biowaste can be collected from different sources such as households, private companies, public services and industry. At the moment, source separated biowaste is mainly used in anaerobic digestion and in composting. Biogas from anaerobic digestion is mainly used for energy production. (Ympäristötilasto, 2013; Rasi et al., 2012) The amount of household biowaste is approximately 90 kg a^{-1} per person (variation 83–100 kg a^{-1} per person) (Rasi et al., 2012). According to Rasi et al. (2012), the biowaste share of private companies, public services and industry is approximately 50% (46–55%) of the total biowaste amount. By using these assumptions and populations in each studied region, the approximate maximum amount of biowaste can be calculated. The collection rate for biowaste is estimated to be 65% from households and 80% from other sectors (Rasi et al., 2012). In the future, stricter legislation will decrease organic material deposited into landfills, and therefore, biowaste utilization potential may slowly be increasing (Ministry of the Environment, 2013).

WWTP production is related to human activities and industrial processes. Sludge amounts by regions were collected from Havukainen et al. (2012B). Approximately half of the WWTP sludge is currently digested, and the rest is composted. Biogas from sludge digestion is mainly used to produce electricity and heat needed at the WWTP. (Pöyry Environment Oy, Ympäristötilasto, 2013). The estimation is that all the sludge could potentially be anaerobically digested.

Manure amounts were calculated by using databases about regional amounts of different animals. (Matilda, 2011). The manure type was calculated by the average manure collection types in the area. In Finland, some of the animals are put on the pasture in summer time, and during that period, manure is left on the fields (Matilda, 2010). Currently, the majority of the manure is being spread on the fields as a fertilizer. If manure were used for biogas production, the nutrients in manure could be collected in digestate which could be used as well, as a fertilizer on fields. Data used in the manure amount modeling is presented in Table 17 and in Table 18.

Table 17: Animal numbers per region. Values are given in thousands. (Matilda, 2011)

Region	dairy cows	suckler cows	heifers	bulls	calves	pigs	sows	poultry	sheep	goats	horses
1 Uusimaa	8.2	1.2	4.3	2.1	6.8	31.4	3.7	13.2	7.7	0.2	3.9
2 Southwest Finland	8.6	4.5	5.9	5.4	12.6	368.6	39.4	3742.5	14.4	0.5	2.3
3 Satakunta	8.3	2.8	5.8	5.2	11.0	153.4	18.7	2202.6	6.1	0.3	1.6
4 Tavastia	15.2	2.6	8.2	5.2	14.0	92.7	8.4	134.5	4.8	0.0	2.9
5 Pirkanmaa	15.8	4.9	9.5	5.0	15.7	89.2	9.6	926.7	6.8	1.3	2.8
6 Southeast Finland	13.6	2.4	7.0	3.3	11.8	32.2	4.4	74.9	5.0	0.0	2.5
7 Southern Savonia	14.2	3.0	8.2	5.5	15.1	13.9	1.4	162.6	5.9	0.1	1.9
8 Northern Savonia	38.3	5.8	21.2	14.3	42.5	33.0	4.0	29.5	3.4	0.3	2.3
9 North Karelia	17.5	4.1	9.9	6.4	19.4	9.1	0.9	32.3	4.9	0.1	1.3
10 Central Finland	14.3	4.2	8.6	6.2	17.9	14.3	2.0	49.9	8.3	0.0	2.4
11 Southern Ostrobothnia	33.5	5.6	18.6	14.5	35.2	227.2	23.1	2293.6	6.6	1.4	2.5
12 Ostrobothnia	32.2	5.2	17.8	12.8	35.4	214.5	20.9	530.1	11.0	0.4	1.7
13 Northern Ostrobothnia	43.5	7.1	23.2	14.3	45.3	51.8	5.8	13.7	11.1	0.1	2.2
14 Kainuu	8.1	1.6	4.0	2.1	6.9	0.9	0.0	10.3	3.4	0.0	0.4
15 Lapland	10.6	1.9	5.9	5.4	10.9	0.0	0.0	4.7	17.1	0.1	0.6

Table 18: Values used for manure amount calculations (Matilda, 2010, Rasi, 2012).

Animal	Pasture period	Share of pasture using farms	Share of slurry manure farms	Share of litter manure farms	Annual slurry manure per animal	Annual litter manure per animal
	mth a^{-1}	-	-	-	-	t
dairy cow	4.1	0.871	0.41	0.59	25.3	24.0
suckler cow	6.1	0.577	0.25	0.75	18.0	16.9
Heifer	6.1	0.577	0.25	0.75	10.0	10.9
Bull	6.1	0.577	0.25	0.75	14.5	13.4
Calf	6.1	0.577	0.25	0.75	7.0	7.6
Pig	0	0	0.73	0.27	2.0	1.5
Sows	0	0	0.73	0.27	7.0	5.4
Poultry	0	0	0.03	0.97	0	0.1
Sheep	5.0	0.835	0.02	0.98	0	1.5
Goat	5.0	0.835	0.02	0.98	0	1.5
Horse	5.5	0.675	0	1.00	0	12.8

Cultivation in greenhouses produces different kinds of side flows such as leaves and plant parts. The amount of greenhouse side flows can be calculated according to greenhouse areas regionally and by using the average side flow yields for greenhouses. Vegetable tops from potato and sugar beet can be regarded as waste, and they can be used for digestion. Silage is produced to feed cattle. It is usually produced as a part of the crop rotation with cereals and other plants. Cultivation areas of silage can be collected regionally from Matilda (2011) database. A certain share of silage could be used for biomethane production. Luostari et al. (2007) presented that in Finland, the field area to produce energy plants is approximately 200 000 ha. According to Niemeläinen et al. (2012), in 2012, there is a 190 000 ha area of fields that are maintained but not under cultivation. In this research, it is estimated that 200 000 ha of fields could be used for biogas feedstock grass cultivation. This area is estimated to be distributed according to the distribution of grass fields in Finland. Also other biofuel feedstock such as rapeseed could be cultivated in this area, which may limit the utilization potential for biogas production.

Straw is a side flow from cereal and plant oil production. Straw amounts can be calculated using the average straw yields per hectare presented in Table 20. Areas in cultivation can be collected regionally from Matilda (2011) database. A part of straw is used as litter for cattle, but there is still additional straw, which is ploughed into fields because there is no better use for it. In this dissertation, it is approximated that 50% could therefore be used for biomethane production. In small scale, straw use in energy production is also tested, but it is not widely used in Finland. The problem of straw as feedstock for anaerobic digestion is the high dry matter content. Therefore, digestion could be done more easily as co-digestion with raw materials with higher water content such as manure. (Hills, 1980; Fischer, 1983)

Field areas in different regions in Finland are presented in Table 19. To calculate the feedstock amount based on these areas, the biomass productivity of different feedstock is needed. Average productivities used in this research are presented in Table 20.

Table 19: Regional use of agricultural land. Values are given in 1 000 hectares. (Matilda, 2011)

Region	cereals	grass	oil plants	potatoes and sugar beet	greenhouses	set-aside
1 Uusimaa	130	29	12	1	0	5
2 Southwest Finland	262	34	20	8	0.1	5
3 Satakunta	120	24	6	10	0	3
4 Tavastia	151	35	11	2	0	4
5 Pirkanmaa	107	44	9	0	0	4
6 Southeast Finland	93	33	7	0.5	0	6
7 Southern Savonia	32	35	1	0.5	0	4
8 Northern Savonia	69	84	2	0	0	4
9 North Karelia	37	44	1	0	0	3
10 Central Finland	47	41	2	0	0	6
11 Southern Ostrobothnia	192	65	11	6	0	9
12 Ostrobothnia	159	62	7	5	0.1	5
13 Northern Ostrobothnia	150	99	3	4	0	6
14 Kainuu	9	22	0	0	0	2
15 Lapland	5	39	0	0	0	0

Table 20: Biomass productivity of agricultural biomasses used in calculations (Rasi et al., 2012).

Raw material	t ha^{-1}
Straw of cereals	3
Straw of oil plants	2
Grass	6
Potato waste	5
Sugar beet tops	7.5
Greenhouse waste	35

To calculate the biogas and further biomethane potential from feedstock, certain assumptions about the total solids (TS), volatile solid (VS) and methane productivity are needed for the calculations. Feedstock properties used in the calculations are presented in Table 21.

Table 21: Feedstock properties (Rasi et al., 2012)

Feedstock	TS -	VS TS^{-1} -	methane productivity $m^3_{CH4}\ t_{VS}^{-1}$
Biowaste	0.27	0.9	400
WWTP sludge	0.20	0.7	300
Slurry manure cows	0.06	0.8	200
Slurry manure pigs	0.04	0.85	300
Litter manure cows	0.19	0.6	200
Litter manure pigs	0.24	0.8	300
Litter manure chicken and turkeys	0.38	0.71	300
Litter manure sheep	0.32	0.6	250
Litter manure goats	0.32	0.6	250
Litter manure horses	0.32	0.6	250
Straw of cereals	0.85	0.91	230
Straw of oil plants	0.9	0.92	250
Potato and sugar beet tops	0.11	0.85	300
Greenhouse waste	0.11	0.85	300
Silage	0.35	0.85	300

To calculate the amount of vehicles that could use the produced biomethane as energy source, some assumptions have to be done related to the car fleet. The average driving distance of passenger cars in Finland is approximately 16 800 km a^{-1} (Tiehallinto 2009). The average consumption of gas-operated passenger cars depends on the car type. For this study, the consumption of Volkswagen Passat, 0.6 kWh km^{-1} is chosen (Lehtomäki & Mykkänen).

3.6.2 Technological limiting factors

After estimating biomethane production potential, the second and the third step in the life cycle of biomethane are the distribution and the use in gas-operated vehicles. The lack of gas-refueling stations or distribution options could be a limiting factor from the infrastructure perspective. The development and spreading of a gas-refuelling station network in Finland is estimated by comparing the gas-refueling station and gas-operated car numbers to other European countries. In addition, different ways for distribution are also estimated. There are approximately 1000 gas-operated vehicles in Finland, and 18 refueling stations for gaseous fuel (NGV global, 2010; Gasum Oy). The total amount of gas-operated vehicles in Europe is approximately 1 800 000 (NGVA Europe, 2013). Data about gas-operated vehicles, car amounts and refueling stations is collected from the statistics of the World Natural Gas Vehicle association and the World Bank (NGV global, 2010; The World bank, 2012). In addition, potential technological limitations for gas-operated vehicles compared to traditional vehicles are studied from the literature.

3.6.3 Economical limiting factors

Economical limiting factors are studied from different operator' perspective and by studying the effects of the feed-in tariff in Finland.

3.6.3.1 Operators in biomethane chain

For economical modeling, the biomethane production, distribution and utilization chain is divided into four main operators based on the life-cycle of biomethane (Figure 30). The economical calculations are mainly carried out by calculating the payback time for investments needed in different cases.

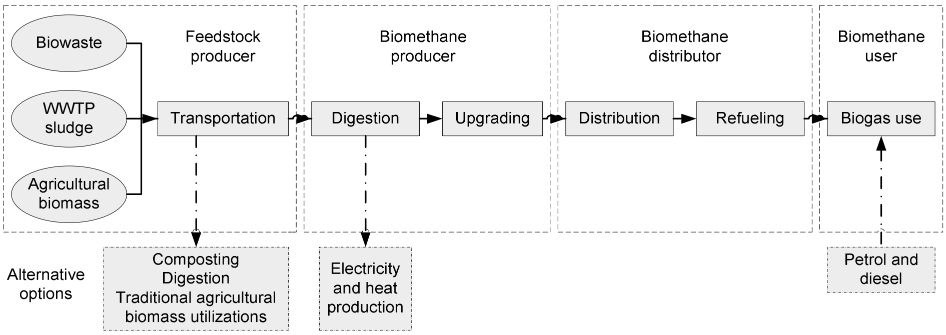

Figure 30: Different operators in the biomethane production and utilization chain. (Publication IV)

The first operator type is the feedstock producer, which may be for example a farmer, a municipal waste company or WWTP. The feedstock for biomethane production is waste or a co-product from their processes. Feedstock producers usually have to transport the feedstock to a biogas plant and pay a gate fee. In Finland, the gate fee is approximately 30–75 € t^{-1} for biowaste, 30–55 € t^{-1} for WWTP sludge and 0–70 € t^{-1} for manure. In addition, the biogas plant usually pays 20–30 € t^{-1} for grass biomass. (Mykkänen, 2009; Pöyry Environment Oy, 2008) In Germany, the gate-fee is 25–40 € t^{-1} (Poeschl, 2010). Producers have also other options to utilize the feedstock. For biowaste and WWTP sludge, one of these other options could be for example composting (Tanskanen 2009). The price of composting and digestion in Finland varies between 72 and 106 € t^{-1} and in Germany between 35 and 95 t^{-1}. In addition, the post aging costs 5–21 € t^{-1}. (Mroueh et al., 2007, Poeschl et al., 2010) The gate-fee for incineration plants in Germany is 60–350 € t^{-1} (Poeschl et al., 2010). For farmers, other options to utilize for example manure could be the traditional manure utilization options at farms which cost 20 € t^{-1} at the minimum (Pöyry Environment Oy, 2008). In Finland, farmers may get support if they distribute the slurry manure to fields (Maaseutuvirasto, 2009).

The second operator type is the biomethane producer. Biomethane producers invest in digestion and upgrading facilities. One concept could be to use 50% of biogas in gas engines to produce the heat and electricity needed in processes and upgrade 50% to biomethane. Another concept could be to upgrade all the biogas to biomethane and produce the energy needed in the process for example by natural gas or wood chips. Biomethane producer gets income from gate-fees and from biomethane sale. Although the biomethane price is not commonly known in Finland, the incomes from biomethane sale should be higher than from electricity production, which is supported by the feed-in tariff. Otherwise biogas will not be directed to biomethane production but to electricity and heat production. In this study, a biogas plant using 120 000 t a^{-1} raw material is used as an example. Table 22 presents the investments and operational costs for the biomethane production process.

Table 22: Investments and operational costs for biomethane producer. (Publication III, Havukainen et al., 2012A)

	Investment million €	Operational costs million € a^{-1}
Digestion plant	7.2	0.72
Gas engines	1.3	0.08
Upgrading	2.5	0.175

The third operator type is the biomethane distributor. Biomethane distributors are for example NG grid and refueling station owners. Biomethane distributors have to invest in gas pipelines, in wheel transportation machinery and in different applications needed in distribution. They also invest in refueling stations. Wheel transportation can be either liquid biomethane (LBG) or compressed biomethane (CBG) transportation. Biomethane distributors pay for biomethane and get incomes from biomethane sale in refueling stations. In some cases they also own the upgrading infrastructure and buy raw biogas from producers. For this study, it is assumed that the biomethane distributor owns the upgrading facilities. The investments and operational costs for biomethane distributor are presented in Table 23.

Table 23: Investments and operational costs for biomethane distributor. (Publication III, Rasi et al., 2012)

	Investment million €	Operational costs million € a^{-1}
Compressing	0.35	0.14
Pipeline (2 km)	1.27	*
Pipeline (10 km)	5.67	*
Existing NG grid	0.17	*
Wheel transportation	0.56	*
Refueling	0.60	0.36

* included in compressing

The fourth operator type is the biomethane user who buys biomethane from refueling stations and invests in gas-operated vehicles. For a consumer, biomethane is a little more expensive than NG, but both gaseous fuels are cheaper compared to petrol or diesel (Gasum Oy). On the one hand, gas-operated vehicles are more expensive than those using liquid fuels (Volkswagen, 2013). In addition to new vehicles, the already existing petrol cars can be modified to use also gaseous fuel with a relatively low price (Oragas Oy). The gas-operated vehicles are approximately 1 000–2 000 € more expensive than the petrol fuelled cars (Volkswagen, 2013). On the other hand, biogas price is lower than the price of petrol. Biogas price as petrol equivalent is 0.96 € l^{-1} while petrol price is 1.5 € l^{-1} (Gasum Oy). In addition, the economics are studied for a case when the maintenance costs are 200 € a^{-1} higher for a biomethane operated vehicle.

3.6.4 Reducing external costs to subsidize biomethane use

The external costs of biomethane use are compared to the external costs of petrol use in the transportation sector. In addition, other external costs can be related to the fuel production chain, but they are excluded from this study. External costs are directed to the society due to different effects such as health effects. In this study, the external costs from climate change, from air pollutants ($PM_{2.5}$, NO_x and SO_x) and from energy dependency are studied. The external costs from climate change can be calculated using avoidance cost or by damage cost approach. Damage cost approach takes into account the costs related sea level rise, energy use, agricultural impacts, water supply, ecosystem and biodiversity, extreme weather effects and other major effects. Avoidance cost approach is based on a cost-effectiveness analysis that determines the least-cost option to achieve the required level of greenhouse gas emission reduction for example related to policy target GHG emissions. External costs from air pollutants are related to health costs, building and material damages, crop losses in agriculture and impacts on biosphere and impacts on biodiversity and ecosystems. Energy dependency costs are related to different cost mechanisms due to the dependency on imported oil. (CE Delft, 2008) The input data for external costs calculations is presented in Table 24. However, it is very difficult to evaluate external costs, and therefore, the uncertainty of the data is high.

Table 24: Input data for external cost calculations (Technical Research Centre of Finland, 2012; Lampinen, 2009; CE Delft, 2008).

Cost type	amounts for petrol	reduction from petrol to biomethane	external cost
CO_{2eq}	210 g km^{-1}	70%	40 € t^{-1}
$PM_{2.5}$	0.003 g km^{-1}	66%	100 000 € t^{-1}
NO_X	0.33 g km^{-1}	57%	800 € t^{-1}
SO_2	0.00094 g km^{-1}	98%	1800 € t^{-1}
Energy dependency	7.8 l $100km^{-1}$	100%	0.03 € l^{-1}

Reductions of the external costs could be directed to certain parts of the life cycle of biomethane chain as subsidy by political decisions. This could help to avoid economic bottle necks along the life cycle and increase biomethane utilization as a transportation fuel. External costs from different transportation energy systems can be seen as a potential way to evaluate and estimate the subsidize need for different options.

3.6.5 Feed-in tariff as a political steering mechanism for electricity from biogas

In Publication III, different utilization options of biogas and biomethane were compared from economic perspective in addition to GHG comparison presented in section 3.5.2.3. In this study, the economic effect when a new feed-in tariff for electricity produced from biogas is implemented in Finland is studied. Economic comparison of different biogas utilization options takes into account investments and operating and maintenance costs that have been gathered for each process step. The sizes and costs of the different components are evaluated according to the biogas amount and costs are considered from the natural gas grids owner´s perspective. The cost information is based mainly on the estimations of the experts from Sarlin Oy and Gasum Oy because there is not enough Finland-specific published data available. The cost information for the studied size of components is presented in the Table 27. Calculations are performed by using a 20-year period, a 5% interest rate and payback time methodology.

Table 25: Cost calculation information (Lammi, 2009[1]; Suomilammi et al., 2009[2]; Energy Market Authority, 2010[3]; Biomeeri Oy, 2009[4])

		Scen 1 Gas engines	Scen 2 Biogas use in transportation	Scen 3 CHPplant
Biogas delivery from bioreactor				
Compressor investment[1]	€	53 000	53 000	53 000
Compressor use	€ a^{-1}	47 000	47 000	47 000
Delivery pipelines[2]	€	55 000	55 000	55 000
Purification and upgrading of biogas				
Siloksan removal investment[1]	€	253 000	0	0
Siloksan removal use	€ a^{-1}	80 000	0	0
Upgrading investment[2]	€	0	2 500 000	2 500 000
Pressurization investment[2]	€	0	350 000	350 000
Upgrading and pressurization use[2]	€ a^{-1}	0	175 000	175 000
Biogas injection into natural gas grid				
Pipeline investment[2]	€	0	550 000	550 000
Connection investment[2]	€	0	62 500	62 500
Analysis investment[2]	€	0	100 000	100 000
Injection and directing in gas grid use[2]	€ a^{-1}	0	144 000	144 000
Power and heat production				
Gas engine investment[1]	€	1 000 000	0	0
Use and maintenance in energy production[1]	€ a^{-1}	100 000	0	120 000
Torch investment (estimation)	€ a^{-1}	50 000	0	0
Delivery systems				
Electric grid investment[3]	€	25 000	0	0
Transformer investment[2]	€	55 000	0	0
District heat pipeline investment (estimation)	€	600 000	0	0
District heat line ventilation investment (estimation)	€	2 000	0	0
Refuelling station 1st investment[2]	€	0	1 200 000	0
Refuelling station 1st use[2]	€ a^{-1}	0	60 000	0
Refuelling station 2nd investment[2]	€	0	600 000	0
Refuelling station 2nd use[2]	€ a^{-1}	0	90 000	0
Speed loading stations for electric cars[4]	€	2 000 000	0	2 000 000
Investments	€	4 090 000	5 470 000	5 670 000
Yearly costs	€	227 000	516 000	486 000
Current value	€	2 830 000	6 433 000	6 057 705
Total costs	€	6930000	11 900 000	11 730 000

The profits from selling biogas are calculated by using the produced energy amounts and energy prices. The calculation of the energy amounts are presented in section 3.5.2.3 with the GHG emission modeling. Prices may vary greatly, and the estimation of long-term price development is uncertain. The prices used in this study are 44 € MWh^{-1} for electricity, 20 € MWh^{-1} for heat and 69 € MWh^{-1} for biogas in transportation use. (Gasum Oy, Ministry of Employment and the Economy, 2009)

A feed-in tariff includes the electricity produced with wind power or biogas in Finland. The tariff provides a guarantee price of 83.5 €MWh^{-1} for electricity produced with biogas. If the total efficiency of the plant is over 50%, an extra price of 50 €MWh^{-1} (heat premium) will be paid. The tariff will be paid for 12 years after the start-up of a plant. The tariff does not include biomethane use in gas-operated vehicles. (Ministry of employment and the economy, 2009)

4 Results

This chapter presents the results of this dissertation. The first section presents the GHG emissions from biomethane production and use from various feedstocks and compares them to the GHG emissions from fossil transportation fuels. It also presents the effects of changes in various factors along the life cycle of biomethane and the effects of different allocation methods for digestate. The first section is based on Publications I and II. The second section presents a GHG emission comparison of various biogas, landfill gas and biomethane utilization options. The first part presents the comparison of GHG emissions from transportation biomethane to electricity and heat production from biogas and biomethane. The second part presents a GHG emission comparison of various landfill gas utilization options. The third part presents a GHG emission comparison of biomethane use in gas-operated vehicles and electricity produced from biogas or biomethane use in electric vehicles. The second section is based on Publications II, III and V. The third section presents the limiting factors for biomethane use in transportation sector. The third section is based on Publications III and IV.

4.1 GHG emissions from biomethane production and use compared to various fossil transportation fuels

This section presents the results related to the GHG emissions from transportation biomethane production and use based on Publications I and II.

4.1.1 Case Biowaste and dedicated energy crops: the effect of uncertainties and allocation methods

Based on the assumptions made and the data used, the GHG emissions for biomethane from biowaste are 22 gCO_{2eq} MJ^{-1}, and for biomethane from dedicated energy crops (timothy and clover) 61 gCO_{2eq} MJ^{-1} without allocation for digestate (Figure 31).

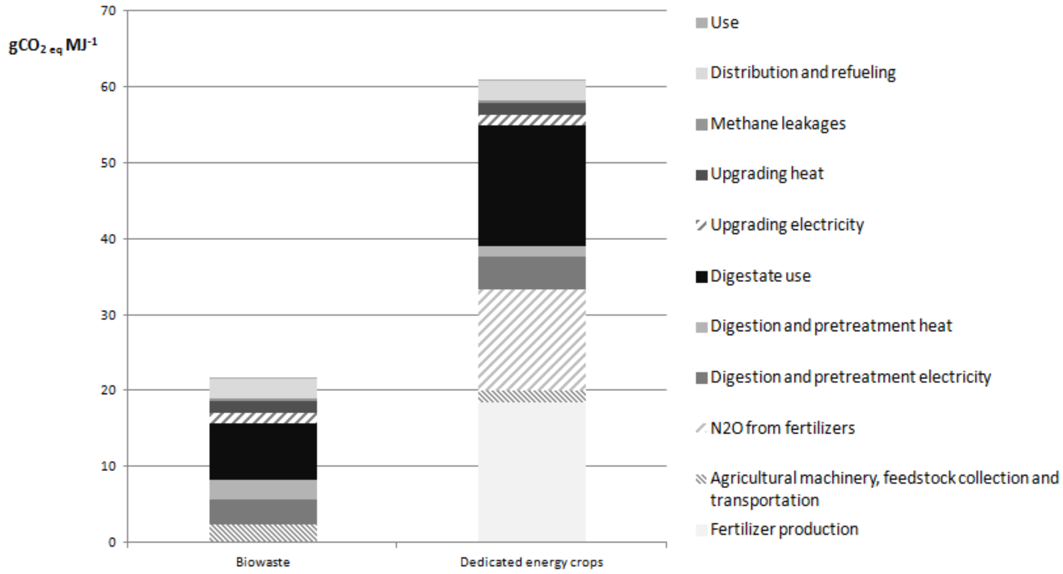

Figure 31: GHG emissions from various process steps for biowaste-based biomethane and dedicated energy crops (timothy and clover) based biomethane. (Publication I)

Dedicated energy crops-based biomethane yields significantly higher GHG emissions mainly because of the relatively high emissions from cultivation processes and digestate utilization. Digestate from biomass of dedicated energy crops contains more N than does digestate from biowaste, and therefore the, usage of the former leads to higher N_2O emissions. GHG emissions related to transportation, digestion, upgrading, distribution and use are relatively low for both types. The majority of emissions from these process phases are related to electricity use. The sensitivity analysis for GHG emissions related to various factors along the process chain is presented in Table 26. High additional emissions can be related to LUC, cultivation, digestate utilization, digestion technology and upgrading technology. On the other hand, low GHG emission reductions can be gained in almost all life cycle steps.

Table 26: Sensitivity analysis of various factors along the process chain influencing the total GHG emissions.

Factor	Variation	GHG emissions compared to the base case [gCO_{2eq} MJ^{-1}] MIN	MAX
Biogas from biowaste			
Biowaste transportation	10–100 km	–2.2	+1.4
Digestion technology	Heat 320 MJ t^{-1} (10% TS) and electricity 230 MJ t^{-1} (10% TS)		+23.4
Digestion methane leakages	5% CH_4 leakage		+22,5
Digestion heat production method	Wood chip heat 4 gCO_{2eq} MJ^{-1} or high heat production emissions 81 gCO_{2eq} MJ^{-1}	–2.5	+1
Digestion electricity production method	Low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	–2	+11
Feedstock quality	Variation in TS-%, VS TS^{-1}-% and CH_4 productivity, effects on electricity and heat consumption	–0.7	+0.3
Digestate utilization	Digestate composting + additional 1% N_2O emissions from compost spreading		+18.3
Biogas from dedicated energy crops (timothy and clover)			
LUC	The conversion of a hectare of boreal forest into cropland, which leads to 114 tC_{eq} emissions over 119 years. Double cropping used.		+81
Cultivation	Dedicated energy crop productivity 6000 t ha^{-1}, N-fertilizer use 150 kg ha^{-1} and phosphorus use 20 kg ha^{-1}		+47.6
Feedstock transportation	10–100 km	–0.9	+2.2
Digestion technology	Heat 320 MJ t^{-1} (10% TS) and electricity 230 MJ t^{-1} (10% TS)		+31.2
Digestion methane leakages	5% CH_4 leakage		+23.4
Digestion heat production method	Wood chip heat 4 gCO_{2eq} MJ^{-1} or high heat production emissions 81 gCO_{2eq} MJ^{-1}	–1.3	+0.5
Digestion electricity production method	Low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	–3	+14
Feedstock quality	Variation in TS-%, VS TS^{-1}-% and CH_4 productivity, effects on electricity and heat consumption	–0.3	+1.0
Digestate utilization	Digestate composting + additional 1% N_2O emissions from compost spreading		+36.1
Biomethane production and use			
Upgrading technology	PSA use in upgrading with higher electricity consumption and methane leakages		+18.8
Upgrading methane leakages	0% CH_4 leakage	–0.5	
Upgrading heat production method	Heat 320 MJ t^{-1} (10% TS) and electricity 230 MJ t^{-1} (10% TS)	–1.4	+0.6
Upgrading electricity production method	Low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	–1.2	+2.8
Distribution technology and electricity use	CNG and back up gas transportation 250 km. Low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	–2.1	+7.0
Use	The emissions from use are not included according to Directive 2009/28/EC or high emissions from gas bus	–0.3	+1.3

In addition, different allocation methods were studied (Figure 32). Emissions from biomethane production are significantly higher in Scenario A than in the other scenarios. In Scenario A, digestate was assumed to be waste; therefore, all emissions related to digestate handling and use are included in the emissions of biomethane. Scenario B depicts that excluding digestate utilization from the calculations will decrease the total GHG emissions significantly. Scenario C shows that with the application of energy or economic allocation methods, the majority of the emissions (87-95 %) from common processes will be allocated to biomethane because of the low heating and economic value of digestate. Therefore, the differences between Scenarios B and C are marginal. In the future, if prices of fertilizers and digestate increase, the allocation rate for digestate would also increase, which would lead to a lower GHG emission load for biomethane in Scenario C. Scenario D shows that the usage of the substitution method and replacement of mineral fertilizers leads to additional GHG emission reduction from mineral fertilizer production. This substitution method results in the lowest GHG emissions especially for biowaste-based biomethane.

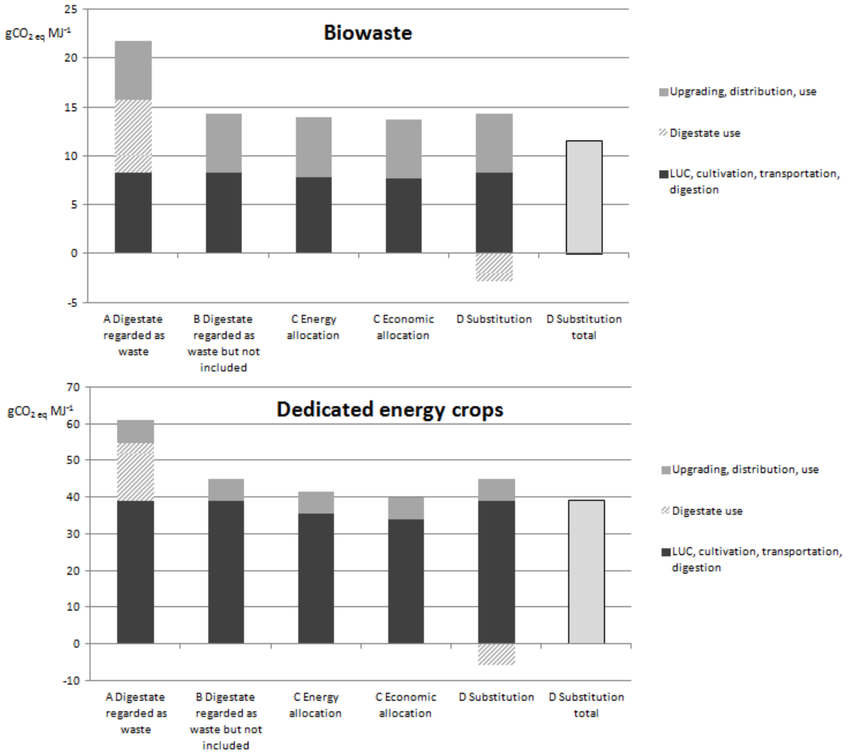

Figure 32: GHG emissions from biomethane production with various allocation methods for digestate. (Publication I)

4.1.2 Case Biowaste, WWTP sludge and agricultural biomass in Helsinki

GHG emissions for transportation use of biomethane from biowaste, WWTP sludge and agricultural biomass were calculated using the Helsinki region as a case area. The results are presented in Figure 33. The results are presented with and without the GHG emission allocation for digestate. In addition, the effects from the options to utilize renewable heat or NG heat for biomethane production are studied.

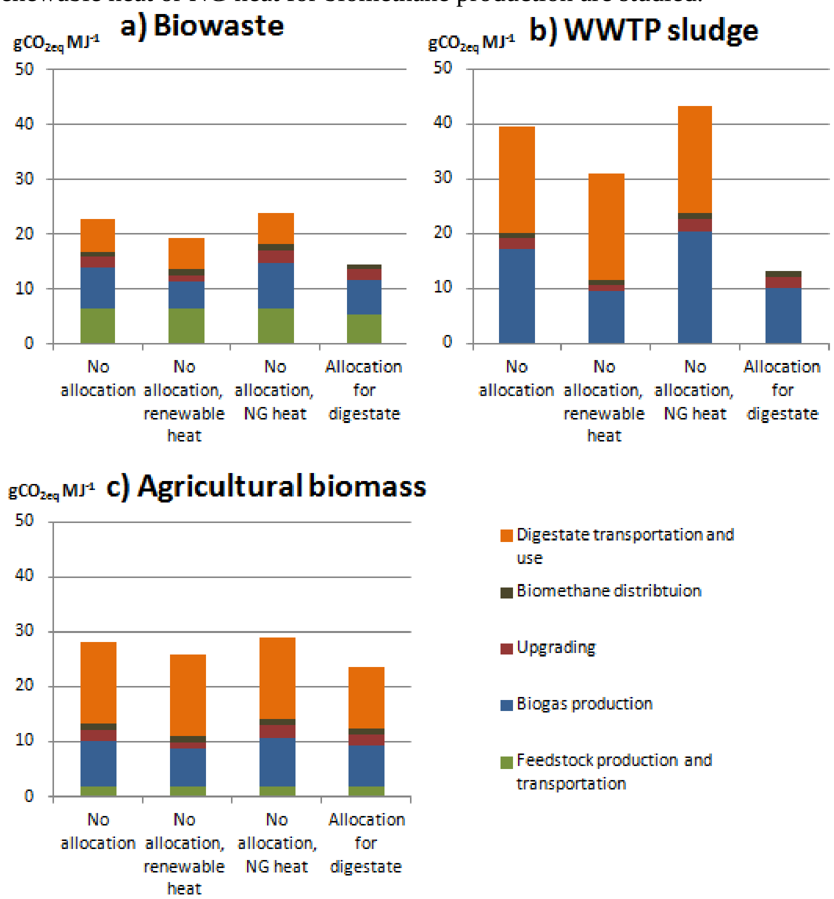

Figure 33: GHG emissions of transportation use of biomethane from different production plants according to the calculation based on the Directive 2009/28/EC. (Publication II)

As can be seen in Figure 33, the GHG emissions are the lowest when biomethane is produced from biowaste. If the GHG emissions are allocated for digestate, the WWTP sludge biogas plant and biowaste plant have the lowest emissions. Using renewable energy for the process heat production decreases emissions only slightly, as there are several emission sources that are not affected by the heat production method. The utilization of NG heat increases the emissions slightly compared to the utilization of average heat. GHG emissions from the digestate use have an important role, especially with WWTP sludge and agricultural biomass. Heat consumption in the WWTP sludge digestion plant is higher than in the other plants because water is not recycled, and therefore, the need for heat is higher. Whether allocation can be used or not, has a strong effect on the results. Using allocation for digestate decreases the GHG emissions from transportation biomethane. Allocation does not have as strong effects on agricultural biogas plants as the majority of the digestate is recycled to silage cultivation process within system boundaries. Biogas upgrading and distribution processes seem to have relatively low emissions, which is mainly due to the low emissions from the AW process studied in this dissertation. In addition, distribution emissions are lower than from the other life cycle stages. The main emission sources in addition to the digestate use are the biogas production stage and biowaste collection and transportation.

4.1.3 GHG emission reduction potential of transportation biomethane compared to fossil transportation fuels

GHG emissions for transportation biomethane (Publications I and II) are compared to GHG emissions from fossil transportation use in Figure 34.

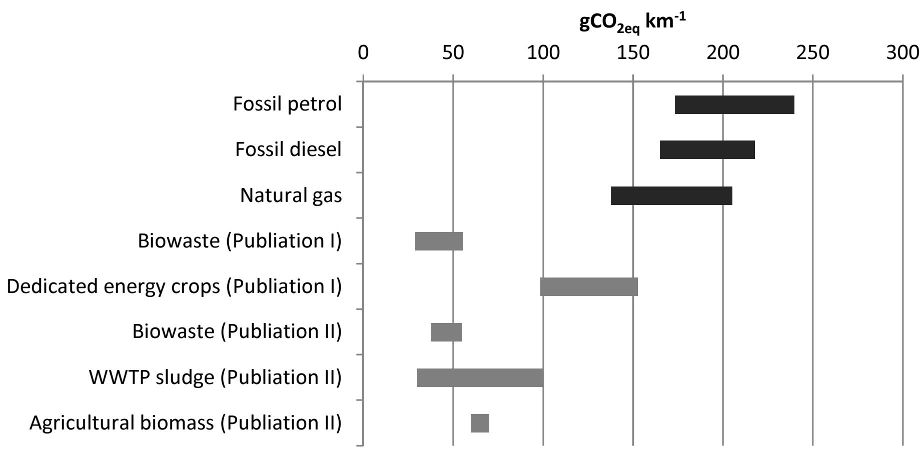

Figure 34: GHG emissions from use of transportation biomethane compared to fossil transportation fuels

As can be seen in Figure 34, the GHG emissions from transportation biomethane are lower than from the use of fossil fuels. The only exception may be if biomethane produced from dedicated energy crops replaces NG use. The variation of factors along the life cycle of biomethane (Publication I) are not included in this figure. The highest emissions for biomethane are when no allocation between digestate and biogas is carried out. The lowest values of the variation are received with allocation or substitution methods when digestate can be utilized.

4.2 GHG emissions from various biogas, landfill gas and biomethane utilization options

This section presents the results of GHG emission comparisons of various feedstock, biogas, landfill gas and biomethane utilization options.

4.2.1 Biogas and biomethane use in energy production and in transportation sector

The GHG emission change achieved by the biogas or biomethane use in the energy sector of Finland´s capital region was studied using the system expansion method. The results of the GHG emissions for different biogas and biomethane to energy options are presented in Figure 35.

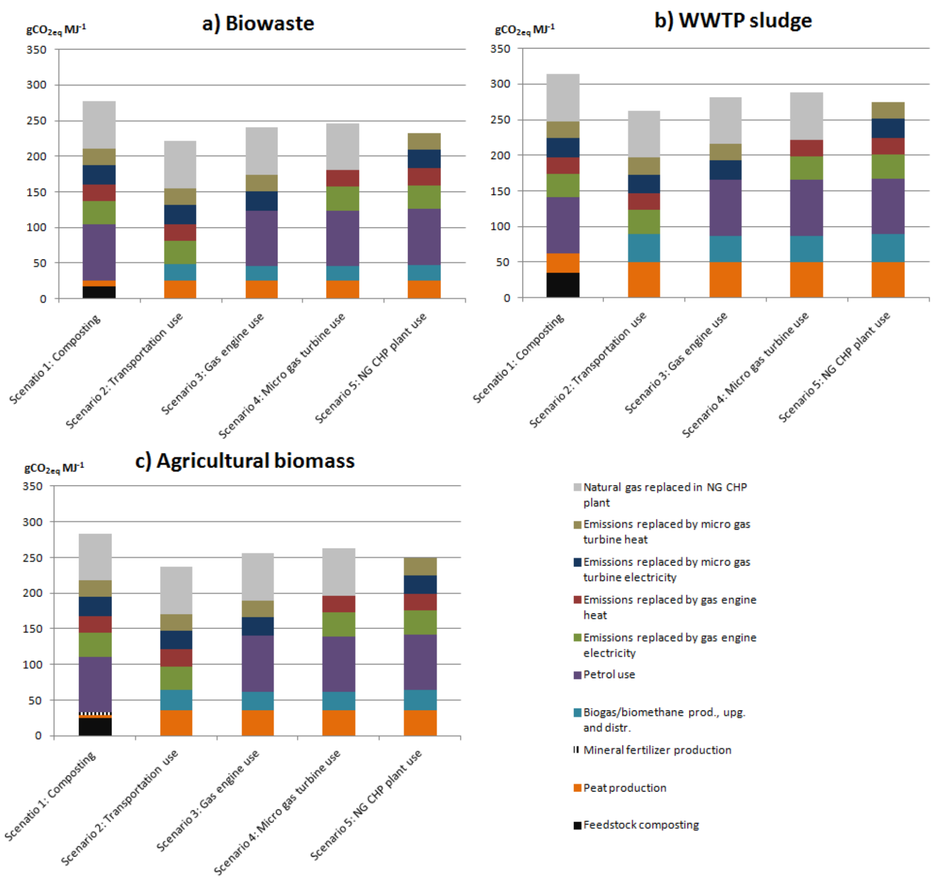

Figure 35: GHG emissions with different biogas to energy options. (Publication II)

As can be seen in Figure 35, the transportation use (Scenario 2) has the lowest overall GHG emissions. GHG emissions from Scenario 2 are 47–56 g_{CO2eq} MJ^{-1} lower than from Scenario 1 and 12–25 g_{CO2eq} MJ^{-1} lower than from Scenarios 3–5. The energy use in the electricity and heat production has also lower GHG emissions than Scenario 1 in which feedstocks are composted and energy has to be produced by alternative methods. Major differences between different energy production methods were not found, but NG CHP plant utilization replacing NG leads to little lower GHG emissions than the other options. This is however highly dependent on the fossil based emissions that are replaced by producing electricity and heat from biogas. In some cases, depending on the legislation and by using hygienization also digestate from biowaste and WWTP could be used as a fertilizer. In this case, instead of peat, mineral fertilizer production could be replaced by digestate, which would improve the GHG emissions from Scenarios 2–5 compared to Scenario 1.

Figure 36 presents the sensitivity analysis of the results. The main focus is on the energy that is replaced by biogas, such as petrol, average electricity and average heat. Changes in the emissions from composting or from biogas production should change dramatically to make Scenario 1 better than the other scenarios. Sensitivity analysis is carried out only for biowaste based biogas and for Scenarios 1–3, as Scenarios 4–5 are acting approximately analogous to Scenario 3. Figure 36a presents the base case. Figure 36b presents the situation when electricity produced by gas engine is replacing marginal electricity. Figure 36c presents the situation when heat produced by gas engine is utilized only during three winter months. Figure 36d presents the situation when biogas is replacing NG in the transportation sector instead of petrol.

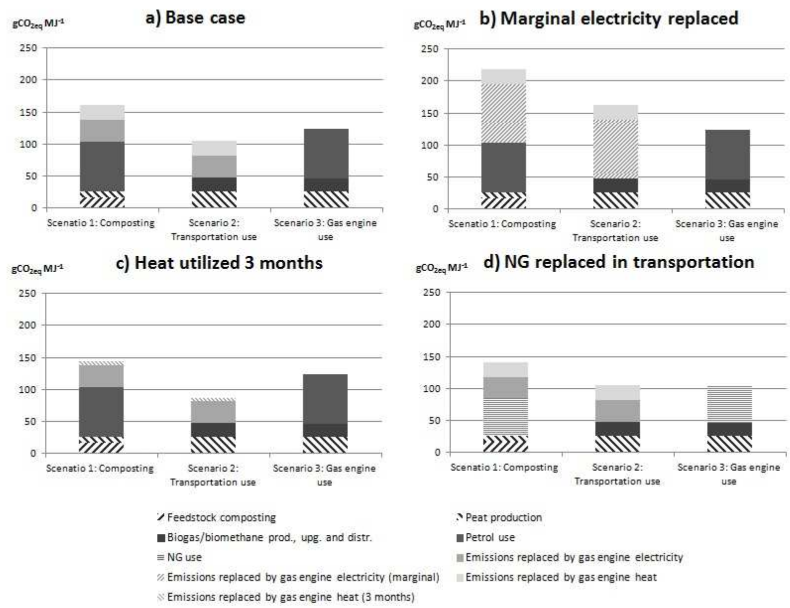

Figure 36: Sensitivity analysis for biowaste biogas plant. (Publication II)

As can be seen in Figure 36, GHG emissions are the lowest in the gas engine (Scenario 3) if marginal electricity is replaced. On the other hand, if heat from gas engine can be utilized only during three months, emissions of Scenario 1 and Scenario 2 become lower compared to Scenario 3 from the GHG perspective. If NG is replaced in the transportation sector instead of petrol, Scenario 2 and Scenario 3 have approximately the same GHG emissions. Therefore, it is important to know the realistic heat utilization rate and what electricity is replaced in a system. NG may be replaced in the transportation sector if the majority of the gas-operated vehicles are using NG and the vehicle amounts are not increasing with the increased biogas production.

4.2.2 GHG emissions from landfill gas utilization options

In addition to biogas produced by anaerobic digestion in Publication V, three different options to utilize landfill gas (LFG) were studied. In Scenario 1, LFG is used in CHP production to produce electricity and heat in a gas engine. In Scenario 2, LFG is used in asphalt production during summer time and in districts heat production during winter time. In Scenario 3, LFG is upgraded to biomethane and then used for CHP production in a NG CHP plant. In the reference situation LFG is flared without utilization.

As can be seen in Figure 37, the highest GHG reduction can be gained when LFG is used for electricity and heat production to replace marginal electricity and local district heat production by NG. The second highest GHG emission reductions are gained through LFG upgrading to biomethane and CHP production. According to the results, improving the quality of LFG by the upgrading process leads to additional GHG emissions due to the electricity consumption in the upgrading process. Gas utilization in asphalt and heat production leads to lower GHG emission reductions than the other scenarios. This is mainly due to lower replaced GHG emissions from heat production than from electricity production. However, using various heat consumption options during the year can improve the GHG performance compared to a situation in which only a single option, such as district heating, is used.

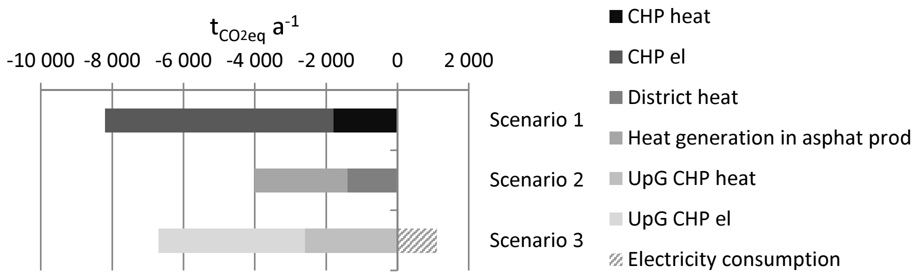

Figure 37: Estimated magnitudes for GHG emissions and emission savings caused by collected gas management on Scenarios 1, 2 and 3. (Publication V)

The results are in line with the results in Publication II, where biogas use in electricity production led to higher GHG savings than transportation use when was marginal electricity was replaced.

4.2.3 Differences between GHG emission reductions of biogas in transportation use versus electricity produced from biogas use in electric vehicles.

In Publication III, GHG emissions from biomethane use in gas-operated vehicles were compared to electricity produced from biogas or biomethane and use in electric vehicles by using the system expansion method. Table 27 presents the energy amounts produced in various scenarios, and Figure 38 presents the GHG emissions from the scenarios compared to the base case (reference situation).

Table 27: Produced energy amounts in different scenarios

	Scenario 1: Gas engines	Scenario 2: Biomethane use in transportation	Scenario 3: NG CHP plant
Biomethane to transportation [MWh a^{-1}]		24 000	
Electricity to transportation [MWh a^{-1}]	9 300		11 400
Heat [MWh a^{-1}]	2 400		10 500

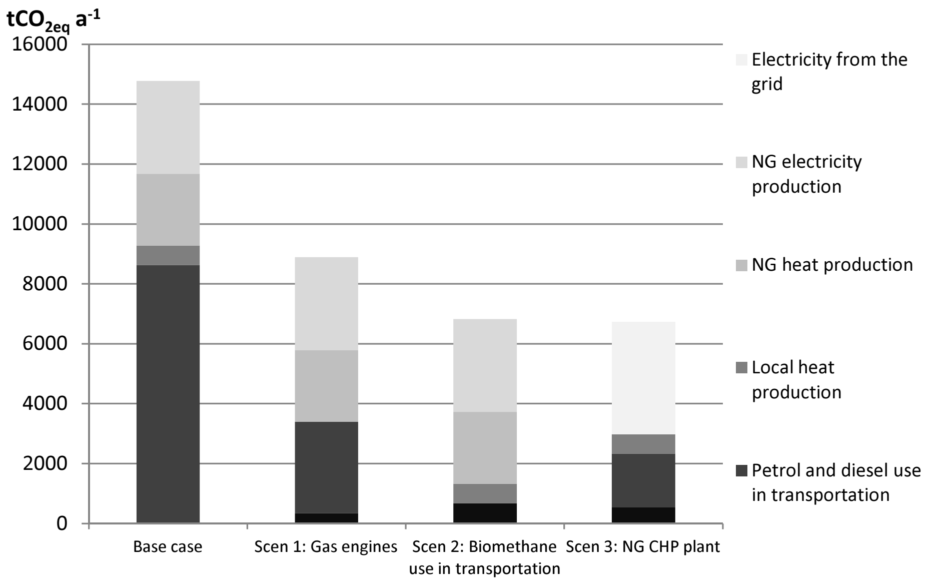

Figure 38: GHG emission reduction when biogas is used in gas-operated vehicles compared to biogas based electricity use in electric vehicles. (Publication III)

As can be seen in Figure 38, GHG reductions are at the same level when biomethane is used in gas-operated vehicles or when electricity is produced from biogas in an efficient NG CHP-plant and electricity is used in electric vehicles and heat in district heating. From the GHG emission point of view, reductions are the lowest when biogas is used in gas engines with lower electric efficiency and low heat utilization rate. However, if the efficiencies for electric vehicles are improving, the GHG reduction for CHP-plant use and electric vehicle use would lead to higher GHG reductions than gas-operated vehicle use because then they are able to replace higher amounts of fossil petrol and diesel. In addition, if heat can be utilized throughout the year, gas-engine options would lead to higher GHG emission reductions than shown in the figure.

4.3 Limiting factors in biomethane use in the transportation sector

4.3.1 Biomethane potential in Finland

Using the assumptions defined in the chapter Materials, methods and case description, the theoretical biomethane potential for Finland was calculated. The potential was divided between different regions based on different feedstocks. The results are presented in Figure 39.

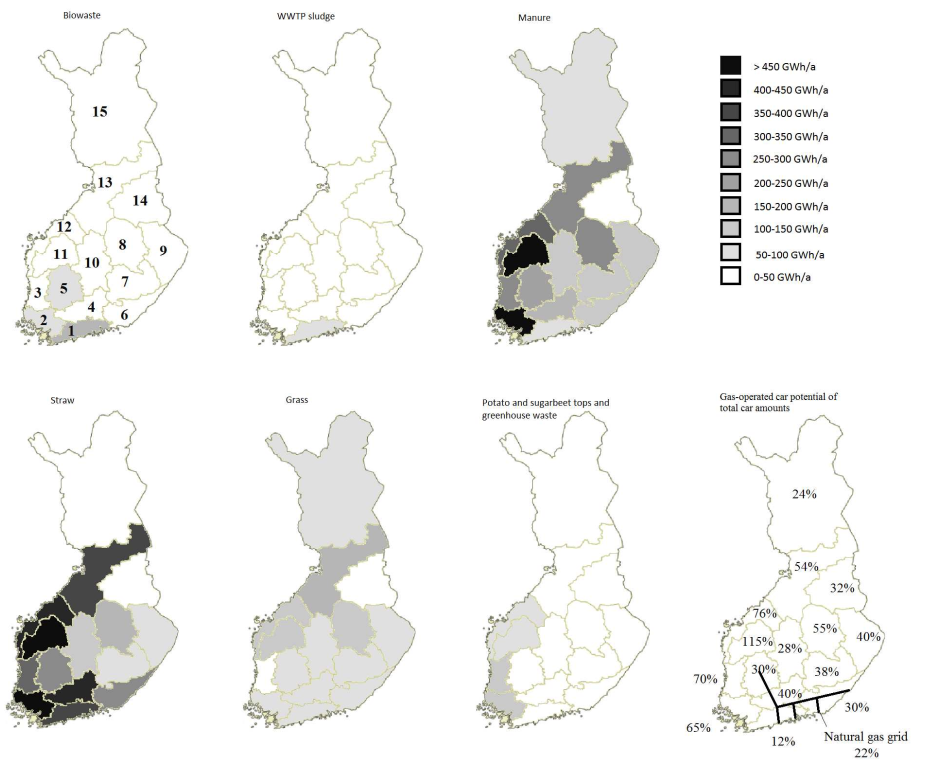

Figure 39: Geographical distribution of biogas potentials from different feedstocks. The first map presents the numbers of each studied region. The last map presents the NG grid location and maximum share of passenger cars that could be fuelled by biomethane in each region. (Publication IV)

As can be seen in Figure 39, the biogas potentials vary a lot between different regions. The highest overall potential is with agricultural biomasses, especially with manure and straw. Biowaste and WWTP sludge have a high importance only in regions with the highest population because they are directly bound on human activities. According to these calculations, the maximum theoretical biomethane potential for Finland is approximately 10 TWh a^{-1}. The highest biomethane potential is located in Western and Southern Finland, where the majority of the population lives and where agriculture is most intensive. In areas with a lot of agriculture, a high share of passenger cars could use biomethane as fuel. In the Uusimaa region, the share is the lowest due to the high number of cars and relatively little agriculture. In the NG grid area, biomethane production and consumption can be studied from a wider perspective because all the biomethane produced in this area can be used along the NG grid. As a result, 22% of the passenger cars in this area could be fuelled by biomethane. This will enable higher biomethane utilization also in the Uusimaa region. In other regions, due to the lack of NG grid, biomethane distribution should be done by local pipelines or by truck transportations.

In theory, Finland could achieve 41% self-sufficiency in passenger car fuels by utilizing the total theoretical biomethane potential. Finland consumes approximately 45 TWh NG annually. By utilizing Finland´s biomethane potential, 22% of the imported NG could be replaced. The results presented previously in this thesis were for a situation where the electricity and heat consumption of biogas production and upgrading are produced by additional energy sources, such as wood chips. It may, however, be likely that biogas plants will be using 50% of the produced biogas for the plant’s own electricity and heat production and only 50% of gas could be distributed to other uses. (Publication III) This would decrease the shares in the previous results by approximately 50%.

4.3.2 Technological limiting factors

There are some countries where gas is the main fuel for the transportation section. For example Germany, Italy and Sweden are examples of countries in Europe where there are a lot of gas-operated vehicles. In this section, technological limiting factors, mainly related to distribution infrastructure and gas-vehicle technology, were studied.

According to EIA (2012A), the absence of a widespread public refuelling infrastructure may impose a serious constrain on NG vehicle purchases. As a key ratio, gas-operated vehicles per a refuelling station were calculated. In Finland, this ratio is approximately 55 gas-operated vehicles per one refuelling station. This is much less than for example the 110 gas-operated vehicles per a refuelling station in Germany, 250 gas-operated vehicles per a refuelling station in Sweden and 990 gas-operated vehicles per a refuelling station in Italy. In Finland, the gas refuelling station network seems to be relatively well developed compared to gas-operated vehicle amounts, but it covers mainly Southern Finland. Therefore, the distribution networks limit the growth in Northern, Western and Eastern Finland, but provide a possibility for growth in Southern Finland. According to EIA (2012A), the worldwide average is 672 vehicles per a refuelling station, and 600–1000 vehicles per a refuelling station is an economically suitable ratio for public refuelling stations. Finland and also many other European countries are way behind this ratio.

Gas-operated cars have been proven to be working technology as they have been used in several countries during several years (EIA, 2012A; U.S. Department of Energy, 2013B; IEA, 2010; NGV global, 2010). According to EIA (2012A), NG can be used as efficiently as diesel in heavy-duty vehicle applications with the current technology. According to the U.S. Department of Energy (2013B), gas-operated vehicles are good choices for high-mileage, centrally fuelled fleets that operate within a limited area.

According to IEA (2010), the vehicle and fuel technology are already available and relatively affordable, particularly in comparison with other alternative fuel vehicles. In addition, gas can cover almost the whole spectrum of different vehicle types. One technical issue, which might be a problem with gas-operated vehicles, is the shorter range by gas. Comparing the ranges of different gas-operated passenger cars it seems that the range with gas is approximately 300–500 km, while in bivalent cars, the range with additional petrol is 150–700 km (Gibgas, 2013). The total range seems to be a little shorter than with traditional petrol or diesel cars. This is mainly due to the larger space need for gas tanks. The gas tanks may also reduce the space in the boot of a car. This has in some car models led to the decision that there is no spare tire in a car.

4.3.3 Economical limiting factors

4.3.3.1 Operators on biomethane chain

For feedstock producers, an important question is whether they should pay gate-fees for the biogas plant instead of alternative utilization options of feedstock. For waste companies and WWTPs, it seems that the gate-fees are lower than the costs of biowaste or sludge utilization as feedstock for compost plants or for own digestion plants. Therefore, biogas production seems to be a competitive utilization option compared to other options. On the other hand, for agricultural producers, there are cheaper options for manure, silage and green waste utilization. Therefore, it might be hard to get agricultural biomasses for biogas plants. In addition, transportations of feedstock cause additional costs, but they are excluded from this study.

Figure 40 presents the payback time of biogas plant investments for biogas producer. The incomes of the biogas plant depend heavily on the feedstock type and gate-fees.

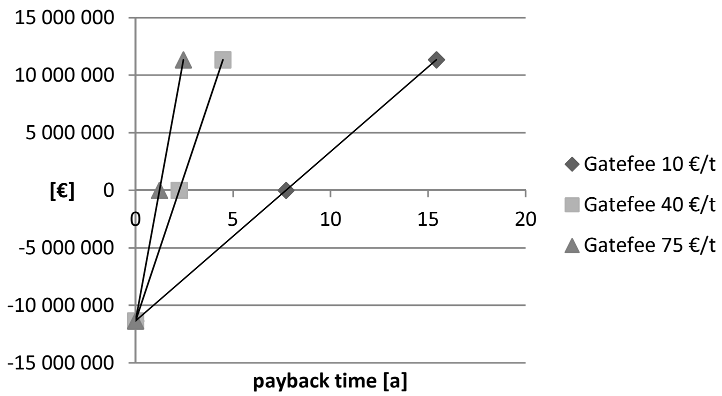

Figure 40: Profitability for biomethane producers. Y-axis presents the investments and x-axis the payback time. (Publication IV)

As presented in Figure 40, the payback times are relatively short, and operations seem to be profitable for biomethane producers if gate-fees are paid for the feedstock. The gate-fee amounts are key factors in the total profitability. On the other hand, without gate-fees or with low gate-fees, the payback times become much longer, and operations do not seem to be as profitable anymore. If the biogas producer has to pay for the feedstock such as grass, the incomes become lower than the expenses, and the operation becomes unprofitable. This limits highly the utilization of cultivated biomasses. Biomethane price does not have a significant effect on the results as the majority of the incomes becomes from gate-fees. For example, if the gate-fee is 40 € t^{-1}, approximately 80% of the biogas plant incomes come from gate-fees. In this study, the incomes from biomethane selling were estimated to be at a comparable level to the feed-in tariff incomes. Figure 41 presents the biogas production potential calculated for Finland and approximate relative costs for biogas produced from different feedstocks. As can be seen in the figure, landfill gas offers the cheapest gas source because the collection pipelines are usually already installed and landfill gas is formed naturally in landfills without energy inputs. WWTP sludge and biowaste are the second cheapest feedstock as the biogas plant gets gate-fees from them. Manure and agricultural wastes have usually traditional utilization options, such as composting, but they could be directed to a biogas plant by offering the collection and transportation. Grass and straw are the most expensive feedstock options. Biogas producer has to pay for grass utilization, and straw is also relatively expensive because it has to be collected and transported from the fields. Grass potential is relatively low in this study because it was assumed to be produced only on set-aside fields and in other fields that are maintained but used in cultivation.

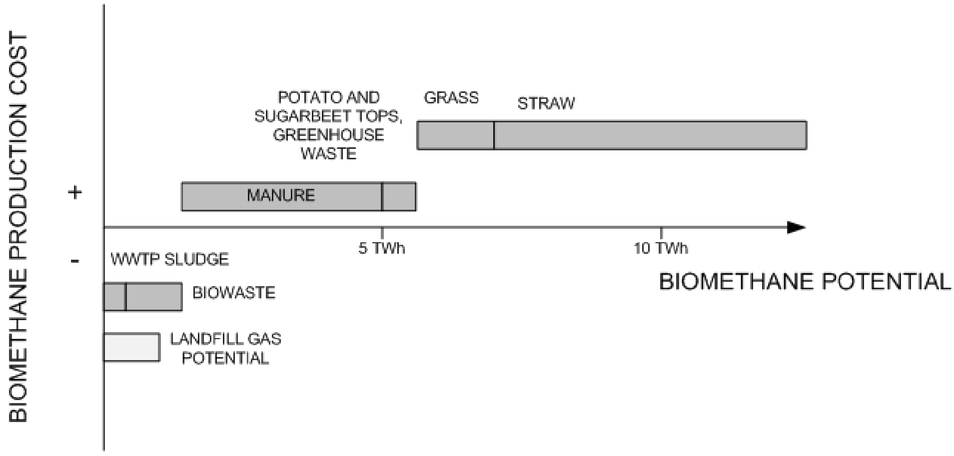

Figure 41: Biomethane production potential and cost comparison of biomethane from various feedstocks (Idea for the figure from Berglund (2006) and Lantz (2007)).

For distributors the payback times are also quite low (Figure 42) due to biogas and biomethane prices. If long distribution pipelines have to be built, investments may increase rapidly and payback times become longer. Using the already existing NG grids or wheel transportations as CBG or LBG seems to lead to shorter payback times than the building of new pipelines and grids. Small changes in biomethane prices for consumers do not have significant effects on payback times.

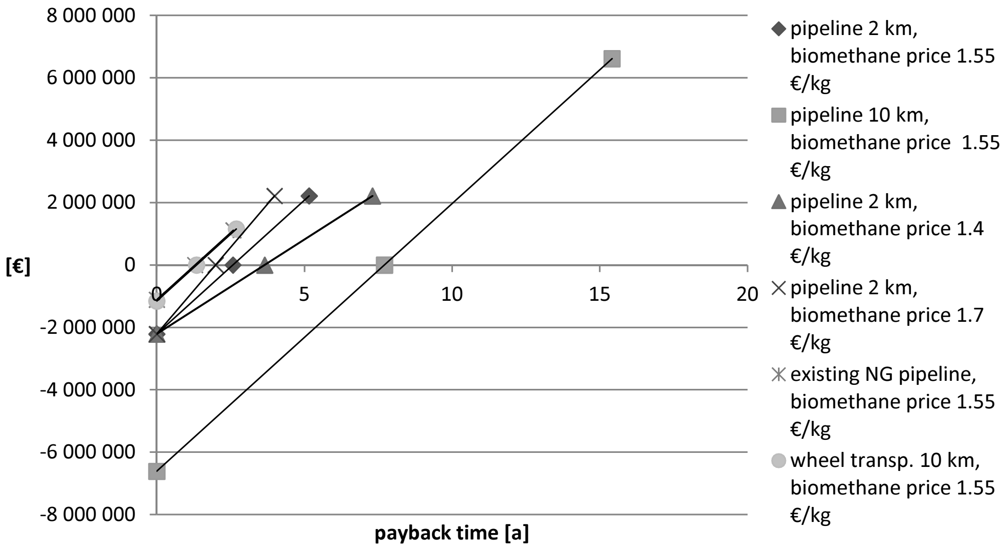

Figure 42: Profitability for biomethane distributors. Y-axis presents the investments and x-axis the payback time. (Publication IV)

The fourth step in the life cycle of biomethane is the biomethane consumers. Ultimately, it is the vehicle owners who make the decisions whether they invest on gas-operated cars. They have to decide whether to buy a more expensive gas-operated car or more expensive petrol fuel for petrol cars. Figure 43 presents the expenses of petrol cars compared to gas-operated cars as a function of the driving distance.

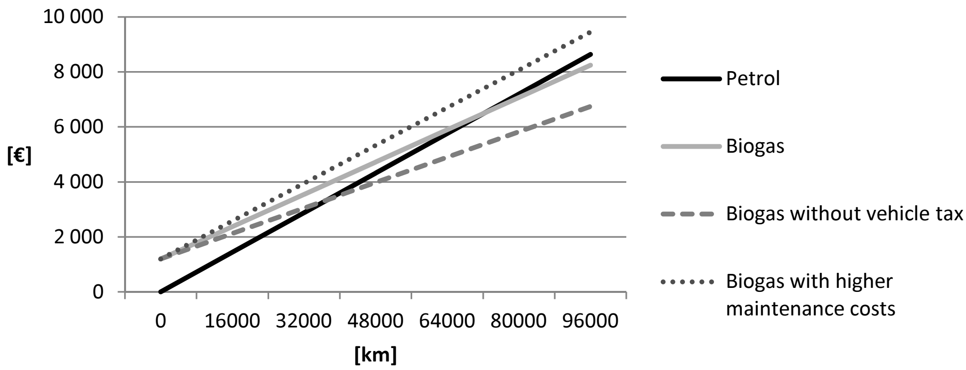

Figure 43: Profitability for biomethane consumers. (Publication IV)

As can be seen in Figure 43, the using of gas-operated vehicles becomes cheaper after four years' driving in the base comparison. However, if there were no vehicle tax on driving power for gas-operated vehicles, it would become an even more feasible option compared to petrol cars. On the other hand, if the maintenance costs are higher for gas-operated vehicles, the total costs are on the same level as with petrol cars.

4.3.3.2 Feed-in tariff

In addition to studying biomethane chain economy from various operators' perspective, an economic analysis related to the effects of feed-in tariff was carried out in Publication III. The feed-in tariff gives a guaranteed price for electricity produced by biogas or biomethane. The feed-in tariff is not paid for transportation biomethane, and therefore, there is a risk that the feed-in tariff hinders the use of biomethane in the transportation sector. This research was carried out from the NG grid owner's perspective by calculating payback times for various biogas and biomethane utilization scenarios. The results without (a) and with (b) the feed-in tariff for electricity produced from biogas are presented in Figure 44.

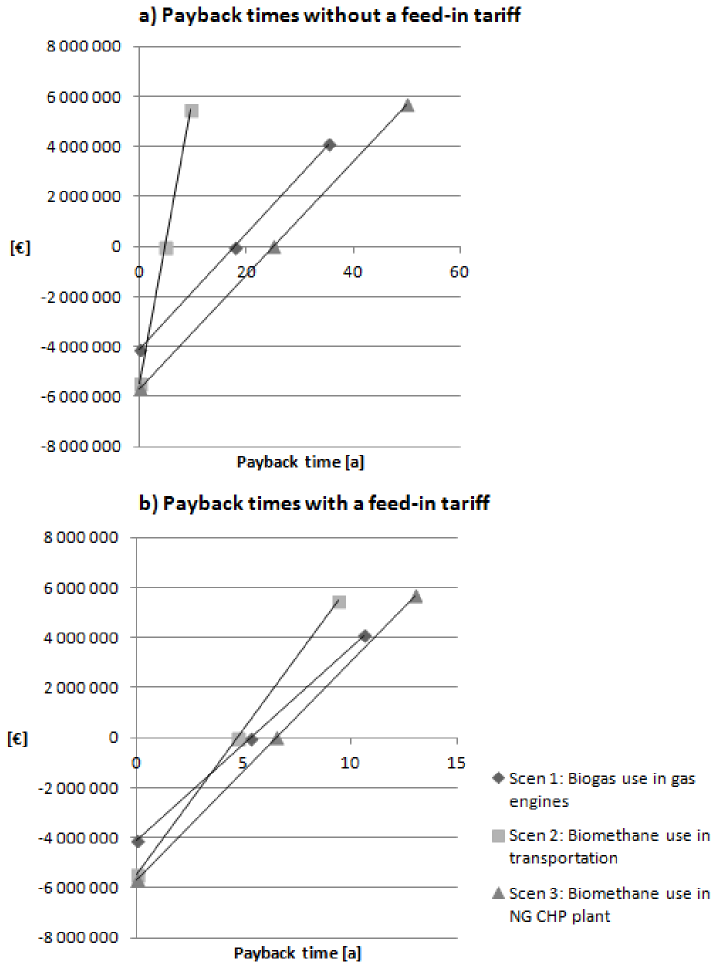

Figure 44: Economics of biogas use in gas-operated vehicles or biogas based electricity use in electric cars. (Publication III)

The results show that selling biomethane for transportation purposes leads to highest incomes and shortest payback times for investments. Investments for electric production in a high efficiency CHP plant were at the same level, but in the gas engine option, investments were much lower. On the other hand, incomes from electricity and heat selling were lower than from biomethane selling to transportation purposes. This is mainly due to the low price of heat and high price of biomethane in the transportation use. Therefore, the payback times for electricity and heat production investments are longer. According to the results, when the feed-in tariff is not put into action, biomethane use as a transportation fuel is economically the most tempting alternative.

According to the results, the feed-in tariff is subsidizing electricity and heat production from biogas and biomethane heavily. This makes the transportation fuel and electricity and heat production option payback times closer to each other. As can be seen in Figure 44b, the payback times of different options have come together. In this figure, also the heat premium is paid for the electricity because the total efficiency of energy production is over 50%. On the other hand, if investment aid would be paid for biomethane use in the transportation sector, the investment would decrease, which would also shorten the payback time.

4.3.4 Potential for reduced external costs to overcome limiting factors

Countries, different areas or communities may reduce external costs if they use biomethane instead of fossil based fuels. These external costs are mainly related to health, environmental or energy dependency problems associated to the utilization of different fuels. By comparing the annual external costs of biomethane, operated car and petrol car possible reductions can be calculated. A comparison of the annual external costs for passenger petrol and biomethane cars is presented in Figure 45.

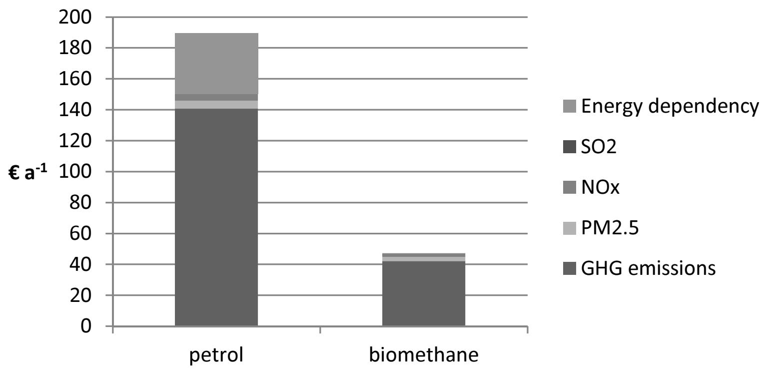

Figure 45: External costs of a petrol and biomethane car. (Publication IV)

As can be seen in Figure 45, the external costs of a petrol car are higher than those of a biomethane car, and the difference in the annual external costs is approximately 140 €. The main external cost sources are related to the GHG emissions and energy dependency. The importance of the external costs from air pollutants was not as high.

5 Discussion

In the Discussion chapter, the research questions presented in the Introduction chapter are answered in the Synthesis section. The research questions are:

- How to maximize the benefits from the climate change point of view when biomethane is utilized for transportation purposes?
- What kind of further instruction can be given for calculation methodologies if applied for different use purposes of biomethane from the climate change point of view?
- What are the factors which are limiting the utilization of biomethane in the transportation sector from the economic perspective and how could these barriers be overcome?

After the Synthesis section, the limitations of the dissertation, effects on the practice, future research topics and the value of the research are discussed in separate sections.

5.1 Synthesis

5.1.1 Maximizing the benefits from the climate change point of view when biomethane is utilized for transportation purposes?

The acceptability of biomethane use as a transportation fuel can be evaluated by comparing the GHG emissions from the biomethane production and use to those of fossil transportation fuels. GHG emissions from fossil petrol and diesel vary from 69 to 95 gCO_{2eq} MJ^{-1}, which can be regarded as an acceptability level. Figure 46 compares the GHG emissions from biomethane production and use in this thesis to other previous studies and to some reference values. As can be seen in the figure, the GHG emissions from biomethane production and use are below the GHG emissions from fossil petrol and diesel in all studied cases. Therefore, biomethane production can be regarded acceptable. However, if compared to NG, GHG reductions are not always obvious.

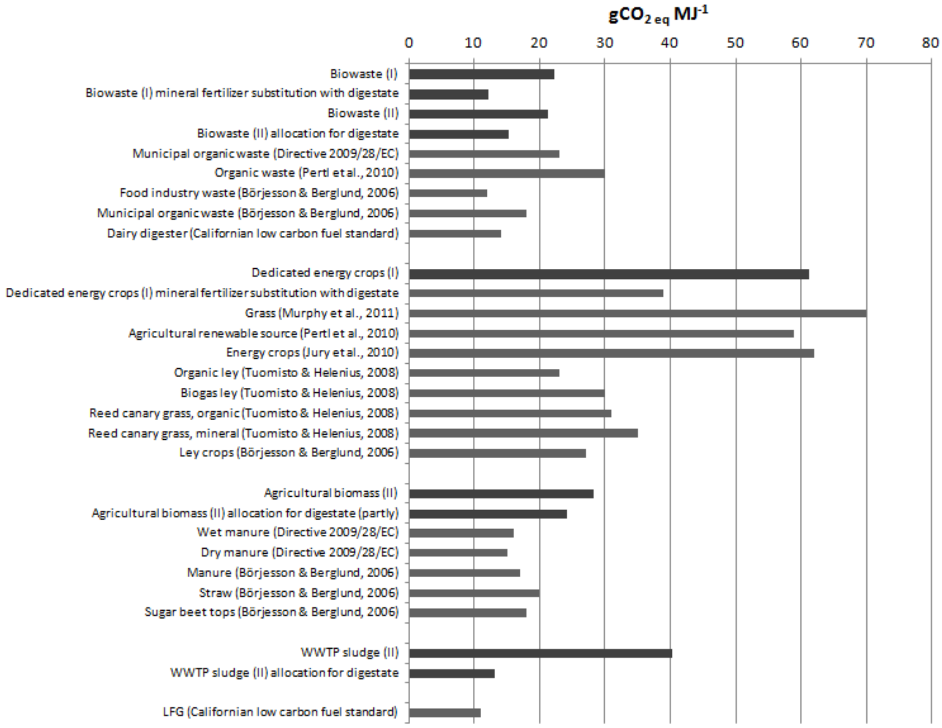

Figure 46: GHG emissions from biomethane production and use calculated in this dissertation compared to previous studies and reference values. Darker bars present the values calculated in this dissertation.

As can be seen in the figure, the results of this thesis are mainly at the same level with the previous studies. However, there are also some small differences. GHG emissions from agricultural biomass are higher than in the previous studies because in this case, cultivated grass was added with other agricultural biomass to the process. The previous studies related to that category concentrated on agricultural "waste" feedstock (manure, straw and sugar beet tops). GHG emissions from WWTP sludge biomethane have not been widely studied previously.

In addition to acceptability calculations various other comparisons were carried out using wider perspective system expansion methods. If waste treatment (composting) is replaced by biowaste digestion, the additional GHG emission saving would be approximately 28 gCO_{2eq} MJ^{-1}. This is an important additional motivator for using biowaste in digestion from the GHG emission perspective. The GHG emission reduction compared to compost processes depend on compost emissions, which were regarded as relatively low in this study.

The advantages of biomethane use in the transportation sector are complicated by the fact that biogas, landfill gas or biomethane can also be used in energy production. According to the results, the energy production options also leads to GHG emission reductions compared to compost processes. The question whether transportation use or energy production leads to higher GHG emission reductions is complicated and depends on the situation and especially on replaced energy production systems. Therefore, comparisons related to actual cases are always needed.

In this dissertation, an additional GHG emission comparison was carried out where the produced electricity was used in electric vehicles replacing fossil transportation fuel. This option was compared to direct biomethane use in the transportation sector. Based on the results, biomethane use in the transportation sector leads to as high GHG emission reductions as electricity produced from biomethane in a NG CHP plant and use in electric vehicles. Electricity produced from biogas in gas engines for electric vehicles led to a little lower GHG emission reduction potential. If the efficiencies of electric vehicles improve compared to gas-operated vehicles, there might be potential to achieve higher GHG emission reductions from electric vehicle utilization.

As a conclusion, the transportation use and energy production by biogas, landfill gas and biomethane usually leads to GHG emission reductions, which was also previously concluded by Börjesson & Berglund (2007), but the best option depends on the replaced or alternative energy systems. Only relatively small advantages can be achieved when the already existing biogas energy production is changed to transportation purposes. A huge challenge is however to recognize what actually are the replaced energy systems, for example, if electricity is produced from biogas, which energy production methods are replaced. However, from the GHG reduction point of view, the transportation use should be favoured for new biogas plants in most cases because they are likely to lead to lower overall GHG emissions by replacing fossil transportation fuels.

There are usually more options to produce renewable energy locally (e.g. solar and wind, biomass) than transportation fuels. This is one motivator why biomethane should primarily be used in the transportation sector. In addition, biomethane is ranked high in the transportation energy hierarchy because it can be used also in heavier vehicles, which is not possible with several other renewable transportation energy systems. For example, heavy vehicles cannot use electricity as a main energy source, and therefore, biomethane would be a potential biofuel for heavy vehicles even if passenger cars started to use electricity in expanding amounts.

5.1.1.1 The significance of various life cycle steps in GHG emissions of transportation biomethane?

The transportation biomethane GHG emissions vary depending on the feedstock selected for biogas production. In both studied cases, the GHG emissions from biowaste-based biomethane were approximately 22 gCO_{2eq} MJ^{-1} without the allocation for digestate. The other feedstocks were studied only once either in Publication I or II. The GHG emissions from dedicated energy crop (timothy and clover) based biomethane were approximately 61 gCO_{2eq} MJ^{-1} without allocation for digestate. Similarly, the GHG emissions for agricultural biomass based biomethane were approximately 28 gCO_{2eq} MJ^{-1} and for WWTP sludge based biomethane 40 gCO_{2eq} MJ^{-1}. This shows relatively high variation in the results based on the feedstock selected. Dedicated energy crops based biomethane, which in this case is timothy and clover, has the highest emissions and waste materials have lower emission levels. Agricultural biomass based biomethane led to relatively low GHG emissions because it consists mainly of waste materials such as manure and other agricultural side flows, and to a smaller extent of grass.

There are various factors along the life cycle of biomethane that may have effects on the overall GHG emissions from biomethane production and use. In this dissertation, the GHG emissions were divided between different life-cycle steps of biomethane and the key factors were recognized. These factors were varied especially in Publication I. For dedicated energy crops based biomethane, the main GHG emission source is the cultivation process of the feedstock. The total GHG emissions from this phase are approximately 33 gCO_{2eq} MJ^{-1}, which is half the total of GHG emissions. Approximately 50% of cultivation emissions are related to fertilizer production and the other 50% are related to N_2O emission from soil and on agricultural machinery use in cultivation and collection. This confirms the results of previous studies that are presenting cultivation emissions from 7 to 37 gCO_{2eq} MJ^{-1} (Tuomisto & Helenius, 2008; Jury et al., 2010; Pertl et al., 2010; Börjesson & Berglund, 2006). According to Tuomisto & Helenius (2008), N_2O emissions are the most important emission source from the cultivation process. They reached a lower cultivation GHG emission because they replaced a part of the fertilizer input by digestate within the system boundaries. Hartmann (2006) concluded that using energy plants with a high productivity per area unit, for instance maize, have lower climate impacts than crops like grass. The lower emissions can be achieved if, for example, recycled fertilizers are used instead of mineral fertilizers, the fertilizer use is low and N_2O emissions are at a low level. However, if the cultivation is carried out on poor land where feedstock productivity is low and fertilizer-use more intensive than the average, the GHG emissions from cultivation alone can be almost 80 gCO_{2eq} MJ^{-1}. On the other hand this is probably not very likely. If dedicated energy crops cultivation leads to land use change, it may result in roughly 80 gCO_{2eq} MJ^{-1} additional emissions if boreal forest is turned to fields. This is also not very likely because cultivation usually takes place in already existing fields and as a part of crop rotation. Emissions from LUC have been often excluded from previous studies. However, LUC may be a highly important factor in increasing GHG emissions if new fields are established for feedstock production, and therefore, it should be included in the studies.

For all the other studied feedstocks, digestate utilization is the most important emission source, and for dedicated energy crops, it is the second most important emission source. However, the use of digestate in replacing mineral fertilizers may lead to additional GHG emission reductions. For biowaste and dedicated energy crops, digestate spreading on fields was studied, and it led to 7 gCO_{2eq} MJ^{-1} and 16 gCO_{2eq} MJ^{-1} emissions. In this case, the emissions were mainly caused by N_2O resulting from nitrogen in the digestate. The GHG emissions for dedicated energy crops were higher due to the higher nitrogen content in the digestate. Agricultural machinery use in spreading had only a small impact on the total emissions. In Publication II, the digestate from biowaste and WWTP sludge were treated by composting, which led to 6 gCO_{2eq} MJ^{-1} and 19 gCO_{2eq} MJ^{-1} emissions. The digestate from agricultural biomass was assumed to be spread on the fields, which led to 15 gCO_{2eq} MJ^{-1} which is at the same level as from dedicated energy crops. Börjesson & Berglund (2006) calculated low GHG emissions for digestate transportation and spreading because they assumed short transportation distances for digestate and no N_2O emissions. The highest emissions for digestate was calculated in Publication I for biowaste and digestate with the combination of composting process and compost spreading to fields. This process was assumed to lead to N_2O emissions from both stages. These maximum emissions were 26 gCO_{2eq} MJ^{-1} for biowaste based biomethane and 52 gCO_{2eq} MJ^{-1} for dedicated energy crops based biomethane. There is a high variety of different compost processes, and in addition, the nitrogen conversion rate to N_2O is not well known. Therefore, the emissions related to digestate use may impose significant uncertainties.

Feedstock collection and transportation emissions were approximately 2 gCO_{2eq} MJ^{-1}. The exceptions were WWTP sludge, which was produced close to digester, and emissions from the transportation of sludge were estimated to be 0 gCO_{2eq} MJ^{-1}. The highest collection and transportation emissions were calculated for biowaste in the Helsinki region. The emissions were 6 gCO_{2eq} MJ^{-1}. This is much higher than the 2 gCO_{2eq} MJ^{-1} calculated with the average transportation distances in Finland. The difference is caused by the facts that there is no digester close to Helsinki, and the collection has to be mainly carried out as urban drive with several stops, which increases the fuel consumption. In sparsely populated areas, the distance for the collection of biowaste may increase, which subsequently increases emissions. On the other hand, with well-planned collection of biowaste, emissions may decrease.

GHG emissions from pre-treatment, digestion, upgrading and distribution are mainly related to energy consumption and to methane leakages. Technologically speaking, the utilization of old technology or of technology with a high rate of energy consumption or a high level of methane leakages may greatly increase the emissions from the production phase. These factors are varying on a large scale depending on the utilized technology. In addition, the energy production method for utilized electricity and heat has importance. GHG emissions from pre-treatment and digestion process varied from 6 to 8 gCO_{2eq} MJ^{-1} for biowaste, dedicated energy crops and agricultural biomass. WWTP sludge digestion led to significantly higher (17 gCO_{2eq} MJ^{-1}) emissions due to lower water recycling rate and therefore higher heat consumption. These values were calculated with the average electricity and heat production and by estimating that methane leakages can be avoided. With a 5% methane leakage, which was presented in the literature, an additional 23 gCO_{2eq} MJ^{-1} emission would result from the digestion process. According to previous studies, digestion emissions vary from 3 to 29 gCO_{2eq} MJ^{-1} and these results were confirmed, and the lowest emissions can be reached if methane leakages are low and average or renewable energy is utilized. (Pertl et al., 2010; Tuomito & Helenius, 2008; Börjesson & Berglund, 2006; Murphy et al., 2011). The highest digestion emissions were calculated by Murphy et al. (2011) with high methane leakages. The use of quality feedstock yielding high methane productivity will further reduce GHG emissions. Feedstock quality impacts digestate quality, digestion energy consumption and feedstock transportation. Small variations in the quality do not significantly impact the total emissions, but high variations in the quality may do so.

Emissions from upgrading and distribution were not affected by feedstock selected. Amine wash (AW) technology was used in base calculations and it led to 2.0–3.5 gCO_{2eq} MJ^{-1} emissions. The contribution of heat and electricity utilization was approximately the same (1–1.5 gCO_{2eq} MJ^{-1}), and the contribution of methane leakage was roughly 0.5 gCO_{2eq} MJ^{-1}. Much stronger effect was with the technology selected. The highest emission was calculated for PSA with high 4% methane leakages (22 gCO_{2eq} MJ^{-1}). For WS with a 1.5 % methane leakage but relatively high electricity consumption, the emissions were 11 gCO_{2eq} MJ^{-1}. The AW technology clearly leads to the lowest emissions with the assumption made in this dissertation. However, it has to be acknowledged that the source data related to AW is from a manufacturer, and therefore, its accuracy may be limited. Based on the previous studies, upgrading emissions vary from 3 to 39 gCO_{2eq} MJ^{-1} (Jury et al., 2010; Pertl et al., 2010; Murphy et al., 2011; Tuomisto & Helenius, 2008; Börjesson & Berglund, 2006). The highest GHG emissions were calculated by Pertl et al. (2010) for MB technology with high methane leakages (6%). However, as was presented in section 2.1.4, the upgrading technologies are developing, and for example methane leakages can be relatively well eliminated from different technologies. Therefore, GHG emissions from the upgrading process are not necessarily technology dependent but more related to energy consumption and methane leakages in each case.

In this dissertation, the main distribution option was the NG grid distribution. In Publication I, also CNG distribution by trucks was studied. GHG emissions from NG distribution and refuelling were approximately 2.5 gCO_{2eq} MJ^{-1}. Using CNG truck transportation leads to higher GHG emissions than NG grid distribution. Natural gas grid distribution is thus promising in regard to GHG emissions reductions. This is highly dependent on the transportation distance. For refuelling stations not located along gas grids, additional emissions are caused by the distribution of back-up gas. Little focus has been directed toward distribution systems in previous studies. In most cases, emissions from distribution are low despite the fact that electricity is usually consumed to pressurize the gas.

The emissions from biomethane use in the transportation sector varied from 0.3 to 1.5 gCO_{2eq} MJ^{-1}. The highest emissions from the use were calculated in bus use and the lowest emissions in passenger car use. The difference is that in bus use, the methane and N_2O emissions are slightly higher. Low use phase GHG emissions were also calculated by Pertl et al. (2010).

As a conclusion for cultivated biomass, the cultivation process and in some cases LUC has the highest GHG emissions from the life cycle of biomethane. For other feedstocks digestate handling and use and N_2O emissions have the most important role. The actual processing (pre-treatment, digestion and upgrading) has a relatively small significance in the total emissions if methane leakages can be avoided or when electricity and heat consumption are relatively low. We also still lack information related to methane leakages throughout the biomethane production chain. Unknown methane leakages may have significant effect on the results from every process step. Berglund (2006) studied that from the GHG perspective eliminating significant methane leakages is essential. In addition, N_2O emissions from digestate use are also unsure. Therefore, more attention should be paid on methane leakages and N_2O emissions in the future.

5.1.2 Further instructions for calculation methodologies if applied for different use purposes of biomethane from the climate change point of view

The selections related to life cycle methodologies are important in gaining reliable results in addition to recognizing various factors along the life cycle of biomethane. GHG emissions from biomethane production chain can be calculated using mainly allocation methodology for co-products. These emissions can be then compared to the emissions from other transportation fuels to evaluate the acceptability of biomethane use as a transportation fuel. The method can be used to produce overall information related to advantages in using biomethane as a transportation fuel, but not in actual decision making situations. When GHG emissions from transportation biomethane production chain are calculated, the main question is related to allocation methodologies for digestate and biogas. The allocation method selection is strongly bound on digestate utilization and whether digestate can be regarded as waste or co-product. In this dissertation, four different scenarios, which were based on calculation instructions or on previous studies, were compared.

In the waste assumption method (Scenario A), GHG emissions from digestate handling and use were added to the emissions of biomethane. This method seems to be justified when digestate does not actually replace any mineral fertilizers or when it cannot be used in fertilizing or there is no other use for it. In these cases, the digestate does not have an economic value. The emissions from digestate use can occasionally be attributed to compost processes or to digestate spreading. According to the Directive 2008/98/EC, a substance (other than main product) from the process is not waste if the further use of the substance is certain. In addition it has to be able to be used directly without further processing, it is an integral part of a production process and its further use is lawful and does not lead to overall adverse environmental to human health impacts. In case of digestate, there may be certain use for it, but some additional processing such as hygienization may be needed. On the other hand, these processes are usually integrated into the biogas plant.

Scenario B, in which digestate is regarded as waste but digestate emissions are not included in biomethane emissions, is against the basic allocation rules (ISO 14040; Greenhouse Gas Protocol, 2011) and should not therefore be used. This option leads to different results from those of Scenario A, and despite the fact that it is a relatively widely used method (Jury et al., 2010; Pertl et al., 2010), the results are misleading because digestate handling and utilization emissions may have high importance in the total emissions.

Economic allocation (Scenario C) appears to be a better-justified method than energy allocation because the former takes into account the real utilization potential of the digestate in terms of its economic value. Energy allocation (Scenario C) should be employed only if the digestate is used for energy production (e.g. at an incineration plant). By using economic or energy allocation, the digestate handling and use emissions are not included in biomethane emissions, what reduces biomethane GHG emissions significantly.

Avoiding allocation by the substitution method (Scenario D) is applicable if digestate is used to replace other fertilizers and it is well known which fertilizers are replaced and what is their origin. The substitution method seems to lead to the lowest GHG emissions for biomethane. It decreases the emissions for biomethane by 10 $gCO_{2eq}\ MJ^{-1}$ and the emissions from dedicated energy crops by 22 $gCO_{2eq}\ MJ^{-1}$. Allocation methods do not lead to as low biomethane emissions because only 5–13% of GHG emissions from the common processes are allocated to the digestate. Economic allocation leads to lower GHG emissions from biomethane than energy allocation, and allocation has higher effects on dedicated energy crops biomethane than on biowaste biomethane.

Waste assumption method is justified especially when there is no use or the use is unsure for the digestate or the digestate use demands further processing. Allocation method, especially economic allocation, is justified if there are markets for digestate and it has an economic value. This is mainly the case when it is known that the digestate is used for example in fertilizing but the actual site is unknown. Energy allocation is misleading when the digestate is used in fertilizing, but if it is used in energy production, it may be justified. Digestate may be relatively moisture and may not have a positive heating value. In these cases, energy allocation cannot be used, even though digestate is combusted. The substitution method is applicable when the actual site of the digestate use is known, as well as what products or processes are replaced. This is the case when it is exactly known that the digestate is for example sold for certain farms and they are using it in fertilizing instead of mineral fertilizers.

In actual decision making situation wider perspective studies are needed to calculate actual GHG emission reductions. Biomethane use in the transportation sector can be compared to other utilization options of feedstock, biogas or biomethane. This is justified to be done by using the system expansion method and the approach is wider and concentrates not only on biomethane production chain but also to other option. These studies should be able to answer the following questions to gain enough reliable results:

1. What is the amount of GHG emissions from feedstock utilization currently?
2. What is the amount of GHG emissions from biogas production and use?
3. If feedstock use is changed, are there products or co-products that have to be produced by other methods and what is the amount of GHG emissions from these methods?
4. What is the amount of GHG emissions of energy production methods or fuels replaced by biogas?

The results of these studies are highly dependent on the replaced energy in different cases. If produced electricity replaces average electricity, the transportation option leads to the highest GHG emission reductions, but if marginal electricity is assumed to be replaced, the energy production option leads to the highest GHG emission reductions. When studying new energy production from the LCA perspective, the replaced energy is usually assumed to be produced by marginal technologies with high GHG emissions. Therefore, the GHG emission reduction potential is usually also high. On the other hand, there is marginal energy in the markets only occasionally during peak hours. If new electricity consumption or production occurs it may lead to increased production or replace marginal electricity (coal power) in the beginning (Voorspools & D´haeseleer, 2000). However, with time, the electricity production structure reacts to the changed consumption or production, and then the consumed or replaced electricity becomes more average electricity. Therefore, the marginal electricity replacement assumption is not always justified. It is, however, very difficult to predict which electricity is actually replaced. On the other hand, in the transportation sector, the majority of fuels in use are fossil fuel, regardless of hour. Therefore, it seems to be more predictable, which are the GHG emissions that are replaced by using biofuels.

Similar challenges are related to biomethane production chain and emissions from energy consumed. Using renewable electricity or renewable heat in digestion could decrease the emissions slightly. On the other hand, if digestion plant leads to increased marginal electricity production, this would lead to over 10 gCO_{2eq} MJ^{-1} higher emissions. In upgrading if AW technology was used the use of renewable electricity and heat almost eliminated the emissions from upgrading stage, but the utilization of marginal electricity and heat with high GHG emissions led to an additional 3 gCO_{2eq} MJ^{-1}. Emissions from distribution would be roughly two times higher if marginal electricity was used.

When system expansion is used in decision making, the calculations involved should always be based on real technology and specific values used in the processes. Rough assumptions may lead to incorrect results or in high variation in the results, as was concluded in this dissertation. The wrong assumptions may subsequently lead to incorrect decision making. Therefore, the initial data should be carefully tested by sensitivity analysis.

The selected calculation methodology plays a vital role in the results. Therefore, the research questions and aims of LCA conducted should be carefully decided. By following only one single calculation rule or previous research may lead to wrong results. For example, the calculation rules of Directive 2009/28/EC may be misleading if it is used in actual decision making because they force to use the allocation method A (waste assumption) even if the digestate has an economic value or is replacing mineral fertilizers. In addition, they do not instruct to use system expansion in cases in which biogas or feedstock is already in some other use. The directive is mainly developed to produce overall GHG acceptability data of biofuels and GHG reduction potential data when fossil fuels are replaced. Due to the complexity of methodological selections, the conductor of LCA should have enough knowledge about the methodologies and risks related to wrong methodological selections. In addition, legislations should not restrict the options to choose methodologies too strongly for decision making. This, however, makes it more difficult to compare the results of different cases.

5.1.3 Factors which are limiting the utilization of biomethane in the transportation sector from the economic perspective and ways to overcome these barriers

From an economic point of view, the most problematic operators are the feedstock producers, especially agricultural biomass producers. If feedstock utilization is more expensive than the biogas plant gate-fees, biogas production is an attractive option. It seems that for waste feedstock, such as biowaste, WWTP sludge and for some agricultural wastes, biogas production may be an attractive option. However, if the traditional utilization options for example of manure are cheaper, it is hard to get manure into a biogas plant. There might be some subsidies which are affecting strongly other manure utilizations, and therefore, manure is not directed to the biogas process. For straw, other utilization options such as ploughing into ground are very cost efficient.

From cultivated biomass the producers are expecting to get price instead of paying gate-fees. This limits strongly the use of dedicated energy crops in biogas production.

For a biogas producer, gate-fees should be high enough to make biogas plants feasible. According to the results, biomethane production is unfeasible if the biomethane producer has to pay for the feedstock. This may confine the utilization of cultivated feedstock very strongly. On the other hand, large scale biogas production would need feedstock from agriculture, especially dedicated energy crops. According to the results, the biomethane potential in case Finland is approximately 10 TWh a^{-1}. The majority of the potential is in agricultural biomasses, but especially in populated areas, biowaste and WWTP sludge have also importance. From technological perspective in some cases, the operation of digester could be a problem. For example straws are relatively dry material, and therefore, they have to be digested with a wetter feedstock. Manure could be a good option for co-digestion with straw. On the other hand, in some regions, the straw potential might be higher than the manure potential, which may cause problems. There are several different kinds of previous potential studies for different regions in Finland. The results between different studies vary at a relatively high level due to different assumptions. Pöyry Energy has estimated that the maximum biogas potential for Finland would be 6.6 $TWha^{-1}$, which is less than the 10 TWh a^{-1} calculated in this study (Ministry of Employment and the Economy, 2009). Even higher potentials have been estimated. For example according to Rasi et al. (2012), the theoretical biomethane potential in Southeast Finland and Southwest Finland regions was approximately 0.5 TWh a^{-1} more than the potentials studied in this dissertation. The difference is mainly due to grass biomethane potential estimations. A biomethane potential study by Kahiluoto & Kuisma (2010) estimated a similar biomethane potential for the Satakunta region, but their estimation for Southern Savonia region was a little lower. (Kahiluoto & Kuisma, 2010)

For a distributor, the investment on the distribution network seems to be a key issue. If long pipelines have to be built, the feasibilities decrease quite rapidly. Therefore, the existing gas grids seem to have an important role in the wider scale utilization of biomethane. Technological challenges can be related to distribution and gas-operated vehicle technology. In the studied case in Southern Finland, the refuelling station network could support higher biomethane utilization, but in other parts of Finland, the distribution network limits the growth of biomethane utilization. However, if the biogas production and utilization are on a high enough level, biomethane grids can be built as has been done in Sweden (IEA 2010). In these cases, the additional gas may have to be transported from the NG grid as the backup gas. Backup gas is needed to ensure the gas delivery in cases when there are problems in the biomethane production. (Torri, 2012)

For consumers or vehicle owners biomethane is a cheaper option than petrol at least when the annual driving distances are long. The feasibility of gas-operated vehicles can be improved by lower taxation, and on the other hand, there is a risk of lower feasibility if the maintenance costs are higher for gas-operated vehicles. For a consumer there might be an additional risk that the residual value of a gas-operated vehicle is lower if the biogas production decreases over time. Political decisions related to biomethane have varied for example in Finland. The taxation of gas-operated vehicles has also changed, and it has probably lifted the threshold to buy gas-operated vehicles. The gas-operated vehicle technology does not seem to put major limitations for the growth as it can be seen that in several countries gas-operated vehicles can be the main vehicle type. Maybe more research could be carried out on gas-operated vehicles in northern climate. The main technical disadvantages of gas-operated vehicles seem to be shorter range with gas and smaller space in boot due to gas tanks.

In addition to feasibility for different operators the feed-in tariff for electricity produced by biogas has effects on the big picture. It is highly likely that the feed-in tariff increases biogas production and use in electricity and heat production. If the feed-in tariff increases the electricity and heat production and heat cannot be utilized, the total GHG emission savings may be lower than with the transportation use. According to the results, biogas use is highly dependent on current policies and subsidies. However, there is a risk that the subsidies are not directing biogas use into the most potential direction. In addition to electricity and heat production, biogas use as a transportation fuel should also be subsidized equally.

Based on this result, the government and communities could subsidize biomethane utilization by approximately 140 € annually per each gas-operated car because of the reduced external costs. This could be directed for example to biomethane car prices and taxation or for subsidizing biomass producers to direct their feedstock for biomethane production instead of alternative utilization options. As was seen in the economical results section, the support based on political decisions would be needed in some parts of biomethane production and utilization chain. There are however huge uncertainties related to external costs and their evaluation.

By using biomethane as a transportation fuel Finland could, in theory reach the EU's biofuel targets. Meeting the targets would demand long term development in gas utilization in the transportation sector. Italy had the fastest growth in gas-operated vehicles in 2009–2011. It has increased the gas-operated vehicle amounts by approximately with an average of 0.23% of all vehicles annually. Sweden posses the second fastest growth which has been approximately 0.08% annually during last ten years. Finland could reach the maximum of 60 000 gas-operated vehicles by year 2020 with the Italian growth rate. This amount of cars is only 5–6 % of the passenger cars in Finland. If those vehicles were passenger cars, they would consume approximately 600 GWh gas annually. This amount could be relatively easily produced by using feedstock with the easiest access, such as biowaste and WWTP sludge. What are the factors that have led to higher gas-operated vehicle amounts in different countries? According to IEA (2010), there are several factors which drive the expanded utilization of gas-operated vehicles. These factors are for example air quality, freeing up oil for exports, reducing governmental spending on subsidies, promotion of local vehicles, improving security and overall gas market development. Taxation and subsidy policies seem to be the most important factors to affect the growth rate of gas-operated vehicles. (IEA, 2010)

The approach to study the limiting factors for biomethane use in the transportation sector can be further developed to be used for all of the transportation energy systems. To find out the key issues, which may limit the increasing utilization of new transportation energy options, the following perspectives should be taken into account: technology, economy and policy. All of these perspectives should be studied along the life cycle of the product. From the technology perspective, the production potential, distribution infrastructure and vehicles should be studied. From the economic perspective, the feasibility for different operators along the life cycle should be studied. From the political perspective, subsidizes should be directed to the bottle necks along the life cycle. Subsidizes can be based on the reductions from the external costs by utilizing alternative transportation fuel options compared to the options in use. Another option could be to reduce subsidizes for fossil fuels. This may however, be very difficult. Using methods presented in this dissertation could be further utilized for local studies for example for hydrogen and electric cars. In addition, there may also be some smaller additional limiting factors, which are not applicable for biomethane but for other fuels.

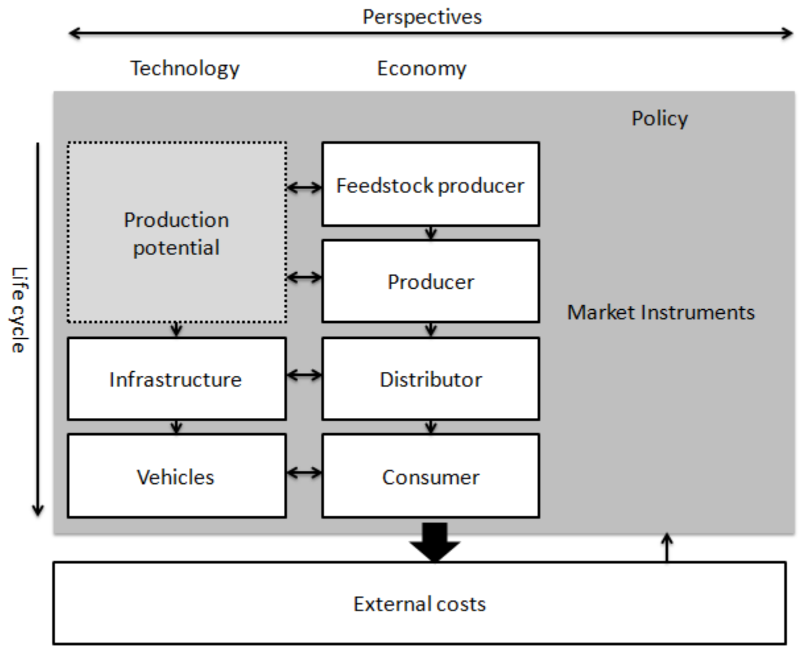

Figure 8. Systematic approach for recognizing limiting factors for transportation energy systems.

5.2 Limitations of the research

Figure 47 presents, which parts of life cycle of biogas, landfill gas and biomethane production and utilization options are included in and excluded from this dissertation.

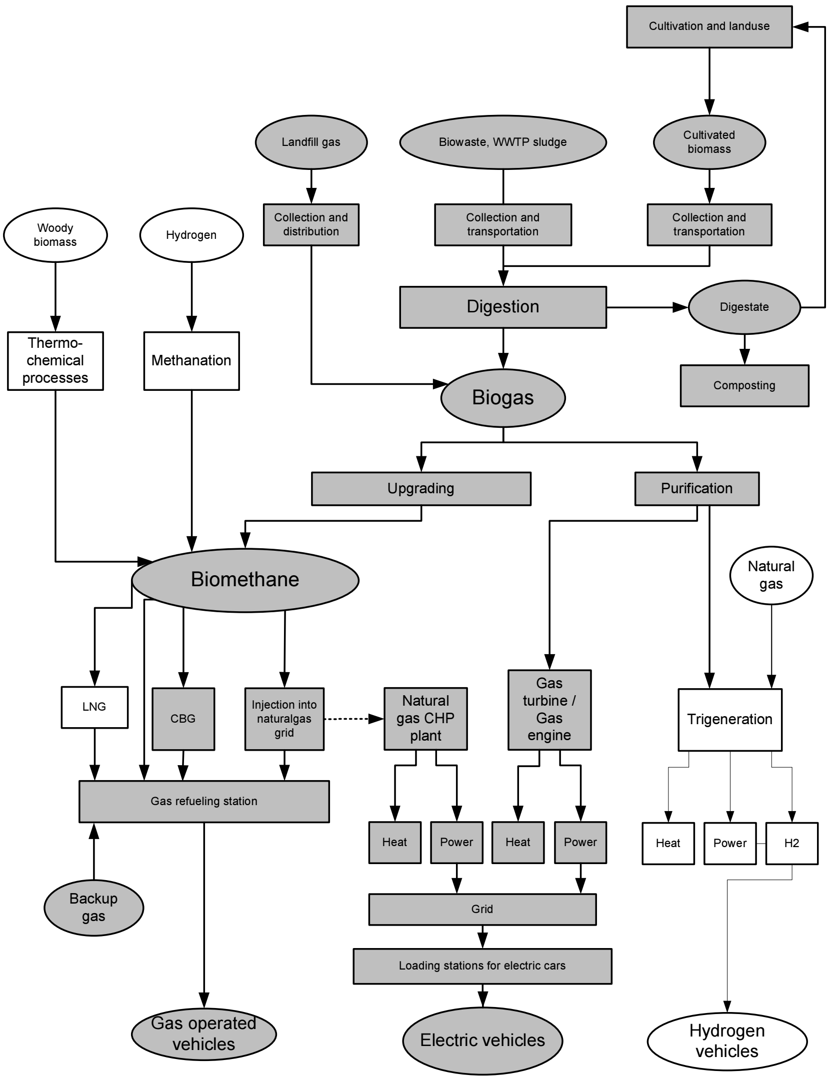

Figure 47: The boundaries of this thesis from the LCA perspective. Grey unit processes are included in the dissertation but the white ones are excluded.

This research concentrates on biogas that is produced by anaerobic digestion. There are, however, other options to produce similar biogas or biomethane from syngas or by methanation processes from hydrogen. Biogas distribution is modeled by pipeline transportation or by CBG transportation. LNG transportation is not included in this research. In addition to gas-operated vehicles and electric vehicles, the energy of biogas could be directed to the transportation sector by producing hydrogen for hydrogen vehicles. This method is not widely used, and due to the undeveloped hydrogen infrastructure, this option was not included in this thesis.

This study was done in a North European operational environment, especially by using Finland related data. Transportation, cultivation methods, land use, emissions from used energy and means of distribution may, however, differ according to the geographical location. For areas with denser population, collection and transportation distances may be even shorter than those used for the purposes of this study. In a warmer climate, GHG emissions from cultivation may be lower due to higher crop productivity and a longer growth season. Therefore, in general, some of the findings and results may not be applicable straight forward in other geographical locations. On the other hand, recommendations for the use of various LCA methodologies are applicable in different geographical locations and for some other transportation energy systems than for biomethane. The study of limiting factors for biomethane use was mainly carried out by using Finnish data. Therefore, the results may differ strongly in other geographical locations. On the other hand the approach in this study is applicable also elsewhere.

This dissertation was carried out by using standardized methods and commonly used techniques. LCA was mainly used in GHG emission calculations. Economic evaluations were carried out by using a payback time approach. Similar methods are utilized also in other scientific studies. There are various assumptions related to methodologies and data, which may cause uncertainty to the results. LCA data has been gathered from various sources, and there may be differences and variation in between the sources. The data that is used in the calculations has been chosen mainly by technological, geographical and temporal representativeness. Other data has also been used in the sensitivity analysis. Assumptions related to scenarios and data utilized have direct impact on the results. To recognize these impacts in Publication I various factors and assumption were varied according to the differences in data and assumptions. For example, technological solutions and assumption related to transportation distances were varied. In addition, emissions related to the production of energy that was utilized in biogas production were varied. Maybe the highest uncertainty is related to the energy systems that could be replaced by energy production with biogas. Therefore, a high scale of variation has been carried out related to the production methods of replaced energy. Additionally, the impacts with the use of different methodological options were studied in Publication I and Publication II. The weakness of economic evaluations is that they are using mainly Finland related data, and sometimes the availability of data is limited. In addition, data related to economy seem to be changing more rapidly. Data related to external costs has also high uncertainty because it is difficult to estimate. Therefore, the uncertainty related to economic calculations is higher than the uncertainty related to GHG studies. The conclusions drawn from economic evaluations are not as detailed but more overall and directional.

5.3 Implications

5.3.1 Practical implications

The dissertation can help in decision-making related to biomethane and biogas systems. It gives methodological recommendations and technical data about how biomethane GHG LCAs should be carried out. It presents how acceptability of biomethane production should be evaluated and how a wider system scale approach should be used in actual decision making situations. The results give information about the climate change performance of biomethane, which can be used for example in marketing. In addition, the effects of various factors along the life cycle on GHG emissions of biomethane are studied. This helps to figure out the hotspots of biomethane chains from the GHG perspective. By recognizing the hot spots it is easier to decrease the carbon footprint of biomethane. The results of this thesis show that only a marginal advantage is received if biogas from electricity and heat production is directed to transportation use. Much higher advantages are received when new biogas production is launched.

Using only narrow calculation instructions such as Directive 2009/28/EC in decision making may lead to wrong conclusions. Therefore, it is highly important to know what are the goals of LCA studies. Some political instruments such as feed-in tariffs are also not necessarily only improving the GHG emission reduction but also reducing them. Therefore, for multi usable fuels, such as biomethane, all the utilization aspects should be taken into account in subsidizing procedures.

From the economic perspective, the bottle necks and an approach to study bottle necks are presented. This helps to direct political subsidizes and to evaluate what are the effects of the subsidizes. The thesis also presents the theoretical biomethane production potential for Finland, which helps to estimate the role of biomethane in reaching the renewable energy targets. In addition, this thesis gives on overview and important steps which have to be taken into account when biomethane utilization in the transportation sector is to be increased.

The comparisons of allocation methods and factors affecting the GHG emissions help researchers and operators to study and develop biogas systems to more environmental friendly direction. The approach to study limiting factors could be applied also for other transportation energy systems.

5.3.2 Theoretical implications

The theoretical implications of the dissertation are mainly related to life cycle assessment methodologies. The recommendations of using allocation procedures in acceptability evaluations and system expansion in real case comparisons are presented. The substitution method was studied as an alternative for the allocation method, but it requires actual data related to the replaced processes. As the theoretical questions related to biofuel LCA are usually complicated, it is important that the LCAs are carried out by persons who how have enough understanding. Wrong assumptions in methodologies may lead to wrong decisions. From the GHG perspective, it is highly important to recognize which products or processes are actually replaced by the main product or process.

When limiting factors for biofuel chains are studied, it is always important to split the life cycle of the biofuel according to different operators. This gives more detailed information, especially on the economic bottle necks in the production chain. An approach to study the limiting factors for alternative transportation energy systems was created. The approach will help in recognizing the bottle necks and in increasing the use of alternative transportation energy systems.

5.4 Future research topics

Improving technologies are probably going to lead to even lower GHG emissions from biomethane production by digestion. This should be taken into account in future studies and comparisons of various biogas and biomethane utilization options. In addition, emissions related to methane leakages and N_2O emissions from cultivation and digestate use are still unclear even though they have a strong effect on the results. Additionally, energy production efficiencies are likely to develop as well as electric vehicles. If electric vehicles break through to markets, the biogas use for electricity production could be the best option from the GHG and infrastructure perspectives. If hydrogen infrastructure expands and becomes a more available technology, biogas use to produce hydrogen may lead to higher GHG emission reductions compared to direct biogas use in gas-operated vehicles. In addition, storing renewable peak electricity such as solar or wind electricity to methane by first producing hydrogen from water and then through methanation processes producing methane, may be an important method to produce methane in the future. Additionally thermo chemical processes to produce methane from lignocellulosic feedstock are also developing. Economic studies would be needed to evaluate which feedstock should be directed to biogas production and how policies could better subsidize biomethane use in the transportation sector to gain as cheap GHG reductions as possible. From the energy system perspective, it would be also important to know, how biomethane should be utilized. A new approach is probably needed to evaluate available options to produce energy and transportation fuels needed at certain areas. This could help to put different energy uses to hierarchical order based on available options to their production.

More attention should also be paid on the comparison of different fuels from also other than GHG perspective. Biomass production and use may also lead to other environmental, social and economic sustainability challenges. Some of these challenges can be avoided by the use of waste feedstock instead of cultivated biomass. Especially biogas production may have a significant contribution on nutrient cycles and on eutrophication. However, the impacts on other sustainability issues should be further studied and the effects of biomethane production compared to other alternative options.

6 Conclusions

In this dissertation, biomethane production for transportation purposes was studied from climate change and economic perspectives by using life cycle assessment approach. Biomethane production and use seem to be acceptable from the GHG perspective because its GHG emissions are lower than those of fossil transportation fuels. Biomethane production may have also additional advantages compared to other feedstock utilization options. However, biogas, landfill gas or biomethane use in energy production leads also to GHG emission reductions that are approximately at the same level as from the transportation use. If biogas is already used for electricity and heat production, the advantages of directing biogas to transportation may be marginal from the GHG perspective. Therefore, to increase biogas use in the transportation sector with the intention to reduce GHG emissions, new biogas production should be built using feedstocks which are currently not used for biogas production. Biogas or biomethane use in electricity production for electric vehicles is also a potential option to increase the use of renewable energy in the transportation sector.

GHG emissions from biomethane production and distribution are relatively low if the energy and especially electricity consumption are at a low level and there are no significant methane leakages. Especially, the use of waste feedstock enables the biomethane production with low GHG emissions. By using waste feedstock, the complicated issues related to land use change can be avoided. Processes related to feedstock cultivation and digestate use may lead to relatively high GHG emissions, particularly via N_2O emissions. In addition, waste water treatment plant sludge with high moisture content leads to higher energy consumption in digestion because more heating is needed. The new technology seems to be developing into a lower energy consumption direction, and methane leakages are also low with new technologies and upgrading applications.

There are various methodological options to study biomethane use in the transportation use. GHG emissions from biomethane production and use can be calculated to evaluate overall acceptability of transportation biomethane compared to other fuels. This methodology is a good option when comparing various transportation fuel options, but actual specific cases are not studied. In these studies, from the methodological perspective, the key issue is whether digestate could be regarded as a co-product and which allocation methods should be applied. Digestate should be handled as a co-product if there is an economic value and use for the digestate. In these cases, economic allocation is the most justified. Energy allocation should be applied only when digestate is directed to combustion. Waste assumption is justified when there is no use for digestate. If it is exactly known where digestate is used, a substitution method could also be applicable. However, if real cases are compared to get information for decision-making, a wider system expansion approach should be used. In system expansion, also the alternative uses for feedstock and biogas can be compared. The use of system expansion demands knowledge of the replaced energy systems. Due to the high variety of methodological options, legislation should not restrict too much the methodological choices in decision making in order to get reliable conclusions.

Despite the fact that biomethane use in the transportation sector seems to lead to GHG emission reductions, the amount of gas-operated vehicles is still low in several countries. From the economic perspective, agricultural biomass seems to have several limitations in biogas production. First, there may be more inexpensive alternative utilization options. For a biomethane producer, gate-fees from the feedstock are essential, but dedicated energy crops producers expect to get paid for the feedstock. Agricultural biomass has the highest biogas production potential. In addition, the use of dedicated energy crops does not lead to as high GHG emission reductions as waste feedstock. For the waste feedstock, similar problems or limitations were not found or the magnitude of the problems was lower. For a distributor, the existing gas grids are essential. Building long gas grids is expensive making the distribution unprofitable. For consumers, the biggest problem is the higher investment cost of gas-operated vehicles. Therefore, despite the cheaper fuel, they are not significantly more inexpensive than traditional vehicles. Political decisions can help to improve the economics of biomethane production and utilization chain for example by subsidizes or tax reliefs. These subsidizing mechanisms could be based on the reductions from the external costs compared to vehicles using fossil fuels. The next step could be to create political instruments to compare subsidizes paid for different transportation energy systems to achieve as high environmental benefits with as low costs as possible.

Biomethane use as a transportation fuel should be favoured over electricity and heat production because the options to produce transportation fuels locally are usually more limited than the options to produce energy. In addition, biomethane is ranked high in the transportation fuel hierarchy because it can be used also in heavier vehicles, where renewable energy choices are otherwise very limited. Biomethane production should start from the cheaper waste feedstock to gain the highest GHG emission reductions. Further more expensive cultivated biomass has to be subsidized to expand the biomethane production potential. With cultivated biomass, it is important to ensure a high enough GHG reduction potential by paying attention on cultivation processes.

It appears that biomethane leads to GHG emissions reductions in transportation use, and the potential for even greater emission reductions may increase in the future with the advent of improved technology, greener energy production methods and higher demand for recycled fertilizers. The methane leakages and N_2O emissions related to digestate use are still unclear and should be studied in a more detail because they have a significant contribution on the total GHG emissions. More detailed economic calculations are also needed to direct subsidizes to the most important parts of biomethane life cycle and to avoid harmful subsidizes. This research did not take into account biomethane production by thermo-chemical methods or from hydrogen by methanation. These developing technologies can increase the biomethane production potential significantly, for example by using wood as a feedstock or excess renewable electricity in hydrogen production. Other sustainability issues than GHG emissions were mainly excluded from this study. With biomass based biofuels other sustainability issues may also posses huge threats. Some of these can be avoided by using waste feedstock instead of cultivated biomass. However, these issues related to biomethane should be further studied.

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Appendix A: Data quality

The Appendix A presents the main initial data sources in modeling at different life cycle stages. Data quality is evaluated based on the instructions of Greenhouse Gas Protocol. The quality is evaluated based on temporal representativeness, geographical representativeness, technological representativeness, completeness and reliability. In the column Quality V is very good, G is good, F is fair and P is poor. More detailed definitions for the categories can be found in Greenhouse Gas Protocol 2011. Data is also divided to primary and secondary data. Primary data is case specific data which is usually measured. Secondary data is average data or other not case specific data. The table also displays publications of this thesis where initial data is used. The last column describes how much initial data is varied in sensitivity analysis in order to figure out the impact related to data selections. Data selections and assumptions are described more detailed in Materials and Methods and in publications.

Main initial data sources	Data source	Temporal representativeness	Geographical representativeness	Technological representativeness	Data type S = secondary data P = primary data	Publication for further information	Quality	Scale of data variation in sensitivity analysis
GHG EMISSIONS MODELING								
Land Use Change								
LUC related GHG								
	Müller-Wenk & Brandão (scientific article)	2010	Boreal	average forest turned to field	S	I	G-V	high
Cultivation								
Fertilizer use								
	Smyth (dissertation)	2010	North Europe (Ireland)	similar cultivation technology and feedstock	S	I	G	high
	BioGrace (GHG calculation tool)	2013	Global and EU (fertilizer markets are global)	provides GHG emissions related to production of fertilizers. In some cases GHG emissions are calculated to represent fertilizer types used.	S	I	G	not incl.
Machinery								
	Technical Research Centre of Finland (database, calculations)	2013	Finland	tractor assumed to be used in all cultivation processes, driving distance is calculated	S	I, II	G-V	not incl.

Productivity								
	Smyth (dissertation)	2010	North Europe (Ireland)	similar cultivation technology and feedstock	S	I	G	high
	Rasi et al. (report)	2012	Finland	similar cultivation technology and feedstock	S	I, II	G-V	high
Feedstock transportation								
Fossil fuel use								
	BioGrace (GHG calculation tool)	2013	Global and EU	average truck	S	I	F-G	not incl.
	Technical Research Centre of Finland (database)	2010	Finland	waste truck and tractor	S	II	G-V	not incl.
Distance								
	Statistic Finland (database)	2010 A	Finland	average transportation distances	S	I	G	relatively high
	Rasi et al. (report)	2012	Finland	distances in Helsinki region	P-S	II	V	not incl.
Biogas production								
Biogas productivity								
	Rasi et al. (report)	2012	Finland	average properties for various feedstock	S	I	G-V	relatively high
	Various national sources (reports and databases)	2008 - 2011	Finland	average properties for various feedstock	P-S	II	F-G	not incl.
Heat use								
	Berglund & Börjesson (scientific article)	2006	Global, provides high variation of data which is modified for Finnish operational environment by calculating	wet mesophilic digestion	S	I, II	F-V	high
	Pöschl et al. (scientific article)	2010	Germany (mainly)	mesophilic two-stage	S	I	F-V	high
	Rasi et al. (report)	2012	Finland (collected from various sources)	mesophilic, single-stage	S	I	F-V	high
Electricity use								
	Berglund & Börjesson (scientific article)	2006	Global	wet mesophilic digestion	S	I, II	F-V	high
	Møller et al. (scientific article)	2002	Global	digestate separation technologies	S	II	F-G	high
	Rasi et al. (report)	2012	Finland (collected from various sources)	mesophilic, single-stage	S	I	F-V	high
Methane leakages								
	Berglund & Börjesson (scientific article)	2006	Global	wet mesophilic digestion	S	I	F-G	very high
	Pertl et al. (scientific article)	2010	Global	mesophilic two-stage	S	I	F	very high

	Börjesson & Berglund (scientific article)	2007	Global	anaerobic digestion	S	I	F	very high
Digestate handling								
	Poeschl et al. (scientific article)	2012	Central-Europe	digestate transportation	S	I	F	not incl.
	Brandão et al. (scientific article)	2011	Global	N_2O emissions from nitrogen use	S	I	F-G	relati vely high
	Rehl et al. (scientific article)	2011	Global	digestate composting	S	I	F-G	relati vely high
	Kahiluoto & Kuisma (report)	2011	Finland	Composting	S	I	F-G	relati vely high
	Tanskanen (report)	2009	Finland	Composting	S	I, II	F-G	relati vely high
Upgrading								
Electricity use, heat use and methane leakages								
	Pertl et al. (scientific article)	2010	Global	pressure swing adsorption, water scrubbing	S	I, II, III, V	F-G	high
	Patterson et al. (scientific article)	2011	Global	pressure swing adsorption, water scrubbing	S	I	F-G	high
	Purac Puregas (product description)	2013	Global	amine wash	S	I, II	F-G	high
	Suomilammi et al. (experts from Gasum Oy)	2009	Finland	water scrubbing	P	III	V	not incl.
Distribution								
Pipeline, truck, refueling station								
	Rasi et al. (report)	2012	Finland	pipeline and truck transportation	S	I, II	G-V	relati vely high
	BioGrace (GHG calculation tool)	2013	Global and EU	average electricity consumption in refueling	S	I, II	F-G	relati vely high
	Suomilammi et al. (experts from Gasum Oy)	2009	Finland	pipeline and refueling station electricity consumption	P	III	V	not incl.
Transportation use								
Transportation emissions								
	Technical Research Centre of Finland (database, calculations)	2011	Finland	gas-operated passenger cars and busses	S-P	II	G-V	not incl.
Other gas use								
Purification								
	Lammi (expert from Sarlin Oy)	2009	Finland	siloxane removal	P	III	V	not incl.
Gas engines								
	Lammi	2009	Finland	gas engines	P	III	V	not

	(expert from Sarlin Oy)							incl.
	MWM (product description)	2009	Global	gas engines	S-P	III	G-V	not incl.
	Niskanen (conference publication)	2009	Finland	gas engine for LFG	S	V	G	not incl.
	Wong et al. (book)	2001	USA	gas engine efficiencies	S	V	F	not incl.
Micro-gas turbines								
	Niskanen (report)	2009	Finland	gas turbines	S	II	G	not incl.
	Nielsen et al. (report)	2013	Denmark	gas turbines	S	II	F-G	not incl.
NG CHP plants								
	Helsingin Energia (online document)	2013	Finland	NG CHP plant	S-P	II, III	G-V	not incl.
Electric vehicles								
	U.S. Department of energy (online document)	2011	USA	average consumption of electric vehicles	S	III	F	Disu ssed
Asphalt production								
	Niskanen (conference publication)	2009	Finland	asphalt production with LFG	S-P	V	G	not incl.
Energy production								
Electricity								
	Energy Statistics Yearbook (report)	2011	Finland	average electricity production	S	I, II	G-V	relati vely high
	Schakenda & Nyland (report)	2013	Sweden	average electricity production	S	I	G	high
	Thyholt & Hestnes (scientific article)	2008	Nordic countries	marginal electricity (coal) production	S	I, II	G	high
Heat								
	Energy Statistics Yearbook (report)	2011	Finland	average heat production	S	I, II; III	G-V	high
	Rasi et al. (report)	2012	Finland	heat production by wood chips	S	I, II	G-V	relati vely high
Fossil transportation fuels								
	2009/28/EC(dir ective)	2009	Europe	fossil transportation fuel use	S	I	F-G	high
	Technical Research Centre of Finland (database)	2011	Finland	passenger cars and busses	S-P	II	G-V	relati vely high
ECONOMIC MODELING								
Cultivation and feedstock								
	Mykkänen (report)	2009	Finland	biogas production feasibility	S-P	IV	G	discu ssed
	Pöyry	2008	Finland	sludge treatment	S-P	IV	F–G	discu

	Environment Oy (report)							ssed
Digestion and upgrading								
	Mroueh et al. (report)	2007	Finland	digestion	S-P	IV	F-G	high
	Havukainen et al. (scientific article)	2012 A	Lithuania	digestion	S	IV	F	high
Distribution								
	Rasi et al. (report)	2012	Finland	pipeline and truck transportation	S	IV	G	high
	Lammi (expert from Sarlin Oy)	2009	Finland	compressor and purification	P	III	V	not incl.
	Suomilammi et al. (experts from Gasum Oy)	2009	Finland	pipeline, upgrading, compression and refueling	P	III, IV	V	high
Transportation use								
	Volkswagen (online document)	2013	Finland	gas-operated car	S-P	IV	G-V	relatively high
	Oragas Oy (online document)	2010	Finland	turning petrol car to gas-operated car	S-P	IV	G-V	relatively high
	Biomeeri Oy (report)	2010	Finland	Electric vehicles and speed loading stations	S-P	III	G	not incl.
Other energy use								
	Lammi (expert from Sarlin Oy)	2009	Finland	gas engines	P	III	V	not incl.
Other biomass use								
	Pyöry Environment Oy (report)	2008	Finland	sludge treatment	S	IV	F–G	not incl.
Energy prices, taxation and supports								
	Ministry of employment and the economy (report)	2009	Finland	feed-in tariff and other costs related to biogas use	S-P	III, IV	F–V	high variation
	Gasum Oy (online document)	2013	Finland	biomethane at refueling station	S-P	IV	V	not incl.
BIOMETHANE POTENTIAL MODELING								
Biomass amounts								
	Rasi et al. (report)	2012	Finland	biowaste and biomass	S-P	IV	G	not incl.
	Havukainen et al. (report)	2012 B	Finland	WWTP sludge	S-P	IV	G-V	not incl.
	Matilda (database)	2010 - 2011	Finland	agricultural waste	S-P	IV	V	not incl.
	Niemeläinen et al. (report)	2012	Finland	area available for biomass cultivation	S-P	IV	F-G	not incl.

Publication I

Uusitalo, V., Havukainen, J., Kapustina, V., Soukka, R., Horttanainen, M.
Greenhouse Gas Emissions of Biomethane for Transport: Uncertainties and Allocation Methods

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Greenhouse Gas Emissions of Biomethane for Transport: Uncertainties and Allocation Methods

V. Uusitalo,* J. Havukainen, V. Kapustina, R. Soukka, and M. Horttanainen

Laboratory of Environmental Engineering, Lappeenranta University of Technology. P.O. Box 20, 53851, Lappeenranta, Finland

ABSTRACT: Employing a life-cycle assessment approach, this paper studies greenhouse gas (GHG) emissions resulting from biomethane used as transportation fuel. It focuses on both GHG allocation methodologies and uncertainties regarding GHG emissions from biomethane. The goal is to calculate GHG emissions of two types of biomethane used in transportation: that produced from biowaste feedstock and that extracted from dedicated energy crop feedstocks. The effects of allocation methods used for digestate and those of other factors arising during the life cycle of biomethane are studied. The GHG emissions of biomethane produced from biowaste with digestate use are approximately 22 gCO_{2eq} MJ^{-1}; those of biomethane extracted from dedicated energy crops are 61 gCO_{2eq} MJ^{-1}. However, using the substitution method for digestate decreases biowaste emissions by 10 gCO_{2eq} MJ^{-1} and dedicated energy crop emissions by 22 gCO_{2eq} MJ^{-1}. The highest emissions uncertainties are related to land use change, cultivation processes, digestate use, and technology selections in digestion and upgrading. Using technology with high energy consumption or methane leakages will significantly increase total emissions. On the other hand, use of renewable energy in processes is one option for decreasing total emissions. It appears that biomethane could be produced with lower emissions than previous studies have shown by optimizing production and implementing new technology. The utilization of digestate in replacing mineral fertilizers, resulting in additional GHG emission reductions, is a key issue which should be accorded more attention in the future. For one to achieve reliable results, factors related to biomethane production and allocation methods for digestate emissions should always be chosen on a case-by-case basis.

1. INTRODUCTION

Approximately 15% of global greenhouse gas (GHG) emissions are emitted from the transportation sector,[1,2] the main cause of these high GHG emissions being the use of gasoline and diesel fossil fuels. One option for replacing fossil fuels, reducing GHG emissions, and increasing the use of renewable energy in the transportation sector is the use of biofuels, for example, ethanol and biodiesel.[3] Biomethane, specifically addressed in this paper, is another biofuel alternative for gas-operated vehicles.

Biomethane can be produced from biogas, which in turn can be produced by means of anaerobic digestion using organic raw materials, such as organic wastes or dedicated energy crops, as feedstock.[4,5] Digestate is a coproduct from the digestion process in biogas production, and it can be used as fertilizer due to its nitrogen and phosphorus content.[6] After the digestion process, the methane (CH_4) proportion of biogas can be increased in an upgrading process to produce biomethane. The quality of biomethane, having a methane content of approximately 98%, is similar to that of natural gas.[7]

Biomethane can be distributed by means of existing natural gas grids and be refueled in gas refueling stations.[7,8] The proportion of European natural gas vehicles in the total European vehicle market in 2012 stood at 0.5% but has been steadily increasing.[9] There are over 4000 refueling stations for gaseous fuels for transportation in Europe.[9] The existing utilization of gaseous transportation fuel creates the basis for increasing biomethane use, as distribution networks and users can be, depending on the country, already in place.

The main goal of biofuel usage is to reduce GHG emissions in the transportation sector; however, biofuel production and utilization also generate GHG emissions in various steps along the life cycle. Some studies have shown that GHG emissions from the production and use of biofuels may be even higher than emissions from those of fossil fuels.[10] In addition, there are great differences in GHG emissions of biofuels depending on the feedstock and production method used.[11,12] In light of this variation, several studies have shown that the GHG emissions from biomethane production and use are lower than GHG emissions from fossil fuels.[13,14] Yet, still other studies have demonstrated that the potential for GHG emissions reductions is only marginal in some cases.[15,16]

According to previous studies, GHG emissions from biomethane production vary from 12 to 70 gCO_2 MJ^{-1}, and thus the GHG emissions reduction potential of biomethane compared to various fossil fuels varies from 10% to 70%.[14−18] Feedstock selection for biomethane production appears to play an important role in total overall GHG emissions: dedicated energy crops seem to lead to lower GHG emission reductions than does the utilization of waste materials due to added environmental burden of cultivation processes.[14−16] However, studies have reached differing conclusions. For example, Pertl et al.[16] calculated relatively high emissions for organic waste-based biomethane, and Directive 2009/28/EC[12] provides low default values for biowaste-based biomethane production. There are also some key issues along the life cycle of biomethane that affect the total GHG emissions reduction potential. Börjesson & Berglund found that the handling of raw materials is often a significant source of GHG emissions.[14] During digestion and upgrading processes, energy consumption and methane

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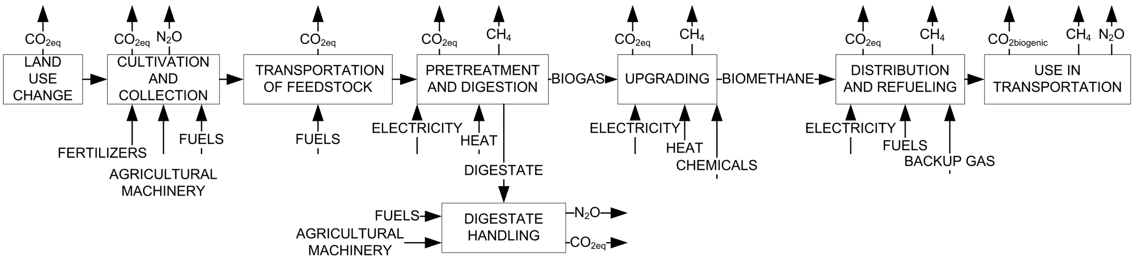

Figure 1. Biomethane production chain and flows related to various process steps.[4,5,13−17]

leakages seem to be the major sources for GHGs.[14,16,19] Pertl et al.[16] compared various upgrading methods and showed that technology selection has a relatively large effect on emissions from the upgrading phase. Cultivation processes may also be an important factor if biomethane is produced from dedicated energy crops.[13,15,16] Despite the emissions released along the life cycle, biogas systems normally lead to environmental benefits, which can be considerable.[20]

From a methodological perspective, much variation exists in the methods used for allocating emissions from digestate handling and utilization. There are four common ways of dealing with GHG emissions from digestate use in the context of studies of biomethane emissions. First, if digestate is not of economic value, it can be regarded as waste, according to the ISO 14040 standards[21] and the Greenhouse Gas Protocol.[22] In this case, GHG emissions from digestate utilization are added to the GHG emissions of biomethane. This method has been applied by Börjesson & Berglund[14] and Murphy et al.[17] Second, in other studies, GHG emissions from digestate utilization are not included for biomethane, and allocation is not done despite the fact that the digestate is regarded as waste.[15,16] Third, if digestate is of economic value, it can no longer be regarded as waste, and thus part of the GHG emissions from the joint production of digestate and biomethane must be allocated.[21,22] Allocation may be done according to economic value or to the instructions of Directive 2009/28/EC,[12] based on the energy content of the products. Fourth, the substitution method is the final calculation method, and it may be employed to avoid allocation.[21,22] In this case, GHG emissions from digestate utilization are included for biomethane, but GHG emissions savings incurred by replacing mineral fertilizers with digestate are subtracted from the total emissions.

Many studies of biomethane utilization and GHG emissions reductions have been carried out. However, previous research has mainly focused on using only one example of various possible biomethane production chains, feedstock, or allocation methods.[15−17] The perspective of those studies has been to replace various reference systems with biogas or biomethane use or to concentrate on a certain part of the biomethane production chain.[16,20] Therefore, there is great variation in the results, and we still lack a clear picture of the importance of various factors of GHG emissions along the life cycle of biomethane and of allocation methods. Biomethane producers need more information to focus on the most important process steps for reducing GHG emissions from biomethane production and for satisfying legislative requirements. In addition, natural gas grid distribution has been viewed as a key issue for the expanded utilization of biomethane,[8] but little related research exists. A range of important factors may affect GHG calculations, for example, emissions from electricity production, cultivation processes, and employed technology. In addition, the effects of a given allocation methodology for digestate utilization are still unclear. The fuel choices in the transportation sector are becoming increasingly important in energy conversations. It is therefore imperative that we discover how biomethane could be produced with low GHG emissions and that we identify which factors increase the risk that GHG emissions from biomethane production will increase. We also still lack a clear picture of the significance of the differences between various allocation methods.

The aim of this study is to fill in the gaps in our knowledge concerning GHG emissions from biomethane production and utilization. The goal is to clarify the big picture of GHG emissions related to transportation biomethane by answering the following questions: What is the role of different life cycle steps in biomethane production and utilization for studied cases? What are the effects of various uncertainties along the life cycle of biomethane on total GHG emissions? What are the effects of a selected allocation method on the results, and when should various methods be used to gain the reliable picture of GHG emissions of biomethane? Are the uncertainties related to allocation methods more significant than uncertainties related to various factors along the life cycle of biomethane?

2. MATERIALS AND METHODS

Assumptions and Boundaries. We have carried out our research using life-cycle assessment (LCA) methodology and Microsoft Office Excel 2007. LCA methods are widely employed in similar GHG emissions research to compare various options and to evaluate the effects of certain parts of the life cycle on the entire process.[23,24] Our calculations are based on the instructions of ISO 14040 standards,[21] the Greenhouse Gas Protocol,[22] and Directive 2009/28/EC.[12] The functional unit in all calculations is 1 MJ of biomethane produced and distributed to the transportation sector. The modeling was carried out by calculating GHG emissions from each process step. For factors used in calculations, a basic assumption of a certain value is presented; thereafter, the variation of the value is presented in parentheses. The variation of the value is used in the sensitivity analysis to determine the significance and uncertainties related to each factor.

In this research, a North European operational environment was selected. The two types of feedstock chosen for the study are biowaste (organic waste) and dedicated energy crops (clover and timothy). Figure 1 presents the biomethane production chain modeled in this paper.

The following global warming potentials are used as carbon dioxide equivalent emissions for carbon dioxide, methane, and nitrous oxide, respectively:

$$1\ gCO_{2eq}gCO_2^{-1}$$

$$23\ gCO_{2eq}gCH_4^{-1}$$

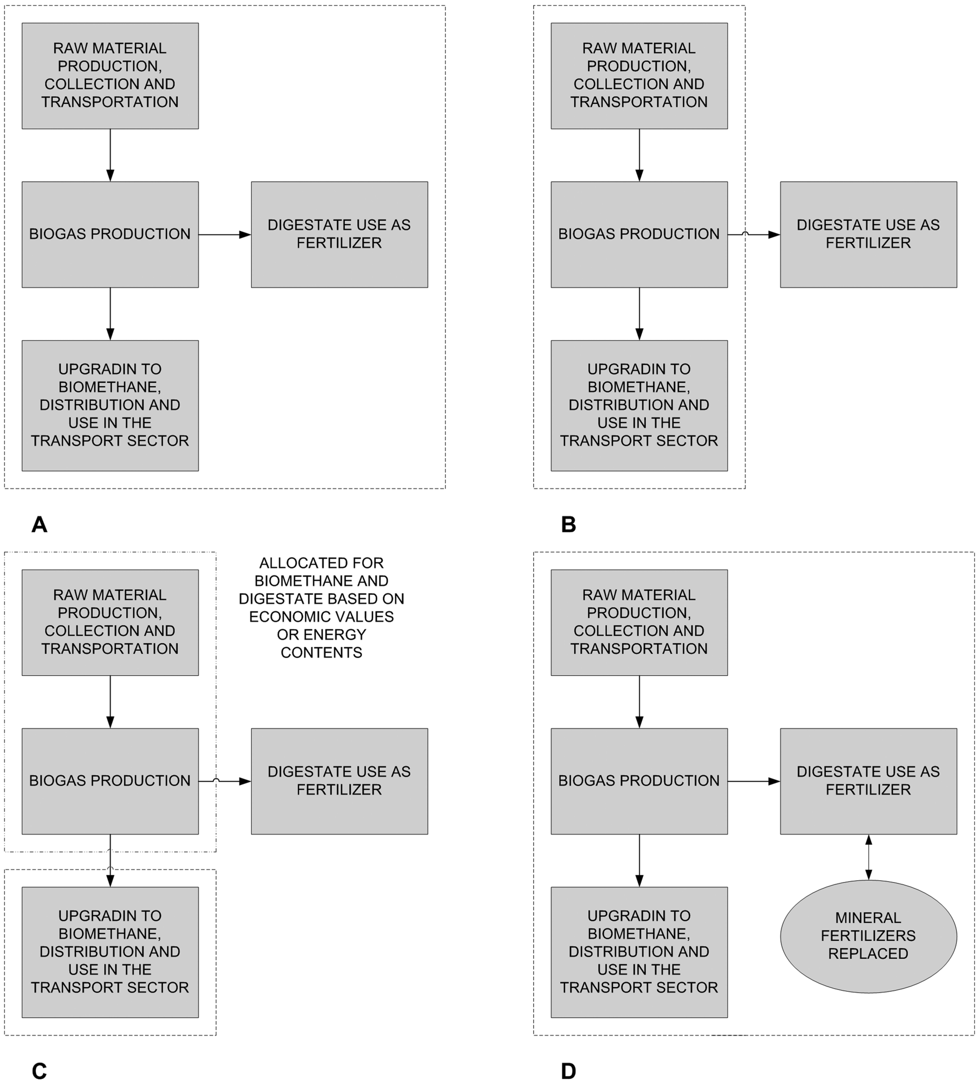

Figure 2. Various allocation methods for dealing with GHG emissions from digestate utilization. Scenario A depicts a waste assumption, whereby GHG emissions from digestate utilization are included in GHG emissions from biomethane production. Scenario B also depicts a waste assumption, but GHG emissions from digestate use are not included in GHG emissions from biomethane production. Scenario C depicts the allocation method based on economic or energy values. Scenario D depicts the substitution method for replacing mineral fertilizers.

$296\ gCO_{2eq}gN_2O^{-1}$ [12]

In biomethane production, digestate is also produced. Digestate consists mainly of nonvolatile feedstock residue and unconverted organic matter, and it can be used as fertilizer due to its nitrogen and phosphorus content. Emissions from digestate handling can be mainly attributed to machinery needed for its transport and spreading and to N_2O emissions resulting from its use on fields.[14,17] This paper studies the effects of four allocation methods applicable for digestate. The various options are presented in Figure 2, represented in scenarios A–D.

When one uses economic allocation methods, the economic value of the products must be defined.[21,22] The opportunity to gain an economic advantage from digestate use depends on the situation and is still somewhat unclear. On the basis of the literature, the maximum price for digestate is approximately 11 € $t^{-1}{}_{dewatered\ digestate}$.[25] The price for biogas and biomethane also varies but is approximately 0.5 € $kg^{-1}{}_{biogas}$ and 1.5 € $kg^{-1}{}_{biomethane}$.[26] For the energy allocation method, the lower heating value for digestate is assumed to be approximately 2.5 MJ kg^{-1}. For the substitution method, the emissions factors for fertilizers are presented in the chapter on cultivation.

If biowaste is used as feedstock for digestion, it can replace other waste management options such as composting. According to Finnveden et al., digestion and biomethane use as a transportation fuel is a better option than composting or landfill deposit from global warming perspective.[27] Replacing composting process will lead to additional GHG emission savings with biowaste biogas. This is discussed in the results section.

Land Use Change. Land use change (LUC) may result in increased GHG emissions because of modifications in soil carbon

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Table 1. Characteristics of Feedstock[26]

	TS^a (%)	VS^b/TS (−)	CH_4 (m^3 tVS^{-1})	N (%-TS)	P (%-TS)
biowaste	27 (27−66)	90 (85−90)	400 (400−450)	2	0.4
dedicated energy crops	35 (28−35)	85 (85−90)	350 (300−350)	3.4	0.6

^{a}Total solids. ^{b}Volatile solids.

stock. If dedicated energy crops are used as feedstocks for biofuels, there are various options pertinent to land use change. First, feedstock from set-aside fields, from buffer strips of water systems, or from landscaping and similar areas can be regarded as waste, thus not leading to land use change. Second, if feedstock production takes place on fields already used in silage production, then there are no significant additional GHG emissions from the land use change, because the carbon stock level does not change with relation to the previous use. Third, if forests are logged and converted into fields, there will indeed be a change in carbon stock resulting in increased GHG emissions. Fourth, indirect LUC is also a possible consideration if feedstock cultivation on agricultural lands leads to LUC somewhere else. The options 1 and 2 are the most relevant to Northern Europe. For the purposes of this paper, land use change emissions are divided up to reflect two annual crops in the calculations.[26] The basic assumption is that cultivation in Northern Europe can be done without significant land use change, so the effects of LUC are presented only in the sensitivity analysis. The worst case scenario for LUC in this paper is the conversion of a hectare of boreal forest into cropland, which leads to 114 tC_{eq} emissions over 119 years (the amount of time the carbon remains in the atmosphere).[28]

Cultivation, Collection, and Feedstock Transportation. Cultivation processes lead to GHG emissions via the utilization of fertilizers and machinery. Feedstock productivity varies greatly depending on the geographical location. For the purposes of this paper, feedstock productivity is estimated to be 10 000 kg ha^{-1} (6000−14 000 kg ha^{-1}).[5,26] The required amounts of fertilizer are 100 kg ha^{-1} (50−150 kg ha^{-1}) for nitrogen (N) fertilizer, 10 kg ha^{-1} (0−20 kg ha^{-1}) for phosphorus (P) fertilizer, and 280 kg ha^{-1} (100−280 kg ha^{-1}) for calcium carbonate ($CaCO_3$) fertilizer.[5] P fertilizer use is relatively low in Europe, as N is the limiting factor for growth.[8,25] The production of mineral fertilizers leads to GHG emissions of 5880.6 gCO_{2eq} kg_N^{-1}, 1010.7 gCO_{2eq} $kg_{P_2O_5}^{-1}$, and 129.5 gCO_{2eq} kg_{CaO}^{-1}.[29] In addition, the utilization of nitrogen fertilizer leads to nitrous oxide (N_2O) emissions.[30] In this research, 1% of nitrogen is estimated to react to N_2O.[30] Cultivation processes also require the use of machinery in fertilizing, harvesting, plowing, and seeding. Emissions from the use of machinery are calculated based on agricultural tractor emissions.[31]

GHG emissions from collection of biowaste and transportation of feedstock are calculated using transportation emission data for transportation trucks.[29] Biowaste must be collected from households, public services, or industry, and the collection distance is estimated to be 50 km (10−50 km).[32] Dedicated energy crops collection is included in agricultural machinery and is carried out by a tractor. The transportation distance after collection for biowaste and dedicated energy crops is also approximately 50 km (10−100 km).[32]

Digestion and Pretreatment Process. Table 1 presents characteristics of the feedstock used in calculations. These values are used to calculate the amount of feedstock needed to produce the functional unit of biomethane and to evaluate the effects of feedstock quality on GHG emissions.

The digestion process is modeled based on anaerobic wet mesophilic digestion. The process is assumed to produce biogas with methane content of 60%. The electricity and heat demand are calculated based on the heating of the feedstock and on energy consumption during the pretreatment and digestion processes. The electricity demand is calculated assuming 55 MJ t^{-1} (10% TS) for feedstock and 16.2 MJ $t^{-1}_{digestate}$ for dewatered digestate.[14] The marking 10% TS refers to mixture of substrate with a 10% dry matter content. This dry matter content is obtained by recycling reject water and adding fresh water. The recycling rates, or water used, is 50% for biowaste and 100% for dedicated energy crops (the recycling rates were calculated). On the other hand, much higher energy demands are presented in the literature. On the basis of these assumptions, the electricity demand for biowaste is 72 MJ t^{-1} (72−230 MJ t^{-1}) (10% TS) and for dedicated energy crops is 76 MJ t^{-1} (76−230 MJ t^{-1}) (10% TS).[14,26] The digestion process heat demand is calculated by summing up the heat needed for heating the material for digestion and the heat losses from the reactor. Heat consumption is 59 MJ t^{-1} (59−320 MJ t^{-1}) (10% TS) for biowaste and 25 MJ t^{-1} (25−320 MJ t^{-1}) (10% TS) for dedicated energy crops. These values may be regarded as typical for new digestion plants but especially energy efficiencies of biogas plants vary at high scale.[14,26,33] Various references provide low values for methane leakages from digestion;[14,16] maximum methane leakages in the digestion process are estimated to be 5%.[20,29]

Digestate Use. Digestate may be used as a raw material for fertilizer production, it may be spread on fields without any additional processing (other than hygienization for biowaste based digestate), or it may be used in the composting process. The energy consumption of hygienization is taken into account in the energy demand of the digestion process. In this study, covered storages for digestate and recovery of residual methane are included in study to avoid methane emissions.[34] If digestate is to be used as a fertilizer, it must satisfy quality requirements.[35,36] For the purposes of this study, digestate is assumed to be transported by trucks to fields estimated to be located within 50 km from the digestion plant and then to be spread using agricultural tractors. A total of 1% of nitrogen in the digestate is estimated to result in N_2O emissions.[30] The Nitrate Directive limits the maximum amount of N that can be used for certain fields;[37] therefore, there may not be an adequate amount of suitable fields close enough to the digester, which may in turn limit the use of digestate as fertilizer. In these cases, additional digestate has to be for example composted. This option is studied in the sensitivity analysis. Composting does consume some electricity, but the majority of its emissions are related to N_2O emissions from N in the digestate.[38] It is estimated that 71 gCO_{2eq} $kg^{-1}_{feedstock}$ is emitted from a compost process (CH_3 and N_2O) and machinery use in handling of compost products.[25,39] In addition, 1% of nitrogen in the compost product is estimated to result in N_2O emissions during a compost product utilization stage.[30] A similar compost process is used to estimate GHG emissions from biowaste composting in waste management.

Upgrading. Upgrading is needed for increasing the methane proportion of the produced gas by removing CO_2. There are several upgrading methods: pressure swing adsorption (PSA), water scrubbing (WS), and amine wash (AW). These methods differ in methane leakages as well as in electricity and heat consumption. Methane leakages from PSA are 4%; from WS, 1.5%; and from AW, 0.1% (0−0.1%).[16,40,41] The electricity use for PSA is 0.72 MJ N m^{-3}_{rawgas}; for WS, 0.97 MJ N m^{-3}_{rawgas}; and for AW, 0.36 MJ N m^{-3}_{rawgas}.[16,40,41] AW also consumes 2.0 MJ N m^{-3}_{rawgas} of heat, and 1.44 MJ N m^{-3}_{rawgas} of heat can be recovered for the digestion process, which in turn decreases the heat consumption in digestion.[40] Heat recovery of upgrading is taken into account within the upgrading process step (so as to prevent misinterpretations). AW technology is assumed to be the basic selection, and emissions from PSA and WS are presented in the sensitivity analysis. After the upgrading process, the methane content of biomethane is assumed to be 98%.

Distribution. Several solutions for distributing biomethane to the transportation sector are available. The natural gas grid and other suitable gas grids can be used to distribute biomethane. In gas grid distribution, biomethane is pressurized to conform to grid pressure, which, for example, is 55 bar for natural gas grid distribution in Finland but may be lower if distribution is done via low pressure grids.[26] Electricity consumption in the compressor is 0.5 MJ m^{-3} for natural

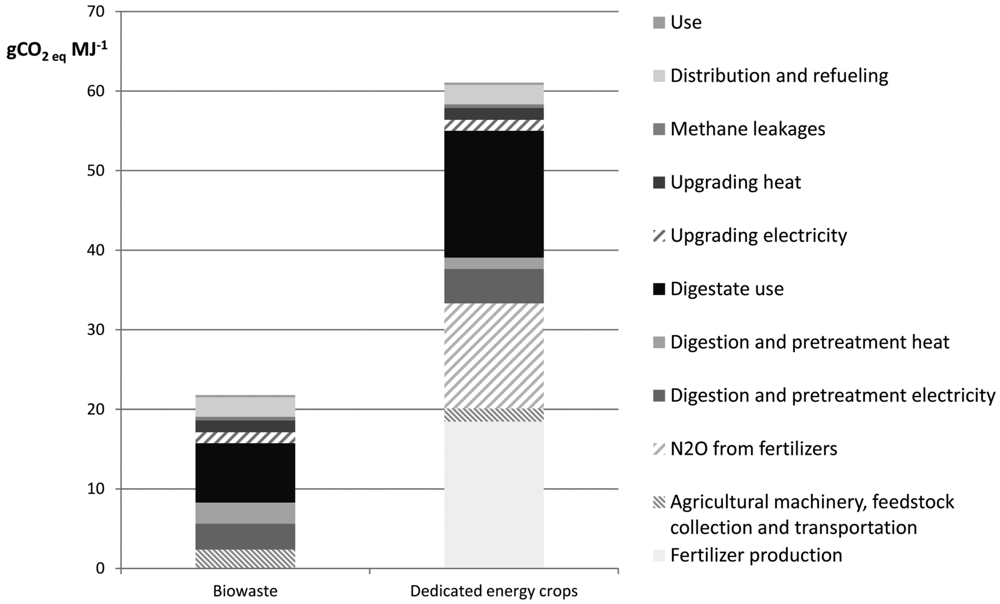

Figure 3. GHG emissions from various process steps for biowaste-based biomethane and dedicated energy crops-based biomethane.

gas grid distribution.[26] If no grids are obtainable, the biomethane must be transported in liquid or compressed form by trucks, rail, or ships. This paper examines both natural gas grid distribution and truck transportation of compressed biomethane. For the latter, biomethane is pressurized to 250 bar, and the transported gas amount is 2000 kg per truck.[26,42,43] The transportation distance for the compressed biomethane is assumed to be 100 km (50−250 km) based on locations of refueling stations and gas grids in North Europe. The amount of dewatered digestate is 0.07 kg MJ^{-1} (TS 30%) for biowaste and 0.134 kg MJ^{-1} (TS 30%) for dedicated energy crops.

Biomethane is refueled in gas-refueling stations, which may be located either along gas grids or in separate locations. For fast refueling, the predominant refueling method in Northern Europe, the pressure of the biomethane should be increased to 250 bar from NG grid's pressure, and refueling takes only minutes.[4,43]

Electricity consumption in refueling station compressors is 0.16 MJ m^{-3}, and in other devices, 0.04 MJ m^{-3}.[26,29] If a refueling station is not located along a gas grid, a back-up gas system is required to ensure gas delivery during shutdowns of bioreactors. In this research, the proportion of back-up gas is estimated to be 10% of the total distributed gas amount, but it should be borne in mind that only a little information related to back-up gas use is available.

Transportation Use. Biomethane can be used in several kinds of vehicles developed to run on gaseous fuel. The most obvious users are buses, taxis, and other vehicles operating in relatively confined areas. For example, local buses can operate with only one refueling station. It is also possible to use biomethane in heavier vehicles, such as waste trucks.[44]

An example passenger car in our research has an average gas consumption of 2.3 MJ km^{-1}, and an example bus has an average consumption of 21.2 MJ km^{-1} in urban driving.[26,31] Vehicle emissions used in this study are 0.0011 gCH_4 km^{-1} and 0.0021 gN_2O km^{-1} for passenger cars and 1.0 gCH_4 km^{-1} and 0.032 gN_2O km^{-1} for busses.[31] On the basis of Directive 2009/28/EC,[12] emissions from the utilization of biofuels in transportation can be excluded from the studies, and this is taken into account in the sensitivity analysis.

Emissions from Energy Production. Emissions levels from processes consuming energy depend largely on the emissions resulting from the method of energy production. Emissions among various energy production methods vary greatly; therefore, various emission factors must be used in calculations. Despite the fact that Finland related values are used in the calculations, the same values are applicable throughout North Europe. In Finland, GHG emissions from average electricity production vary from 45 to 86 gCO_{2eq} MJ^{-1}.[45] However, GHG emissions originating from electricity production may be significantly lower if a high share of renewable energy is used. In other Nordic Countries, emissions from electricity production are lower than in Finland. For example, in Sweden, GHG emissions from average electricity production may be as low as 14 gCO_{2eq} MJ^{-1}.[46] On the other hand, if new electricity consumption occurs, it may utilize marginal electricity (coal power) in the beginning.[47] This may occur if a high capacity of new biomethane production is produced. GHG emissions from marginal electricity vary from 222 to 250 gCO_{2eq} MJ^{-1}.[48,49] On the basis of this information, 83 gCO_{2eq} MJ^{-1} (14−250 gCO_{2eq} MJ^{-1}) is chosen for this study to determine the effects of the utilized electricity type.

Emissions from average heat production in Finland are 58 gCO_{2eq} MJ^{-1}.[45] The highest emissions from the heat use by energy method in Finland were 81 gCO_{2eq} MJ^{-1} during 2005−2009, which is close to the emissions from natural gas-based heat.[45] The lowest emissions from heat production are 4 gCO_{2eq} MJ^{-1}, occurring when heat is produced by wood chips.[26] In this research, emissions from heat production are assumed to be 58 gCO_2 MJ^{-1} (4−81 gCO_{2eq} MJ^{-1}).

3. RESULTS AND DISCUSSION

On the basis of the assumptions made and data used GHG emissions for biomethane from biowaste are 22 gCO_{2eq} MJ^{-1}, and for biomethane from dedicated energy crops, they are 61 gCO_{2eq} MJ^{-1} with allocation method A (Figure 3).

Dedicated energy crops-based biomethane yields significantly higher GHG emissions mainly because of the relatively high emissions from cultivation processes and digestate utilization. Digestate from biomass of dedicated energy crops contains more N than does digestate from biowaste, so usage of the former leads to higher N_2O emissions. GHG emissions related to transportation, digestion, upgrading, distribution, and use are relatively low for both types. The majority of emissions from these process phases are related to electricity use.

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Table 2. Sensitivity Analysis of Various Factors along the Process Chain Influencing Total GHG Emissions

factor	variation	GHG emissions compared to the base case [gCO_{2eq} MJ^{-1}] min	max
	Biogas from Biowaste		
biowaste transportation	10−100 km	−2.2	+1.4
digestion technology	heat 320 MJ t^{-1} (10% TS) and electricity 230 MJ t^{-1} (10% TS)		+23.4
digestion methane leakages	5% CH_4 leakage		+22.5
digestion heat production method	wood chip heat 4 gCO_{2eq} MJ^{-1} or high heat production emissions 81 gCO_{2eq} MJ^{-1}	−2.5	+1
digestion electricity production method	low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	−2	+11
feedstock quality	variation in TS-%, VS TS^{-1}-% and CH_4 productivity, effects on electricity and heat consumption	−0.7	+0.3
digestate utilization	digestate composting + additional 1% N_2O emissions from compost spreading		+18.3
	Biogas from Dedicated Energy Crops		
LUC	The conversion of a hectare of boreal forest into cropland, which leads to 114 tC_{eq} emissions over 119 years. Double cropping used.		+81
cultivation	dedicated energy crop productivity 6000 t ha^{-1}, N-fertilizer use 150 kg ha^{-1} and phosphorus use 20 kg ha^{-1}		+47.6
feedstock transportation	10−100 km	−0.9	+2.2
digestion technology	heat 320 MJ t^{-1} (10% TS) and electricity 230 MJ t^{-1} (10% TS)		+31.2
digestion methane leakages	5% CH_4 leakage		+23.4
digestion heat production method	wood chip heat 4 gCO_{2eq} MJ^{-1} or high heat production emissions 81 gCO_{2eq} MJ^{-1}	−1.3	+0.5
digestion electricity production method	low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	−3	+14
feedstock quality	variation in TS-%, VS TS^{-1}-% and CH_4 productivity, effects on electricity and heat consumption	−0.3	+1.0
digestate utilization	digestate composting + additional 1% N_2O emissions from compost spreading		+36.1
	Biomethane Production and Use		
upgrading technology	PSA use in upgrading with higher electricity consumption and methane leakages		+18.8
upgrading methane leakages	0% CH_4 leakage	−0.5	
upgrading heat production method	heat 320 MJ t^{-1} (10% TS) and electricity 230 MJ t^{-1} (10% TS)	−1.4	+0.6
upgrading electricity production method	low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	−1.2	+2.8
distribution technology	CNG and back up gas transportation 250 km		+7.0
distribution electricity use	low electricity production emissions 14 gCO_{2eq} MJ^{-1} or marginal electricity 250 gCO_{2eq} MJ^{-1}	−2.1	+4.9
use	The emissions from use are not included according to directive 2009/28/EC or high emissions from gas bus	−0.3	+1.3

GHG emissions from the production and utilization of fossil fuels are from 72 to 95.9 gCO_{2eq} MJ^{-1}. On the basis of this value, usage of biowaste-based biomethane in the transportation sector leads to 70−77% GHG emissions reductions; usage of dedicated energy crops-based biomethane leads to 15−36% GHG emissions reductions.[11,12,15] These results confirm the conclusion of previous studies that biomethane use in transportation could indeed lead to GHG emissions reductions.[13−17] If waste treatment (composting) is replaced by biowaste digestion, additional GHG emission saving would be approximately 28 gCO_{2eq} MJ^{-1}. This is an important additional motivator for using biowaste in digestion from a GHG emissions perspective.

The sensitivity analysis for GHG emissions related to various factors along the process chain is presented in Table 2. There may be significant additional GHG emissions for dedicated energy crops if feedstock production thereof leads to land use change or if demand for nitrogen fertilizer is high. In previous studies, emissions from LUC are often excluded. However, LUC may be a highly important factor in increasing GHG emissions if new fields are established for feedstock production. Previous studies show that cultivation emissions vary from 7 to 37 gCO_{2eq} MJ^{-1}.[13,15,16] On the basis of the findings of this paper, these emissions are 32 gCO_{2eq} MJ^{-1} (0−81 gCO_{2eq} MJ^{-1}). This demonstrates that cultivation with high usage of nitrogen fertilizer results in emissions which may be significantly higher than previous studies have shown. Using energy plants with a high productivity per area unit; for example, maize has lower climate impacts than crops such as grass.[6]

Raw material collection and transportation vary according to the location of the raw materials and the digestion plant but based on the assumptions made in this paper does not correspond to a high increase in emissions. In sparsely populated areas, the distance for the collection of biowaste may increase, which subsequently increases emissions. On the other hand, with well planned collection of biowaste emissions may decrease.

Technologically speaking, the utilization of old technology or of technology with a high rate of energy consumption or a high level of methane leakages may greatly increase the emissions from the production phase. This can particularly be noticed in the case of digestion technologies (Table 2). During the digestion process, small methane leakages and energy-intensive technology usage increase GHG emissions. However, using renewable energy in production enables the further reduction of emissions. If the latest technology has already been implemented, further potential for emissions reduction at this stage then chiefly lies in the utilization of renewable energy. According to previous studies, digestion emissions vary from 3

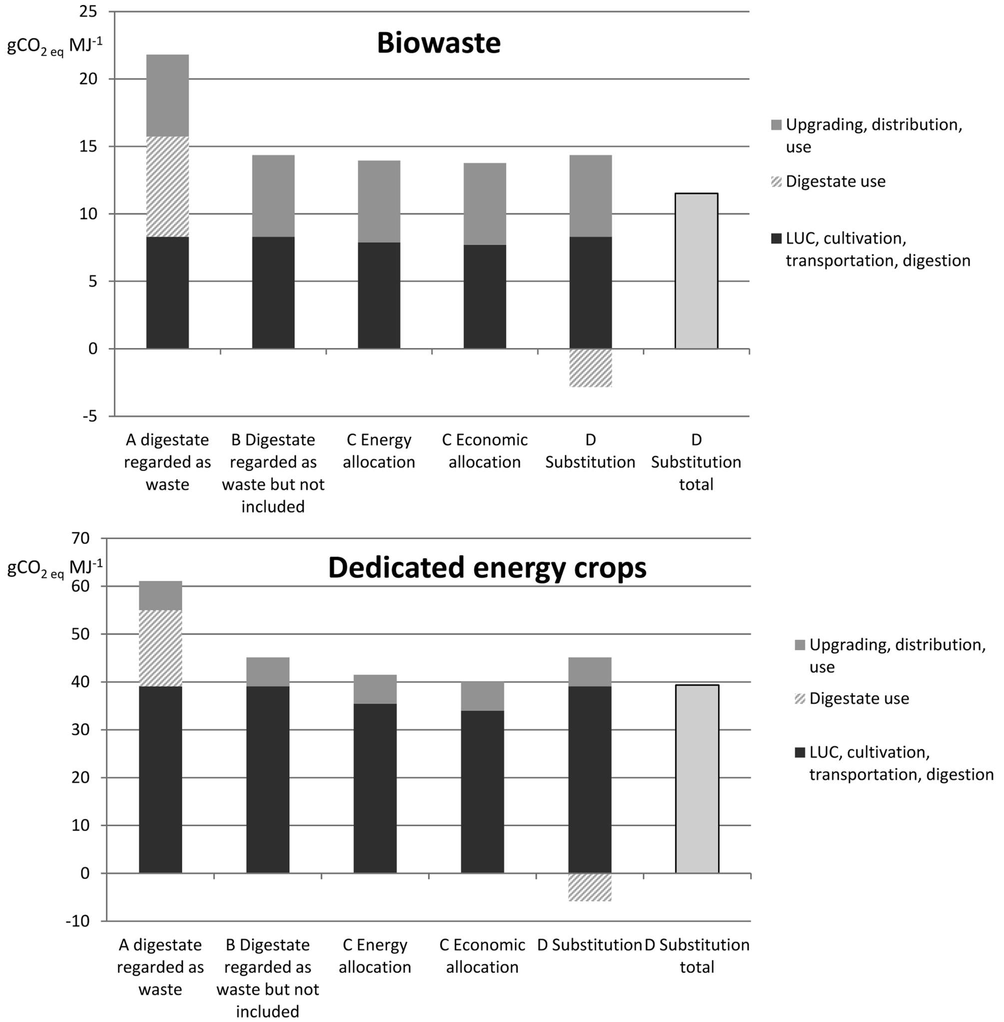

Figure 4. GHG emissions from biomethane production with various allocation methods for digestate.

to 12 gCO_{2eq} MJ^{-1}.[14,16] This study shows that emissions from digestion are 6 gCO_{2eq} MJ^{-1} (1−37 gCO_{2eq} MJ^{-1}). With low energy consumption and low methane leakages, emissions from digestion become low, and with renewable energy, emissions may virtually be eliminated. The use of quality feedstock yielding high methane productivity will further reduce GHG emissions. Feedstock quality impacts digestate quality, digestion energy consumption, and feedstock transportation. Small variations in quality do not significantly impact total emissions, but high variations in quality may do so. If digestate from the digestion process is directed to compost processes, then emissions are significantly higher than if the digestate is directed to usage on fields as fertilizer. This is mainly due to higher N_2O emissions from the compost process.

Emissions from the three upgrading options differ considerably. AW technology clearly leads to the lowest emissions with assumption made in this paper. However, it has to be acknowledged that the source data related to AW is from a manufacturer, and therefore its accuracy may be limited. PSA and WS technologies lead to high emissions, especially owing to methane leakages. PSA and WS technologies would improve considerably if methane leakages could be eliminated for example by changing the configuration of the plant. On the basis of previous studies, upgrading emissions vary from 6 to 12 gCO_{2eq} MJ^{-1};[15−17] we found upgrading emissions to be significantly lower than those values when AW technology is implemented: 3.4 gCO_{2eq} MJ^{-1} (0.3−22 gCO_{2eq} MJ^{-1}).

In terms of distribution, natural gas grid distribution leads to lower GHG emissions than does compressed biomethane distribution by trucks. Natural gas grid distribution is thus promising with regard to GHG emissions reductions. Poeschl et al. found that the natural gas grid distribution would be an important factor in enabling wide-scale production and utilization of biomethane.[8] For refueling stations not located along gas grids, additional emissions are caused by the distribution of back-up gas. Little focus has been directed toward distribution systems in previous studies. In most cases, emissions from distribution are low despite the fact that electricity is usually consumed to pressurize the gas. This paper assumes that distribution emissions are 2.5 gCO_{2eq} MJ^{-1} (0.4–9 gCO_{2eq} MJ^{-1}). What was not previously known is that compressed natural gas distribution with back-up gas distribution may greatly impact results. Emissions from grid distribution appear to be lower and are highly dependent on the electricity used in compression. In the use phase, low nonbiogenic methane and N_2O emissions are emitted by passenger cars, and slightly higher emissions are released by buses. The CO_2 from use is regarded as biogenic and is therefore excluded from this study.

For the digestion and other electricity-consuming process stages, the amount of consumed electricity is an important issue. When new production in tandem with electricity consumption is launched, it initially possibly uses marginal electricity with high GHG emissions. Over time, the structure of electricity production reacts to the changed level of consumption, and the consumed electricity will be closer to the average electricity usage. However, there is always a base consumption of lower emission electricity; therefore, the electricity used in processes may be categorized as somewhere between marginal and average electricity.[47] In Table 2, the effects of electricity use with marginal and low emissions as well as those of heat use with low and high emissions are studied for digestion, upgrading, and distribution. The effect of the chosen energy production methods are studied only for the basic technologies selected for the study. The synergy of using energy-intensive technology and emission-intensive energy production methods is not, however, studied in this paper.

In addition, different allocation methods were studied in this paper (Figure 4). Emissions from biomethane production are significantly higher in scenario A than in other scenarios. In scenario A, digestate was assumed to be waste; therefore, all emissions related to digestate handling and use are included in the emissions of biomethane. Scenario B depicts that excluding digestate utilization from the calculations will decrease the total GHG emissions significantly. Scenario C shows that with the application of energy or economic allocation methods, the majority of the emissions from common processes will be allocated to biomethane because of the low heating and economic value of digestate. Only 5–13% of GHG emissions from common process steps are allocated for the digestate. Therefore, the differences between scenarios B and C are marginal. In the future, if prices of fertilizers and digestate increase, the allocation rate for digestate would also increase, which would lead to a lower GHG emissions load for biomethane in scenario C. Scenario D shows that usage of the substitution method and replacement of mineral fertilizers with digestate leads to additional GHG emissions reduction from mineral fertilizer production. This substitution and replacement method clearly results in the lowest GHG emissions especially for biowaste based biomethane.

For biowaste-based biomethane, the effect of the allocation method is a maximum 10 gCO_{2eq} MJ^{-1}; for dedicated energy crops, it is 22 gCO_{2eq} MJ^{-1}. The usage of digestate to replace mineral fertilizers seems to play a significant role in total GHG emissions. The waste assumption method (scenario A) seems to be justified when digestate does not actually replace any mineral fertilizers or when it cannot be used in fertilizing. In these cases, emissions from digestate use can occasionally be attributed to compost processes. Economic allocation appears to be a better justified method than energy allocation, because the former takes into account the real utilization potential of digestate in terms of its economic value. Energy allocation should be employed only if the digestate is used for energy production (e.g., at an incineration plant). Scenario B, in which digestate is regarded as waste but digestate emissions are not included in biomethane emissions, is against the basic allocation rules[21,22] and should therefore be excluded. This option leads to different results than those of scenario A, and despite the fact that it is a relatively widely used method,[15,16] the results are misleading. The calculation instructions of Directive 2009/28/EC[12] define digestate as a waste because biomethane production process is not aiming to produce digestate. Therefore, calculations are made according to the methodology of scenario A, even if the methodology of scenario D would better suit the situation. Therefore, the digestate waste assumption (scenario A) of Directive 2009/28/EC may lead to unfair results if digestate replaces mineral fertilizers.

When GHG emissions from biofuel production are studied, the calculations involved should always be based on real technology and specific values used in the processes. Rough assumptions may lead to incorrect results and subsequently to incorrect decision making. As this paper has demonstrated, GHG emissions may be even lower due to specific decisions such as the use of renewable energy in production. However, the calculations were carried out by using the average GHG emission factors for renewable electricity. In addition, the selected calculation methodology plays a vital role in the results. If the various options are not taken into account, the advantages of biofuels could even be underestimated. If decision makers base their decisions on results from average calculations, they might drive biofuel development in the wrong direction, because with certain optimizations, the results might differ a fair amount. This puts business opportunities at risk, as good options may be discarded because of inexact estimations.

This study was done in a North European operational environment, but geographically speaking, our result could be more widely applied especially those related to differences between various allocation methods. Transportation, cultivation methods, land use, emissions from used energy, and means of distribution may, however, differ according to geographical location. For areas with denser population, collection and transportation distances may be even shorter than those used for the purposes of this study. In a warmer climate, GHG emissions from cultivation may be lower due to higher crop productivity and a longer growth season. According to this study, emission reductions are likely when biomethane is used in the transportation sector. This is good news, as biomethane offers a domestic fuel option that also improves energy security.

4. CONCLUSIONS

In this paper, GHG emissions from biomethane production for transportation purposes were studied from a life-cycle perspective. Both production-related factors and allocation methodologies were examined. GHG emissions of biomethane are usually lower than those of fossil fuels in the case studies. In most cases, the highest GHG emissions are emitted from cultivation and digestate use. Technologies with low energy consumption and with the utilization of renewable energies further reduce already low emissions from the production, upgrading, and distribution stages. However, technology selections have a significant effect on the results via energy consumption and methane emissions.

The selected allocation methodologies for digestate have a notable effect on biomethane GHG emissions. The effect is approximately at the same level as the variation of other important factors along the life cycle of biomethane. When mineral fertilizers are replaced with digestate and the substitution method is used, the GHG emissions of biomethane are at their lowest. In the selection of the most suitable allocation method, the actual use of digestate should be known. On the other hand, the calculation instructions and legislation may restrict the use of allocation methodologies. Depending on the given situation, digestate may be regarded as waste, it may have an economical value, it may be employed in energy production, or it may be used to replace mineral fertilizers. Emissions from digestate use should never be completely excluded from studies.

There are also several other allocation methodologies and technical solutions for biomethane production, which were not studied in this paper. In the future, changes in biomethane and digestate prices may affect the allocation results. To get a clear picture of the advantages of biomethane transportation use, comparisons should be carried out also between various waste treatment options, various other feedstock utilization options, and various biogas use options.

It appears that biomethane leads to GHG emissions reductions in transportation use, and the potential for even greater emissions reductions may increase in the future with the advent of improved technology, greener energy production methods, and higher demand for recycled fertilizers. Increasing the use of biomethane in the transportation sector may well result in significant GHG emissions reduction. Because of the limited amount of biowaste resources, wide-scale biomethane production would require the use of dedicated energy crops.

■ AUTHOR INFORMATION

Corresponding Author

*Tel.: +358 40 586 4486. Fax: +358 5 621 6399. E-mail: ville.uusitalo@lut.fi.

Notes

The authors declare no competing financial interest.

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