Master's thesis

NTNU
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Assessment of environmental benefits of cooperative biogas treatment of wet organic wastes

- A case study of a food industry company in Gjøvik

Master's thesis in Sustainable Manufacturing
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Abstract

Businesses are increasingly aiming to be sustainable and practice circular economy in their efforts to contribute positively to human and environmental health. The master thesis investigates a medium size potato processing company in Gjøvik, which presents their production line as circular, but that would like to test alternative waste management options for the excess potato ethanol stillage, which is spread on farm fields. Through literature review on waste management, circular economy and sustainability, biogas treatment was found to be an alternative. The hypothesis to be tested: Biogas treatment of potato ethanol stillage is an environmentally sustainable solution compared to today’s waste management at the company. There are few studies in Norway on environmental aspects of medium sized biogas treatment of wet organic wastes in collaboration and the thesis is a contribution to the knowledge on cases of industrial symbiosis.

Two scenarios were considered the most optimal for further analysis. Scenario 1, co-digestion of stillage, cattle manure and vegetables and potatoes farm field residues and scenario 2, co-digestion of stillage, cattle manure and clean food waste from the neighbouring area.

An analysis based on a literature review of economic, and technical aspects was done. A more in-depth environmental assessment was carried out through a Life Cycle Assessment (LCA), analysing the impact categories climate change, acidification, terrestrial eutrophication, mineral and fossil resource depletion, and human toxicity (non-cancer and cancer effects). The data for the assessment were largely secondary data, as the biogas scenarios are not current practices.

It was found that biogas treatment in both scenarios have the most positive environmental impact, except for acidification. Biogas for the use of bus transport fuel has the most positive impacts on climate change, while biogas for the use of electricity and heat was the best option in terms of human toxicity, and terrestrial eutrophication. The first confirms literature, while there are fewer studies on the other categories in similar scenarios.

The conclusion is that biogas is environmentally the best option compared with current practices. However, rough cost/income estimations of the biogas scenarios suggest that financial support for investments and higher biogas yield per amount of substrate is needed to make biogas treatment an economically viable option for the company in the nearby future.

Sammendrag

Bedrifter ønsker i stadig større grad å være bærekraftige og praktisere sirkulær økonomi in deres mål for å bidra positivt til samfunnet og naturen. Denne masteroppgaven undersøker en mellomstor potet foredlingsbedrift på Gjøvik som presentere deres produksjonslinje som sirkulær praksis, men som ønsker å teste ut alternative muligheter for avfallshåndtering av overflødig drank fra etanol-produksjon, som blir spredt på åker. Gjennom litteraturgjennomgang om avfallhåndtering, sirkulær økonomi og bærekraft, ble biogass produksjon ansett som en alternativ mulighet. Hypotesen for studien for denne oppgaven er: Biogassproduksjon av drank er en miljømessig bærekraftig løsning for avfallshåndtering sammenlignet med dagens praksis for avfallshåndtering. Det er får studier i Norge om miljømessige aspekter av biogassproduksjon fra våtorganisk avfall i samhandling og samarbeid og denne studien er et bidrag til kunnskapsbasen om caser av industriell symbiose.

To scenarier ble valgt for videre analyse. Scenario 1, sambehandling av drank, storfegjødsel og restavlinger av grønnsaker og poteter, og scenario 2, sambehandling av drank, storfegjødsel og rent matavfall fra naboområdet.

Det ble gjort en analyse av økonomiske, og tekniske aspekter basert på litteraturgjennomgang. En mer grundig miljøanalyse ble gjort gjennom en livssyklusanalyse der kategoriene klimaendringer, forsuring, eutrofiering, utarming av minerale og fossile ressurser og menneskelig toksisitet ble undersøkt. Data for analysen var i stor grad basert på sekundære kilder da biogass-scenariene ikke er nåværende praksiser.

Funn tilsier at biogassproduksjon av drank har mest positiv effekt på miljøkategoriene, unntatt for forsuring. Biogass for transportbrensel hos busser har mest positiv effekt for klimaendringer, mens biogass for elektrisitet og varme-bruk er det beste valget når det gjelder menneskelig toksisitet, og eutrofiering. Det første bekrefter litteratur, mens det er færre studier som undersøker lignende scenarier for toksisitet.

Konklusjonen er at biogassproduksjon er miljømessig det beste alternativet sammenlignet med nåværende praksiser. Men grove kostnads -og inntektsestimater av biogass-scenariene antyder at økonomisk støtte for investeringer og høyere biogassutbytte per volum av substrat trengs for å gjøre dette produksjonen til et økonomisk levedyktig alternativ for bedriften i nær framtid.

Preface

This paper was written as part of the master programme, Sustainable Manufacturing at NTNU Gjøvik. The master programme has introduced me to an interesting field of knowledge that has really complemented previous studies of social science, as well as added value to my professional life.

I thank my supervisor Lizhen Huang for always being very encouraging and supportive, even when I faced some obstacles along the way. This thesis would not have been possible to write without the staff and leadership at HOFF SA, who have given me the opportunity to learn about the company’s production, challenges and plans. Among those, Gaute Njå, at HOFF Jæren, who has answered questions throughout the whole process. In addition, Egil Andersen has been kind to answer many (stupid) questions about the biogas process and let me observe a production facility in its making.

The learning curve has been steep, as I used this thesis to learn more about life cycle assessment and renewable resources.

I thank friends and family for their patience during this time when full time work and part time studies took most of my time. And finally, my better half for having listened to biogas talk for over a year.

Leyla Kutlu

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Abbreviations

AD	Anaerobic Digestion
C:N	Carbon Nitrogen ratio
CBG	Compressed Biogas
CE	Circular Economy
CH4	Methane
CO2	Carbon dioxide
CSTR	Continous Stirred Tank Reactor
DM	Dry Matter
EU	European Union
FAO	Food and Agriculture Organization
fU	Functional Unit
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
N2O	Dinitrogen monoxide
NH3	Ammonia
NOx	Nitrous oxides
NTNU	Norwegian University of Science and Technology
SO2	Sulfur dioxide
UNEP	United Nation Environmental Programme
VS	Volatile Solids

1 Introduction

1.1 Sustainable companies

As global actors, companies should contribute to the UN Sustainable Development Goals. Goal number 12 is most relevant: “Ensure sustainable consumption and production patterns”. Targets for this goal are among others waste reduction, sustainable management of natural resources, and to report and inform the public on environmental issues of the product or service (United Nations, 2019).

Environmental issues, and in particular climate change, have increasingly appeared higher on the agenda of governments and the public. Many companies, too, want to take part in the development of making the earth healthier for the generations to come. Some may argue that they are only doing so to be “green” and sell more products, while others argue real engagement to the cause. Whatever the reasons are for contributing to less environmental footprint, to succeed it is important that the drivers of consummation of commodities and services play a big part in the reduction of the related footprint.

In Norway, there are several companies that promote themselves as drivers of solutions rather than being drivers of the problems. And circular economy is the global buzz word in the private sector that give companies an entry point to discuss sustainable solutions.

1.2 HOFF – a circular food-based company in Gjøvik

HOFF SA, with their main office in Gjøvik, is a company that would like to find the highest utility and value of its production resources. HOFF is a potato product production company, which uses about 1/3 of Norwegian potatoes for the production of frozen potato products, such as pommes frites and vegetable burgers, as well as fabricated mashed potatoes and potato starch. In addition, HOFF produces industrial products for the use in other food products, such as ethanol and glucose. Their production factories are located in Gjøvik/Brummundal, Innerøya and Jæren, and most of the shareholders in the company (244 of 519) are potato contract farmers that provide the raw material to the factories. Today, HOFF produces around 100 different products for households and the food industry, of which some under their own brand and some under other companies’ brands (HOFF SA, 2018a, 2018b, 2018c).

HOFF uses potato waste to make ethanol for aquavit and starch from potatoes that cannot be utilised for food and otherwise had been disposed. They receive incentives for the reception of "non-edible" potatoes from farmers and other potato manufacturing companies through the agriculture agreement between farmers and the government. With these funds, HOFF is able to produce ethanol, which the company Arcus uses for aquavit production (HOFF SA, 2018c). In Norway, ethanol production may be valuable, as HOFF is the only source of ethanol based on Norwegian potatoes for the traditional Christmas liquor, aquavit. The waste products from the ethanol production, a stillage, is used as fodder for cattle in the surrounding farms. HOFF refers to circular economy when presenting their production line and waste management, (Figure 1.1) and states that the practice is efficient (Norsk Landbrukssamvirke, 2017). From interviews with the leader and other staff at HOFF, it appears that they do not have a specific strategy for circular economy, however, they are looking into making a sustainability strategy or similar. Even though the potato material flow is circular, HOFF expresses that the company would like to use the ethanol and starch waste products in an even more economically useful way, as the waste management are costly (Flønes, 2017). This thesis research will focus on options for the potato ethanol stillage to limit the study to the factory in Gjøvik.


Sirkulær økonomi i HOFF

- verdens beste poteter

Figure 1.1 Circular economy in HOFF, as presented by HOFF (not published)

1.3 HOFF's challenges

The waste from the ethanol production, is a water-based stillage, containing around 6% (according to tests by HOFF) dry matter (DM) from the potato and yeast nutrients. According to HOFF staff, there are considerable costs every year on the current practice of transporting the stillage to farms and their challenge is to increase their income from by-products from both ethanol and starch production (Njå, 2018a). Consequently, HOFF has investigated several options of waste value addition, and the following were mentioned by several HOFF staff during interviews for this study:

- Protein for fodder (at HOFF Brumunddal)
- FiberBind – ingredient for food items (KMC Danmark)
- Potato peel for medicine (IDIA biotech) – Hedemark Høgskolen Innlandet
- Biogas – (at Jæren municipality waste management facility)
- Paper fibre/micro fibre (Papir og fiberinstituttet)

HOFF has initiated pilots on a few of these alternatives, but none of them have so far gained any momentum for scaling up. When asked about prospects and interest to invest in any of these, biogas and paper fibre products are mentioned as the most interesting. One main technical challenge in the development of the products is the fact that there is plenty of water in the stillage, which requires costly methods for reducing the water. HOFF would like to start this process; however, they have not invested resources for it yet (Njå, 2018a). Generally, HOFF is much more invested in their major products, which are the food items for household consumption, and they are spending resources in diversifying their product base of these (HOFF SA, 2018c). According to Njå, HOFF wishes to maintain the delivery of the stillage by-product as fodder to cattle even though it is costly, because farmers regard it as a useful supplement to the regular fodder. This usefulness was also mentioned in a study of the stillage from the ethanol production at HOFF in Innerøya (Nesheim, 2010). The challenge is, however, that there are not enough farms to receive the stillage and much of it must be spread out on the farmers' fields as fertiliser. Although providing nutrients to the soil, the stillage is not counted by the farmers as fertiliser in their fertiliser plan (Njå, 2018a). In 2018, HOFF moved their ethanol production in Innerøya to Gjøvik, leading to greater amounts of stillage. In 2015 and 2016 the amount of stillage was almost 30 000 m3, whereas now it is around 45 000 m3, according to numbers from HOFF. In 2016, the amount spread on farmers' fields was about 30% (10 000 m3), however even with the increase in total stillage in 2018, HOFF is only left with 15% of it for spreading (around 7000 m3). It means that they have been able to deliver stillage as fodder to more farms. The situation may be different the following year, as the greater amount of deliveries in 2018 was probably connected to the fact that weather conditions without any rain led to lack of fodder to the cattle in the Southern parts of Norway. This situation shows that extreme weather events can influence the amounts from year to year and viable solutions for HOFF may require some amount of flexibility.

1.4 Management of stillage waste

At a global level, very few factories produce potato-based ethanol (Nesheim, 2010) and the ones that exist are mostly located in Norway, Poland and Germany. Through literature search, few studies were found on the usage of stillage from this type of ethanol. Ethanol productions from crops such as maize, wheat, barley, sugar cane, sweet potato and beet roots are found on a much bigger scale and even though nutrient content may be different, one can base ideas of alternative waste management methods on these productions. In a literature review of new technologies and potential uses of corn thin stillage, Reis, Rajendra and Hu (2017) go through researches on many different value addition options of the stillage waste stream. Today, removing the water content from the stillage is associated with costly operations. And profit margins of ethanol production itself are narrow and thus the sector can be increasingly dependent on benefits from co-products. Some of the reviewed options are oil extraction, anaerobic digestion, re-fermenting the stillage in the ethanol production, extraction of high-value products, and energy production.

Potato ethanol stillage is a wet organic waste type. Wet organic wastes, which are food waste and organic waste from food industries, make up 4% of total waste in Norway (in 2017) (Miljødirektoratet, 2019). It became illegal to deposit wet organic waste to landfills in 2002, after regulations from the EU were included in Norwegian regulations with the aim to decrease environmental problems such as emissions of greenhouse gases. The result was that wet organic waste in landfills decreased, while the total wet organic waste production increased.

In terms of other waste management options of wet organic waste, two alternatives have increased after the prohibition, namely management for energy recovery (mainly through biogas) and composting (Miljødirektoratet, 2015). According to Statistics Norway (2019b), however, waste from food based industries that are composted have decreased from 90 000 ton in 2008 to 22 000 ton in 2015, while treatment through biogas has increased from 21 000 ton to 70 000 ton in the same period. A study by Nofima on wastes from industrially processed organic material, such as fruits and vegetables and animals, finds that there is around 415 000 ton waste in total per year. Wet organic waste from potato ethanol and potato flower (which to a large degree are produced by HOFF), make up 70-85 000 m3 per year. As described in above chapters, it is used as fodder and spread at farm fields. The brewery sector is one HOFF can be compared with. In this sector, it is assumed a total of 17 000 ton of waste products, such as spent grain, which is usually used as animal fodder (Lindberg *et al.*, 2016, p. 32). Spent grain usually has a much higher dry matter content than ethanol stillage, meaning less water content per organic matter (Store Norske Leksikon, 2017).

All though changing waste management types has decreased environmental problems, the most important effort, mentioned by the Norwegian Environmental Agency is to decrease the amount of waste through measures that reduce the amount of wet organic waste from production (Miljødirektoratet, 2015).

Considering waste management in Gjøvik and surrounding areas, the municipal waste is handled by the inter-municipal company, Horisont (former GLT). Horisont collects household waste of food, paper, plastic, tin cans and glass, and general residue waste. Special and more dangerous wastes must be delivered at their waste facilities, including one landfill area (Horisont Miljøpark IKS, 2019). Horisont, together with other municipal renovation companies in the area, own Mjøsanlegget, which is a biogas facility close to Lillehammer. Much of the municipal food waste are sent there for biogas treatment and upgrading to gas for transport fuel (Mjøsanlegget, 2019b). In 2016, Horisont managed 59 000 ton, of which 5000 went to landfill, 25 400 to biogas, and 9500 to recycling or reuse. 5663 ton of the total was food waste (GLT Avfall, 2016, p. 8). According to HOFF, the potato ethanol stillage waste is not interesting as substrate in this biogas process as it contains much water (Njå, 2018a), although in theory the municipal facility could accept waste from private companies to certain costs (Nesbakk, 2018).

1.5 Waste and policy goals

Horisont has many environmental goals with related on-going projects, such as using landfill gas to energy, increasing biodiversity, replacing diesel renovation trucks with biogas, and reducing CO2 emissions from waste management processes (Berg, Jarstad and Rønning, 2019, p. 4). From the perspective of Gjøvik Municipality, they emphasise mostly on climate change reduction and energy production in policy papers and plans regarding waste management. Their plan (2018-2022) describes some of the climate change issues. Calculations of emissions of CO2 equivalents in 2015 by The Norwegian Bureu of Statistics show that the Municipality emits over half in the transport sector (51%), followed by emissions in the agriculture sector, of which most is related to livestock farming (25%), and gas from landfills (13%) (Gjøvik kommune, 2018a, p. 18). Compared to 2009, emissions in the transport and agriculture sectors have been stable, but increased somewhat, while emissions from households and companies have decreased and it is assumed that the establishment of district heating from Eidsiva (wood waste incineration), contributed to this decrease. Further, emissions from landfill gas has decreased by 30% (ibid, p. 20).

Based on the above-mentioned information, Gjøvik has planned for the reduction of greenhouse gases. Gjøvik wishes to promote itself as active and hired its second environmental and climate advisor in 2018 (Dale, 2018). The municipal plan for Gjøvik states a goal for the reduction of climate gases and to eventually become climate neutral. One strategy to achieve this goal is to use more renewable energy sources through for instance expanding the use of the existing district heating system for heating of buildings. In relation to waste, the goals are to further decrease landfill emissions, and to use link a waste treatment plant to the district heating network (Gjøvik kommune, 2018b). Oppland district also shares some of the same climate change challenges and goals, and they also emphasise the reduction of landfills and energy production (Oppland fylkeskommune, 2013). In neither of the policy plans, wet organic waste is mentioned. In Gjøvik Municipality's policy plan for the agriculture sector (2017-2022) (Gjøvik kommune, 2017, p. 16), which HOFF is part of, it is stated that agriculture should contribute to sustainability, and knowledge and skills on bioenergy should be developed. In addition, that facilities for bioenergy with production capacity of above 50 Gwh should be established, something that must be a wrong figure as it will imply the potential of two biogas plants at Mjøsanlegget.

At a national level, several ministries in the Norwegian Government joined forces to publish a 10 year strategy for bio economy, where it emphasises the importance of circular economy and states that it would like to support more usage of wasted resources to profitable products and that reduction in market insecurities for bio-based products shall be supported, through for instance investment support and increasing the required share of vehicle fuel from biofuel and the share of biofuel from waste (Nærings -og Fiskeridepartementet, 2016). Likewise, circular economy and the better utilisation of waste products has been emphasised in the white paper from 2017 on waste as resource and circular economy. Regarding wet organic waste, there is an aim to facilitate sorting of household waste and the same for wet organic waste from companies. They expect that increased sorting will lead to cleaner general waste and the opportunity to increase the production of biogas (Klima og Miljødepartementet, 2017a).

The ideas of waste as a resource are to a great degree inspired by the European Union. The European Commission launched an ambitious package and action plan for stricter waste management directives in 2015 aiming for waste to be more circular resource efficient (Klima og Miljødepartementet, 2017a).

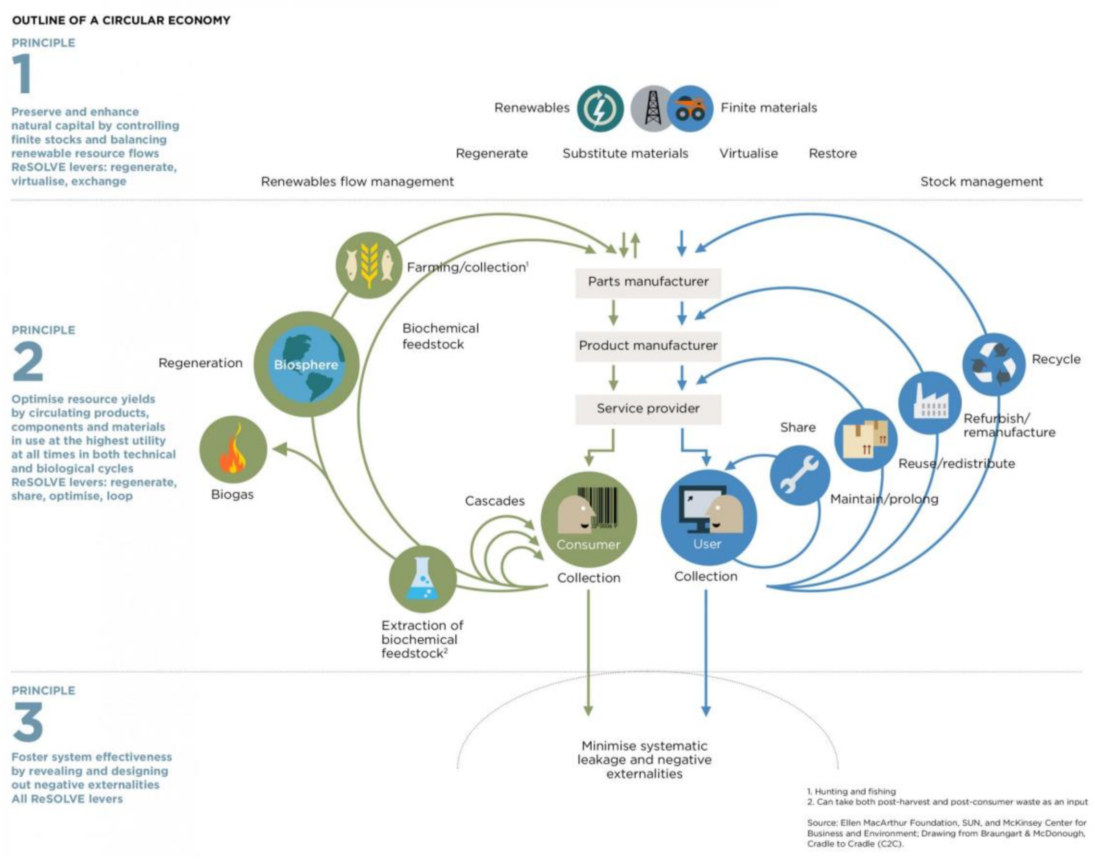
2 Theoretical approaches

Some of the frameworks that are used to discuss and find waste management options and other types of production for sustainability are presented in this chapter. These are useful for the analysis and discussion for this thesis. As EU, the Norwegian government, and even HOFF use the terms circular economy and sustainability, it is useful to understand them to understand waste management options.

2.1 Circular economy

Circular economy (CE) has emerged as a possible solution in manufacturing to tackle resource supply scarcity, as well as to carry out obligations in relation to environmental legislation on waste management and other environmental issues. Because of this, reuse and so-called "closing the loop" of resources are ideal solutions. Some of the underlying assumption and theorising around circular economy come from thermodynamics where the laws are saying that all materials/energy are inputs to other materials/energy (Lieder and Rashid, 2016). CE's definitions have been various since, however, the definition and understanding mentioned by many researchers (Lieder and Rashid, 2016, Geissdoerfer *et al.*, 2017) is the one by Ellen MacArthur Foundation, "A circular economy is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all time" (Ellen MacArthur Foundation, 2019). This foundation is also said to have done a lot for the development of the research field and discussion of concepts related to circular economy. Furthermore, some countries have put CE on the agenda with their policy papers on the issue. Germany and Japan were early out, talking about "closed resource cycle" and "recycle-based society" and later China and EU talking about circular economy (Geissdoerfer *et al.*, 2017, p. 759). In these policies and implementation papers about circular economy, there is also an emphasis on the fact that being more circular will also have economic benefits (Lieder and Rashid, 2016). Based on double benefits, the thinking attracts many businesses and manufacturing companies.

From Ellen MacArthur Foundation we have learned that CE thinking has many elements and that CE is about making an optimal system, more than just thinking about the material of the item. The Foundation promotes closed loops and these loops should be as small as possible, meaning that it is most often better that a user of an item maintains the item and keeps it longer than having the manufacturer of the item to collect it after use for the reuse of the next user or purpose. Additional principles in this understanding of CE are the use of renewable sources of energy, and making as little leakage of energy and waste from the system as possible. The most used illustration for these ideas can be found in the figure 2.1.



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Figure 2.1 Outline of a closed loop system - circular economy (Ellen MacArthur Foundation, 2016)

From the description of the Foundation’s ideas, it may seem as they only focus on the environmental issues regarding circular economy, however, it is somewhat the contrary as they also emphasise the fact that product design, business models and system thinking, among others are important for the implementation of CE.

All though Ellen MacArthur Foundation focuses on the business elements of circular economy, there may not be a clear consensus on CE’s content among researchers and practitioners. In the research review *Towards circular economy implementation: a comprehensive review in context of manufacturing industry* (Lieder and Rashid, 2016), the authors had found that there is a lack of research on benefits in economic terms and also little mention in the reviewed papers of competitive advantage, something that businesses must deal with on a daily basis. They propose a comprehensive framework, including economic, social (managerial) and environmental issues at the manufacturer, as well as policies and collaboration at the national or governmental level that promote CE. There is a need to also deal with stakeholders outside the company.

Other criticism of the CE concepts, by for instance Murray (2017), cited in Rizos, Tuokko og Behrens (2017), has been related to the lack of social aspects, such as equality and social opportunities.

These ideas lead to a more systemic view and focuses more on holistic approaches that we can find in theories around sustainability.

2.2 Sustainability

As mentioned above, researchers seem to suggest a holistic approach for circular economy. It can be useful to take a look at sustainability, as these theories are sometimes linked. During interviews, the HOFF management mentioned plans to outline a sustainability strategy in the near future.

A commonly used definition of sustainability consists of 3 aspects; namely economic, social and environmental sustainability (Harris, 2000). Further, to make a company sustainable it is among other issues, necessary to look at how the company is serving the needs of the costumers in the future. It should also serve these needs without compensating the needs of the coming generations, according to the Brundtland Commission’s definition of sustainability (World Commission on Environment and Development, 1987).

Sustainability is important for any company and nonetheless a manufacturing company as the reality is that it needs to relate to what is outside the four walls of the manufacturing system. Sustainability analysis is needed as the company's future will depend on how it coexists, affects and is affected by economic, environmental and social factors (Haapala *et al.*, 2013). Many theorists have linked sustainability with systems theories, as these theories help describe and understand complex systems, which sustainability can be regarded as. Because sustainability is not a static situation, but rather a non-linear and a dynamic process (Hjorth and Bagheri, 2006), systems theories offer a better framework to understand how elements of sustainability interplay, than other conventional cause-effect methods. One example is through looking at viability loops in Hjort and Bagheri (2006). These theories offer visualisations or modelling of complex systems, including how strong a system is over time or how well adapted or flexible it can be. The theories look at sustainability as a process and the system should cope with changes, for it to survive over time.

The focus on external environment is also emphasised by Josef Fiksel (2003) as he introduces resilience in the definition of sustainability. A resilient system is able to withstand many stressed situations or rearrange to balance again rather quickly after a bigger disturbance and learn from the situations for further improvement. If resilience of the manufacturing system is the goal, we also need to design it with external factors in mind, according to Fiksel.

Understanding sustainability as a system is in line with the broader understanding of circular economy. However, there are a few issues that may not be obvious when thinking in terms of circular economy. Chaos theory is described in the article from Hudson and Vissing (2013), *Sustainability at the Edge of Chaos: Its Limits and Possibilities in Public Health.* The article states that sustainability theory should not only consider whether a system should continue to exist, but whether it meets the needs we have. Needs can be the needs of the humans or nature. When looking at needs, the system under consideration may expand or cease to exist depending on the dynamics of the needs over time. Further, the authors emphasise that it is important to make sustainability a more concrete subject of analysis and make the suggestion of looking at the needs in particular to make it more concrete and assess whether we are meeting these needs.

2.3 Circular and sustainable businesses

In the literature review, *The Circular Economy – A new sustainability paradigm?,* Geissdoerfer *et al.* (2017), are looking at the differences and similarities between CE and sustainability in previous research papers. The authors conclude that the best way to understand circular economy in relation to sustainability is by looking at CE as one of many solutions for sustainability, as a “subset relation” (Geissdoerfer *et al.*, 2017, p. 766). Furthermore, this approach makes it possible for a business that is going to implement a more sustainable production to complement CE with other approaches, such as sustainable business models. The authors propose an approach that includes focus on stakeholders involved in the circular system, to combine the specific with the more holistic.

Introducing sustainable business models as complementary to CE, is in line with the first presented understanding of circular economy from the Ellen MacArthur Foundation. In the research paper by Bocken et al. (2016) the authors ask the question about how a business can move to a more circular economy and what business strategies can they use. When designing a product, the authors say that there are two main strategies to take, namely closing the loop or slowing the loop. The first has to do with using resources again in the production cycle, and the latter has to do with making the product last longer, for instance through maintenance services for the user. Business model strategy for slowing the loop can be quality product assessment (long lasting), as for closing the loop it can be to extend resource value, or industrial symbiosis. The latter is collaborating with other businesses on closing/slowing the loop. Collaborations are often promoted for sustainable business models, such as in the paper *Towards a more Circular Economy: Proposing a framework linking sustainable public procurement and sustainable business models* (Witjes and Lozano, 2016). The authors propose a collaborative framework between supplier and procurer for the improvement of sustainable procurement processes -and business models for the reduction of costs and waste for both parties. Further, in this article, sustainability and CE are discussed as interlinked concepts.

Sustainable business model concepts are linked to both circular economy and sustainability. In an article about business model evolution (Short *et al.*, 2014), a case of British Sugar is presented as an example of how different business models have been developed within the company. The authors emphasise the innovativeness, during the developments, in particular, how waste streams continuously have been used as new products. The company has gone through 3 stages of focuses, namely focus on reducing costs through efficiency, to focus on minimising waste through new opportunities, and lastly to focus on sustainability as a driver of competitive advantage. The latter requires proactive innovation, meaning that more radical innovation is needed. This article touches into the fact that businesses are able to deliver sustainable impacts, and at the same time, sustainability is a business driver.

2.4 Waste hierarchy aspects

Another approach to consider in waste discussions, and which is linked to circular economy and often referred to when discussing waste options, is the waste hierarchy. “The waste hierarchy is the cornerstone of EU policy and legislation on waste and a key to the transition to the circular economy”, states the European Commission in it communication paper (European Commission, 2017, p. 3). The waste hierarchy illustrates the environmentally preferred waste management options by categorising them in five management options. Reducing waste is the preferred method, followed by reuse, recycling, recovery (e.g. energy recovery), and disposal.

To illustrate, HOFF’s practice today could be considered as reuse, as the potato ethanol stillage is utilised as fodder. The rest, which is not utilised as fodder, can be considered as recycling or in worst case even disposal, as the farmers at the moment do not count the stillage as fertiliser. In terms of wet organic waste, it would, as also mentioned in the introduction chapter, be preferable to reduce the amount of the waste in the first place. Reusing waste may happen if one can extract some products from the waste, for instance by dewatering the waste and make medicine, as was one idea at HOFF, or with their current use. In addition to animal fodder, energy recovery has been mentioned the most times in Norwegian policy papers regarding the use of wet organic waste, and disposal is avoided.

Although this is the preferred hierarchy, it may not be a fact that the waste management options on top are more environmentally friendly than the lower options in every case. There is a need to investigate the best option case by case. However, the waste hierarchy is useful to follow, as one can get lost in circular economic options of reusing waste rather than reducing the waste in the first place. But again, it comes down to whether the reuse can be more environmentally friendly.

2.5 Biogas as a waste management solution

Returning to HOFF's challenge, the review of waste management options and policies, as well as understanding circular economy and sustainability, biogas treatment of potato ethanol stillage is chosen as the focus of this thesis research. The reason is that biogas may also work well with waste management of potato waste, and thus reduces risks if the agreement of ethanol production subsidises breaks. Biogas production can possibly offer the same waste management function as does ethanol production of potato waste. In this way it can offer some flexibility, which is important in sustainability terms. Another flexibility it can offer is that biogas production is not limited to one substrate. It means that if HOFF would choose to focus on value addition of other crops from farmers, such as vegetables, biogas production can still be utilised. In this way, it can provide possible future needs of the farmers. Farmers can also send manure to a biogas plant. In circular economic terms, biogas can facilitate cooperation with other stakeholders in Gjøvik with suitable other organic waste types, as bigger biogas units are often more efficient. In term of the waste hierarchy, biogas treatment of waste is energy recovery , production of biogas, and recycling, as the by-product digestate is considered recycling material of the substrate if utilised as fertiliser (European Commission, 2017).

To summarise, HOFF's practice today may be better in the framework of waste hierarchy, however, biogas may be more environmentally sustainable and better in terms of circular economic concepts, such as industrial symbiosis and collaboration for flexibility. In this paper options of biogas production is investigated further, with a particular focus on environmental benefits, as HOFF's management today may already prove to be environmentally friendly.

3 Research objectives

It is interesting to find out whether a waste management type as biogas really is more sustainable than the way HOFF already treat the waste today. Many studies have been carried out on biogas production benefits, but there are not many on biogas treatment in cooperation from the perspective of a company. To limit the research, the environmental aspects are focused upon. The hypothesis the research tries to answer is:

- Biogas treatment of potato ethanol stillage is an environmentally sustainable solution compared to today's waste management at HOFF.

To investigate the above, related research questions are:

    - What are possible solutions for sustainable biogas production for HOFF?
    - What are environmental impacts from the possible solution of biogas treated waste compared to today's waste management?

4 Methodology

To understand more about biogas and today's situation at HOFF, first-hand semi-structured and informal interviews on telephone or in person were carried out. Observations have also been used – to observe potential biogas plant facilities and to understand more about HOFF's production of potato ethanol stillage.

Most of the data gathered for the analyses are based on secondary data and a literature review has been carried out, concentrating sources related to biogas and waste management in Norway. The most well-known research institutions for waste management, LCA and agriculture have been used to get the most valid information. Swedish sources, and other international sources have been used where few Norwegian data were found.

To find the environmental impacts of the suggested scenarios of biogas, the chosen method is Life Cycle Assessment (LCA). LCA is a method to assess a product's life cycle, which is included in the International Standards (ISO) 14040 standards. One can assess specific environmental impacts of this product based on a functional unit of that product. It does not, however, assess other sustainability aspects, such as social aspects (Klöpffer and Grahl, 2014, p. 1). Allthough the starting point was sustainability issues; social aspects are not included to limit the focus of the thesis. The software SimaPro was used to carry out the assessment. The Ecoinvent database version 3 was used and the chosen method to analyse the data was ILCD

2011 Midpoint+ version 0.10, which is a method published by the European Commission, Joint Research Centre.

The LCA method has a framework that all users of the method must apply to the assessment. Figure 4.1 shows the framework’s principles that shall ensure transparency in data and analysis to enable validation of the assessment and possibilities for comparing the assessment with other assessments. The arrows in the framework represent the iterative nature of LCA, which means that during the different framework phases, one need to go back and forth, adjusting the goal and scope, inventory and the impact categories chosen (Klöpffer and Grahl, 2014).

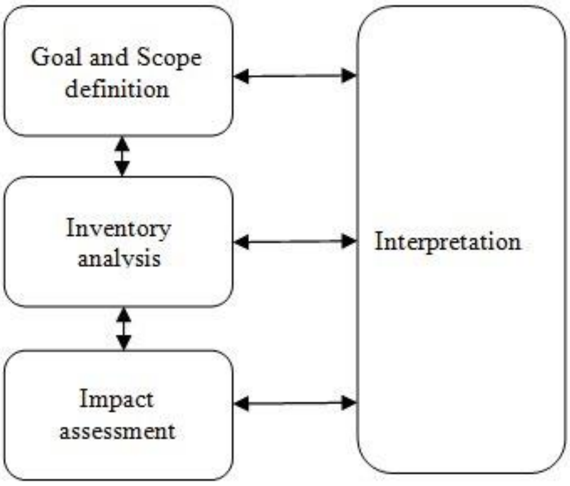


Figure 4.1 LCA phases according to ISO 14040 2006

Goal definition should answer the questions of what the objectives of the study are; why the LCA is conducted; for whom; and whether comparative assessments are intended. The scope definition must define the boundaries of the assessment. This is important for knowing which processes and functions of the system are included in the assessment. Including in the scope definition are cut-off criteria, where one may exclude more insignificant process units based on mass, energy or environmental relevance. The system boundary is also geographically boundaries or time horizons. Further, the functional unit shall be defined as the reference for the data of all processe. The functional unit should reflect the goal of the assessment and in other words the function the process is dealing with (Klöpffer and Grahl, 2014). For instance, in waste management, a waste mass unit (e.g. m3, ton) to be treated is often used as a functional unit. The impact categories to be used in the assessment shall also be carried out when scoping, as it guides the type of data to collect (ibid).

The life cycle inventory (LCI) analysis is a compilation of data on input and output of the product, in terms of quantified data on material and energy flows. Inputs are materials or electricity used to make the product and outputs are the finished product, the emissions and waste from the process of making that product. One important aspect of LCI is the definition of allocation methods, meaning how the environmental burdens are allocated, for instance when there are two outputs of co-products from a process. As it is challenging to find the exact burden on each product, allocation rules are applied, normally based on mass. System expansion is another allocation method that give the opportunity to for instance include co-products in the system assessed. For instance, it can be useful to do this when comparing systems' environmental burdens or benefits overall. In this case, the co-product is regarded as an added value (ibid.).

Impact assessment are different ways of analysing the inventory data, and there are several methods to choose from. Many of these impact assessments are also standardised, so that it is easier to compare assessments. Interpretation, which is a discussion of the uncertainties, must be carried out based on the mentioned three phases. Included here is the sensitivity analysis of the data and results (Klöpffer and Grahl, 2014).

5 Biogas potential

A literature review of biogas production and related issues were carried out to enable an analysis of possible optimal biogas solutions for HOFF. This chapter presents important issues to consider in the analysis of biogas production options. In chapter 6, information on and arguments for choosing certain biogas scenarios for further investigation are presented.

Biogas is made through a process of anaerobic digestion (AD). AD happens when organic matter is broken down by microorganisms without access to oxygen. Different organic substrates can be utilised to make biogas, however, depending on which, the biogas potential can be very different. Especially substrates containing a lot of fat, proteins and carbohydrates have a greater potential of yielding gas. The AD process most often happens in a cylinder tank, where the gas is collected on the top of the tank. There are also other types of tanks on the market with different features. The process normally takes 14 to 30 days in the cylinder tanks. The rest of the product that is not biogas, is a wet slurry (digest) that can be utilised as fertiliser. The biogas normally consists of about 60 % methane and can be utilised for energy, and most often it is utilised for vehicle fuel (if upgraded) or electricity and heating. Benefits of biogas are seen in environmental terms when the biogas substitutes products that are less climate friendly and economically when it can reduce costs for fuel, electricity and heating (Biogass Oslofjord, 2018).

5.1 Policies and incentives for biogas investments

Policies and incentives are important factors for a company to consider as they are often a driver to start initiatives with high risk. The recent years, biogas production has been promoted as a waste management option mainly because it can contribute to reduced environmental problems. The major driver for the Norwegian Government to put investments in biogas on the agenda is that it has the potential to contribute to decreased climate gases in the atmosphere that cause climate changes. The Government's climate strategy until 2030 (Klima og Miljødepartementet, 2017b) presents Norway's emission goals, which are mainly based on the goals of the European Union. The use of biofuels is mentioned as one strategy to reduce emissions in the transport sector. For the transport sector, which is outside the quota system, which all the signatory countries to the IPCC climate agreement must follow, Norway has its own reduction aims. These aims are reduced emissions in the sector by 35-50 % from 2005 to 2030, and further zero emissions by 2050. Further, to reach these aims, to develop a national plan for the development of infrastructure for alternative fuels, for instance charging or filling stations for electricity, hydrogen and biofuel driven vehicles. These infrastructures shall only be supported in the beginning and have to be profitable after some time (ibid., pp. 53-54).

Numbers from 2016 show that 99% of biofuel used in Norway are imported, which are mostly conventional biofuels (based on food crops). The European Commission, of which Norway follows the regulations, has also stated that it will no longer recommend counting biofuels made from food crops as a renewable source as it is it competing with land areas and food consumption by humans/animals. This means that other more renewable sources of biomass will be preferred in the future. Per January 2017, the Norwegian Government requires that fuel must be mixed with at least 7% bio-based fuel, as of which 1,5% must come from advanced biofuel types (based on waste). The target for the first will be increased to 20% and for the latter to 8% towards 2020. There are no CO2 taxes for biofuel use and from 2010 there are no road taxes for vehicles using biofuels above the required share, however, there is no differentiation between conventional and advanced biofuels (Klima og Miljødepartementet, 2017a, p. 28). All though the taxes apply to biogas, biogas cannot be used to fulfil the required share in a fuel mix as of today's regulations, mainly because the availability in Norway is low (Klima og Miljødepartementet, 2017b, pp. 74-76). Biogas is mentioned as a strategy to decrease emissions in the agriculture sector, more specifically to manage manure as a biomass to make biogas for local heating (ibid., p. 80). The above implies that it is difficult today to invest in biogas to fulfil the climate change goals in the transport sector, even when policy papers mention biogas as a source of transport fuel (as described in chapter 1). Jens Måge at the Norwegian organisation for waste management and recycling businesses, Avfall Norge, points out in an article that the current Government has not lowered the taxes for biogas compared to other non-renewable fuels in the national budget for 2018, nor have it given biogas vehicles the same benefits as electric and hydrogen driven vehicles. (Måge, 2018).

There are several examples of biogas being rejected, and recently the Norwegian public transport company, Ruter, chose imported biodiesel driven buses over locally produced biogas in a tender competition because the latter was too expensive, even when the district authorities preferred the use of biogas (Johnsen, 2019).

The Government also launched an intersectoral biogas strategy in 2014 (Klima og Miljødepartementet, 2014), stating that they want to facilitate better the production and utilisation of biogas as a strategy for Norway to emit less carbon gases when it is an economically good solution. Further, the Government will give incentives for investments in the sector and for facilitating market for biogas. The incentives are to support knowledge enhancement on biogas production through research support; to further develop a fund for biogas plan development support, which is administered by Enova; to consider a decrease of road taxes for vehicles on biogas; to give incentives to increase the access of wet organic waste for biogas production, which is low in the country; to be stricter on regulations for storing and spreading manure, something which may increase the biogas use from manure; to give support to farmers that deliver manure to biogas plants; and to establish a national contact forum for biogas interested (Klima og Miljødepartementet, 2014, pp. 17-19).

5.1.1 Government incentives

Until 2018, many of the incentives have been established, however according to Riksrevisjonen (2018), much more needs to be done to meet the goals. As of today, the government has different support funds for biogas development, which are also reflecting the above-mentioned policies. Innovation Norway, a government and county municipalities owned company that distribute and administer funds for innovations, has two support funds for biogas production. The first are funds up until 50% of the total costs to companies for piloting biogas plants that do not use wet organic waste from households or sewage sludge (Innovasjon Norge, 2018a). Another is a maximum 45% support fund for farm owners that want to produce energy from biogas (Innovasjon Norge, 2018b).

Enova, an organisation owned by the Ministry of Climate and Environment, gives funds to companies for the development of biogas plants that make waste to biogas (minimum 100.000 Nm3 methane) for transport fuel (Enova, 2018b). In addition, companies can apply for district heating plants using renewable energy sources (Enova, 2018a). On the biogas user side, Enova supports companies in their purchase of biogas vehicles with up to 50% (Enova, 2018c). To contribute to increased access of manure for biogas production and to reduce climate gas emissions from agriculture, The Agriculture Directorate gives grants to livestock farmers for the amount dry matter of manure they deliver to plants. Today the grant is NOK 500 per ton dry matter manure (Lovdata, 2015). In addition, general support to research projects on biomass use can be applied for through The Research Council of Norway and SIVA, an investment fund for the industry, can offer funds for innovation and infrastructure development within the bio economy (Nærings -og Fiskeridepartementet, 2016, p. 16).

5.1.2 Local governmental policies and plans

Gjøvik Municipality would like to support renewable sources of fuels, and charging stations for electric vehicles and filling stations for hydrogen seems to be the focus, according to the background material to the climate and energy strategy (Gjøvik kommune, 2018a, pp. 27-28). Biogas is mentioned as an option for fuel, however, no specific plans are mentioned. On the other hand, biogas production is mentioned more in the strategies related to the agriculture sector with the aim of making it more climate friendly. Two of the plans they would like to support are testing of biogas (and other renewable sources) as a fuel for agriculture machines and plans of biogas production development from manure (Gjøvik kommune, 2018b, p. 8).

Looking at the district municipality level, Oppland has its own climate and energy plan for 2013-2024. Here, biogas production on farms is specifically mentioned to not be a viable strategy as of the writing of the strategy (Oppland fylkeskommune, 2013, p. 19). Generally, it mentions biomass as a source for energy and fuel (Oppland fylkeskommune, 2013), but the plan is general in its presentation and few details are presented. On the 13th of June 2018, the municipality agreed on what they call a biogas package, where they set aside targeted funds for the support of several development, research, and business initiatives for biogas production in the district. Biogas fuel filling stations, support development of biogas fuel upgrading plants, support purchase of buses on biogas fuel in Lillehammer, and support to biogas production from manure (Oppland fylkeskommune, 2018).

To summarise, Gjøvik emphasises biogas production in the agriculture sector. The same is true for Oppland, however, the latter also plans for other types of biogas production support. Where Gjøvik seems to emphasise electric transport and hydrogen types of fuels, Oppland plans to develop a market specifically for biogas fuels.

5.2 Economic aspects of biogas production

The Environmental Agency in Norway has calculated investment costs of wastes from wet organic wastes and animal manure. The first has much lower costs than the latter, as wet organic wastes have a higher methane gas production potential per kg of waste. (Klima og Miljødepartementet, 2014).

All though there is a great potential of using wet organic waste for biogas production, there is an issue with access to the actual waste product. This is because the producers do not get sufficient income from the waste, meaning that there are few incentives to deliver the waste to biogas treatment (Klima og Miljødepartementet, 2014). For an industrial company to invest in biogas production, it needs economic incentives. If not, other waste by-products from the production will be more lucrative.

A report from NIBIO (Sørheim *et al.*, 2010), states that several incentives need to be in place for the biogas production to be lucrative for investments. The agriculture sector may be part of the Paris Agreement of the Parties quota system, which it is not today, and there could be more regulations in terms of environment and climate change friendly regulations, as well as support to make the industries shift to more renewable energy.

Most often, the biogas production plants today are not very economically interesting if income is the only issue that matter. Therefore, there is a need to manage the production in an optimal matter and find the best solutions possible for the given context (Morken *et al.*, 2017). However, from an environmental perspective and for waste management, one may argue that it has value for money.

5.3 Environmental aspects of biogas production

Norway has a small biogas production compared to other European countries and the biogas today is mostly used for transport. The potential of biogas production from organic waste substitution of transport fuel is achieved, it has a potential of reducing CO2-equivalent emissions by 500 000 tons. (Klima og Miljødepartementet, 2014). Other researchers in agriculture and biogas, from NIBIO (previously Bioforsk) and Østfoldforskning, which is a leading research institute in Norway on biogas value chain environmental assessment, also support the recommendation of using the biogas for fuel in a Norwegian context if one shall reduce the climate gases (Grønlund, 2013, Brekke *et al.*, 2017). In its report on environmental studies of biogas, Brekke et al. emphasise that using biogas for electricity and heat is not the environmentally best option as the energy is based on hydropower, a renewable resource. Further, it is more important what the biogas is used for than which substrate is used, as the result for transport fuel would most often be the best with all options. However, it is also important to consider whether the substrate for biogas production is a problematic waste – if so it can have an even more positive environmental impact, all though other products would be preferred for making biogas (e.g. algea).

Based on these, it is also safe to say that the environmental impacts depend on the context of how the raw material is handled in the biogas production, but more importantly, how the biogas and the digestate, which is the by-product from the biogas production are actually used. The digestate often yield high positive environmental impacts when the assumption is that it is substituting the use of mineral fertilisers. One need to do specific studies to see the effect and not only use these general averages, all though these are useful for indications (Morken *et al.*, 2017).

5.4 Technological aspects of biogas production

In the literature review of Mao, C. et. al (2015), research papers on biogas from different organic sources were studied and it looked specifically at what the future for further research on the area should include. They conclude that optimisation of biogas production should be studied, to understand which process steps and ingredients for degradation of organic matter (in anaerob process) are the most optimal. In addition, they say that because of investment costs, the biogas plants should be big and that there is a need of research in laboratory on scaling-up at industry level.

Many research papers have investigated the biogas and methane (CH4) yields from different mixes of substrates in the digestion process of biogas. From these, it seems as mixing different materials, such as food waste, animal waste and manure and sewage sludge together, have the best yields compared to cases where the materials are used alone. So-called co-digestion, using more materials, are common in bigger biogas facilities. However, it is not easy to just mix the materials. To get the optimal result, it is necessary to test and experiment with how much material from each is the best (Poulsen and Adelard, 2016).

One example of a research that investigated co-digestion, is the research of Pavi et. al (2017). Here, the biogas and methane yield from a mixture of municipal solid waste and fruit and vegetable waste was evaluated. They found that the optimal mixing ratio was 1/3 and that the mixing had a much greater potential than mono-digestion of the two.

Important factors when considering biogas treatment of waste, is to look at the balance of carbon and nitrogen and the dry matter content of the waste going into the reactor. In the digester, a ph value between 6,5-8,5 is recommendable (Modahl *et al.*, 2016). Other factors, such as carbohydrate content and time in the reactor also matters. In addition, the bio waste product used for fertiliser should also have a good level of nitrogen and phosphorous content to have value as nutrition to plants (Morken *et al.*, 2017).

Another factor to consider, is the development of technologies of reactors, which seem to increasingly improve when it comes to efficiency. One needs to consider the different types of biogas digestion reactors and the rest of the technical solutions of a plant.

6 The biogas scenarios

In the case of HOFF, building its own biogas plant for smaller amounts may be the best option of the two. To find out whether biogas production can be viable, it is important that an optimal solution is investigated more in depth. There are numerous options and according to circular economy and sustainable business approaches, the analysis should not be limited to only looking at HOFF, but also considering the locality where HOFF is placed. As mentioned, there are also several empirical examples of collaboration between actors in Norway for biogas production and the challenge is to look at availability of waste streams and the possible technical solutions locally, which may give the best results. In this chapter, the reasoning behind choosing potential cases to invest in for HOFF are presented, considering the literature study in the previous chapter. The main arguments are based on possible combinations of substrate, as this has much effect on how biogas can be produced. It is assumed in literature that the combinations can give more biogas yield digested together than the sum of the same substrates digested alone. It has been shown that a substrate with low nitrogen content and another with high level could have a yield of 60% more than mono-digested. These estimations are uncertain, however, but for all calculations of co-digestion in the scenarios, it is included an increase of 10% on the methane yield.

There are many factors that determine whether the substrate will be efficient for biogas production or not. As the suggested substrates are not tested together in an anaerobic reactor, the assumptions of the substrate are based on literature. The following are considered when investigating possible substrate combinations.

- % dry matter per m3 stillage – for finding wet weight per ton DM
- Kg methane yield per ton DM – methane yield produced per ton DM and per year
- Carbon nitrogen (C:N) ratio – for usable digestate

An additional factor, which is very important for the process stabilisation of anaerobic digestion and for the digestate, is the ph level. It is not considered here as a factor that is calculated for the given substrates in the scenarios. Nevertheless, it is something that must be tested to decide whether the given substrates can together yield biogas. The potato ethanol stillage is probably very low and would need other substrates with higher ph level to be stable, all though there are studies that show that wheat ethanol stillage biogas production can be considered as mono substrate if liquids are added (Wiberg, 2007).

This chapter also present other considerations about the set-up of the chosen scenarios and economic considerations.

6.1 Cattle manure and potato ethanol stillage scenario

In the beginning of this research, a potential scenario of biogas production with potato ethanol stillage and cattle manure as substrates was considered. First, the substrate characteristics and their availability are presented and second, the findings from calculations of co-digestion of these substrates.

6.1.1 Potato ethanol stillage substrate characteristics

There are very few studies on potato ethanol stillage as a substrate for biogas and literature searches for this paper has not been successful in finding information. Based on chemistry, one can calculate the theoretical potential of methane yield from the nutrient content of the substrate, but as theoretical calculations are uncertain, and the nutrient content of the stillage is uncertain, assumptions are made based on research where substrates have been tested in practice. One study (Nesheim, 2010) tested the nutrient content of ethanol stillage from HOFF Innerøya, as well as summarising previous tests. This study gives some useful information for understanding the stillage as biogas substrate. A widely used source for finding characteristics of biogas substrates is the Swedish *Substrathandbok för biogasproduktion* (Carlsson and Uldal, 2009), which includes an overview of substrate characteristics based on several researches. It is also used to find information about substrates in the scenarios in this paper, however the data on ethanol stillage are mainly based on wheat ethanol stillage. Table 6.1 summarises the data found and assumed about the potato ethanol stillage. The kg methane yield per ton DM is based on the methane yield per ton VS. The % methane content is not known for this substrate. Commonly used substrates have a methane yield of around 60-65%, but the few literature found on ethanol stillage methane content suggests a lower % (e.g. a test by (Wiberg, 2007) suggests 45-50% for wheat ethanol). Therefore, 55% is assumed for this scenario. The C:N ratio is based on the nitrogen content (calculated to 21 kg per ton DM) found in Nesheim (2010) and the carbon content used in Modahl et al.'s (2016) model for life cycle assessment of biogas. In the model, it is assumed 400 kg per ton DM for food waste and manure substrates, however, this figure is uncertain. Carlsson and Uldal (2009) assume that the C:N ratio is only 8 for wheat ethanol stillage, however, the nitrogen content is assumed much higher than the nitrogen tests by Nesheim (2010), and therefore Carlsson and Uldal data are not used here.

Factor	**Value**	**Calculations based on source**
% dry matter (DM) in substrate	6 %	HOFF's own measures
m3/ton wet weight per ton DM	16,67	
% volatile solids (VS) per DM	93 %	(Carlsson and Uldal, 2009)
m3 methane yield per ton DM	300,39	(Carlsson and Uldal, 2009)
m3 methane yield per year	126 164	
% methane content in biogas	55 %	Estimation (e.g. based on (Wiberg, 2007))
C:N ratio per ton DM	19,2	(Nesheim, 2010), (Modahl *et al.*, 2016)

Table 6.1 Summary of HOFF's potato ethanol stillage substrate characteristics

The availability of potato ethanol stillage is, as suggested in the background chapter, 7000 ton. With a DM of 6%, the DM amount per year is 420 ton. From the assumptions made, 7000 ton stillage can yield 126 164 kg methane a year, which means an energy potential of 1 261 638 kwh. Theoretically, if testing the substrate well, with additional liquids to stabilise the process, it may be possible to only use potato ethanol stillage as substrate for biogas. However, as this is very uncertain, it is not investigated further through this thesis research.

6.1.2 Cattle manure substrate characteristics

From the literature review, it was obvious that co-digestion of substrates would be more efficient in terms of yielding the most biogas. Further, as the ph level of potato ethanol stillage is probably low, there is a need for substrate with higher ph level. A commonly used substrate for this purpose is manure, as it may increase bacteria growing in the reactor and thus higher and more stable biogas yields (Modahl *et al.*, 2016). Manure is therefore considered as a necessary substrate in the mix for these scenarios, even when the kg methane yield is low as a single substrate. As HOFF already has collaborations with cattle farms for the distribution of fodder, cattle manure is chosen as the co-substrate. In the literature, there is more information on cattle manure as a biogas substrate, and most of the information is taken from Modahl et al. (2016). Assumptions about carbon and nitrogen is also uncertain for cattle manure. Research institutions in Norway give different nitrogen contents for different water cattle manure. Therefore, the nitrogen content in the model of Modahl et al. is used.

Factor	**Value**	**Calculations based on source**
% dry matter (DM) in substrate	10 %	(Nesheim and Sikkeland, 2013)
m3/ton wet weight per ton DM	10	
% volatile solids (VS) per DM	80 %	(Carlsson and Uldal, 2009)
m3 methane yield per ton DM	170,4	(Carlsson and Uldal, 2009)
% methane content in biogas	65 %	(Carlsson and Uldal, 2009)
C:N ratio per ton DM	8,33	(Modahl *et al.*, 2016)

Table 6.2 Summary of cattle manure substrate characteristics

The availability of cattle manure in the area close to Gjøvik is high as there are cattle farms surrounding the small city. In Gjøvik municipality, there were 1850 milk cows in 2016 (Gjøvik kommune, 2017, p. 9). With an assumed yearly manure production of 19,7 tons per milk cow (Nesheim and Sikkeland, 2013, p. 11), the available amount of manure only from this type is 36 445 ton, which is many times more than the yearly extra potato ethanol stillage waste.

6.1.3 Cattle manure and potato ethanol stillage combined

According to a study that tried to optimise the mix of ethanol stillage (not from potato) and manure, the preferred mix was 15 % manure and 85 % based on VS (Westerholm, Hansson and Schnürer, 2012), but the conditions and the technologies will be a different than in a scenario of HOFF. In the scenarios, however, it is assumed that cattle manure should be around 20% of the total VS content of the substrate. The mix would therefore yield the characteristics shown in table 6.3, where values are weighted on the % VS, potato ethanol stillage with 80% and cattle manure with 20% of VS. The share of dry matter in the substrate mix is then 77% DM of potato ethanol stillage and 23% DM cattle manure. The same calculations are done to compare if one had a 50% share of cattle manure. In case of the latter there will be 46% DM potato ethanol stillage and 54% cattle manure.

Factor	**Value 20 % manure**	**Value 50 % manure**

Ton substrate per year	8221	11 883
Ton DM per year	542	908
% dry matter (DM) in substrate	6,59 %	7,64 %
m3/ton wet weight per ton DM	15,2	13,1
m3 methane yield per ton DM	298,23	253,56
m3 methane yield per year	161 660	230 298
C:N ratio per ton DM	14,84	11,28

Table 6.3 Summary of cattle manure and potato ethanol stillage substrate characteristics in co-digestion

If adding 20% manure, the methane yield per ton DM is higher than with 50% manure, however, because of the lower amount of substrate a year, the potential methane yield (and energy production) per year will be lower. With 20% manure the energy potential is 1 616 000 kwh and with 50 % manure is 2 302 980 kwh. Potential income from this may not cover costs of the investments of a biogas plant, as the yield per year should be higher. With 20 % manure, the wet weight per ton DM is also high, something that implies more transportation of digestate per m3 methane yield. The same is true for the other alternative, but it is a bit lower. The C:N ratio for the 20 % alternative could be acceptable, but it is still low if not extra liquids are included in the mix. It is even lower for the other alternative and not recommendable. Vegetable and potato farm residues with cattle manure, and potato ethanol stillage scenario

As yields are low per year, biogas option in collaboration with other stakeholders were considered for the further investigations of possible scenarios.

6.2 Vegetable residues with cattle manure and potato ethanol stillage scenario

As mentioned above, the farmers are greatly connected to HOFF and HOFF should be able to solve issues for farmers for the future. One great challenge for farmers is always weather conditions and crop yield may fail. Farm residues may be an option for co-digestion as it is usually left on the fields and emitting climate gasses (Grønlund, 2013). It can also be transport to HOFF with the potato products they usually deliver for value addition processing.

To understand the availability of this product in the nearby area, data on the applications for governmental support to farmers per agriculture activity in 2017 from the Norwegian Agriculture Agency were used. There are many potato and vegetable farms surrounding Gjøvik, the closest being Østre Toten and Ringsaker municipalities. In the data, it was found that there are 18 00 hectares (18 000 dekar in Norwegian) of either potato and vegetable production (approximately 50/50) (Landbruksdirektoratet, 2018). The same is found in the data for 2018.

In a report by Grønlund (2013), opportunities for the removal of potato and vegetables residues are discussed as a measure to reduce climate gasses. He also calculates the national potential for biogas production of these and concludes that there is a small reduction of CO2-equivalents by removing the residues, however, if utilised as biogas and substituting it with transport fuel, it will have a great effect. There are few other studies of farm residues for biogas production in Norway, but in the scenario of HOFF, these residues can offer extra dry matter to the mix and therefore interesting if farmers can bring these with the potato deliveries.

If using assumptions by Grønlund, it is found that 2400 kg potato and vegetable are produced per dekar (2013, p. 6), which give 43 200 ton in this scenario. In the climate calculator (Grønlund, 2015), based on IPCC data for Norway, it is assumed that the share of residues per produce is 10%. This gives an actual availability of 4320 ton. In Grønlund's report from 2013 it is in addition assumed that 90% of the residues will actually be removed. Therefore, in this scenario, the amount of substrate to HOFF is assumed to be 3888 ton. Before presenting the assumptions for the mix with cattle manure and potato ethanol stillage, residues as stillage is presented.

6.2.1 Vegetable and potato farm residues substrate characteristics

As potato and vegetable have high % of dry matter content, it is not assumed a one to one ratio between ton measurements and m3 measurements of the substrate. According to converter calculators, 1 ton potato is regarded as 1,3 m3. This volume is therefore used in scenario calculations. To find the methane yields, an average yield from the assumptions of potato yield (411 m3 per ton DM) in Carlsson and Uldal (2009), and yields for vegetables (460 m3 per ton DM) in Bernstad (2011) are used.

The C:N ratio is calculated from different sources. Again, the carbon content for food waste and manure suggested by Modahl et al. (2016) is used (400 kg per ton DM). Further, the nitrogen content of both vegetable and potato residues are assumed to be 19 kg per ton DM (Grønlund, 2015).

Factor	**Value**	**Calculations based on source**
% dry matter (DM) in substrate	20 %	(Grønlund, 2013)
m3 wet weight per ton DM	6,5	
Ton wet weight per ton DM	5	
% volatile solids (VS) per DM	95 %	(Carlsson and Uldal, 2009)
m3 methane yield per ton DM	413,73	(Carlsson and Uldal, 2009), (Bernstad, la Cour Jansen and Aspegren, 2011)
m3 methane yield per year	321 713	

% methane content in biogas	53 %	(Carlsson and Uldal, 2009)
C:N ratio per ton DM	21,05	(Grønlund, 2015), (Modahl *et al.*, 2016)

Table 6.4 Summary of vegetable/potato residues substrate characteristics

The substrate has a much higher dry matter content that than the potato ethanol stillage and cattle manure and will reduce the wet weight in the mix and the amount of methane yield per volume of substrate will be higher.

6.2.2 Vegetable/potato farm residues, cattle manure and potato ethanol stillage combined

In practice, HOFF may choose to not harvest 90% of the residues available at farms in Østre Toten and Ringsaker, however, in the scenario it is assumed that all is utilised as substrate feed into the biogas production. It is also assumed that there will be a need of 20% cattle manure for the same reasons mentioned in the scenario with only potato ethanol stillage, and because of this, the cattle manure substrate is 3529 ton, around 3 times more. Therefore, for this scenario, the total amount of substrate for biogas production is around 14 400 ton or almost 15 600 m3 biomass, which is double the amount of potato ethanol stillage and in other words a substantial sized biogas plant. To compare, it is around half of the amount treated at Mjøsanlegget (2019b). The substrate characteristics based on the substrate combinations are presented in table 6.5. With the amount of potato ethanol stillage from HOFF, the available vegetable/potato residues for harvest and assuming 20% cattle manure, the share of each substrate going into the biogas plant per ton DM is 27 %, 50 % and 23 % respectively. The share of ton substrate is 49%, 27% and 24% respectively. As mentioned, it is calculated a methane potential per DM weighted on share of ton DM + 10 % as this is co-digested.

Factor	Value
Ton substrate per year	14 417
m3 substrate per year	15 584
Ton DM per year	1551
% dry matter (DM) in substrate	10,75 %
ton wet weight per ton DM	9,3
m3 methane yield per ton DM	360,41
m3 methane yield per year	558 814
C:N ratio per ton DM	15,33

Table 6.5 Summary of vegetable/potato residues, cattle manure and potato ethanol stillage substrate characteristics in co-digestion

The amount of wet weight is lower and methane potential per ton DM is higher than in the scenario with only cattle manure and potato ethanol stillage. However, the C:N ratio is still a bit low, but acceptable. It can be higher if some additional liquids with carbon content are added to the mix. Additional substrates are not included in the scenario study.

The scenario is interesting, but as the amount of substrate going into the biogas plant is high, consequently the amount of digestion for distribution on farm fields is also high. The substrate will probably reduce somewhat when going through the biogas plant, but not much. In the scenarios it is assumed that 90% of the substrate comes out from the anaerobic digestion in the form of digestate (Høyvik Holmstrøm, Styve and Nesse, 2018). With this assumption, the digestate is 8,37 m3 per ton DM and yearly digestate of 12 975 ton. The amount of substrate would also require anaerobic digestion reactors with a volume of at least 300 m3. More about the biogas plant assumption below. The scenario is promising and is further investigated for environmental impact.

6.3 Food waste with cattle manure and potato ethanol stillage scenario

In circular concepts, the availability of local cooperation is interesting to create resource efficient production systems based on short travelling products. Having this in mind, it was interesting to investigate a scenario where substrates available even closer to HOFF than cattle manure and farm residues, which are all outside the city area. Possible and perhaps easily available organic wastes are food waste. Looking at the map of Gjøvik, there are first and foremost several restaurants and grocery shops in the area. These have necessities of managing their waste. There is very little information of amounts of waste from restaurants in Norway, and this research did not allow time to visit each restaurant and grocery store in Gjøvik city to find actual waste amounts. However, studies in Sweden give some estimations of kg food waste shown per person (Naturvårdsverket, 2018). It says that on average, there are 7 kg waste per person in the user area from bigger kitchens, such as in restaurants and hotels. There are 3 kg per person from grocery shops. Based on this, it is possible to make estimations for the restaurants and grocery shops in the area closest to Gjøvik. There are almost 30 000 inhabitants in Gjøvik, and around 20 000 in the city area (Statistics Norway, 2018). If the 20 000 represent the users of the restaurants in the down town area of the city, the total waste amount is 200 ton. This is a small amount compared to HOFF’s waste and will probably not make any substantial difference to the input, however it would add some dry matter (62 ton when % DM is 31%).

Additional waste types in the Gjøvik area is food waste from households. As mentioned, the food waste with municipal responsibility is today sent to Mjøsanlegget, which makes biogas and digestion. The household waste from Gjøvik travels at least 50 km and is treated there.

Would it be possible to treat it in Gjøvik? As it is already a municipal waste, it may not offer a huge benefit to the households that own the waste, rather it requires investments from the municipality. For HOFF, it may offer benefits to the company, as it may lead to value added to inhabitants of the city. Regarding the near future of Gjøvik city area, more apartments are planned, as the previously industrial owned area just south of HOFF, Huntonstranda, will be utilised for building a new residential area, including cultural buildings and restaurants. It can be an opportunity for HOFF to plan to be a cooperative neighbour. Gjøvik Municipality may also consider waste management facilities closer than the one at Mjøsanlegget with an increasing number of inhabitants. It can be a possibility to supply the apartments with bio-based heating. Therefore, this scenario may look further into the future than the scenario with vegetables and potato residues. All though there are opportunities, it is perhaps not interesting to replace an already established system of biogas treatment of waste with another in terms of environmental impact.

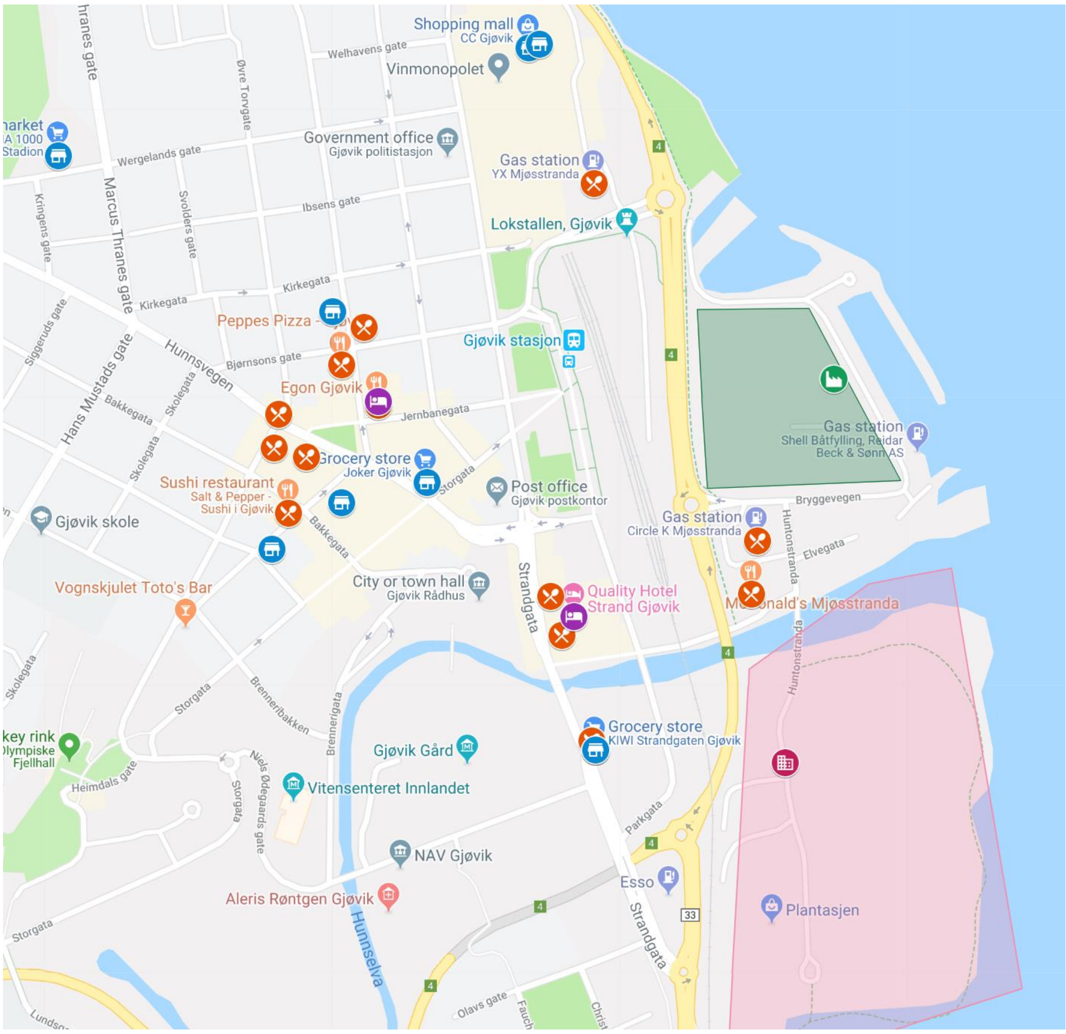


Figure 6.1 Map of restaurants, grocery shops, hotels nearby HOFF (green) and Huntonstranda (pink) - made in Google maps

For the scenario, however, today's situation is considered for an estimate of how much food waste may be available. It is assumed that food waste is managed as separated waste. Newer estimations based on waste analysis shows that one can expect an average of 50 kg of food waste per habitant per year (Syversen, Hanssen and Bratland, 2018). With an estimation of 15 000 inhabitants deliver clean food waste to HOFF, they will deliver altogether 750 tons food waste. In addition, it is assumed that the restaurants will deliver food waste, and it is assumed that the restaurants have 7 kg á 15 000 inhabitants making a total of 105 tons. With these estimations, the amount of food waste available as substrate is 855 tons.

6.3.1 Food waste substrate characteristics

The model of Modahl *et al.* (2016) includes, as mentioned earlier much information on food waste based substrates. The data on the substrate characteristics are taken from tests of household food waste by Eklind et al. in 1997. It estimates a dry matter content of 33%. However, as the scenario also assumes some restaurant food, the DM content is set somewhat lower, closer to the dry matter content of restaurant waste (27%) assumed in Carlsson and Uldal (2009, p. 25). Therefore 31% DM is chosen for the scenario. The same is valid for methane potential. With some restaurant food in the mix, the methane potential is assumed somewhat higher than for food waste, the same assumption for % VS per DM. The volume and weight assumptions for vegetable and potato residues are also made for food waste. The Carbon (400 kg per ton DM) and the nitrogen (23 kg per ton DM) data are taken from Modahl et al.'s model. The characteristics for food waste are shown in table 6.6.

Factor	**Value**	**Calculations based on source**
% dry matter (DM) in substrate	31%	(Carlsson and Uldal, 2009), (Modahl *et al.*, 2016)
m3 wet weight per ton DM	4,33	
Ton wet weight per ton DM	3,33	
% volatile solids (VS) per DM	90 %	(Carlsson and Uldal, 2009)
m3 methane yield per ton DM	450	(Carlsson and Uldal, 2009)
m3 methane yield per year	119 273	
% methane content in biogas	63 %	(Modahl *et al.*, 2016)
C:N ratio per ton DM	17,39	(Modahl *et al.*, 2016)

Table 6.6 Summary of food waste substrate characteristics

6.3.2 Food waste, cattle manure and potato ethanol stillage combined

As the amount of food waste available is potentially much lower per year than the mount of vegetable and potato residues, the yearly potential methane yield is supposedly much lower.

However, as the dry matter content is much higher for food waste, there is a greater potential per ton DM of substrate. Again, it is assumed 20% of the VS of cattle manure in the mix. With the amount of potato ethanol stillage, food waste and cattle manure, the share of each in the ton DM is 48%, 30% and 22% respectively. The share of ton substrate is 71%, 9% and 20% respectively. As mentioned, it is calculated a methane potential per DM weighted on share of ton DM + 10 % as this is co-digested.

Factor	**Value**
Ton substrate per year	9821
m3 substrate per year	10 078
Ton DM per year	882
% dry matter (DM) in substrate	8,95 %
ton wet weight per ton DM	11,2
m3 methane yield per ton DM	348,02
m3 methane yield per year	306 832
C:N ratio per ton DM	14,52

Table 6.7 Summary of food waste, cattle manure and potato ethanol stillage substrate characteristics in co-digestion

With the same assumptions as for the scenario with vegetable/potato residues, the digestate out of the digester is assumed to have reduced by 90%, resulting in digestate weight of 10,05 per ton DM. The yearly ton digestate is then 8865 ton, only 27% more than HOFF's stillage today. The substrate would need at least 200 m3 anaerobic digestion reactor. The C:N ratio is not favourable for this mix. It will therefore be necessary to add extra liquids. As the C:N ratio for food waste can vary (Carlsson and Uldal, 2009), the nitrogen content could also be lower in reality. Nevertheless, it may be a more difficult substrate to work with and to continuously find the optimal C:N ratios for the substrate.

6.4 Assumptions of biogas scenarios set-up

For the scenarios, there are several assumptions made in terms of how the scenarios are built. In this chapter, some of the assumptions of the technologies used and biogas use are presented. The details of assumptions are found in Appendix A, however, the most general assumptions and the reasoning behind them are presented here.

I general, much of the assumptions about processes built in the scenario are based on the BioValueChain model by Modahl *et al.* (2016). This model has been developed over some years and the last publication of model has been used as inspiration. Data from this model has been used to a great degree, however, as much of the underlying data for the model is not published, many assumptions have been taken based on other literature, which may or may not be the same sources as in the model. The purpose of the model is to create a common tool for investigating biogas possibilities and the environmental impacts in different scenarios in Norway. This, to be able to compare across cases.

6.4.1 Biogas plant

As mentioned, there are different types of technologies available for the anaerobic digestion process. All though the most common digestion reactor is the CTSR-reactor, there are many new reactors that promise and have shown that they reduce the retention time considerably. This has implications for the size of plant that is necessary. As HOFF does not have a considerable amount of space to build a biogas plant, the size is an important factor. In the scenarios, it is therefore assumed plug-flow-reactors with a retention time of 7-8 days. With these types of reactors, there is a need for 300 m3 reactors in the scenario with vegetable/potato residues and 200 m3 reactors in the scenario with food waste. Examples of suppliers of this type of reactors are Adigo (www.adigo.no) and Antec biogas (www.antecbiogas.com/). They also promote a more efficient biogas yield from the process with these technologies, however, there are few scientific knowledge that can document this, and is therefore not considered in this research. One example of such a biogas plant, and close to Gjøvik, is a farm-based plant connected to a high school at Presteseter in Vestre Toten. There, they use manure as the main substrate and use the biogas for electricity and heat production (Lena-Valle videregpende skole, 2018). According to Antec biogas (informal meeting and their own web page), a benefit of using such reactors is that they are modular and can be put together in system according to shifting needs of waste management amounts.

Using a plug-flow reactor in the scenario does not have many effects on the how the scenarios are set-up, except for the data on plant infrastructure and the volume of reactors needed to manage the yearly volume. It may be so that the volume varies throughout the year as substrates may not be in constant demand.

Figure 6.2 Antec Biogas plug flow reactor - picture taken by Antec Biogas (in presentation received on mail from CEO, E. Andersen)

Adigo has made an estimate of how much land area is needed for 2 300 m3 reactors. Figure 6.2 shows Adigo's estimate of a plant on an area of 27x18 meter (Adigo, 2019). This plant manages waste from municipal sewage sludge, including gas turbine for electricity and heat generation. In HOFF's case, one would perhaps only need one reactor tank of that size and reduce the space to approximately 20x15 meters. It can be possible to include this space on the factory's space. Or, in the case of the scenario with food waste, there are possibilities of allocating shared spaces for biogas treatment of the waste. Figure 6.3 shows an example of biogas plant dimentions at HOFF. This example assumes space of 25x15 meter, represented by a red square. In addition, storage space may be needed. On farm-based biogas plants it is common to storage the digestate at farm for use. However, in the BioValueChain model, it is assumed that the digestate is transported and stored on farms. Dewatering facility is not included, nor is it included in the scenarios. If there is a need of digestate storage at HOFF, this would need a considerably bigger area.

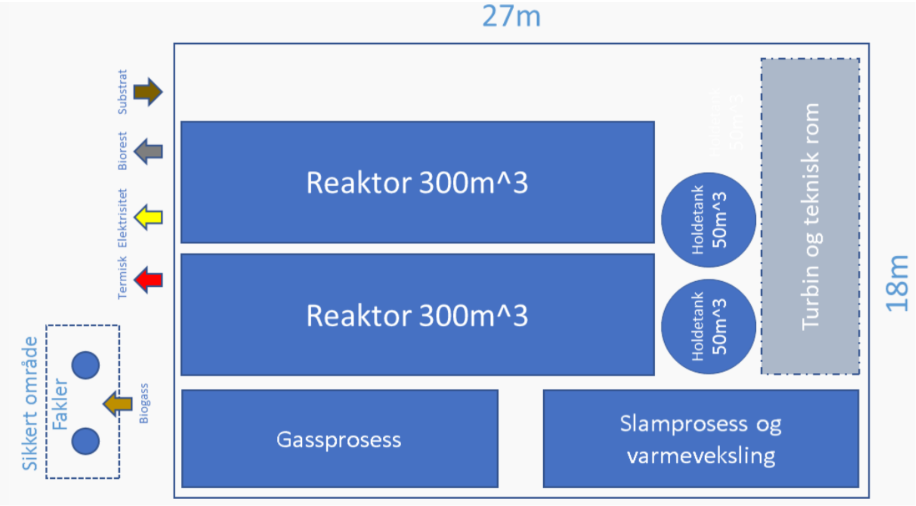


Figure 6.3 Adigo biogas plant set-up example

Figure 6.4 Illustration of possible placement of a biogas plant at HOFF - satellite photo from Google maps

6.4.2 Biogas for electricity and heat use

The most common utilisation of biogas from smaller production units is to generate electricity and heat or one of the two. In the scenarios, it is assumed co-generation of electricity and heat in a so-called combined heat and power (CHP) unit generating 50% heat and 40% electricity. The detailed assumptions are found in appendix A, calculation B7 and B13.

In the case of HOFF, the assumption is that the electricity and heat can be used by the factory energy needs. Heat can be used to heat substrate in the biogas plant and to other heat needs in the factory. Today, HOFF already uses waste heat from own processes. The biogas plant may therefore generate heat that is not used. However, excess heat may be used for neighbouring buildings. In the scenarios, it is assumed own use of heating, however, the scenario may also be valid for other purposes, although extra infrastructure for the transport of heat is not accounted for. Electricity is supplied by Eidsiva in Gjøvik. Today, HOFF uses a substantial amount of electricity for the processes and the electricity generated from the biogas process will reduce costs.

6.4.3 Biogas for transport fuel use

In most cases, transport fuel is the best use of biogas in environmental terms. However, the investment costs of upgrading the biogas to biomethane, which can be used as transport fuel, is substantial and the infrastructure takes additional land area. Morken *et al.* (2017) assume that, with today’s technology, the cost of investing in upgrading facilities is high when the amount of gas produced is lower than 100 m3 per hour. In the case of HOFF, the potential m3 biogas per hour, based on the tables 6.5 and 6.7 and without calculating reductions through the process are 115 m3 per hour for the scenario with vegetable/potato residues, and 60 m3 per hour for the scenario with food waste. It could be viable for the first scenario, however, with reductions, the output will nevertheless be closer to 100.

A possibility is to collaborate with others to invest in upgrading facilities. Gjøvik Municipality plans to make Skjerven an industry park, including other bio-based industries, such as Hunton Fiber AS (Eidstuen, 2019). Although HOFF would like to keep its factory where it is today, in a future scenario, there may be possibilities for collaboration with the park. Together, one could build both upgrading facilities and fuel supplying facilities for vehicles. Therefore, the scenarios also include analysis of biogas to transport fuel through upgrading in Skjerven.

Further, the biogas is to replace biodiesel for public city buses. This is because it is the most probable market for Gjøvik. Today, there are no market for biogas run vehicles in Gjøvik and the surroundings. The only vehicles on biogas are a few renovation trucks of GLØR, the renovation company in Gjøvik (GLØR, 2018). These fill their tanks at Mjøsanlegget.

For details, see appendix A, calculation B8 and B14.

6.4.4 Digestate use

Digestate can be utilised for different purposes. At Mjøsanlegget, the digestate is dewatered and compost is made (see more details in appendix A, calculation R10). Dewatering of HOFF's digestate could be an option. However, for the scenarios, spreading of digestate as fertiliser is chosen, as this is similar to HOFF's practice today with the potato ethanol stillage. In addition, when spreading the digestate, phosphorous that was taken out from the nature is spread back to more or less the same areas (Modahl *et al.*, 2016, Sørfonn, 2012).

It is assumed that the digestate is transported directly to farmers storage facilities and spread with manure. Tests of digestate as fertiliser have shown that it is a good substitute to mineral fertiliser and compared to manure, the nutrients in the digestate have been changed in the anaerobic process in such way that the nutrients are easier available to the plants (Modahl *et al.*, 2016).

The details on digestate assumptions are found in appendix A, calculations B11, B12, B13, B15. These calculations are based on general assumptions of the digestate. One is, as mentioned above, it is assumed that the ton digestate is 90% of that of the substrate going into the anaerobic digestor. Other assumptions are related to the degradability of the substrate in the biogas reactor. To find out how much dry matter content there is in the digestate, one must consider the degradability. It also has implications for the emissions data of for instance storage and spreading of the digestate. The data from Modahl *et al.* (2016) assume degradability share for food waste of 0,7 and 0,4 for cattle manure. This lead to the assumptions of % DM in a food based digestate of 5,5% and 4,96% for cattle manure based digestate. The calculation is based on the formula % DM of substrate*(1-share of degradability)*((1/% DM of substrate)/(1/%DM of substrate-share of degradability)) (ibid., pp. 41-42). Weighing the share of degradability on the different substrates in the 2 scenarios (20% cattle manure, 80% food waste), the degradability is 0,64. With these data and the data assumed % DM in the substrates, the % DM in the digestate is 4,15% for the scenario with vegetable/potato residues and 3,42% for the scenario with food waste.

7 Analysis of the economy of biogas scenarios

This thesis research does not include a full economic analysis; however, some assumptions and estimates can be made after modelling the biogas scenarios, from literature, and from suppliers' estimates. The estimates can give a general picture and are important for discussions on investments. This chapter presents general findings from income and cost estimations that HOFF must bear.

7.1 Economic overview of biogas to electricity and heat

In economic terms, biogas to energy to own building or for other buildings would be a better solution than upgrading it to transport fuel, however, as the electricity prices are rather low, the investments should be very low for it to be feasible. It may be a better solution to weigh the environmental gains from using it as biofuel. Another economic and technical risk for HOFF, is of course the varied volumes of wastes. For this reason, it may be an added value to collaborate with others for additional wastes. However, in technical terms, a different ratio of substrates in the mix may cause problems if not tested.

In the tables 6.5 and 6.6, a summary of main costs and income for HOFF for the biogas scenarios when biogas is used for electricity and heat is presented.

The available electricity and heat have been calculated and presented in appendix A. As it has been difficult to find accurate calculations on biogas plant investments for plug flow type of plants, an estimation of investment and maintenance cost of a biogas plant with reactors of a total of 300 m3 investments is used, as presented by Antec biogas in mail correspondence (Andersen, 2018). It is estimated a certain reduction in investment cost for the investment of 200 m3 reactors (scenario 2). Greve biogas plant has an agreement about cost sharing with farmers that deliver manure to their plant. Their agreement is that Greve biogas receives the farmers' governmental support to manure delivery up to 30 NOK/ton manure and everything above will be split equally between the parties. The farmer has to pay for own investments of storage facilities and other equipment and infrastructure (these can vary between 7 to 90 NOK/ton over a 15 years period). To compensate, Greve pays the farmers 55 NOK/ton digestate stored at farm and in addition they pay transportation costs (Lyng, Prestrud and Stensgård, 2019, p. 24). To find the support amount to farmers, one has to use the formula ((2*DM)-(DM)^2) and multiply with the Government support rate of 583 NOK (Lovdata, 2015). In the case of HOFF, the farmer would have received 110,8 NOK per ton cattle manure. With Greve's model, HOFF receives 70,3 NOK of this. It is assumed the same transportation cost for cattle manure and digestate per m3 as what HOFF pays today for the transporting potato ethanol stillage to farmers (84 NOK/m3). It is assumed that the farm residues are transported for free with the potato deliveries.

None of the government incentives apply for biogas production by a company that produce for electricity and heat. However, Innovation Norway gives funding for research project on the establishment of biogas plants (Innovasjon Norge, 2018b), but the support amount is not presented. It is assumed here support of 2 000 000 NOK. For electricity and heat, it is assumed an average price of 0,65 NOK/kwh, as presented by HOFF in mail correspondence (Njå, 2018b).

Table 7.1 shows the overview of costs and income for the scenario where vegetable/potato residues are used with cattle manure and potato ethanol stillage.

Description	**NOK**	**Source**
Investment costs		
Investments in biogas plant and CHP	33 000 000	Estimate Antec biogas
Annual costs		
Transport cattle manure (3529 m3*84 NOK)	296 500	Calculations appendix A
Electricity use biogas (103884 kwh*0,65 NOK)	67 500	Calculations appendix A
Maintenance costs	200 000	Estimate Antec biogas
Operator	600 000	Assuming less than 100% work
Transport digestate (12978 m3*84 NOK)	1 090 200	Calculation appendix A
Storage digestate at farm (12978 ton*55 NOK)	713 800	Calculation appendix A + Greve
Investment income		
Support from Government	2 000 000	Innovation Norway
Annual income		
Electricity and heat generated (3,20 Gwh*0,65 NOK)	2 079 200	Calculations appendix A
Support manure delivery (3529 ton*70,4 NOK)	248 500	Calculation appendix A + Greve
Total annual income - annual costs	**-640 000**	
Total investment income - costs	**-31 000 000**	

Table 7.1 Cost and income estimates biogas scenario 1 - biogas to el&heat

The same assumptions apply to the scenario where food waste is used. However, in addition, it is assumed that companies pay a fee for treatment of their food waste. Applications to Enova shows that biogas plants that receive food waste receive between 500 and 950 NOK/ton (Lind *et al.*, 2018). However, in this scenario, it is assumed that there is no pre-treatment and a conservative estimate is therefore given.

Table 7.2 shows the same where food waste is used with cattle manure and potato ethanol stillage.

Description	**NOK**	**Source**
Investment costs		
Investments in biogas plant and CHP	25 000 000	Estimate Antec biogas
Annual costs		
Transport cattle manure (1966 m3*84 NOK)	165 200	Calculations appendix A
Electricity use biogas (62712 kwh*0,65 NOK)	40 800	Calculations appendix A
Maintenance costs	200 000	Estimate Antec biogas
Operator	600 000	Assuming less than 100% work
Transport digestate (8860 m3*84 NOK)	744 300	Calculation appendix A
Storage digestate at farm (8860 ton*55 NOK)	487 300	Calculation appendix A + Greve
Investment income		
Support from Government	2 000 000	Innovation Norway
Annual income		
Electricity and heat generated (1,83 Gwh*0,65 NOK)	1 187 500	Calculations appendix A
Support manure delivery (1966 ton*70,4 NOK)	138 500	Calculation appendix A + Greve
Fee food waste treatment (855 ton*450 NOK)	384 800	Calculation appendix A +Enova
Total annual income - annual costs	**-526 800**	
Total investment income - costs	**-23 000 000**	

Table 7.2 Cost and income estimates biogas scenario 2 - biogas to el&heat

With the assumed biogas yields, it is not advisable to invest in biogas plant unless there is support for the investment. It is estimated negative results over 500 000 NOK for annual costs. It is also a similar result of HOFF’s practice today of transporting potato ethanol stillage (7000 ton per year). The total methane yield of 10% more in co-digestion can be a conservative estimate. For instance, some biogas suppliers operate with higher yields in co-digestion and many researches use theoretical energy production without subtracting losses throughout the process. If the same cost estimations are used to find electricity and heat production when the methane yields 30% more in co-digestion (originally 10 % more), the substituted energy would be above 4 Gwh a year for scenario 1, which would increase the income with around 600 000 NOK more than originally assumed. A conservative estimate is also given for the loss of energy through the transformation of biogas to CHP power. Further, the result will be impacted significantly by changed energy prices. If the price is lower, the benefit will also be much lower.

For scenario 2, it may be an option to invest in a biogas plant together with restaurants and shops. If so, there may be investment support and a much lower yearly fee for biogas treatment.

7.2 Economic overview of biogas to transport fuel

The same assumptions as biogas to electricity and heat are made for transport fuel. However, because biogas for transport fuel is covered with more financial incentives, a higher amount of investment support is assumed. As described, Enova can support biogas plant investment with 50 % if the plant is able to produce above 1 Gwh of energy per year (Enova, 2018b). One can also assume support from the district, however, double financial support for investments are not assumed. Further, it is assumed that raw biogas is sold to an upgrading facility at Skjerven. The transport gas pipeline is not included here because the project assumes that a pipeline is supported by collaborators or the municipality.

Through literature search, it is difficult to find potential price for sale of raw biogas. However, one can make some assumptions according to what the price on CBG should be if it is going to compete with diesel prices. According to a study by Carbon Limits (Pederstad *et al.*, 2018), CBG should not cost more than 1 NOK per kwh. As the biogas production is considered more expensive than upgrading, one can estimate that the raw biogas should not cost more than 0,65 NOK per kwh. This estimation is however highly uncertain.

Description	**NOK**	**Source**
Investment costs		
Investments in biogas plant and CHP	33 000 000	Estimate Antec biogas
Annual costs		
Transport cattle manure (3529 m3*84 NOK)	296 500	Calculations appendix A
Electricity use biogas (103884 kwh*0,65 NOK)	67 500	Calculations appendix A
Maintenance costs	200 000	Estimate Antec biogas
Operator	600 000	Assuming less than 100% work
Transport digestate (12978 m3*84 NOK)	1 090 200	Calculation appendix A
Storage digestate at farm (12978 ton*55 NOK)	713 800	Calculation appendix A + Greve
Investment income		
Support from Government	16 500 000	Enova
Annual income		
Raw biogas (4,45 Gwh*0,65 NOK)	2 891 700	Calculations appendix A
Support manure delivery (3529 ton*70,4 NOK)	248 500	Calculation appendix A + Greve
Total annual income – annual costs	**172 200**	
Total investment income - costs	**-16 500 000**	

Table 7.3 Cost and income estimates biogas scenario 1 - biogas to transport fuel

Description	**NOK**	**Source**
Investment costs		
Investments in biogas plant and CHP	25 000 000	Estimate Antec biogas
Annual costs		
Transport cattle manure (1966 m3*84 NOK)	165 200	Calculations appendix A
Electricity use biogas (62712 kwh*0,65 NOK)	40 800	Calculations appendix A
Maintenance costs	200 000	Estimate Antec biogas
Operator	600 000	Assuming less than 100% work
Transport digestate (8860 m3*84 NOK)	744 300	Calculation appendix A
Storage digestate at farm (8860 ton*55 NOK)	487 300	Calculation appendix A + Greve

Investment income		
Support from Government	12 500 000	Enova
Annual income		
Raw biogas (2,54 Gwh*0,65 NOK)	1 649 100	Calculations appendix A
Support manure delivery (1966 ton*70,4 NOK)	138 500	Calculation appendix A + Greve
Fee food waste treatment (855 ton*450 NOK)	384 800	Calculation appendix A +Enova
Total annual income - annual costs	**-65 200**	
Total investment income - costs	**-12 500 000**	

Table 7.4 Cost and income estimates biogas scenario 2 - biogas to transport fuel

The difference between producing biogas to transport and el&heat is that it is easier to find investment support for the first. In the above overviews, it is assumed that the market price of the raw biogas produced at HOFF is the same for both uses and should assume a similar income level. The difference, however, is that a greater loss of energy is assumed by CHP transformation to electricity and heat than by pumping the gas through gas pipe for transport fuel upgrading. The results in table 7.3 and 7.4 are close to zero income. Also here, a less conservative estimate of methane yields will change the result positively and collaboration for cost sharing should be considered.

8 Life Cycle Assessment

8.1 Goal

The goal of the LCA study is to compare the environmental impact of current waste management practice with waste management system with biogas production. Based on the literature review, two biogas scenarios are defined, with two added values each. The objective is to compare the environmental impacts of these four different scenarios with how the included waste streams are managed today.

There are several LCA studies on biogas production from organic waste compared with alternative waste scenarios, such as incineration, landfill and others. However, there are few studies comparing biogas production with other types of waste management options not based on the traditional waste management types. Further, the biogas scenarios consider newer technologies (such as fewer retention days in digester), and which can be used for the medium size company.

8.2 Scope

The system boundaries start when the substrates are wastes (See figure 9.1 for flow charts). The production of the waste is not included. The system further includes the waste management processes, including all resources needed for these processes, and the use of that waste. For the LCA to show the differences in benefits of the scenarios, it also includes the production and use of avoided products the waste product can substitute.

Not considered are:

- Phosphorous uptake in plants – In the substrates, there are phosphorous. Although it is an important nutrient as fertiliser, it is not included as data are scarce. As it is assumed that approximately 100% of the phosphorous in the substrate comes out in the digestate and spread on fields that it came from, meaning that it is not taken out from the nature (Modahl *et al.*, 2016), it is not included.
- CO2 emissions from biogenic CO2 – According to the IPCC model, CO2 emissions from biogenic sources, such as organic waste, shall not be included as CO2-equivalents. The assumption is that when the organic waste the CO2 is emitted from is renewable with relative high frequency of growth (e.g. yearly), the CO2 is not taken out from the natural system – and the emissions are carbon neutral (Liu *et al.*, 2017). Excluding these emissions, had little implications for the other impact categories.
- Storage infrastructure is not considered, as it is assumed that the units are already at the farms. All though biogas scenarios consider storage at farms with cover for less air emissions, as this is not the most normal practice today, it is still not considered in the LCA.
- Burning of sieve residues in the pre-treatment process before anaerobic digestions of mixed food waste is not considered. If there is sieve residues, it may have been burned and used for energy, however, data is scarce, and it is considered to not have a major impact on the results.
- Especially the food waste, depending on type, needs to be heated to 70 C to avoid unwanted bacteria in the substrate mix. However, this is not considered in the analysis. Nor is pre-treatment of food waste in the biogas scenario as it is assumed that the food waste is clean.

The geographical scope is for biogas waste management in Norway, as the assessment is specific to Gjøvik and data from Norwegian context is used where available, although some information is based on European averages.

8.2.1 Functional unit (fU):

To make the potato ethanol stillage waste comparable in different scenarios together with the manure and other substrates in biogas production, the functional unit is: the waste management of 1 ton dry matter. This is an fU commonly used in the LCA literature on biogas because it is possible to compare various materials for digestion, as the dry matter is a determinant for how much biogas can be produced. As the system is expanded to include the added value of 1 ton dry matter, the functional unit is in total: The waste management of 1 ton dry matter and the energy supply and use.

8.2.2 Data availability

As the biogas scenario is not an existing scenario, the data is taken from secondary literature. Accurate data of the biogas scenario were difficult to find and many estimations are made based on literature. Especially data on the potato ethanol stillage as a biogas substrate was challenging to find.

Mainly, data from the BioValueChain model (Modahl *et al.*, 2016) have been used. This is a biogas modelling tool, which has been developed by researchers from Østfoldforskning, University of Life Sciences, Bioforsk and Re Bioconsult and supported by the Norwegian Agriculture Agency and The Research Council of Norway. Data in this model are averages and estimations made by the researchers based on literature and own calculations. The impact categories of the model are climate change, acidification and cumulative energy demand. The tool in itself is not used for this research and the scope may differ in some respects, however, much of the emissions data are used, as they were found useful. In addition, emissions data from other researchers in Norway that have researched the knowledge area extensively are used where there is not useful information from the BioValueChain model – see tables 8.1-8.4 for emission data sources. In addition, where applicable, data and processes from the Ecoinvent 3 database are used. This database is developed in Switzerland and is often used in Life Cycle Assessment as it consists of vast amounts of data regularly updated based on research. The data in Ecoinvent are mostly averages estimated based on different sources.

Using averages and data based on examples of biogas production processes, may not be accurate, however, for this LCA of comparing different scenarios of waste management, the depth of the study is found sufficient to give meaningful results. All though six impact categories are chosen, there may be some processes without a complete set of data representing the six impact categories fully. Consideration of the use of for instance terrestrial and freshwater eutrophication was done, however, the latter needs data on the main stressor, phosphorous, which is not included completely in the scenarios. Terrestrial eutrophication is used.

8.2.3 LCA impact categories

For the case of biogas, six impact categories are chosen. Of these, climate change, acidification and eutrophication are the most common to find in LCA on biomass, as the related emissions are mostly within these categories. For eutrophication, terrestrial is chosen. Freshwater eutrophication had similar relative results and is not further interpreted. Instead other categories are chosen. Other impact categories are seldom used, but to give a fuller picture of the environmental impact, three additional categories were included; human toxicity (non-cancer), human toxicity (cancer) and mineral and fossil resource depletion. Land use could be relevant to agriculture/biomass, however, as the indicator of land use in ILCD is soil organic matter, which the ILCD handbook (European Commission and Joint Research Centre - IES, 2011, p. 92) authors recommend following with caution, it is not chosen as a category in this study. Below are descriptions of the chosen categories.

Climate change

Climate change shows the CO2-equivalents and is the most commonly used category as it is related to the international and national reduction goals of climate gases to the atmosphere. The climate gases are shown in kg CO2-equivalents, which can also be called the global warming potential (Klöpffer and Grahl, 2014). This category in the ILCD method use data from IPCC 2007 with a 100 years perspective, according to the SimaPro software. Note that the CO2 biogenic is not included in this 2007 version, and therefore this type of emission data is excluded, as in the IPCC 2013 version. Some of the main gases contributing to climate change are CO2, CH4, N2O, different types of Hydrofluorocarbons and Perfluorinated compounds, the two latter is not common in biomass cases.

Acidification

Acidification is commonly seen related to agriculture activities. Much of the gases from agriculture becomes the gases NH3 and NH4, which then enter soils and waters, but acidification can happen also on the basis of other sources. Acidification levels are often shown in SO2, however, the ILCD impact assessment method, molc H+-equivalents are used. Some of the main gases contributing to acidification are SO2, NO2, NOx, NH3 (Klöpffer and Grahl, 2014).

Terrestrial eutrophication

Terrestrial eutrophication calculations are mostly based on emissions to air. This category is related to excess supply of nutrients (Klöpffer and Grahl, 2014). In Norway, it is not considered as a major challenge, however, relevant for agriculture assessment. Gases NOx and NH3 are the most important and in the inventory, these gases are chosen as Norwegian specific emissions. ILCD uses a method of Accumulated Exceedance (European Commission and Joint Research Centre - IES, 2011).

Human toxicity (cancer and non-cancer)

Human toxicity is shown in terms of Comparative Toxic Unit for humans in the ILCD method. It expresses the estimated increase in morbidity in the total human population per unit mass of chemical emitted (according to the SimaPro software). This category is not commonly used when analysing biogas studies. It is therefore interesting to understand how biogas scenarios effect human population, which is more of a health issues than an issue on the environment. However, it is important to note that inventory does not include data on the biomass itself related to human toxicity. For instance, the spreading of digestate on the farm field does not include any data on this impact category. However, processes from the Ecoinvent database has data for the category. Substances important in this category are toluene, and formaldehyde. The category in itself is difficult to collect data for, especially regarding organic material-based cases and little is known on the causal relations between the chemicals and human health (Klöpffer and Grahl, 2014). ILCD uses methods from USEtox, where human toxicity, cancer related and non-cancer related are separate (European Commission and Joint Research Centre - IES, 2011).

Mineral, and fossil depletion

The category shows the scarcity of mineral and fossil resources and is based on Oers et al. (2002) characterisation based on economic reserves and reserve base figures from the US Geological Survey (European Commission and Joint Research Centre - IES, 2011). In other words, the characterisation factor, shown in kg Sb-equivalents, is influenced by the depletion and the reserves of mineral and fossil resources.

8.2.4 Sensitivity analysis

A sensitivity analysis is carried out through classifying each Ecoinvent inventory data base unit in three categories based on the uncertainty of data. This is to check whether changes in values per FU will considerably change the results. The analysis is only carried out for Reference and Biogas scenarios 1 – without storage cover on storage units at farm. The categories are:

- Low uncertainty: The value per unit is set to 90% of the original value. Among other, set for transportation data, and emissions from buses.
- Medium uncertainty: The value per unit is set to 70% of the original value. Among other, set for storage of stillage/digestate and diesel use for spreading the same, vegetable/potato residues emissions, mineral fertiliser substitution and electricity use.
- High uncertainty: The value per unit is set to 50% of the original value. Among other, set for emissions from spreading stillage/digestate, biogas plant infrastructure, pipeline construction and substitution of heat.

For details of the parameters set, see appendix B.

9 Life Cycle Inventory

The tables 8.1 to 8.4 are overviews of the processes, including showing which unit processes made in Simapro are modelled under which process categories shown in the results chapter. The last column shows the calculation number presented in Appendix A. The calculations are detailed description of the reasoning and calculations behind the value per fU. The output per ton DM is the output of each process unit made in Simapro. The Simapro units created with unit number ending with “x” represents the units used when modelling scenarios with storage at farm with storage cover. These are replaced with the unit process with the corresponding number. Likewise, numbers in the unit names ending with “E” represent the units used for the scenarios when biogas is used for electricity and heat. The ones ending with “D” are used for scenarios where biogas is used for transport fuel (diesel).

The allocation method used is based on mass. To calculate data per substrate mix, the data was weighted on the percentage each substrate contributed to the mix of 1 ton dry matter (fU). This method was used as tests of the proposed substrate mix was not tested through this thesis work.

Figure 9.1 shows the processes of each scenario in a flow diagram. Biogas scenarios 1 and 2 are similar, the only difference is the substrate type going into the system.

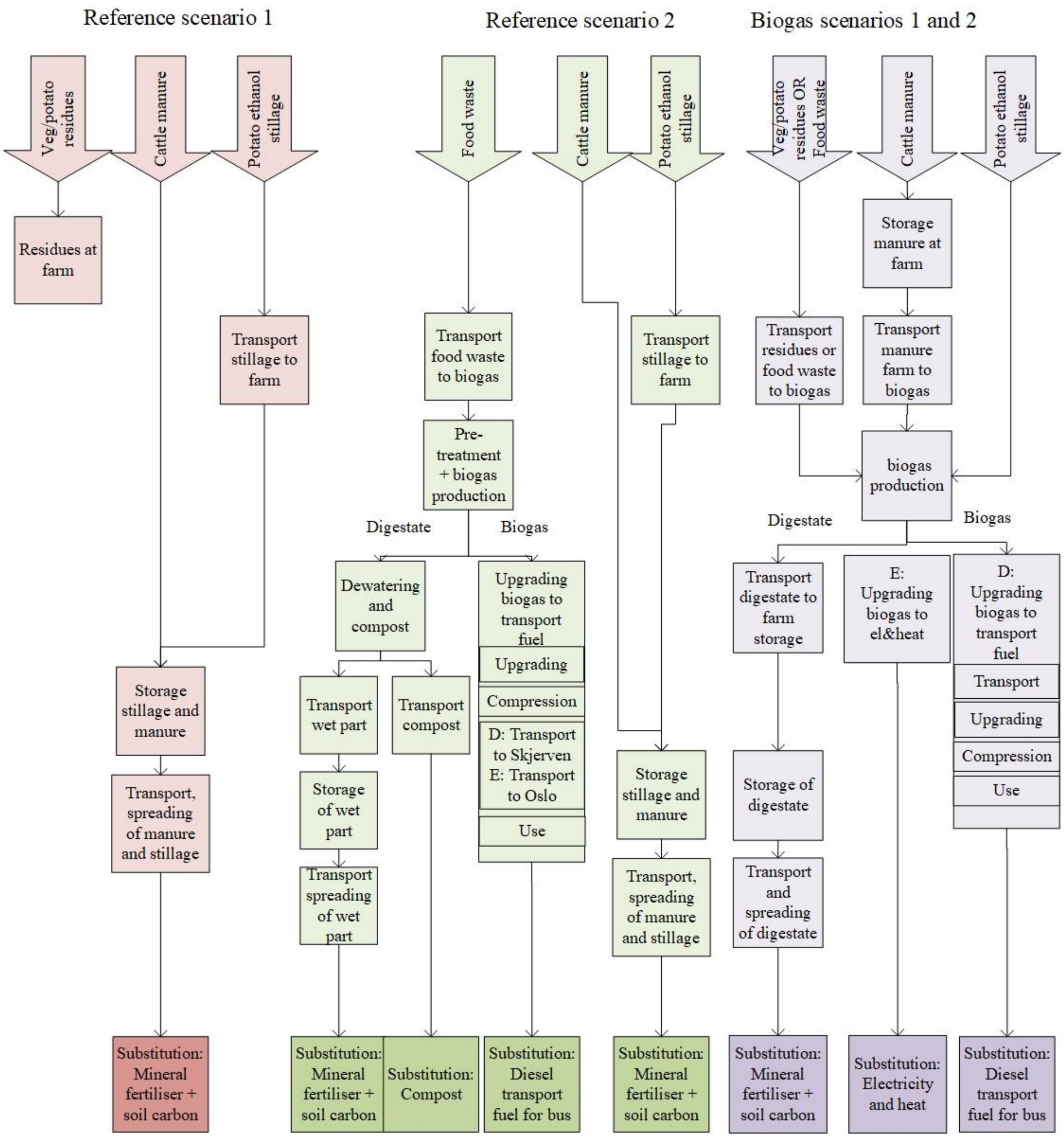


Figure 9.1 Scenarios flow diagram

Process category	**Simapro unit created**	**Output per ton DM**	**Description of inventory**	**Ecoinvent inventory name**	**Value per FU**	**Unit**	**Emission data**	**Appendix A references**
Transport and storage of substrate	Ref 1.1_Transport potato stillage to farms	4,5 ton potato ethanol stillage	Transport potato stillage to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	155,9	tkm	Ecoinvent 3	R1
	Ref 1.2_Storage of potato stillage with cattle manure at farm	6,8 ton potato ethanol stillage and cattle manure	Storage potato stillage with cattle manure, CH4 emission	Methane, biogenic	8,306	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, N2O emission	Dinitrogen monoxide	0,028	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, NH3 emission	Ammonia, NO	0,343	kg	based on Modahl et al. 2016	R2
	Ref 1.2x_Storage of potato stillage with cattle manure at farm_no emissions	6,8 ton potato ethanol stillage and cattle manure	Storage potato stillage with cattle manure, CH4 emission	Methane, biogenic	0,000	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, N2O emission	Dinitrogen monoxide	0,000	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, NH3 emission	Ammonia, NO	0,000	kg	based on Modahl et al. 2016	R2
Transport to spreading and spreading for use	Ref 1.3_Spreading of potato stillage with cattle manure on farm	6,8 ton potato ethanol stillage and cattle manure	Diesel use, stirring of stillage with cattle manure	Diesel (RER)| market group for | Alloc Rec, U	0,260	kg	Ecoinvent 3	R3
			Diesel use, pumping from storage to field	Diesel (RER)| market group for | Alloc Rec, U	0,578	kg	Ecoinvent 3	R3
			Diesel use, tractor for spreading	Diesel (RER)| market group for | Alloc Rec, U	1,618	kg	Ecoinvent 3	R3
			Spreading of stillage and manure, N2O emission	Dinitrogen monoxide	0,174	kg	based on Modahl et al. 2016	R3
			Spreading of stillage and manure, NH3 emission	Ammonia, NO	1,928	kg	based on Modahl et al. 2016	R3
	Ref 1.4_Potato and veg residues on farm field	2,51 ton veg/potato residues	Potato and vegetable residues on field, N2O emission	Dinitrogen monoxide	0,095	kg	based on Grønlund 2015	R4
Digestate substitutes mineral fertiliser or compost	Ref 1.5_Substitution of mineral fertiliser	9,94 kg nitrogen in mineral fertiliser	Production of nitrogen fertiliser as N	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	9,94	kg	Ecoinvent 3	R16
			Spreading of nitrogen fertiliser, emission N2O	Dinitrogen monoxide	0,099	kg	based on Grønlund 2015	R16
			Spreading of nitrogen fertiliser, emission NH3	Ammonia, NO	0,094	kg	based on Grønlund 2015	R16
	Ref 1.6_Substitution of carbon to soil	39,88 carbon in soil	Carbon to soil	Carbon, organic, in soil or biomass stock	39,88	kg	Ecoinvent 3	R17

Table 9.1 Inventory list Reference scenario 1

Process category	**Simapro unit created**	**Output per ton DM**	**Description of inventory**	**Ecoinvent inventory name**	**Value per FU**	**Unit**	**Emission data**	**Appendix A references**
Transport and storage of substrate	Scenario 1.1_Storage manure at farm before going to biogas	2,3 ton cattle manure	Storage cattle manure at farm, NH3 emission	Ammonia, NO	0,026	kg	based on Modahl et al. 2016	B1
Transport of substrate to waste mng facility	Scenario 1.2_Transport manure from farm to HOFF biogas	2,3 ton cattle manure	Transport manure from farms to HOFF biogas	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	78,6	tkm	Ecoinvent 3	B2
	Scenario 1.3_Transport potato and vegetable residues from farm to HOFF biogas	2,51 ton veg/potato residues	Transport veg/potato residues from farms to HOFF biogas	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	69,0	tkm	Ecoinvent 3	B3
Biogas production	Scenario 1.4_Biogas production from potato stillage, manure and farm residues	640,46 m3 biogas, 8,37 ton digestate	Electricity for production from Norwegian electricity mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	67,24	kwh	Ecoinvent 3	B5
			Biogas plant material	Anaerobic digestion plant, agricultural (RoW)| construction | Alloc Rec, U	3,22E-05	unit	Ecoinvent 3	B6
Upgrading of biogas	Scenario 1.5E_CHP power transformation of biogas	1153,3 kwh electricity, 1441,6 kwh heat	CHP power conversion	Mini CHP plant, common components for heat+electricity (Arapoglou *et al.*)| market for | Alloc Rec, U	6,45E-05	units	Ecoinvent 3	B7
	Scenario 1.5D_Converting biogas to transport fuel and use of biogas in buses	452,62 km biogas driven bus	Electricity for pumping through pipe, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	25,72	kwh	Ecoinvent 3	B8
			Biogas transport pipe, infrastructure	Pipeline, natural gas, low pressure distribution network (RoW)| construction | Alloc Rec, U	1,29E-04	km	Ecoinvent 3	B8
			Electricity for upgrading biogas to transport fuel, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	128,61	kwh	Ecoinvent 3	B8
			Upgrading biogas to transport fuel, CH4 emission	Methane, biogenic	2,41	kg	based on Modahl et al. 2016	B8
			Electricity for compression of upgraded biogas, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	48,48	kwh	Ecoinvent 3	B8
			Use of biogas in buses, Nox emission	Nitrogen oxides, NO	45,26	g	based on Hagman 2016	B9
			Use of biogas in buses, PM emission	Particulates, < 10 um	12,67	g	based on Hagman 2016	B9
			Use of biogas in buses, CO2 emission	Carbon dioxide, biogenic	0,00	g	based on Hagman 2016	B9
Transport to storage and storage of digestate	Scenario 1.6_Transport digestate from HOFF biogas to farms	8,37 ton digestate	Transport digestate HOFF biogas to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	404,6	tkm	Ecoinvent 3	B10
	Scenario 1.7_Storage of digestate at farm	8,37 ton digestate	Storage digestate at farm, CH4 emission	Methane, biogenic	13,196	kg	based on Modahl et al. 2016	B11
			Storage digestate at farm, NH3 emission	Ammonia, NO	0,560	kg	based on Modahl et al. 2016	B11
	Scenario 1.7x_Storage of digestate at farm_no emission	8,37 ton digestate	Storage digestate at farm, CH4 emission	Methane, biogenic	0,000	kg	based on Modahl et al. 2016	B11

			Storage digestate at farm, NH3 emission	Ammonia, NO	0,000	kg	based on Modahl et al. 2016	B11
Transport to spreading and spreading for use	Scenario 1.8_Spreading of digestate on farm fields	8,37 ton digestate	Diesel use, stirring of stillage with cattle manure	Diesel (RER)| market group for | Alloc Rec, U	0,320	kg	Ecoinvent 3	B12
			Diesel use, pumping from storage to field	Diesel (RER)| market group for | Alloc Rec, U	0,712	kg	Ecoinvent 3	B12
			Diesel use, tractor for spreading	Diesel (RER)| market group for | Alloc Rec, U	1,994	kg	Ecoinvent 3	B12
			Spreading digestate on farm fields, N2O emission	Dinitrogen monoxide	0,229	kg	based on Modahl et al. 2016	B12
			Spreading digestate on farm fields, NH3 emission	Ammonia, NO	3,691	kg	based on Modahl et al. 2016	B12
Biogas substitutes energy carrier or transport fuel	Scenario 1.9E_Substitution of electricity and heat	1153,30 kwh electricity, 909,78 kwh heat	Norwegian electricity mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	1153,30	kwh	Ecoinvent 3	B13
			Heat, from district heating	Heat, district or industrial, other than natural gas (RoW)| heat production, hardwood chips from forest, at furnace 1000kW, state-of-the-art 2014 | Alloc Rec, U	3275,22	MJ	Ecoinvent 3	B13
	Scenario 1.9D_Substitution of diesel fueled busses	620,92 km diesel driven bus	Production and distribution of diesel to market	Diesel (RER)| market group for | Alloc Rec, U	211,36	kg	Ecoinvent 3	B14
			Use of diesel in buses, Nox emission	Nitrogen oxides, NO	93,14	g	based on Hagman 2016	B14
			Use of diesel in buses, PM emission	Particulates, < 10 um	8,69	g	based on Hagman 2016	B14
			Use of diesel in buses, CO2 emission	Carbon dioxide, fossil	693999,23	g	based on Hagman 2016	B14
Digestate substitutes mineral fertiliser or compost	Scenario 1.10_Substitution of mineral fertiliser	15,66 kg nitrogen in mineral fertiliser	Production of nitrogen fertiliser as N	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	15,66	kg	Ecoinvent 3	B15
			Spreading of nitrogen fertiliser, emission N2O	Dinitrogen monoxide	0,157	kg	based on Grønlund 2015	B15
			Spreading of nitrogen fertiliser, emission NH3	Ammonia, NO	0,149	kg	based on Grønlund 2015	B15
	Scenario 1.11_Substitution of carbon to soil	80 kg carbon to soil	Carbon to soil	Carbon, organic, in soil or biomass stock	80	kg	Ecoinvent 3	B16

Table 9.2 Inventory list Biogas scenario 1

Process Category	**Simapro unit created**	**Output per ton DM**	**Description of inventory**	**Ecoinvent inventory name**	**Value per FU**	**Unit**	**Emission data**	**Appendix A references**
Transport and storage of substrate	Ref 2.1_Transport potato stillage to farms	7,9 ton potato ethanol stillage	Transport potato stillage to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	274,2	tkm	Ecoinvent 3	R1
	Ref 2.2_Storage potato stillage with cattle manure at farm	10,2 ton potato ethanol stillage and cattle manure	Storage potato stillage with cattle manure, CH4 emission	Methane, biogenic	12,798	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, N2O emission	Dinitrogen monoxide	0,027	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, NH3 emission	Ammonia, NO	0,360	kg	based on Modahl et al. 2016	R2
	Ref 2.2x_Storage potato stillage with cattle manure at farm_no emission	10,2 ton potato ethanol stillage and cattle manure	Storage potato stillage with cattle manure, CH4 emission	Methane, biogenic	0,000	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, N2O emission	Dinitrogen monoxide	0,000	kg	based on Modahl et al. 2016	R2
			Storage potato stillage with cattle manure, NH3 emission	Ammonia, NO	0,000	kg	based on Modahl et al. 2016	R2
Transport to spreading and spreading for use	Ref 2.3_Spreading of potato stillage with cattle manure on farm	10,2 ton potato ethanol stillage and cattle manure	Diesel use, stirring of stillage with cattle manure	Diesel (RER)| market group for | Alloc Rec, U	0,389	kg	Ecoinvent 3	R3
			Diesel use, pumping from storage to field	Diesel (RER)| market group for | Alloc Rec, U	0,865	kg	Ecoinvent 3	R3
			Diesel use, tractor for spreading	Diesel (RER)| market group for | Alloc Rec, U	2,423	kg	Ecoinvent 3	R3
			Spreading of stillage and manure, N2O emission	Dinitrogen monoxide	0,209	kg	based on Modahl et al. 2016	R3
			Spreading of stillage and manure, NH3 emission	Ammonia, NO	2,436	kg	based on Modahl et al. 2016	R3
Transport of substrate to waste mng facility	Ref 2.4_Transport food waste to Mjøsanlegget	1 ton food waste	Transport food waste to Mjøsanlegget	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	50,1	tkm	Ecoinvent 3	R5
Biogas production	Ref 2.5_Biogas production industrial plant food waste	180,38 m3 biogas, 1,81 ton digestate	Electricity for production biogas production	Electricity, medium voltage (NO)| market for | Alloc Rec, U	22,55	kwh	Ecoinvent 3	R6
			Biogas plant material, industrial size	Anaerobic digestion plant, for biowaste (RoW)| construction | Alloc Rec, U	4,01E-06	units	Ecoinvent 3	R6
			Electricity for pre-treatment	Electricity, medium voltage (NO)| market for | Alloc Rec, U	14,43	kwh	Ecoinvent 3	R6
			Water use for pre-treatment	Water, unspecified natural origin, NO	0,48	m3	based on Modahl et al. 2016	R6
			Pre-treatment, COD emission	COD, Chemical Oxygen Demand	0,74	mg	based on Modahl et al. 2016	R6
			Pre-treatment, N emission	Nitrogen, total	0,14	mg	based on Modahl et al. 2016	R6
			Pre-treatment, P emission	Phosphorus, total	0,01	mg	based on Modahl et al. 2016	R6

Upgrading of biogas	Ref 2.6_Converting food waste biogas to transport fuel and use of biogas in buses	162,00 km biogas driven bus	Electricity for upgrading biogas to transport fuel, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	41,12	kwh	Ecoinvent 3	R7
			Upgrading biogas to transport fuel, CH4 emission	Methane, biogenic	0,86	kg	based on Modahl et al. 2016	R7
			Electricity for compression of upgraded biogas, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	17,35	kwh	Ecoinvent 3	R7
			Use of biogas in buses, Nox emission	Nitrogen oxides, NO	16,20	g	based on Hagman 2016	R8
			Use of biogas in buses, PM emission	Particulates, < 10 um	4,54	g	based on Hagman 2016	R8
			Use of biogas in buses, CO2 emission	Carbon dioxide, biogenic	0,00	g	based on Hagman 2016	R8
	Ref 2.7E_Transport compressed gas food waste to Oslo	162,00 km biogas driven bus	Transport compressed gas to Oslo	Transport, freight, lorry >32 metric ton, EURO5 (RER)| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec, U	12,0	tkm	Ecoinvent 3	R9
	Ref 2.7D_Transport compressed gas food waste to Skjerven	162,00 km biogas driven bus	Transport compressed gas to Skjerven	Transport, freight, lorry >32 metric ton, EURO5 (RER)| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec, U	3,9	tkm	Ecoinvent 3	R9
Dewatering and composting	Ref 2.8_Production of wet part and compost of food waste digestate	0,16 ton compost, 1,65 ton wet digestate	Energy use dewatering of digestate, from le mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	1,813	kwh	Econinvent 3	R10
			Composting, CH4 emission	Methane, biogenic	0,391	kg	based on Modahl et al. 2016	R10
			Composting, N2O emission	Dinitrogen monoxide	0,033	kg	based on Modahl et al. 2016	R10
			Composting, NH3 emission	Ammonia, NO	0,993	kg	based on Modahl et al. 2016	R10
			Composting, NMVOC emission	NMVOC, non-methane volatile organic compounds, unspecified origin	0,163	kg	based on Modahl et al. 2016	R10
Transport to storage and storage of digestate	Ref 2.9_Transport of wet part food waste to farm	1,65 ton wet digestate	Transport wet part to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	41,1	tkm	Ecoinvent 3	R12
	Ref 2.10_Storage of wet part digestate of food waste at farm	1,65 ton wet digestate	Storage digestate wet part food waste at farm, CH4 emission	Methane, biogenic	2,646	kg	based on Modahl et al. 2016	R13
			Storage digestate wet part food waste at farm, NH3 emission	Ammonia, NO	0,018	kg	based on Modahl et al. 2016	R13
	Ref 2.10x_Storage of wet part digestate of food waste at farm_no emission	1,65 ton wet digestate	Storage digestate wet part food waste at farm, CH4 emission	Methane, biogenic	0,000	kg	based on Modahl et al. 2016	R13
			Storage digestate wet part food waste at farm, NH3 emission	Ammonia, NO	0,000	kg	based on Modahl et al. 2016	R13
Transport to spreading and spreading for use	Ref 2.11_Transport of compost to customer	0,16 ton compost	Transport of compost to customer in truck	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	7,3	tkm	Ecoinvent 3	R11
	Ref 2.12_Spreading of wet part of food waste digestate on farm	1,65 ton wet digestate	Diesel use for steering	Diesel (RER)| market group for | Alloc Rec, U	0,063	kg	Ecoinvent 3	R14

			Diesel pumping	Diesel (RER)| market group for | Alloc Rec, U	0,140	kg	Ecoinvent 3	R14
			Diesel tractor	Diesel (RER)| market group for | Alloc Rec, U	0,392	kg	Ecoinvent 3	R14
			Spreading, N2O emission	Dinitrogen monoxide	4,77E-05	kg	based on Modahl et al. 2016	R14
			Spreading , NH3 emission	Ammonia, NO	0,399	kg	based on Modahl et al. 2016	R14
Biogas substitutes energy carrier or transport fuel	Ref 2.13_Substitution of diesel fueled busses	222,24 km diesel bus	Production of diesel, market for	Diesel (RER)| market group for | Alloc Rec, U	75,65	kg	Ecoinvent 3	R15
			Use of diesel in buses, Nox emission	Nitrogen oxides, NO	33,34	g	based on Hagman 2016	R15
			Use of diesel in buses, PM emission	Particulates, < 10 um	3,11	g	based on Hagman 2016	R15
			Use of diesel in buses, CO2 emission	Carbon dioxide, fossil	248397,19	g	based on Hagman 2016	R15
Digestate substitutes mineral fertiliser or compost	Ref 2.14_Substitution of mineral fertiliser	13,93 kg nitrogen in mineral fertiliser	Production of nitrogen fertiliser as N, from potato stillage and manure	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	12,38	kg	Ecoinvent 3	R16
			Spreading of nitrogen fertiliser from potato stillage and manure, emission N2O	Dinitrogen monoxide	0,124	kg	based on Grønlund 2015	R16
			Spreading of nitrogen fertiliser from potato stillage and manure, emission NH3	Ammonia, NO	0,061	kg	based on Grønlund 2015	R16
			Production of nitrogen fertiliser as N, from food waste digestate	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	1,55	kg	Ecoinvent 3	R16
			Spreading of nitrogen fertiliser food waste, emission N2O	Dinitrogen monoxide	0,016	kg	based on Grønlund 2015	R16
			Spreading of nitrogen fertiliser food waste, emission NH3	Ammonia, NO	0,015	kg	based on Grønlund 2015	R16
	Ref 2.15_Substitution of carbon in soil	55,95 kg carbon in soil	Carbon to soil	Carbon, organic, in soil or biomass stock	55,95	kg	Ecoinvent 3	R17
	Ref 2.16_Substitution of compost	0,08 ton compost	Transport of compost to customer in truck	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	8,8	tkm	Ecoinvent 3	R18
			Composting, CH4 emission	Methane, biogenic	0,195	kg	based on Modahl et al. 2016	R18
			Composting, N2O emission	Dinitrogen monoxide	0,016	kg	based on Modahl et al. 2016	R18
			Composting, NH3 emission	Ammonia, NO	0,496	kg	based on Modahl et al. 2016	R18
			Composting, NMVOC emission	NMVOC, non-methane volatile organic compounds, unspecified origin	0,081	kg	based on Modahl et al. 2016	R18

Table 9.3 Inventory list Reference scenario 2

Process category	**Simapro unit created**	**Output per ton DM**	**Description of inventory**	**Ecoinvent inventory name**	**Value per FU**	**Unit**	**Emission data**	**Appendix A references**
Transport and storage of substrate	Scenario 2.1_Storage manure at farm	2,2 ton cattle manure	Storage cattle manure at farm, NH3 emission	Ammonia, NO	0,025	kg	based on Modahl et al. 2016	B1
Transport of substrate to waste mng facility	Scenario 2.2_Transport manure from farm to HOFF biogas	2,2 ton cattle manure	Transport manure from farms to HOFF biogas	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	77,0	tkm	Ecoinvent 3	B2
	Scenario 2.3_Transport of food waste to HOFF	1 ton food waste	Transport of food waste within Gjøvik	Transport, freight, lorry 7.5-16 metric ton, EURO5 (RER)| transport, freight, lorry 7.5-16 metric ton, EURO5 | Alloc Rec, U	4,0	tkm	Ecoinvent 3	B4
Biogas production	Scenario 2.4_Biogas production from potato stillage, manure and food waste	585,62 m3 biogas, 10,05 ton digestate	Electricity for production from Norwegian electricity mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	71,13	kwh	Ecoinvent 3	B5
			Biogas plant material	Anaerobic digestion plant, agricultural (RoW)| construction | Alloc Rec, U	4,54E-05	unit	Ecoinvent 3	B6
Upgrading of biogas	Scenario 2.5E_CHP power transformation of biogas	1113,66 kwh electricity, 1392,1 kwh heat	CHP power conversion	Mini CHP plant, common components for heat+electricity (Arapoglou *et al.*)| market for | Alloc Rec, U	1,13E-04	unit	Ecoinvent 3	B7
	Scenario 2.5D_Converting biogas to transport fuel and use of biogas in buses	453,73 km biogas driven bus	Electricity for pumping through pipe, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	24,42	kwh	Ecoinvent 3	B8
			Biogas transport through pipeline low pressure, infrastructure	Pipeline, natural gas, low pressure distribution network (RoW)| construction | Alloc Rec, U	2,27E-04	km	Ecoinvent 3	B8
			Electricity for upgrading biogas to transport fuel, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	122,08	kwh	Ecoinvent 3	B8
			Upgrading biogas to transport fuel, CH4 emission	Methane, biogenic	2,41	kg	based on Modahl et al. 2016	B8
			Electricity for compression of upgraded biogas, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	48,59	kwh	Ecoinvent 3	B8
			Use of biogas in buses, Nox emission	Nitrogen oxides, NO	45,37	g	based on Hagman 2016	B9
			Use of biogas in buses, PM emission	Particulates, < 10 um	12,70	g	based on Hagman 2016	B9
			Use of biogas in buses, CO2 emission	Carbon dioxide, biogenic	0,00	g	based on Hagman 2016	B9
Transport to storage and storage of digestate	Scenario 2.6_Transport digestate from HOFF biogas to farms	10,05 ton digestate	Transport digestate HOFF biogas to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	382,0	tkm	Ecoinvent 3	B10
	Scenario 2.7_Storage of digestate at farm	10,05 ton digestate	Storage digestate at farm, CH4 emission	Methane, biogenic	12,356	kg	based on Modahl et al. 2016	B11
			Storage digestate at farm, NH3 emission	Ammonia, NO	0,552	kg	based on Modahl et al. 2016	B11
	Scenario 2.7x_Storage of digestate at farm_no emission	10,05 ton digestate	Storage digestate at farm, CH4 emission	Methane, biogenic	0,000	kg	based on Modahl et al. 2016	B11
			Storage digestate at farm, NH3 emission	Ammonia, NO	0,000	kg	based on Modahl et al. 2016	B11

Transport to spreading and spreading for use	Scenario 2.8_Spreading of digestate on farm fields	10,05 ton digestate	Diesel use, stirring of stillage with cattle manure	Diesel (RER)| market group for | Alloc Rec, U	0,385	kg	Ecoinvent 3	B12
			Diesel use, pumping from storage to field	Diesel (RER)| market group for | Alloc Rec, U	0,856	kg	Ecoinvent 3	B12
			Diesel use, tractor for spreading	Diesel (RER)| market group for | Alloc Rec, U	2,396	kg	Ecoinvent 3	B12
			Spreading digestate on farm fields, N2O emission	Dinitrogen monoxide	0,228	kg	based on Modahl et al. 2016	B12
			Spreading digestate on farm fields, NH3 emission	Ammonia, NO	3,676	kg	based on Modahl et al. 2016	B12
Biogas substitutes energy carrier or transport fuel	Scenario 2.9E_Substitution of electricity and heat	1113, 66 kwh electricity, 958,45 kwh heat	Norwegian electricity mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	1113,66	kwh	Ecoinvent 3	B13
			Heat, from district heating	Heat, district or industrial, other than natural gas (RoW)| heat production, hardwood chips from forest, at furnace 1000kW, state-of-the-art 2014 | Alloc Rec, U	3450,40	MJ	Ecoinvent 3	B13
	Scenario 2.9D_Substitution of diesel fueled busses	622,43 km diesel driven bus	Production of diesel, market for	Diesel (RER)| market group for | Alloc Rec, U	211,88	kg	Ecoinvent 3	B14
			Use of diesel in buses, Nox emission	Nitrogen oxides, NO	93,37	g	based on Hagman 2016	B14
			Use of diesel in buses, PM emission	Particulates, < 10 um	8,71	g	based on Hagman 2016	B14
			Use of diesel in buses, CO2 emission	Carbon dioxide, fossil	695693,83	g	based on Hagman 2016	B14
Digestate substitutes mineral fertiliser or compost	Scenario 2.10_Substitution of mineral fertiliser	16,53 kg nitrogen in mineral fertiliser	Production of nitrogen fertiliser as N	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	16,53	kg	Ecoinvent 3	B15
			Spreading of nitrogen fertiliser, emission N2O	Dinitrogen monoxide	0,165	kg	based on Grønlund 2015	B15
			Spreading of nitrogen fertiliser, emission NH3	Ammonia, NO	0,157	kg	based on Grønlund 2015	B15
	Scenario 2.11_Substitution of carbon to soil	80 kg carbon to soil	Carbon to soil	Carbon, organic, in soil or biomass stock	80	kg	Ecoinvent 3	B16

Table 9.4 Inventory list Biogas scenario 2

10 Results

The results are shown separately for scenario 1 and 2. Each are presented with and without cover on storage facility at farm. Each biogas scenario has two sub-scenarios: when biogas is utilised for electricity and heat and when the biogas is substituted with diesel as transport fuel. For reference scenario 2, the scenario is from a concrete case (Mjøsanlegget). Therefore, the use of biogas is fixed. However, the reference scenario 2 has a change in where the compressed biogas is transferred (to Skjerven) when comparing with the biogas scenario where there is a market for transport fuel in the Gjøvik area, and therefore not sent to Oslo. The reference scenarios are shown with storage cover for the sake of comparing, although storage cover may not be the common practice today.

The results are illustrated per process category, which are the same categories shown in tables 9.1 to 9.4. The diagram shows the net impact on the category. If the net impact is a negative number, it means that the scenario is positive for the impact category. The results are shown in characterisation factors.

10.1 Scenario 1 – Vegetable/potato residues with cattle manure and potato ethanol stillage

The results for six impact categories are shown in figures 10.1 and 10.2. For climate change, acidification, and some for terrestrial eutrophication and, cover on the storage facilities at farms contribute positively to the results of these impacts, as expected. Even for the reference scenario, storing the potato stillage with cover would improve today's practice for the units that do not have cover, especially for climate change because of the high methane emissions from stillage and manure storage at farms. For climate change benefits, there are few gains from biogas production to electricity and heating if there are storage units without cover as the reference scenario contributes to 205,9 kg CO2 equivalents, while biogas for el&heat contributes to 199,5 kg.

The reference scenario is the best option for minimal acidification. This is mainly because the amount of stillage for spreading at farms is less per ton DM than the amount of digestate spread. When using farm residues as biogas substrate (50% of total substrate DM) that otherwise do not stress acidification, the biogas scenarios contribute to almost double the amount of acidification than the reference scenario.

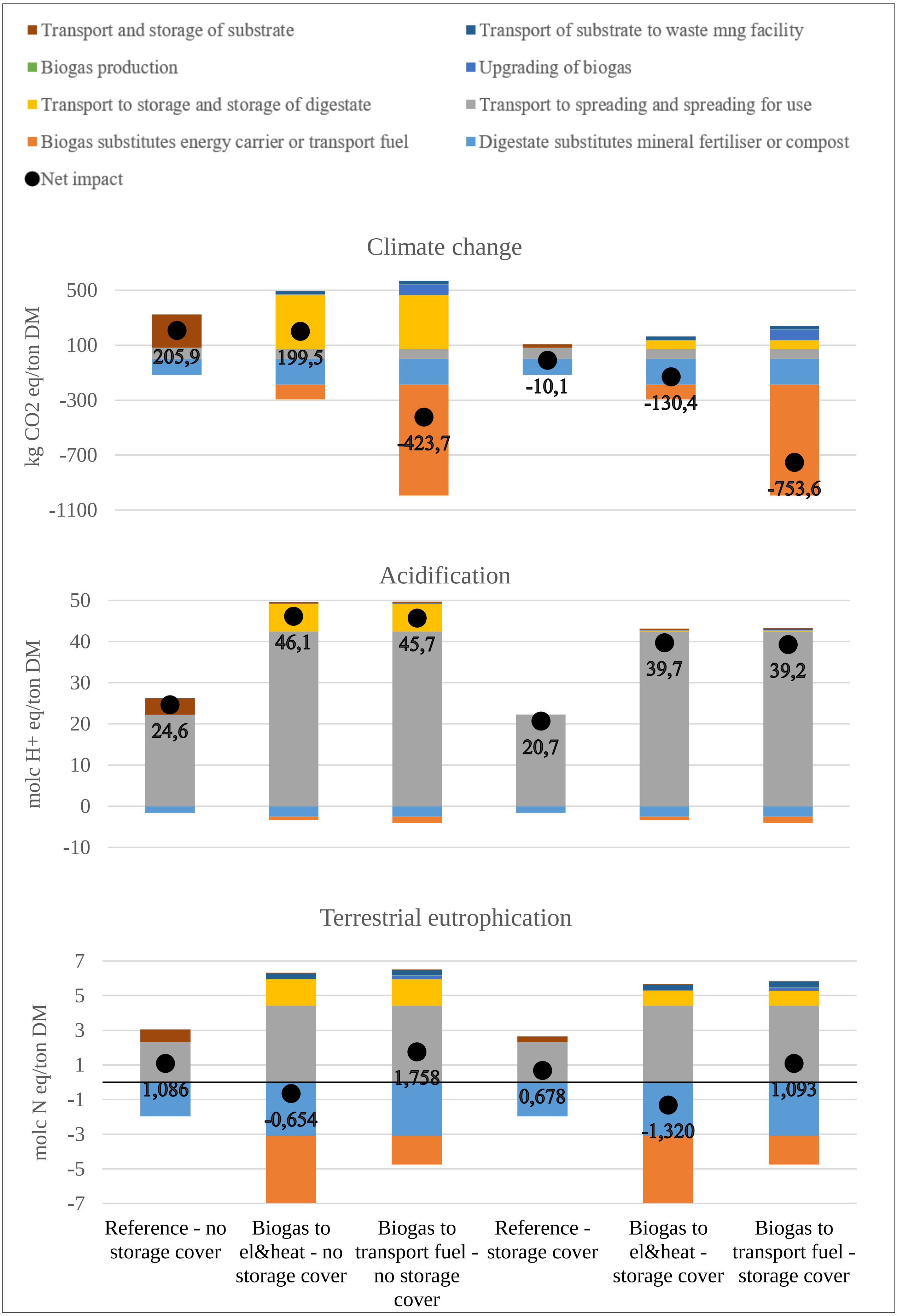


Figure 10.1 Results Scenario 1 Climate change, acidification and terrestrial eutrophication

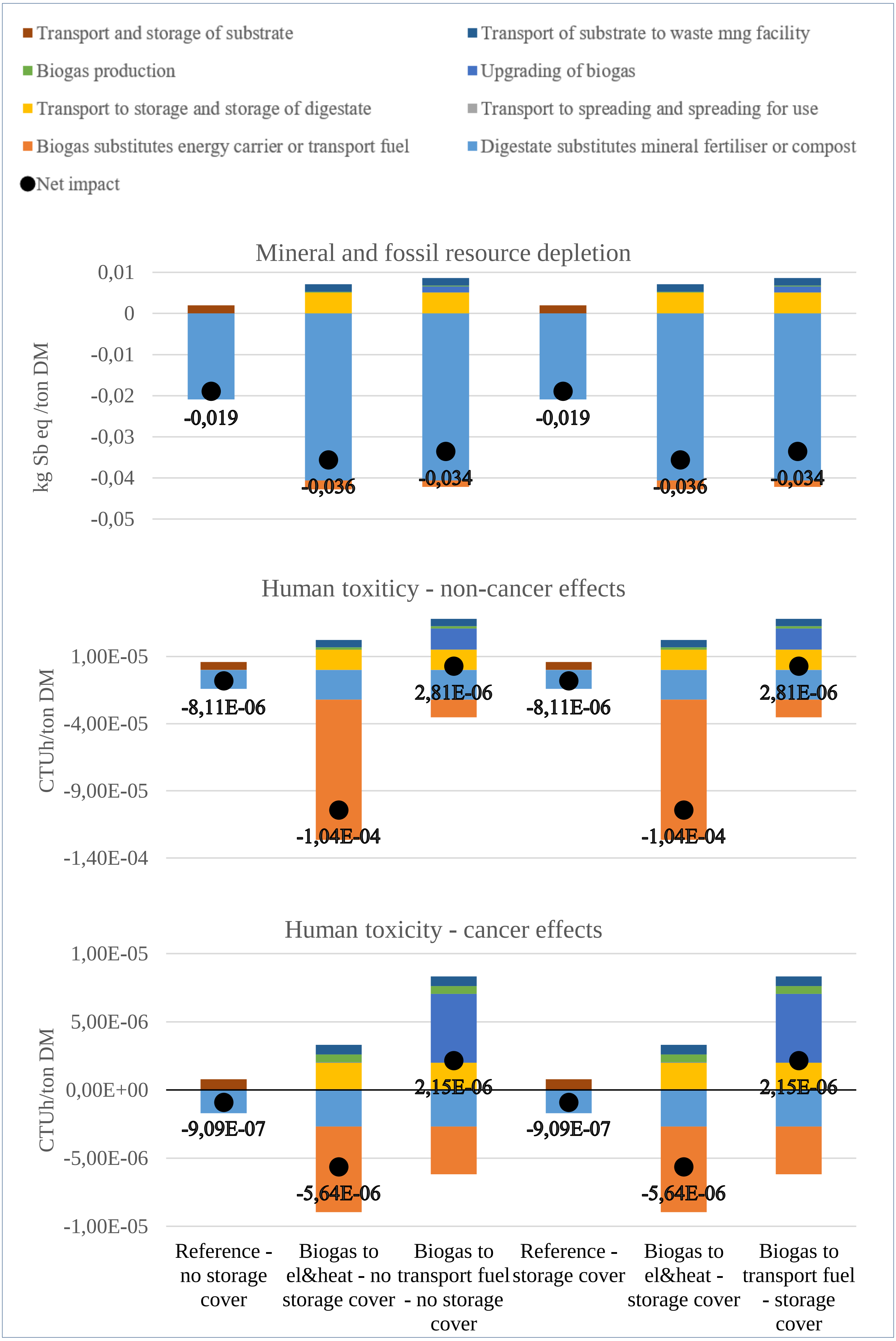


Figure 10.2 Results Scenario 1 mineral and fossil resource depletion, human toxicity - non-cancer and cancer effects

The biogas scenario when biogas is used for electricity and heat is the significantly best option for minimal eutrophication, and both impact categories on human toxicity. The substitution of heat as well as mineral fertiliser are the biggest contributors to decrease eutrophication. For human toxicity non-cancer effects, substitution of heat is giving the most positive result, while substitution of electricity gives the most positive results for cancer effects.

The biogas scenario when biogas is used as transport fuel is the best for positive contributions to climate change impact. This is mainly due to the substitution of the use of diesel in buses and thus emissions of CO2 to air when burning the diesel. If this use stage was not included in the system boundaries of this LCA, the digestate would be the biggest positive contributor to climate change and biogas to transport fuel would be more similar to the scenario when biogas is used to heat and electricity. Biogas to transport fuel is significantly worse than biogas to el&heat in the human toxicity categories. The main negative contributors are the upgrading processes, in particular the 8 km long gas pipeline construction to Skjerven and secondly the electricity needed in the process.

Biogas scenarios for transport and el&heat have similar benefits on mineral and fossil resource emissions. This is mainly due to the substitution of mineral fertiliser.

Overall, when biogas substitutes el&heat, it has a positive impact on more categories than the other scenarios, especially if storage facilities have cover. However, knowing that policies and projects support the decrease of greenhouse gases, biogas for transport fuel would be the best option.

10.2 Scenario 2 – Food waste with cattle manure and potato ethanol stillage

The results for scenario 2 are shown in figure 10.3 and 10.4. Here, the diagram shows a reference scenario for each of the biogas scenarios, one for comparing with biogas to el&heat and another for comparing with biogas to transport fuel.

Analysing the results of the reference scenario, it is obvious that transporting the compressed biogas to Skjerven instead of Oslo, does not have significant effects on any of the impact categories. There are more processes of biogas production included in the reference scenario 2 compared to the reference scenario 1. This fact also shows the great differences in the reference scenario 2 results. The reference scenario is not significantly better in any of the six impact categories, however, like in scenario 1, it has the least negative impact for acidification.

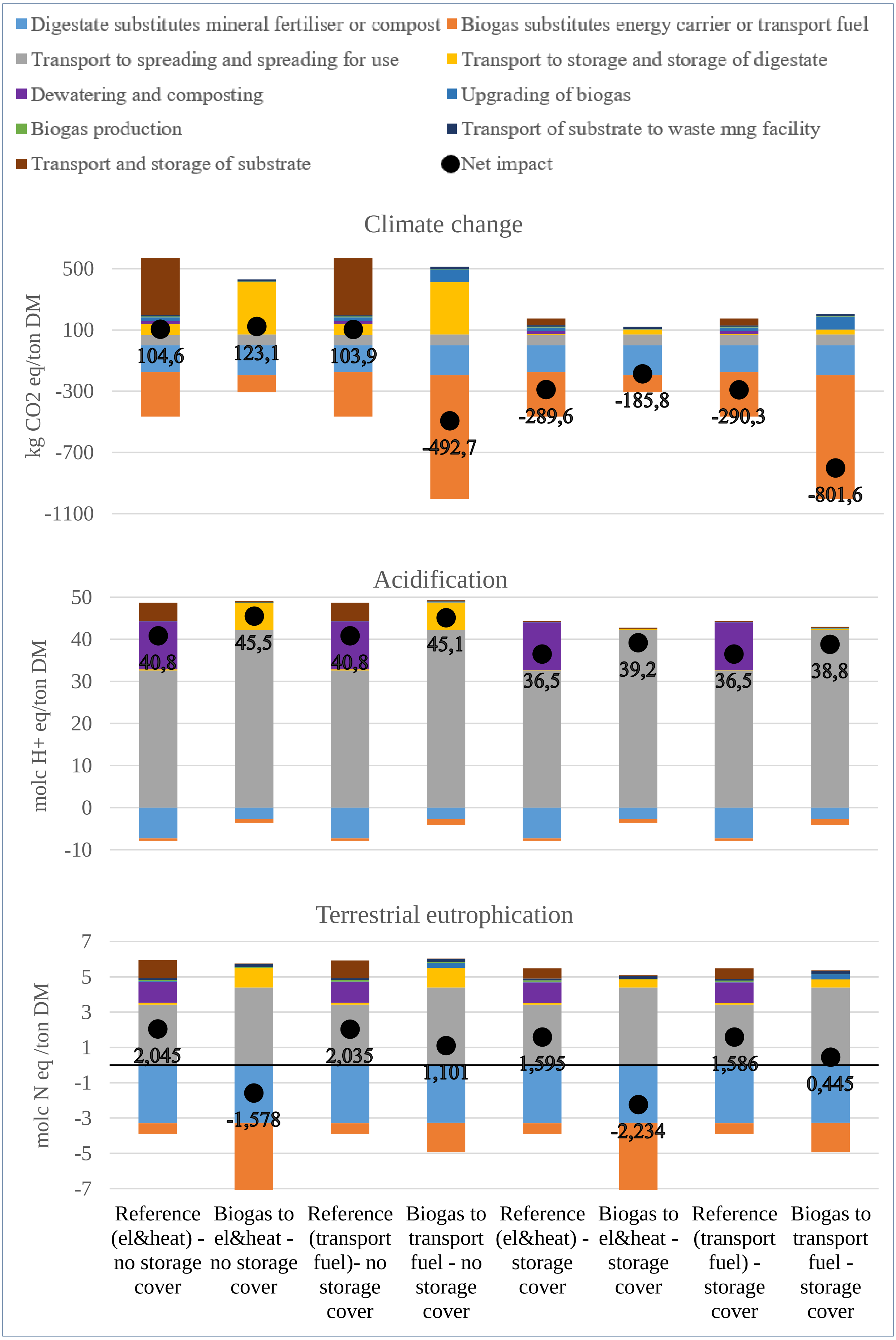


Figure 10.3 Results scenario 2 climate change, acidification and terrestrial eutrophication

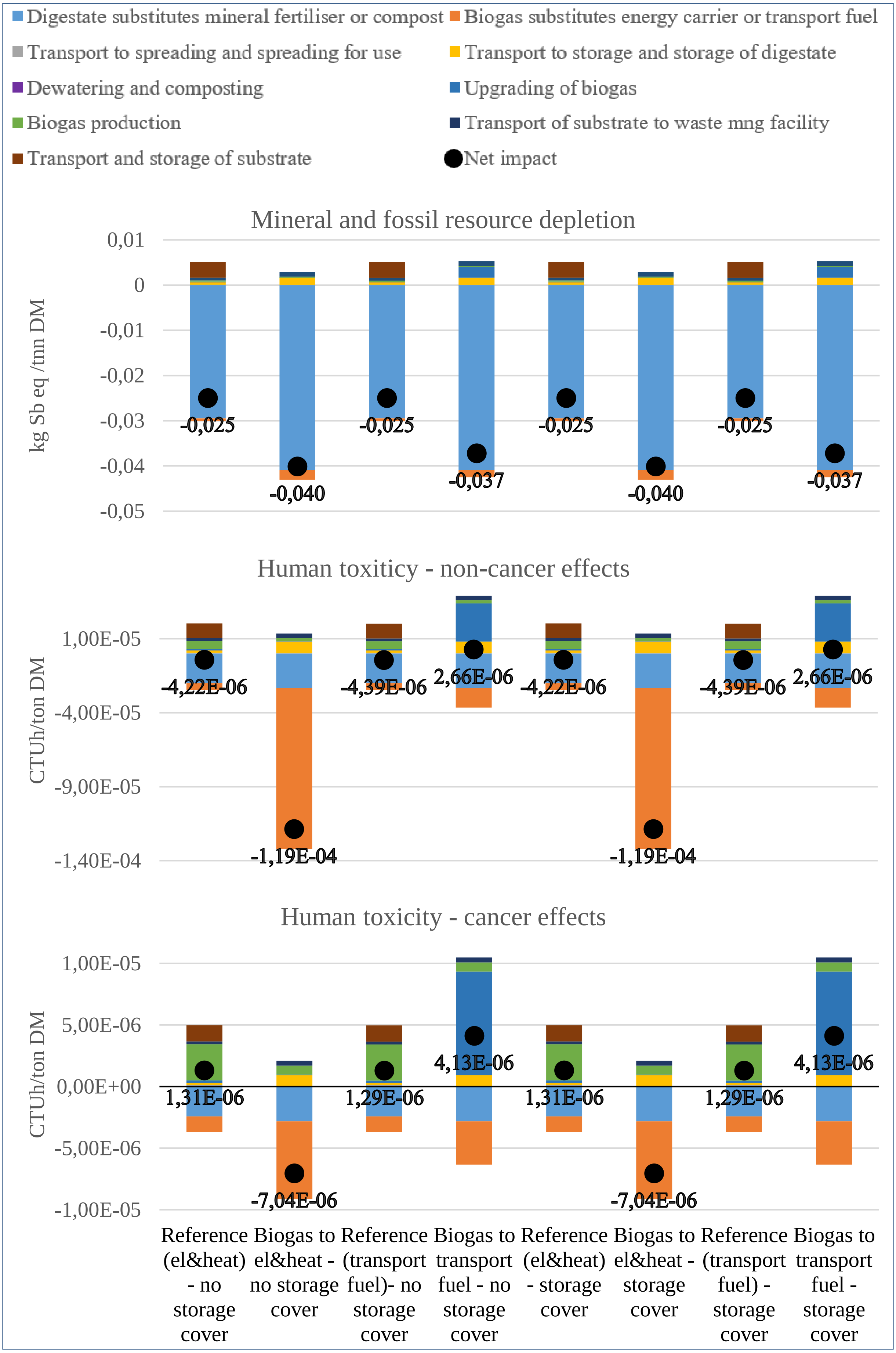


Figure 10.4 Results scenario 2 mineral and fossil resource depletion, human toxicity non-cancer and cancer effects

It is important to note that when storage facilities have storage cover, the reference scenario have more positive impact on climate change compared to the biogas scenario when used for el&heat. In the reference scenario, dewatering and composting seem to have significant negative effects on terrestrial eutrophication and acidification.

As in scenario 1, the biogas scenario when biogas is used for electricity and heat is the significantly best option for minimal eutrophication, and both impact categories on human toxicity. This is for the same reasons mentioned for scenario 1. Further, the biogas scenario when biogas is used as transport fuel is the best for positive contributions to climate change impact for the same reasons as mentioned for scenario 1.

Reference and biogas scenarios have similar effects on mineral and fossil resource depletion and acidification, with smaller benefits in the reference scenario. It is interesting to see the contribution of the biogas production on human toxicity. The reference scenario has considerable negative impact from biogas plant construction. This calculation was somewhat uncertain and perhaps assumed higher number of units per ton DM. If the unit was somewhat lower, the reference scenario would have less impact on cancer effects, but not better than the biogas scenario to el&heat.

Overall, the conclusion for scenario 1 can also be drawn for scenario 2. The most significant change is that it would not be recommendable in terms of climate change to produce biogas for el&heat even when there are storage facilities with cover.

10.3 Sensitivity analysis scenario 1 without storage cover

A sensitivity analysis of scenario 1 was done – and only including the scenario without cover on storage facilities at farms. The results are presented in Figure 10.5 and 10.6. The sensitivity test is on the left side of the diagrams and the compared original scenario 1 is on the right side. As mentioned in chapter 7, parameters have been changed according to the assumed data quality and insecurities in data. See appendix B for details of the new unit values.

For climate change, the results in the sensitivity analysis are similar to the original, but the scenario of biogas to el&heat has slightly changed to be worse than the reference scenario. The same proportionally relation between the scenarios are held for acidification. For terrestrial eutrophication, the conclusion is still valid, however, the great difference between the biogas to el&heat and biogas to transport fuel has decreased, as the heat and el substitution is lower. The same applies for human toxicity. The results are similar for mineral and fossil resource depletion. In conclusion, the sensitivity analysis confirms the conclusion made above.

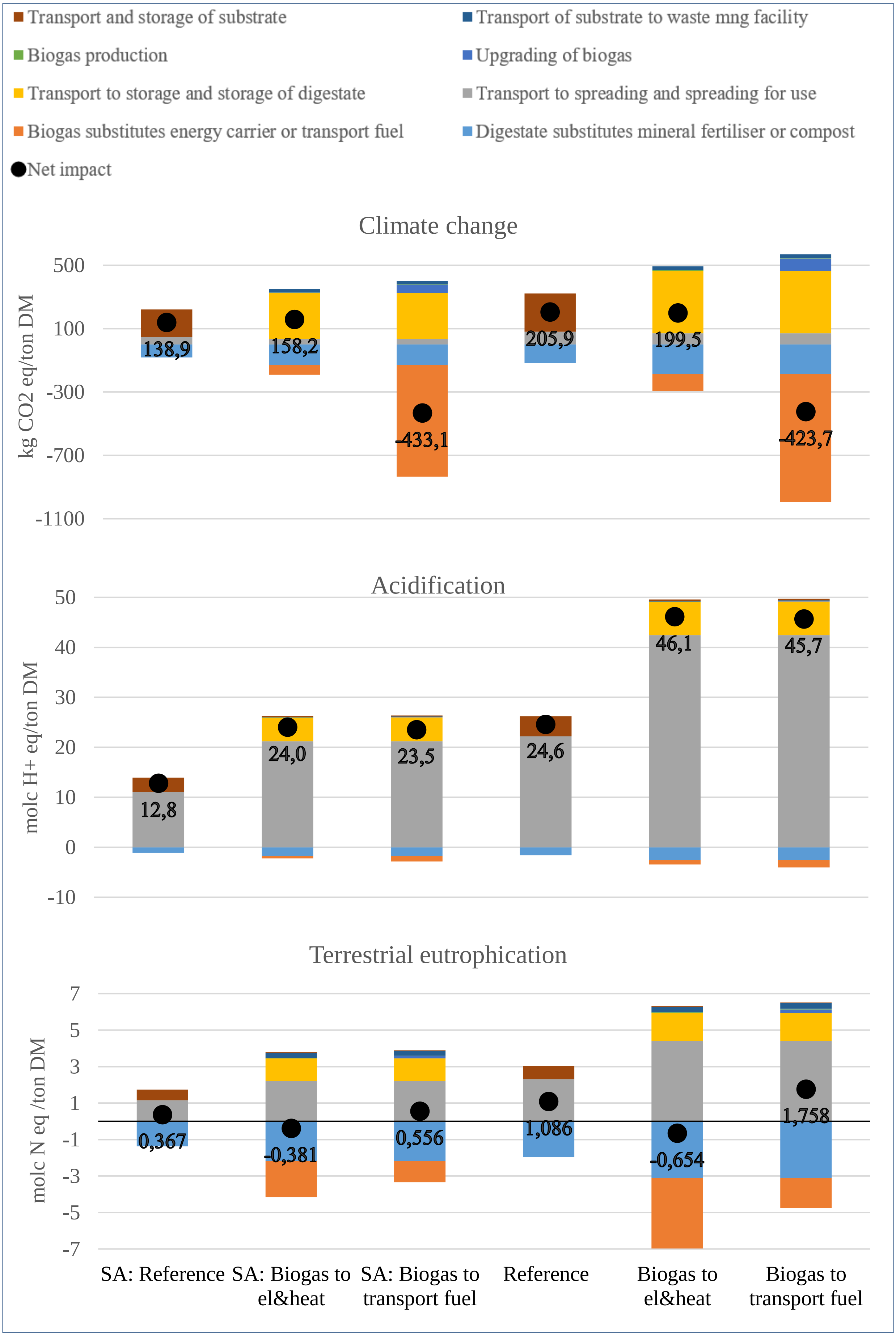


Figure 10.5 Results sensitivity analysis scenario 1 - climate change, acidification and terrestrial eutrophication

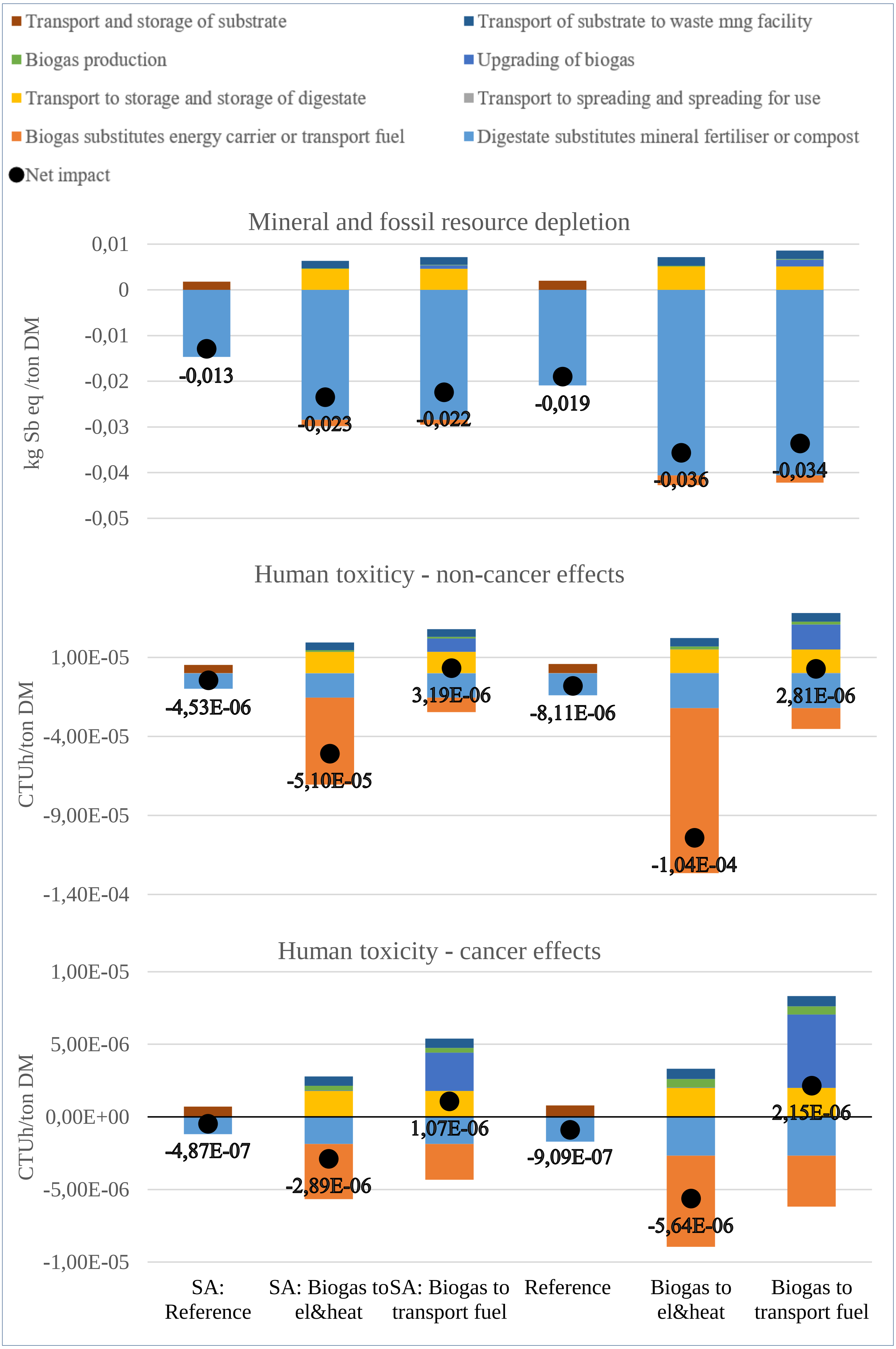


Figure 10.6 Results sensitivity analysis scenario 1 - mineral and fossil resource depletion, human toxicity non-cancer and cancer effects

11 Discussion and conclusion

The starting point for HOFF’s challenge was to find good solutions for waste management of excess potato ethanol stillage. Inspired by circular economy and sustainability, as well as the increased biogas focus in Norway in recent years, biogas as an option for a sustainable business was therefore found to be a good alternative to today’s waste management practice.

First, two biogas scenarios were found to be possible solutions. These required collaboration with other stakeholders in the nearby area. As biogas should be produced and used locally because it reduces costs and environmental footprints, close neighbours were considered.

The first collaboration option was with farmers. Whether vegetable and potato residues collection is realistic must be further considered. For scenario 2, it is not certain that the amount of food waste can be found. If this is the case, a scenario where substrates are based on parts of the suggested amount of residue and food waste may be a better solution.

Considering the economy in the two scenarios, they are not viable with today’s support system and with the suggested biogas yields. Although cost estimations are uncertain, they give some estimates to investigate further. In line with the literature, it seems as it is not economically advisable to use biogas to electricity and heat. It may only be possible to invest, if collaborators, for instance future apartment entrepreneurs at Huntonstranda wish to invest in a biogas plant that can treat bigger amounts of waste for electricity and heating of buildings and where one can document higher biogas yields form the substrate mix.

A better option is to send the biogas to be upgraded to transport fuel, mainly because it is prioritised for support by political frameworks. But it also does not yield enough methane for it to be economically viable, as the annual costs are too high. Scenario 1 with transport fuel was the best option of the four cost and income analysis – this had more kwh output and more amount of total waste treated.

Comparing the two biogas scenarios, the scenario with food waste collaboration may have more potential of financial support, as more stakeholders can contribute. Only collaborating with farmers, as suggested in scenario 1, may limit financial support. On the other hand, there has recently been news of possible collaboration between farmers in Østre Toten for biogas treatment of manure, and it may be possible for treatment collaborations in the future. An important issue regarding economic sustainability and investments, is that biogas technologies and regulations to benefit biogas production facilities are increasingly evolving and thus costs may be reduced. It is therefore quite challenging to make cost estimates, and this is an area that needs to be investigated, both in terms of optimal substrate mixes and suppliers' plant option.

The main part of this thesis was to understand the environmental impacts of biogas scenario options compared to today's treatment practices and uses of the waste. As few studies were found on comparing efforts of cooperation for biogas production in Norway, the result was not given. The data on climate change and acidification impact categories should be considered as the most complete. Therefore, the results for the remaining categories may be less secure.

The Life Cycle Assessment showed that the environmental benefits of biogas production are in most impact categories the best way to treat waste compared to the reference scenario. The result is also in line with other LCAs that compare biogas treatment with other reference scenarios, such as incineration of for instance food waste, even if system boundaries are different. Storage with cover at the farms in the area should be prioritised to reduce negative impacts on climate change, acidification and eutrophication. Today's practices in scenario 1, and less in scenario 2 are best for acidification as there is less stillage/digestate spread at farm fields. To reduce acidification for spreading, improved technologies should be prioritised. Further, dewatering and composting of the digestate could be an option for HOFF, however, according to reference scenario 2, it seems as these processes also have significant negative impact particularly on acidification and terrestrial eutrophication, the same categories as spreading is negative for.

Biogas to transport is best to reduce climate change impacts and biogas to el&heat are best to reduce human toxicity, mineral and fossil depletion and terrestrial eutrophication, with the clearest compared effect in the first category. Therefore, it can be considered as the best option. Literature comparing the two biogas use options, most often favour transport fuel use. This is because they mostly consider climate change impact and sometimes acidification. However, the positive results in favour of el&heat are in the categories with less secure data completeness and further studies should therefore be carried out, especially interesting is human toxicity, as related dangerous pollutants, such as PCD, is found in the Mjøsa area (Mattilsynet and Miljødirektoratet, 2018).

It is interesting to note that reference scenario 1 is similar to HOFF's management practice today, even though the cattle manure should not be allocated to HOFF's environmental impact calculator. The vegetable and potato residues have very small environmental impact, and only on climate change. Therefore, the results on reference scenario 1 can give some useful information for HOFF. It seems to be positive for climate change when the potato ethanol stillage is stored with cover. If HOFF wishes to reduce climate change impact, the company could contribute in changed practices for this initiative. However, the result is only positive because the stillage is considered to replace nitrogen in mineral fertiliser.

As shown in the biogas set up and economic overview, biogas options is realistically challenging for HOFF. To contribute to further environmental gains of biogas production for transport fuel, the authorities should secure a local market for biogas. As proposed in the scenarios, businesses such as HOFF can only contribute if the infrastructure is in place, for instance upgrading in Skjerven, and if long term focus to invest in the sector holistically is seen among authorities. But even for collective upgrading facility, it may be challenging for biogas yields to be viable.

As we know that new technologies increasing the yield of substrates, it would be recommendable for HOFF to get in contact with other stakeholder with interest in wet organic waste management alternatives, researchers to test substrates, and suppliers to document their promises. It would be necessary to get a good economic result to continue. Success is dependent on local markets and political will to develop it and infrastructure. Biogas, is however, on the rise, both in terms of the number of plants and in terms of biogas vehicles, even bigger trucks.

While testing, HOFF can reduce the amount of stillage waste by reducing the amount of water added to the production through changing the capacity of pipes and pumping system to enable pumping of thicker liquid mass through the system, something that was mentioned by one staff member during informal talks. This is also favoured by the waste hierarchy framework. The same framework would favour the continuation of delivering ethanol stillage as fodder.

In terms of sustainability and circular economy, the thesis on biogas has opened to thinking outside the box and to more cooperative efforts. Biogas can provide flexibility, collaboration, and circularity of nutrients going back to the nature. The remaining issue is that it must be profitable.

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APPENDIX A: CALCULATIONS AND ASSUMPTIONS

Reference scenarios:

Calculation R1: Transport potato ethanol stillage to farms

The transportation distance of stillage is found through estimating where the farms receiving stillage for spreading on fields and/ or for cattle fodder. Two monthly transportation bills from the transport company HOFF uses is the basis of information. Google map is used to locate the receivers of the stillage. The mapping shows that stillage is transported the furthest to Løten (65 km) and shortest just to western part of Gjøvik (10 km). The average was found to be 34,54 km one way after weighing. The Ecoinvent 3 process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used.

A: Average km transported	34,54	
	Ref 1 (27%)	Ref 2 (48%)
B: Ton delivered	4,5	7,9
C: Tkm per ton DM in Ref (A*B)	**155,9**	**274,2**

Calculation R2: Storage potato ethanol stillage and cattle manure at farm

In today's scenario, the stillage is stored with cattle manure at farms before being spread. The same applies with the cattle manure. Cattle manure is usually used to fertilise the farm land when not going to a biogas plant. Figures for emissions are based on SSB (Modahl *et al.*, 2016, p. 25) and presented for storage of cattle manure to be spread on fields. The numbers in the model for food waste are calculated from the data on cattle manure. The Modahl et al. does not model storage of food waste in a reference scenario, however, the model assumes that the CH4 emissions are 67% more and NH3 emissions are 28,6% less from storage of cattle manure than storage of digestate from cattle manure. As the scenarios on potato stillage digestate storage are based on Modahl et al.'s emission calculation on storage of digestate based on food waste, it is assumed for this reference scenario process that the storage of potato stillage lead to emission of CH4 with 67% (17,638*1,67) more and NH3 with 28,6% (0,159*(1-0,286)) less than that of food waste digestate. These reductions and increments are proportionally the same as for cattle manure. Further, potato ethanol stillage has less methane yield per VS than the food waste (320 and 430 respectively), and it can therefore be assumed that the CH4 emissions from stillage storage is also lower. Therefore, as an estimate, it is chosen 75% lower CH4 emissions per ton DM than food waste. The rest of the emissions are chosen to be the same as the nitrogen and phosphorous content are assumed to be very similar.

As a zero-waste scenario for storage is modelled in the biogas scenarios, the same is done in the reference scenario (see calculation B11).

Potato ethanol stillage:		Ref 1 (27%)	Ref 2 (48%)
kg CH4/ton DM (75% lower)	22,090	5,984	10,524
kg CO2/ton DM	0	0,000	0,000
kg N2O/ton DM	0	0,000	0,000
kg NH3/ton DM	0,114	0,031	0,054
Cattle manure:		Ref 1 (23%)	Ref 2 (22%)
kg CH4/ton DM	10,2	2,322	2,275
kg CO2/ton DM	0	0,000	0,000
kg N2O/ton DM	0,123	0,028	0,027
kg NH3/ton DM	1,37	0,312	0,306
Total emissions:		Ref 1 (100%)	Ref 2 (100%)
kg CH4/ton DM		8,306	12,798
kg N2O/ton DM		**0,028**	**0,027**
kg NH3/ton DM		**0,343**	**0,360**

Calculation R3: Spreading of potato stillage and cattle manure on farm field

The potato stillage and cattle manure are spread together on farm fields and the environmental impacts are related to transport, steering and pumping of digestate for the fertilisation of fields, as well as emissions related to spreading and emissions during growing season. It is assumed the use of tractor for spreading. The use of diesel is therefore included; however, the infrastructure is not included as the tractor is not allocated to these scenarios and used only for spreading. The calculations from Modahl et al.’s model (2016, pp. 26-27) are used for cattle manure. The model’s food waste data, which is used here for potato ethanol, is calculated based on cattle manure. As the scenarios on potato stillage digestate spreading are based on Modahl et al.’s emission calculation on spreading of digestate based on food waste, it is assumed for this reference scenario process that the spreading of potato stillage lead to emission of N2O with 14,4% (0,159*1,145) more and NH3 with 12,5% (2,96*(1-0,125)) less than that of food waste digestate. These reductions and increments are proportionally the same as for cattle manure. In the model, it is assumed litre/m3 for stirring is 0,045, for pumping 0,1 and for tractor use 0,28. For diesel use, the Ecoinvent 3 process *Diesel (RER)| market group for | Alloc Rec, U* is used. Diesel use is shown in kg. Therefore, calculations from litre to kg are done with the assumption that diesel has a density of 0,851kg/litre.

		Ref 1	Ref 2

A: m3 substrate spread		6,80	10,20
B: kg/litre density diesel		0,851	0,851
Kg diesel use for stirring (A*B*0,045)		**0,260**	**0,389**
Kg diesel pumping (A*B*0,1)		**0,578**	**0,865**
Kg diesel tractor (A*B*0,28)		**1,618**	**2,423**
<u>Emissions from spreading</u>			
Cattle manure:		Ref 1 (23%)	Ref 2 (22%)
kg CH4/ton DM	0,000	0,000	0,000
kg N2O/ton DM	0,547	0,125	0,122
kg NH3/ton DM	5,390	1,227	1,202
Potato ethanol stillage:		Ref 1 (27%)	Ref 2 (48%)
kg CH4/ton DM	0,000	0,000	0,000
kg N2O/ton DM	0,182	0,049	0,087
kg NH3/ton DM	2,590	0,702	1,234
Total emissions:		Ref 1 (100%)	Ref 2 (100%)
kg N2O/ton DM		**0,174**	**0,209**
kg NH3/ton DM		**1,928**	**2,436**

Calculation R4: Vegetable and potato residues on farm field

The reference scenario 1 for vegetables and potato residues are that they are kept on the farm field and dissolved eventually. Calculations of emissions are based on The Norwegian Emission Inventory (Sandmo (ed.), 2016), which is the Statistics Norway (SSB) report on country specific calculations for IPCC 2006 climate gas emission models. There are N2O emissions for this process, and IPCC tier 1 formula (equation 11.1) for residues with Norwegian specifications for potato and vegetable residues are used to find the nitrogen content (Sandmo (ed.), 2016, p. 184), and further the emission factor for N2O per N (0,01) is used (IPCC, 2006, p. 11.11). The formula requires the below information, where D to G are provided by Sandmo 2016.

A: Kg vegetable and potato production per year	38880000
B: share dry matter content	20 %
C: kg production dry matter per year (A*B)	7776000
D: Fraction of total area renewed	1
E: Share of residues to harvested crops	10 %
F: Share of nitrogen content in dry matter	0,019
G: Fraction removed for other purposes	0
H: kg nitrogen per year (C*D*(E*F*(1-G)))	14774,4
I: kg nitrogen per ton DM (H/(C/777,6)	19
J: direct N2O emission factor for N addition from residues	0,01

K: kg N2O emission per ton DM (I*J)	0,19
L: kg N2O emission per ton DM in Ref 1 (50%) (K*50%)	**0,095**

Calculation R5: Transport food waste to Mjøsanlegget

The reference scenario 2 of food waste includes biogas production, which is utilised for diesel buses in Oslo. The first process is transportation of food waste to Mjøsanlegget, where all household food waste from the areas in Oppland and Hedemark is treated today (Mjøsanlegget, 2019b, Statistics Norway, 2019a). It is not known whether all food waste from hotels and restaurants are treated to biogas today, however, it is assumed that it is the case in the reference scenario. A simple calculation of transport is carried out, meaning that the process only includes the distance from Gjøvik city area to Mjøsanlegget, not considering extra trips between the restaurants/hotels before transported the longer way to waste treatment. The Ecoinvent 3 process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used.

A: km Gjøvik - Mjøsanlegget	50
B: Ton delivered	1,00
C: Tkm per ton DM Ref 2 (A*B)	**50,10**

Calculation R6: Biogas production of food waste, industrial plant

The biogas production of food waste at Mjøsanlegget is taking place in a large scale, industrial plant. As the food waste is delivered with other type of wastes, it needs pre-treatment, something which is assumed to not be a need in the biogas scenarios. The process includes electricity use for pre-treatment of waste and biogas production, emissions to water and water use in pre-treatment, and infrastructure of an industrial biogas plant. From Modahl et al. (2016), it is assumed that there are no emissions from a biogas production. It is assumed that heat use in the biogas production comes from the biogas production itself. The calculated heat use is therefore not part of the inventory list; however, the heat use is subtracted from the total heat output to use for other purposes.

Pre-treatment of food waste:

The pre-treatment process includes emissions to water, water use and electricity use according to calculations based on data from Norwegian plants (Modahl *et al.*, 2016, pp. 143-144). The treatment of sieve residues is not included in this process, such as the burning of residues and energy substitution. Modahl et al.'s model assume that the sieve residues are 1 % of the total substrate going into the anaerobic digester and this is taken into account for the rest of the process data (p. 17).

		Ref 2 (30%)
Kwh electricity use per ton DM	48	**14,43**
ton water used per ton DM	1,6	**0,48**
mg COD emission per ton DM	2,47	**0,74**
mg Nitrogen emission per ton DM	0,48	**0,14**
mg Phosphorous emission per ton DM	0,019	**0,01**

Electricity and heat use in biogas production:

It is assumed that electricity use comes from electricity mix in Norway, represented by the Ecoinvent 3 process *Electricity, medium voltage (NO)| market for | Alloc Rec,* U. HOFF receives electricity through regular grid network from Eidsiva.

Modahl et al. (2016, pp. 40-45) assume the use of electricity of 75 kwh per ton DM and the use of heat of 250 kwh per ton DM. The calculations are based on Bernstad et al. 2011.

		Ref 2 (30%)
A: Kwh electricity use per ton DM	75	**22,55**
B: Kwh heat use per ton DM	250	75,16

Biogas plant infrastructure use:

The Ecoinvent 3 process *Anaerobic digestion plant, for biowaste (RoW)| construction | Alloc Rec, U* is used as inventory for the large-scale infrastructure. It assumes the treatment of 10 000 tons for waste per year and includes Infrastructure for the pre-treatment process, digestion of bio-waste and the successive treatment of the fermented material (de-watering and post composting). Because Mjøsanlegget's treatment of 30 000 tons waste (Mjøsanlegget, 2019b), it is assumed that the infrastructure of the Ecoinvent process weigh 1,5 unit more per ton DM. To calculate the amount of infrastructure units per ton DM, it is assumed life expectancy of 25 years, according to Ecoinvent 3, and a DM share of 15% of the substrate.

A: Life expectancy	25
B: ton DM per year (30000*15%)	4500
C: ton DM per life expectancy (A*B)	112500
D: Unit plant infrastructure per ton DM (1/C)	8,89E-06
E: Unit plant infrastructure per ton DM with 1,5 weight (D*1,5)	1,33E-05

F: Unit plant infrastructure per ton DM for ref 2 (30%)	**4,01E-06**

Calculation R7: Upgrading, transportation and compression of food waste biogas to biomethane for transport fuel

The scenarios where it is assumed that the biogas is utilised for transport fuel, the processes needed are upgrading of the biogas to 98% biomethane, and compression of the upgraded biogas. Both upgrading and compression of the gas takes place at Mjøsanlegget. The output of these processes is 0,51 m3 compressed gas (CBG).

To find the inventory data for these processes, calculations of how much biogas was available is needed.

Biogas available:

It is assumed also in the scenarios where biogas is used for transport fuel that heating is coming from own production. The utilised heat is therefore subtracted from the available biogas for upgrading. It is assumed that the effect of heat conversion is 75% (Modahl *et al.*, 2016, p. 41). In all calculations it is assumed that 1 m3 methane gas (CH4) is 10 kwh (Fjørtoft *et al.*, 2014, p. 75)

		Ref 2 (30%)
A: m3 biogas available per ton DM	600,00	180,38
B: m3 methane gas available per ton DM	378,00	113,64
C: Kwh available per ton DM	3780,00	1136,37
D: Kwh heat used including conversion to heat (calculation R6 B/75%)	333,33	100,21
E: Kwh available after heat use per ton DM (C-D)	3446,67	1036,16
F: m3 available methane per ton DM (E/10)	344,67	103,62
G: m3 available biogas per ton DM (F*(A/B))	547,09	164,47

Upgrading of biogas to biomethane (98% methane) at Mjøsanlegget:

Upgrading consists of inventory for electricity use and methane loss in the process. The Ecoinvent process *Electricity, medium voltage (NO)| market for | Alloc Rec, U* is used for electricity. According to Modahl et al (2016, p. 44), 0,25 kwh electricity is used per m3 biogas. It is also assumed that there is 1,5 % loss of methane during the process. The methane loss is shown in kg. The loss in m3 is calculated with a density of 0,554 kg/m3. Upgrading infrastructure is not included, as was also not included in the biogas scenarios.

		Ref 2 (30%)
H: Kwh electricity use kwh (0,25*G)	136,77	**41,12**
I: m3 methane loss to air (1,5%*F)	5,17	1,55
J: Kg methane loss to air (0,554*I)	2,86	**0,86**

Compression of biomethane:

Biogas for transport fuel comes in compressed form (CBG). It is assumed that the compression process takes place at Mjøsanlegget after upgrading. The Ecoinvent process *Electricity, medium voltage (NO)| market for | Alloc Rec, U* is used for electricity. According to Modahl et al (2016, p. 44), 0,17 kwh per m3 biogas is used for compression. The infrastructure for compression is not included for the same reason as mentioned under upgrading of biogas. To calculate the use of electricity per gas compressed, it is necessary to subtract the energy lost through methane loss in the upgrading process.

		Ref 2 (30%)
K: m3 methane available for compression (F-I)	339,50	102,06
L: Kwh electricity use for compression (K*0,17)	57,71	**17,35**

Calculation R8: Use of food waste biogas in buses

Biogas is used for commuting buses with gas driven motor. The related inventory for this use stage is the direct emission when driving the buses. Bus infrastructure is not included as one can assume that the same bus as with diesel motor is used. One only needs to change some parts of the bus, for instance the diesel motor to gas motor, which would represent minor environmental impact. Data for emissions are taken from Institute of Transport Economics' testing of Euro 6 buses, which are continuously used in greater extent. It is important to mention that many of the buses today, which are still Euro 5, pollute considerably more (Hagman, 2016), however, in order to compare with a near to future biogas scenarios, Euro 6 buses are chosen. According to Hagman (2016), the emissions are the same for biogas methane (CBG) as for natural gas methane (CNG). Emissions per km driven are: Nox 0,1 g/km, particles 0,028 g/km and CO2 1068 g/km. The emission for CO2 is assumed to be biogenic, meaning that the CO2 emitted is part of the natural CO2 cycle. This is different from CO2 from fossil fuels, which are emissions coming from fossil related resources (diesel, natural gas).

The emission data is based on grams emitted per km. To find km driven with gas motor, assumptions from Ruter (Oslo and Akershus public transportation company) and Analyse & Strategi. The latter's report for Agder commuting transportation, use average numbers from studies of gas busses in Trondheim in their calculations, which is 0,65 m3 gas per km (Martinsen *et al.*, 2014, p. 25). In Ruter's (2014) strategy, the company assumes the use of around 0,61 m3 gas per km. In the scenarios, the assumption is therefore 0,63 m3 per km.

		Ref 2 (30%)
A: km driven per ton DM (calculation R7 K/0,63)	538,88	162,00
B: grams Nox ton DM (A*0,1)	53,89	**16,20**
C: grams PM (particles) per ton DM (A*0,028)	15,09	**4,54**
D: grams CO2 biogenic per ton DM (A*1068)	575527,68	**173019,07**

Calculation R9: Transport of food waste compressed biogas to customer

Today, the compressed biogas from Mjøsanlegget is sent to Oslo, through the company AGA, which offers biogas transport and infrastructure development (Nesbakk, 2018). As of today, public transport buses in Oslo/Akershus (Ruter) is the market for the transport fuel.

However, in the biogas scenarios, it is included scenarios where the biogas is utilised as transport fuel. This is only assumed viable if upgrading and compression, as well as the use of the biogas from HOFF takes place in the Gjøvik area. When this is the case, the reference scenario 2 also assumes the same situation. It is therefore modelled one scenario where the compressed biogas is transported from Mjøsanlegget to Oslo (used when comparing with biogas scenario when biogas is used for electricity and heat), and another that assumes a market in Gjøvik, and the biogas is instead transported to Skjerven (used when comparing with biogas scenario when biogas is used for transport fuel).

The Ecoinvent 3 process *Transport, freight, lorry >32 metric ton, EURO5 (RER)| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec,* U is used, as a 4 axled truck is assumed (Sund, Utgård and Christensen, 2017, p. 30).

According to Modahl et al. (2016, p. 44), there is 0,005 m3 compressed gas per m3 gas produced. Compressed gas weighs 200 times more than non-compressed gas. Further, the weight for methane gas at 0 degrees Celsius is 0,67 kg.

Transport to Oslo:

A: km Mjøsanlegget - Oslo	175	
B: Kg of compressed gas per m3 methane (200*0,67)	134	
		Ref 2 (30%)
C: m3 compressed gas per ton DM (calculation R7 K*0,005)	1,70	0,51
D: Ton compressed gas per ton DM (B*C/1000)	0,227	0,068

E: Tkm per ton DM (A*D)	39,81	**11,97**

Transport to Skjerven:

F: km Mjøsanlegget - Oslo	57	
G: Kg of compressed gas per m3 methane (200*0,67)	134	
		Ref 2 (30%)
H: m3 compressed gas per ton DM (calculation R7 K*0,005)	1,70	0,51
I: Ton compressed gas per ton DM (G*H/1000)	0,227	0,068
J: Tkm per ton DM (F*I)	12,97	**3,90**

Calculation R10: Production of wet part and composting of food waste digestate

According to Mjøsanlegget (Mjøsanlegget, 2019a), the digestate is dewatered into a wet part for spreading at farm fields and into a dry part used as compost. This process includes use of electricity in the dewatering process and emissions to air from the composting making process. Calculations in Modahl et al. (2016, pp. 45-48) are used. Emission of process water is not the case at Mjøsanlegget (Sørfonn, 2012).

Dewatering:

According to Modahl et al., electricity use for dewatering of the digestate is assumed to be 6,03 kwh per ton DM into the biogas production. The ton DM into the process is calculated to be 15%. It means that ton weight into the process is 6,68. As the substrate without extra water is 3,33 ton with 31% ton DM, 3,35 ton waster has to be added to get to 15% ton DM. This is according to the waste flow in the model (Modahl *et al.*, 2016, p. 59). 6,68 tons substrate is going into the biogas process per ton DM. The Ecoinvent 3 process *Electricity, medium voltage (NO)| market for | Alloc Rec, U* is used.

		Ref 2 (30%)
A: ton substrate into biogas per ton DM	6,68	2,01
B: ton DM into the biogas (A*15%)	1	0,301
C: kwh electricity use for dewatering per ton DM	6,03	**1,81**

Composting:

The environmental impact from making compost are in the form of emissions to air. The numbers are from Modahl et al.'s calculations of emissions from compost based on food waste. CO2 emissions are assumed to be 0. The other emission calculations are based on data from Jansen la Cour et al. (2007) and Andersen (2010) Modahl et al. (2016, pp. 45-48). The emissions are given in kg per ton wet weight of compost. Per ton wet weight of compost, CH4 emissions are 2,4 kg, N2O emissions are 0,2 kg, NH3 emissions are 6,1 kg and NMVOC emissions are 1 kg.

To find the wet weight for this reference scenario, Govasmark et al. (2011) measured that the digestate from Mjøsanlegget was parted in 9% dry part to compost, with DM content of 28,2% and 91% to wet part, with DM content of 2,8%. In this scenario, A in calculation R10 showed that the ton substrate going into the biogas was 2,01 ton. Assuming that the wet weight is reduced to 90% in the anaerobic digestor (same assumption as for the biogas scenarios), the digestate is 1,81 tons. To calculate the amount of compost: 1,81*9%=0,16 ton and the wet part: 1,81*91%=1,65 ton.

D: ton compost from digestate	0,16
E: Kg CH4 emission per ton compost (D*2,4)	**0,391**
F: Kg N2O emission per ton compost (D*0,2)	**0,033**
G: Kg NH3 emission per ton compost (D*6,1)	**0,993**
H: Kg NMVOC emissions per ton compost (D*1)	**0,163**

Calculation R11: Transport of food waste compost to customer

From a master thesis by Sørfonn on the environmental impact of digestate from Mjøsanlegget, it is assumed that the compost is transported to customer by truck and car. In this scenario, only transport by truck is included/replaced car transport. Sørfonn (Sørfonn, 2012, p. 78) finds that 35% of the compost is transported 100 km by truck. The rest, 65%, is transported 15 km by car and truck. For the scenario, it is assumed only 15 km by truck, and not picked up by private persons. The Ecoinvent 3 process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used.

A: ton compost delivered by truck trip 1 (calculation R10 D*35%)	0,06
B: Tkm compost delivered by truck trip 1 (A*100)	5,70
C: ton compost delivered by truck trip 2 (calculation R10 D*65%)	0,11
D: Tkm compost delivered by truck trip 1 (C*15)	1,59
E: Tkm total compost delivered (B+D)	**7,3**

Calculation R12: Transport of food waste wet part digestate to farm

Mjøsanlegget facilitates transport of the wet part to nearby farms to be spread on fields, in the same way as done regarding digestate in the biogas scenarios. The Ecoinvent 3 process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric* *ton, EURO5 | Alloc Rec, U* is used. It is assumed that the transportation is 25 km on average to areas around Lillehammer, according to Sørfonn (2012). As mentioned in calculation R10, the wet weight from digestate weighs 1,65 ton for this reference scenario.

A: Average km transported	25
B: Ton delivered	1,65
C: Tkm per ton DM in ref 2 (A*B)	**41,1**

Calculation R13: Storage of food waste wet part of digestate

The same process for storage is assumed for this digestate as for the digestate in the biogas scenarios. At the farms, there are already storage facilities already, as it is assumed that the digestate is delivered to the farms that have storage for manure. Therefore, storage infrastructure is not included in the biogas scenarios. The process inventory consists of emission to air from the stored wet digestate. The emission data is based on calculations by Modahl et al. (2016, p. 49), based on Amon et al (2006) and Hartmann (2008) (p. 48).

Modahl et al. assumes also that the storage may be closed with roof, especially when considering that in a future scenario, the storage units at farms will be closed to reduce greenhouse gases. In this case, there would be zero emissions in the biogas scenarios. For this research, it is therefore also included separate scenarios where zero emission from storage is shown. One must keep in mind, however, that in today's situation, most of the storages are open (Bechmann *et al.*, 2016, p. 14)

The wet part of the digestate in this reference scenario weighs 1,65 ton and has a DM content of 2,8% (Govasmark *et al.*, 2011). This gives 0,046 ton DM. For the dry part to compost, this also gives 0,046 ton DM (0,16*28,2%), meaning that half of the DM is allocated for the wet part of digestate. Further, as 75% of nitrogen in digestate end up in the wet part, it is assumed 75% lower emissions for NH3.

Digestate from wet part food waste:		Ref 2 (30%*50%)
kg CH4/ton DM	17,638	2,646
kg CO2/ton DM	0,000	0,000
kg N2O/ton DM	0,000	0,000
kg NH3/ton DM (75% lower)	0,159	0,018

Calculation R14: Spreading of food waste wet part of farm fields

The digestate is spread on farm fields and the environmental impacts are related to transport, steering and pumping of digestate for the fertilisation of fields, as well as emissions related to spreading and emissions during growing season. It is assumed the use of tractor for spreading. The use of diesel is therefore included; however, the infrastructure is not included as the tractor is not allocated to these scenarios and used only for spreading the digestate. The calculations from Modahl et al.'s model (2016, pp. 47, 51-52) are used. In the model, it is assumed litre/m3 for stirring is 0,045, for pumping 0,1 and for tractor use 0,28. For diesel use, the Ecoinvent 3 process *Diesel (RER)| market group for | Alloc Rec, U* is used. Diesel use is shown in kg. Therefore, calculations from litre to kg are done with the assumption that diesel has a density of 0,851kg/litre.

The emissions from spreading consists of N2O and NH3 emissions to air based on the wet weight's nitrogen content. The Modahl et al. model assumes that N2O emissions are 75% lower than those from digestate that is not dewatered, and that NH3 emissions are 90% lower (the model gives the kg NH3 per ton DM, which is calculated in the same way as in R13).

		Ref 2
A: m3 digestate spread Ref 2		1,65
B: kg/litre density diesel		0,851
Kg diesel use for stirring per m3 (A*B*0,045)		**0,063**
Kg diesel pumping per m3 (A*B*0,1)		**0,140**
Kg diesel tractor per m3 (A*B*0,28)		**0,392**
Emissions from spreading of wet part		Ref 2
ton wet part from digestate		1,65
kg N2O/ton wet part	2,90E-05	**4,77E-05**
kg NH3/ton DM (2,66*30%*50%)	2,66	**0,399**

Calculation R15: Food waste biogas substitutes transport fuel

The produced biogas is used for public transport buses in Oslo, where they are substituting diesel driven buses.

The inventory for this process therefore consists of the production of diesel to the market and the emissions from driving the buses. Bus infrastructure is not included as one can assume that the same bus is used for biogas and diesel.

To find the amount of diesel to be substituted, one assumes that 1m3 biomethane (upgraded biogas) substitutes 1 l of diesel. However, because the conversion energy efficiency is very low in gas motor, Modahl et al. (2016, p. 54) assume that the share of energy from biogas of energy from diesel is only 0,871. For diesel use, the Ecoinvent 3 process *Diesel (RER)| market group for | Alloc Rec, U* is used. Diesel use is shown in kg. Therefore, calculations from litre to kg are done with the assumption that diesel has a density of 0,851kg/litre.

The emission data is based on grams emitted per km. To find km driven with diesel, assumptions from Analyse & Strategi are used. They use 0,4 litre per km driven (Martinsen *et al.*, 2014, p. 25).

Data for emissions are taken from Institute of Transport Economics' testing of Euro 6 buses (Hagman, 2016), the same buses as in the biogas use process (see calculation B9). Emissions per km driven are: NOx 0,15 g/km, particles 0,014 g/km and CO2 1117,7 g/km. The emission for CO2 is assumed to be fossil based (diesel), meaning that the CO2 is not emitted as part of the natural cycle.

		Ref 2 (30%)
A: litre diesel substituted (calculation R7 K*0,871)	295,70	88,90
B: Kg/litre density diesel	0,851	0,851
C: Kg diesel substituted (A*B)	251,64	**75,65**
D: km driven per ton DM (A/0,4)	739,25	222,24
E: grams Nox per ton DM (D*0,15)	110,89	**33,34**
F: grams PM (particles) per ton DM (D*0,014)	10,35	**3,11**
G: grams CO2 fossil per ton DM (D*1117,7)	826264,19	**248397,19**

Calculation R16: Food waste wet part digestate/potato ethanol stillage and cattle manure substitution of mineral fertiliser

In reference scenario 1, potato ethanol stillage is spread with cattle manure on farm fields. According to Nesheim (2010), the potato ethanol stillage is not counted as part of farmers' fertilising budget, however, the study shows that the stillage can be used as fertiliser. HOFF is also of the opinion that it is useful as fertiliser. It is therefore modelled as substituting mineral fertiliser together with the cattle manure. The same applies for reference scenario 2, where the wet part of digestate from food waste is used in the same way as the digestate in the biogas scenarios. The inventory consists of the fertiliser product and the emissions when used.

As in the Modahl et al. (2016) model, the amount of fertiliser substituted is based on the kg nitrogen that is available to the plant after spreading the digestate/stillage/manure. There are normally different fertiliser types that are used. According to the Norwegian Food Safety Authority's statistics on the amount of mineral fertiliser sold in Hedemark and Oppland area, the fertilisers with the highest turnover, are NPK fertilisers (Mattilsynet, 2019, p. 4) with a nitrogen share of around 20-25%. Therefore, in the scenarios, an Ecoinvent 3 process representing a nitrogen fertiliser with 26,5% is chosen; *Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U.* The process represents production and transportation of the inputs in the fertiliser. These may be somewhat different than for instance the Yara fertilisers, which are common in Norway. The environmental impact of Yara fertilisers, especially regarding the production, may be lower than in the BAT (best available technology) scenarios that Yara presents, however, the Ecoinvent 3 is still used as data basis.

To find the amount of nitrogen, the model assumes 60% of the nitrogen content in the spread digestate/stillage/manure per ton DM is available for the plant (p. 28). In the model, it is assumed 60% for all digestate from manure and food waste, and for manure spread directly on fields. 60% is therefore also used for potato ethanol stillage. For the wet part of digestate from food waste, it is assumed that 75% of the nitrogen content from the digestate end up in the wet part (Modahl *et al.*, 2016, p. 45). The wet part of the digestate in this reference scenario weighs 1,65 ton and has a DM content of 2,8% (Govasmark *et al.*, 2011). This gives 0,046 ton DM. The dry part to compost also gives 0,046 ton DM (0,16 ton*28,2%), meaning that half of the DM into the biogas plant is allocated for the wet part of digestate. Further, as 75% of nitrogen in digestate end up in the wet part, it is assumed 75% lower emissions for NH3.

Transportation for spreading is not included as it is assumed that one can carry many more kg of mineral fertiliser compared to digestate.

The emissions to air when the fertiliser has been used are calculated with assumptions from the Norwegian emission inventory 2016, as presented in (Grønlund, 2015). The main emissions are of N2O-N when spread to the field (0,01 of nitrogen) and NH3 through deposition (0,0095 of nitrogen).

		Ref 1 (27%)	Ref 2 (48%)
A: kg nitrogen available to plant potato ethanol stillage (21*60%)	12,5	3,39	5,95
		Ref 1 (23%)	Ref 2 (22%)
B: kg nitrogen available to plant cattle manure (48*60%)	28,8	6,56	6,42
			Ref 2 (30%*50%)
C: kg nitrogen available to plant food waste digestate (23*60%*75%)	10,35		1,55
		Ref 1	Ref 2
E: kg nitrogen per ton DM from all substituted mineral fertiliser (A+B+C)		**9,94**	**12,38 + 1,55**

Emissions from use:			
F: Kg N2O (0,01*E)		**0,099**	**0,124 + 0,016**
G: Kg NH3 (0,0095*E)		**0,094**	**0,061 + 0,015**

Calculation R17: Food waste wet part digestate/potato ethanol stillage and cattle manure substitutes carbon in soil

Carbon and phosphate content are important in the cycle of nutrients going from nature into the technological cycle and back to the nature again. In the model of Modahl et al., (2016), phosphate is not included because the use of phosphate differs very much from area to area in Norway. Further, phosphate content in the substrates going into the biogas plant is assumed to not change when it comes out as digestate. In the scenarios, it is assumed that the digestate is spread on farm fields. In this way, phosphate is brought back into the natural cycle and is not changed from the reference scenario.

Regarding carbon, the same model assumes that 20% of the carbon content in the substrates is available to the soil as digestate is spread. This is the same as the percentage assumed for digestate from biogas production. The wet part of the digestate in this reference scenario weighs 1,65 ton and has a DM content of 2,8% (Govasmark *et al.*, 2011). This gives 0,046 ton DM. For the dry part to compost, this also gives 0,046 ton DM (0,16*28,2%), meaning that half of the DM is allocated for the wet part of digestate.

The Ecoinvent 3 process *Carbon, organic, in soil or biomass stock* is used as input from nature.

		Ref 1 (27%)	Ref 2 (48%)
A: kg carbon available to soil potato ethanol stillage (400*20%)	80	21,67	38,11
		Ref 1 (23%)	Ref 2 (22%)
B: kg carbon available to soil cattle manure (400*20%)	80	18,21	17,84
			Ref 2 (30%*50%)
D: kg carbon available to soil food waste (400*20%)	80		12,0
		Ref 1	Ref 2
E: kg carbon per ton DM from all substrates		**39,88**	**55,95 + 12,00**

Calculation R18: Compost from food waste digestate substitutes compost

According to Sørfonn (2012, p. 78), it is assumed that only 50% of the compost from Mjøsanlegget is substituting another similar product from another supplier in the market. This part is the 50% of the compost that is made into a soil improvement product. The reason is that

Sørfonn assumes that the Mjøsanlegget compost product partly made the demand for this product and did not supply an already existing demand. It can be assumed that 50% of the 0,16 ton compost for reference scenario 2 is substituted.

Transported compost:

Sørfonn (2012, pp. 85-86) further finds that the distance of transport is 150 km for 35% of the compost (to a bioroof customer) and 85 km for 65% of the compost (to garden centers). As for Calculation R11, the travel from the customer is not included. The Ecoinvent 3 process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used.

A: ton compost delivered by truck trip 1 (calculation R10 D/2*35%)	0,03
B: Tkm compost delivered by truck trip 1 (A*150)	4,27
C: ton compost delivered by truck trip 2 (calculation R10 D/2*65%)	0,05
D: Tkm compost delivered by truck trip 1 (C*85)	4,50
E: Tkm total compost delivered (B+D)	**8,8**

Production of compost:

The production of the compost is assumed to be done in the same way as the compost product from Mjøsanlegget (reference 2) (Sørfonn, 2012). Therefore, the emissions from the production have the same assumptions as in calculation R10, but with half of the amount of emissions.

F: ton compost from digestate (calculation R10 D/2)	0,08
G: Kg CH4 emission per ton compost (F*2,4)	**0,195**
H: Kg N2O emission per ton compost (F*0,2)	**0,016**
I: Kg NH3 emission per ton compost (F*6,1)	**0,496**
J: Kg NMVOC emissions per ton compost (F*1)	**0,081**

Biogas scenarios:

Calculation B1: Storage cattle manure at farm before going to biogas

The storage time at the farms of cattle manure is assumed to be shorter when going to a biogas plant, according to (Modahl *et al.*, 2016, p. 35). It is assumed storage for one month.

Emissions per ton dry matter (DM) of cattle manure:

		Scenario 1 (23%)	Scenario 2 (22%)
0,000	kg CH4/ton DM	0,000	0,000

0,000	kg CO2/ton DM	0,000	0,000
0,000	kg N2O/ton DM	0,000	0,000
0,114	kg NH3/ton DM	**0,026**	**0,025**

The assumption in Modahl et al.'s report is based on calculations from SSB and John Morken.

Data quality: medium

Calculation B2: Transport cattle manure from farms to HOFF biogas

The transport distance of cattle manure is assumed to be the same as for the transport of potato ethanol stillage from HOFF to farms in the reference scenarios. One can assume that the same farmers receiving stillage and mixing it with manure are the same as will deliver manure to HOFF. The Ecoinvent 3 database process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used, including emissions from use, infrastructure, and maintenance. RER means "represents Europe".

A: Average km transported	34,54	
	Scenario 1 (23%)	Scenario 2 (22%)
B: Ton delivered	2,3	2,2
C: Tkm per ton DM in scenario (A*B)	**78,6**	**77,0**

Data quality: high

Calculation B3: Transport veg/potato residues from farms to HOFF biogas

The biogas scenario 1 assumes vegetable and potato residues to be available as biogas substrate from farms in Østre Toten and Ringsaker. An average transportation distance is calculated based on where most of the vegetable and potato cultivation take place. The Ecoinvent 3 database process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used, including emissions from use, infrastructure, and maintenance. RER means "represents Europe".

	Scenario 1 (50%)	Weight
A: Km and weight from Østre Toten	20	25 %
B: Km and weight from Ringsaker	30	75 %
C: Average km ((A*Aweight)+(B*Bweight))/(Aweight+Bweight))	27,5	
D: Ton delivered	2,51	
E: Tkm per ton DM (C*D)	**69,0**	

Data quality: high

Calculation B4: Transport of food waste within Gjøvik

The biogas scenario 2 assumes clean food waste from hotels and restaurants within the city area of Gjøvik to be available as biogas substrate. It is assumed a distance of transport of 4 km, which for instance is the distance from HOFF to Hunndalen. The Ecoinvent 3 database *process Transport, freight, lorry 7.5-16 metric ton, EURO5 (RER)| transport, freight, lorry 7.5-16 metric ton, EURO5 | Alloc Rec, U* is used, including emissions from use, infrastructure, and maintenance. RER means "represents Europe".

	Scenario 2 (30%)
A: Km transported Bryggevegen- Hunndalen	4
B: Ton delivered	1,00
C: Tkm per ton DM (A*B)	**4,01**

Data quality: high

Calculation B5: Electricity and heat use for biogas production from potato stillage, manure and farm residues/food waste

The biogas production scenario 1 and 2 require electricity and heat use. From Modahl et al. (2016), it is assumed that there are no emissions from an industrial biogas production, the same is assumed for the biogas scenarios. The same is also mentioned by Antec, the producer of the plug-flow reactor and biogas plant provider. It is assumed that heat use in the biogas production comes from the biogas production itself. The calculated heat use is therefore not part of the inventory list; however, the heat use is subtracted from the total heat output to use for other purposes. It is assumed that electricity use comes from electricity mix in Norway, represented by the Ecoinvent 3 process *Electricity, medium voltage (NO)| market for | Alloc Rec,* U. HOFF receives electricity through regular grid network from Eidsiva.

Heat use:

Heat from own biogas production is utilised for heating the substrates. The substrate is a mix of the potato ethanol stillage, which holds around 95 degrees Celsius (Nesheim, 2010, p. 3), cattle manure and vegetable/potato residues and/or food waste. Because the potato stillage is hot, it is assumed in these scenarios that the mix is already 20 degrees Celsius in scenario 1 (27% potato stillage) and 30 in scenario 2 (48% potato stillage). Regular substrates can be assumed to hold 10 degrees Celsius (Andersen, 2018). Necessary heating to 55 degrees Celsius (thermophile) is therefore 35 and 25 degrees Celsius respectively. Heat factor per m3 is assumed to be the same as for water (4200000 J=1,63 kwh) for 1 degree Celsius.

In addition to heating the substrate, heat loss must be included in heat use from own biogas production. In the winter time, the heat loss is much greater than during warmer periods

(Fjørtoft *et al.*, 2014). There is little data on heat loss in smaller and medium sized biogas plants with low retention time. Gebremedhin and Inglis (2007), found that in a plug-flow reactor in New York, the use of internal heating is 18% of total heat produced, while Berglund and Börjesson (2006), assumed 69 kwh per ton substrate in farm based biogas plants in Sweden, something which means that the % use in the scenarios had been around 50%. A bit higher percentage would be the result if using the numbers found for biogas production of cow slurry in Norway (Fjørtoft *et al.*, 2014). The producers of the plug-flow reactors, which the scenarios are based on, on the other hand, states that the total energy use is 15% (Adigo, 2019) and 10% (Antec presentation), suggesting that heat use is somewhat lower than these percentages. In the scenarios, it is assumed 30% of the kwh needed for heating the substrate added to the heat use. The reason is because the heat loss in a plug flow reactor may have less surface than other reactors. The retention time is also assumed to be less in the scenarios than in biogas plants in most literature. The total heat use will with this be 37% for scenario 1 and 31% for scenario 2 of the total heat production, which may represent a conservative estimate.

	Scenario 1	Scenario 2
A: Degrees heating to thermophile	35	25
B: kWh needed per m3 (1,163 kwh*A)	40,71	29,08
C: m3 per ton DM	10,05	11,47
D: Kwh needed per ton DM (B*C)	409,11	333,56
E: Kwh additional heat loss (30%*D)	122,73	100,07
F: Kwh total heat use from own production per ton DM (D+E)	531,84	433,62

Electricity use:

Electricity use consists mainly of electricity for pumping and stirring of the substrate. Different sources give different results. In the documentation report of Tomb high school biogas plant (Fjørtoft, Morken and Gjetmundsen, 2014), the researchers found that the plant used 65 kwh per day for pumping and stirring of 14 m3 substrate. In the scenarios, three times more m3 substrate would be treated a day in scenario 1 and twice as much in scenario 2. In scenario 1, the electricity use per ton DM would have been kwh 44,02 and 51,80 in scenario 2. In Modahl et al (2016) biogas model , it is assumed 75 kwh use of electricity per ton DM in an industrial plant. Berglund and Börjesson (2006) estimate that 9 kwh is used per ton substrate, which would be 90,45 kwh per ton DM in scenario 1. In the scenarios, it is used an average between the assumption from the Tomb plant and the plants researched in Berglund and Börjesson.

	Scenario 1	Scenario 2
G: Kwh per ton DM in Fjørtoft, Morken and Gjertmundsen	44,02	51,80

H: Kwh per ton DM in Berglund and Börjesson	90,45	90,45
I: Average Kwh per ton DM ((G+H)/2)	**67,24**	**71,13**

Calculation B6: Biogas plant infrastructure for biogas production from potato stillage, manure and farm residues/food waste

The biogas plant is medium sized and modular. In scenario 1, it is assumed that the digestion tanks must take around 300 m3 volume, while in scenario 2, the amount of substrate is less and only need at least 200 m3. In the latter scenario, the chosen plant unit is chosen to only represent with 80% of its unit. First hand data have not been collected, but rather secondary data from Ecoinvent 3 have been used. Usually, biogas plant infrastructure does not affect much the total environmental impacts, except use of land area.

For the scenarios, the Ecoinvent process *Anaerobic digestion plant, agricultural (RoW)| construction | Alloc Rec, U* is chosen. The plant is a typical agriculture biogas plant with a capacity of 300 m3 and a life expectancy of 20 years, according to Ecoinvent. Data is sampled from Switzerland. The data set includes infrastructure for pre-treatment, digestion and storage of the digestate. All though the latter is possibly not assumed in the case of HOFF, it is relevant to include, because it represents the maximum infrastructure potentially needed.

	Scenario 1	Scenario 2 (80% plant)
A: Life expectancy	20	20
B: Total ton DM per year	1550,5	881,7
C: Total ton DM per life expectancy (A*B)	31010,3	17633,2
D: Unit plant infrastructure per ton DM (1/C) (*80% for scenario 2)	**3,22E-05**	**4,54E-05**

Calculation B7: CHP power conversion

In the scenarios where biogas is used for electricity and heat, it is assumed that the upgrading happens through a cogeneration of heat and power micro turbines. The Ecoinvent 3 process *Mini CHP plant, common components for heat+electricity (GLO)| market for | Alloc Rec, U* is used. There are in fact many different CHP products on the market and with different motors. Therefore, a general process is chosen. It is assumed very little emissions from the process of CHP (KILDE), therefore only inventory is included in this process.

In a CHP process, it is assumed 80% conversion energy efficiency (Norwegian Encyclopaedia assumes 75%-90% (Rosvold and Hofstad, 2013)). According to Antec biogas, it is assumed that about 40% goes to electricity and 55% to heat (from talks), however, in the scenarios it is given a more conservative estimate. In addition to 80% energy efficiency, it is assumed that not all heat is utilised. 40% goes to electricity and 50% to heat in the scenarios. In reality, it is difficult to set a fixed conversion energy efficiency, as the technologies and fuels will give different outcomes (Khalil, Skreiberg and Sørum, 2008). The electricity and heat output after conversion is given in the table.

	Scenario 1	Scenario 2
A: Kwh available per ton DM	3604,06	3480,17
B: Kwh power after CHP conversion (A*80%)	2883,25	2784,14
C: Kwh share to Electricity (B*40%)	1153,30	1113,66
D: Kwh share to Heat (B*50%)	1441,62	1392,07

To find the amount of inventory for this process, it is assumed that the life time of the plant is 10 years. According to Khalil, Skreiberg and Sørum (2008, p. 37), a micro turbine in a CHP plant lasts for approximately 10 years.

	Scenario 1	Scenario 2
E: Life expectancy	10	10
F: Total ton DM per year	1550,5	881,7
G: Total ton DM per life expectancy (E*F)	15505,1	8816,6
H: Unit plant infrastructure per ton DM (1/G)	**6,45E-05**	**1,13E-04**

Calculation B8: Upgrading, transportation and compression of biogas to biomethane for transport fuel

The scenarios where it is assumed that the biogas is utilised for transport fuel, the processes needed are upgrading of the biogas to 98% biomethane, transportation of this biogas through pipeline for compression, and compression of the upgraded biogas. The output of these processes is 1,43 m3 compressed gas (CBG) in both scenario 1 and 2.

To find the inventory data for these processes, calculations of how much biogas was available is needed.

<u>Biogas available:</u>

It is assumed also in the scenarios where biogas is used for transport fuel that heating is coming from own production. The utilised heat is therefore subtracted from the available biogas for upgrading. It is assumed that the effect of heat conversion is 75% (Modahl *et al.*, 2016, p. 41). In all calculations it is assumed that 1 m3 methane gas (CH_4) is 10 kwh (Fjørtoft *et al.*, 2014, p. 75)

	Scenario 1	Scenario 2

A: m3 biogas available per ton DM	640,46	585,63
B: m3 methane gas available per ton DM	360,41	348,02
C: Kwh available per ton DM	3604,1	3480,2
D: Kwh heat used including conversion to heat (calculation B5 F/75%)	709,1	578,2
E: Kwh available after heat use per ton DM (C-D)	2894,9	2902,0
F: m3 available methane per ton DM (E/10)	289,49	290,20
G: m3 available biogas per ton DM (F*(A/B))	514,44	488,33

Transport of biogas to upgrading facility:

The scenarios assume that an upgrading facility exists at Skjerven in Gjøvik. As the distance is not very long, it is assumed that the transportation can take place through a pipeline. The distance between Skjerven and HOFF is about 8 km. Ecoinvent 3 data is used for the pipeline infrastructure through the process *Pipeline, natural gas, low pressure distribution network (RoW)| construction | Alloc Rec, U.* According to Ecoinvent, the life expectancy of the pipeline is 40 years. The whole pipeline is allocated to the biogas scenarios as it is assumed that the pipeline would not be built or shared with other biogas plants if it had not been for HOFF’s biogas plant.

Electricity use from is assumed for pumping and the Ecoinvent 3 process *Electricity, medium voltage (NO)| market for | Alloc Rec, U* is used. According to the model in Modahl et al (2016, p. 44), the kwh energy used for pumping is 0,05 per m3 biogas, which are numbers for a pipeline of 10 km, from Arnøy et al. 2013. It is assumed the same in these scenarios.

	Scenario 1	Scenario 2
H: Km pipeline HOFF-Skjerven	8	8
I: Life expectancy in years	40	40
J: Total ton DM per year	1550,5	881,7
K: Km pipeline per ton DM (H/I/J)	**1,29E-04**	**2,27E-04**
L: Kwh electricity use for pumping (G*0,05)	**25,72**	**24,42**

Upgrading of biogas to biomethane (98% methane) at Skjerven:

The upgrading at Skjerven consists of inventory for electricity use for upgrading and methane loss in the process. The Ecoinvent process *Electricity, medium voltage (NO)| market for | Alloc Rec, U* is used for electricity. According to Modahl et al (2016, p. 44), 0,25 kwh electricity is used per m3 biogas. It is also assumed that there is 1,5 % loss of methane during the process. The methane loss is shown in kg. The loss in m3 is calculated with a density of 0,554 kg/m3.

Infrastructure is not allocated to the scenarios as it is assumed that the upgrading facility would be shared by many biogas plants and was built before HOFF would have chosen biogas production for transport fuel.

	Scenario 1	Scenario 2
M: Kwh electricity use kwh (0,25*G)	**128,61**	**122,08**
N: m3 methane loss to air (1,5%*F)	4,34	4,35
O: Kg methane loss to air (0,554*N)	**2,41**	**2,41**

Compression of biomethane:

Biogas for transport fuel comes in compressed form (CBG). It is assumed that the compression process takes place at Skjerven after upgrading. The Ecoinvent process *Electricity, medium voltage (NO)| market for | Alloc Rec, U* is used for electricity. According to Modahl et al (2016, p. 44), it is used 0,17 kwh per m3 biogas for compression. The infrastructure for compression is not included for the same reason as mentioned under upgrading of biogas. To calculate the use of electricity per gas compressed, it is necessary to subtract the energy lost through methane loss in the upgrading process.

	Scenario 1	Scenario 2
P: m3 methane available for compression (F-N)	285,15	285,85
Q: Kwh electricity use for compression (P*0,17)	**43,42**	**48,59**

Calculation B9: Use of biogas in buses

In the scenarios, it is assumed that the biogas is used for commuting buses with gas drive motor. The related inventory for this use stage is the direct emission when driving the buses. Bus infrastructure is not included as one can assume that the same bus as today is utilised. One only needs to change some parts of the bus, for instance the diesel motor to gas motor, which would represent minor environmental impact. Data for emissions are taken from Institute of Transport Economics' testing of Euro 6 buses. These buses are the ones that will be most relevant if biogas should be utilised as transport fuel. However, it is noticeable that many of the buses today, which are still Euro 5, pollute considerably more (Hagman, 2016). According to Hagman (2016), the emissions are the same for biogas methane (CBG) as for natural gas methane (CNG). Emissions per km driven are: Nox 0,1 g/km, particles 0,028 g/km and CO2 1068 g/km. The emission for CO2 is assumed to be biogenic, meaning that the CO2 emitted is part of the natural CO2 cycle. This is different from CO2 from fossil fuels, from which emissions come from fossil related resources (diesel, natural gas).

The emission data is based on grams emitted per km. To find km driven with gas motor, assumptions from Ruter (Oslo and Akershus public transportation company) and Analyse & Strategi. The latter's report for Agder commuting transportation, use average numbers from studies of gas busses in Trondheim in their calculations, which is 0,65 m3 gas per km (Martinsen *et al.*, 2014, p. 25). In Ruter's (2014) strategy, the company assumes the use of around 0,61 m3 gas per km. In the scenarios, the assumption is therefore 0,63 m3 per km.

	Scenario 1	Scenario 2
A: km driven per ton DM (calculation B8 P/0,63)	452,62	453,73
B: grams Nox ton DM (A*0,1)	**45,26**	**45,37**
C: grams PM (particles) per ton DM (A*0,028)	**12,67**	**12,70**
D: grams CO2 biogenic per ton DM (A*1068)	**483399,59**	**484579,95**

Calculation B10: Transport digestate HOFF biogas to farms

The assumptions for transportation distance of digestate is the same as for transportation of potato ethanol stillage in the reference scenario. However, because there will be more m3 digestate to transport and spread at farm plots per year compared to potato stillage (85 % more in scenario 1 and 27 % more in scenario 2), it is assumed that the digestate must be transported further away from HOFF in both scenarios. It is therefore assumed that the average km transported is 40 % more for scenario 1 and 10 % more for scenario 2. The Ecoinvent 3 process *Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U* is used.

	Scenario 1	Scenario 2
A: Average km transported	48,35	37,99
B: ton digestate transported per ton DM	8,37	10,05
C: Tkm per ton DM (A*B)	**404,6**	**382,0**

Calculation B11: Storage of digestate at farm

The digestate is stored at the farm before spreading it on the farm plots. At the farms there are storage facilities already as is in the reference scenarios, as it is assumed that the digestate is delivered to the farms that have storage for manure. Therefore, storage infrastructure is not included in the biogas scenarios. The inventory consists of emission to air from the stored digestion. The emission data is based on calculations by Modahl et al. (2016, p. 49), based on

Amon et al (2006) and Hartmann (2008) (p. 48). Modahl et al. estimate emissions for digestate based on cattle manure and food waste separately.

It is therefore assumed that the parts (parted on % ton DM in the biogas plant) of the digestate from potato ethanol stillage, vegetable/potato residues and food waste are based on food waste digestate emission numbers. However, because the methane yield per VS is so much lower for potato ethanol stillage (323) than for food waste (430), one can assume that the CH4 emissions to air when stored are also lower. It is assumed 75% lower emissions per ton DM. The rest of the emission types are the same as food waste in Modahl et al.' model as nitrogen and phosphorous content is similar. The methane yield per VS from potato stillage is somewhat lower than the yield from food waste in Modahl et al., suggesting that CH4 emissions to air from the digestate also may be lower.

Modahl et al. assume that the storage may be closed with roof, especially when considering that in a future scenario, the storage units at farms will be closed to reduce greenhouse gases. In this case, there would be zero emissions in the biogas scenarios. For this research, it is therefore also included separate scenarios where zero emission from storage is shown. One must keep in mind, however, that today, most of the storages are open (Bechmann *et al.*, 2016, p. 14).

Digestate from potato ethanol stillage:		Scenario 1 (27%)	Scenario 2 (48%)
kg CH4/ton DM (75% lower)	13,229	3,583	6,302
kg CO2/ton DM	0,000	0,000	0,000
kg N2O/ton DM	0,000	0,000	0,000
kg NH3/ton DM	0,159	0,043	0,076
Digestate from cattle manure:		Scenario 1 (23%)	Scenario 2 (22%)
kg CH4/ton DM	3,370	0,767	0,752
kg CO2/ton DM	0,000	0,000	0,000
kg N2O/ton DM	0,000	0,000	0,000
kg NH3/ton DM	1,920	0,437	0,428
Digestate from veg/potato residues or food waste:		Scenario 1 (50%)	Scenario 2 (30%)
kg CH4/ton DM	17,638	8,846	5,302
kg CO2/ton DM	0,000	0,000	0,000
kg N2O/ton DM	0,000	0,000	0,000
kg NH3/ton DM	0,159	0,080	0,048
Total emissions:		Scenario 1 (100%)	Scenario 2 (100%)
kg CH4/ton DM		**13,196**	**12,356**
kg NH3/ton DM		**0,560**	**0,552**

Calculation B12: Spreading of digestate on farm fields

The digestate is spread on farm fields and the environmental impacts are related to transport, steering and pumping of digestate for the fertilisation of fields, as well as emissions related to spreading and emissions during growing season. It is assumed the use of tractor for spreading. The use of diesel is therefore included; however, the infrastructure is not included as the tractor is not allocated to these scenarios and used only for spreading the digestate. The calculations from Modahl et al.'s model (2016, pp. 51-52) are used. In the model, it is assumed litre/m3 for stirring is 0,045, for pumping 0,1 and for tractor use 0,28. As the emissions from spreading and emissions related to the growing season are different depending on which substrate the digestate is from, the calculations are parted in the same way as for the calculation of storage of the digestate (B11). For diesel use, the Ecoinvent 3 process *Diesel (RER)| market group for | Alloc Rec, U* is used. Diesel use is shown in kg. Therefore, calculations from litre to kg are done with the assumption that diesel has a density of 0,851kg/litre.

		Scenario 1	Scenario 2
A: m3 digestate spread		9,05	10,33
B: kg/litre density diesel		0,851	0,851
Kg diesel use for stirring (A*B*0,045)		**0,346**	**0,395**
Kg diesel pumping (A*B*0,1)		**0,770**	**0,879**
Kg diesel tractor (A*B*0,28)		**2,155**	**2,460**
<u>Emissions from spreading</u>			
Digestate cattle manure:		Scenario 1 (23%)	Scenario 2 (22%)
kg CH4/ton DM	0	0,000	0,000
kg N2O/ton DM	0,468	0,107	0,104
kg NH3/ton DM	6,17	1,404	1,376
Digestate potato ethanol stillage:		Scenario 1 (27%)	Scenario 2 (48%)
kg CH4/ton DM	0	0,000	0,000
kg N2O/ton DM	0,159	0,043	0,076
kg NH3/ton DM	2,960	0,802	1,410
Digestate veg/potato residues or food waste:		Scenario 1 (50%)	Scenario 2 (30%)
kg CH4/ton DM	0	0,000	0,000
kg N2O/ton DM	0,159	0,080	0,048
kg NH3/ton DM	2,960	1,484	0,890
Total emissions:		Scenario 1 (100%)	Scenario 2 (100%)
kg N2O/ton DM		**0,229**	**0,228**
kg NH3/ton DM		**3,691**	**3,676**

Calculation B13: Biogas substitution of electricity and heat

The scenarios where the biogas is used for electricity and heat, it will substitute electricity mix in Norway (Ecoinvent 3 process *Electricity, medium voltage (NO)| market for | Alloc Rec, U)* and heat from district heating system based on wood furnace (Ecoinvent 3 process *Heat, district or industrial, other than natural gas (RoW)| heat production, hardwood chips from forest, at furnace 1000kW, state-of-the-art 2014 | Alloc Rec, U).* These are chosen on the assumption that HOFF will use electricity produced in its own factory. Today, the electricity is coming from the electricity grid of Eidsiva. Regarding heat, it is uncertain whether there will be more use for heat in the factory production. In the biogas scenario, it is assumed that the heat can be used by other nearby buildings. All though not fully built out in Gjøvik today, a future heat provider may be Eidsiva's district heating from wood/wood residues furnace (Norsk Fjernvarme, 2019). It is with this assumption the heat produced from biogas, may substitute heat from hardwood chips. The chosen process in Ecoinvent 3 does not include residue wood but will be a close representation of what is substituted, as wood comes from sustainable forest management (in ILCD analysis method, hardwood and softwood based heat create very similar results).

To calculate how much electricity and heat biogas will substitute, the amount of heat used in own production must be subtracted. From calculation B7, the electricity and heat output after CHP conversion and subtracted heat, were shown. In calculation B5 the heat loss from anaerobic digestion was shown. Heat is presented in MJ with the calculation of MJ/kwh of 3,6.

	Scenario 1	Scenario 2
A: Kwh electricity substituted (calculation B7 C)	**1153,30**	**1113,66**
B: MJ heat substituted ((calculation B7 D – calculation B5 F)*3,6)	**3275,22**	**3450,40**

Calculation B14: Biogas substitutes transport fuel

In the scenarios where biogas is used for diesel transportation fuel, it is assumed that the use of the diesel is through public transport busses. This is the most common scenario when biogas is sold for this purpose. For instance, the biogas from Mjøsanlegget is sent to Oslo and used in the Ruter buses, where they are substituting diesel driven buses.

The inventory for this process therefore consists of the production of diesel to the market and the emissions from driving the buses. Bus infrastructure is not included as one can assume that the same bus is used for biogas and diesel.

To find the amount of diesel to be substituted, one assumes that 1m3 biomethane (upgraded biogas) substitutes 1 l of diesel. However, because the conversion energy efficiency is very low in gas motor, Modahl et al. (2016, p. 54) calculate that the share of energy from biogas of energy from diesel is only 0,871. For diesel use, the Ecoinvent 3 process *Diesel (RER)| market group for | Alloc Rec, U* is used. Diesel use is shown in kg. Therefore, calculations from litre to kg are done with the assumption that diesel has a density of 0,851kg/litre.

The emission data is based on grams emitted per km. To find km driven with diesel, assumptions from Analyse & Strategi are used. They use 0,4 litre per km driven (Martinsen *et al.*, 2014, p. 25).

Data for emissions are taken from Institute of Transport Economics' testing of Euro 6 buses (Hagman, 2016), the same buses as in the biogas use process (see calculation B9). Emissions per km driven are: NOx 0,15 g/km, particles 0,014 g/km and CO2 1117,7 g/km. The emission for CO2 is assumed to be fossil based (diesel), meaning that the CO2 is not emitted as part of the natural cycle.

	Scenario 1	Scenario 2
A: litre diesel substituted (calculation B8 Q*0,871)	248,37	248,97
B: Kg/litre density diesel	0,851	0,851
C: Kg diesel substituted (A*B)	**211,36**	**211,88**
D: km driven per ton DM (A/0,4)	620,92	622,43
E: grams Nox per ton DM (D*0,15)	**93,14**	**93,37**
F: grams PM (particles) per ton DM (D*0,014)	**8,69**	**8,71**
G: grams CO2 fossil per ton DM (D*1117,7)	**693999,23**	**695693,83**

Calculation B15: Digestate substitute mineral fertiliser

When the digestate is spread on farm fields, it is expected to substitute mineral fertiliser. The inventory consists of the fertiliser product and the emissions when used.

As in the Modahl et al. (2016) model, the amount of fertiliser substituted is based on the kg nitrogen that is available to the plant after spreading the digestate/stillage/manure. There are normally different fertiliser types that are used. According to the Norwegian Food Safety Authority's statistics on the amount of mineral fertiliser sold in Hedemark and Oppland area, the fertilisers with the highest turnover, are NPK fertilisers (Mattilsynet, 2019, p. 4) with a nitrogen share of around 20-25%. Therefore, in the scenarios, an Ecoinvent 3 process representing a nitrogen fertiliser with 26,5% is chosen; *Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U.* The process represents production and transportation of the inputs in the fertiliser. These may be somewhat different than for instance the Yara fertilisers, which are common in Norway. The environmental impact of Yara fertilisers, especially regarding the production, may be lower than in the BAT (best available technology) scenarios that Yara presents.

To find the amount of nitrogen, the model assumes 60% of the nitrogen content in the substrate per ton DM is available for the plant (pp. 55-56). The model assumes the same amount of available nitrogen in manure when spread directly on fields in a reference scenario. As the digestate consists of different substrates, the calculations are split based on share of ton DM. Transportation for spreading is not included as it is assumed that one can carry many more kg of mineral fertiliser compared to digestate.

The emissions to air when the fertiliser has been used are calculated with assumptions from the Norwegian emission inventory 2016, as presented in (Grønlund, 2015). The main emissions are of N_2O-N when spread to the field (0,01 of nitrogen) and NH_3 through deposition (0,0095 of nitrogen).

		Scenario 1 (27%)	Scenario 2 (48%)
A: kg nitrogen available to plant potato ethanol stillage (21*60%)	12,5	3,4	6,0
		Scenario 1 (23%)	Scenario 2 (22%)
B: kg nitrogen available to plant cattle manure (48*60%)	28,8	6,6	6,4
		Scenario 1 (50%)	
C: kg nitrogen available to plant veg/potato residues (19*60%)	11,4	5,7	
			Scenario 2 (30%)
D: kg nitrogen available to plant food waste (23*60%)	13,8		4,1
		Scenario 1 (100%)	Scenario 2 (100%)
E: kg nitrogen per ton DM from all substrates		**15,66**	**16,53**
Emissions from use:			
F: Kg N_2O (0,01*E)		**0,157**	**0,165**
G: Kg NH_3 (0,0095*E)		**0,149**	**0,157**

Calculation B16: Digestate substitutes carbon in soil

Digestate consists of carbon and phosphate. In the model of Modahl et al., (2016), phosphate is not included because the use of phosphate differs very much from area to area in Norway. Further, phosphate content in the substrates going into the biogas plant is assumed to not change when it comes out as digestate. In the scenarios, it is assumed that the digestate is spread on field areas. In this way, phosphate is brought back into the natural cycle and is not changed from the reference scenario.

Regarding carbon, the same model assumes that 20% of the carbon content in the substrates is available to the soil as digestate is spread. The Ecoinvent 3 process *Carbon, organic, in soil or biomass stock* is used as input from nature.

		Scenario 1 (27%)	Scenario 2 (48%)
A: kg carbon available to soil potato ethanol stillage (400*20%)	80	21,7	38,1
		Scenario 1 (23%)	Scenario 2 (22%)
B: kg carbon available to soil cattle manure (400*20%)	80	18,2	17,8
		Scenario 1 (50%)	
C: kg carbon available to soil veg/potato residues (400*20%)	80	40,1	
			Scenario 2 (30%)
D: kg carbon available to soil food waste (400*20%)	80		24,1
		Scenario 1 (100%)	Scenario 2 (100%)
E: kg carbon per ton DM from all substrates		**80,00**	**80,00**

APPENDIX B: SENSITIVITY ANALYSIS PARAMETERS

Sensitivity analysis reference scenario 1:

Process category	Simapro unit created	Description of inventory	Ecoinvent inventory name	Data quality	Value per FU	Unit
Transport and storage of substrate	Ref 1.1_Transport potato stillage to farms	Transport potato stillage to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	90 %	140,3	tkm
	Ref 1.2_Storage of potato stillage with cattle manure at farm	Storage potato stillage with cattle manure, CH4 emission	Methane, biogenic	70 %	5,814	kg
		Storage potato stillage with cattle manure, N2O emission	Dinitrogen monoxide	70 %	0,020	kg
		Storage potato stillage with cattle manure, NH3 emission	Ammonia, NO	70 %	0,240	kg
Transport to spreading and spreading for use	Ref 1.3_Spreading of potato stillage with cattle manure on farm	Diesel use, stirring of stillage with cattle manure	Diesel (RER)| market group for | Alloc Rec, U	70 %	0,182	kg
		Diesel use, pumping from storage to field	Diesel (RER)| market group for | Alloc Rec, U	70 %	0,405	kg
		Diesel use, tractor for spreading	Diesel (RER)| market group for | Alloc Rec, U	70 %	1,133	kg
		Spreading of stillage and manure, N2O emission	Dinitrogen monoxide	50 %	0,087	kg
		Spreading of stillage and manure, NH3 emission	Ammonia, NO	50 %	0,964	kg
	Ref 1.4_Potato and veg residues on farm field	Potato and vegetable residues on field, N2O emission	Dinitrogen monoxide	70 %	0,067	kg
Digestate substitutes mineral fertiliser or compost	Ref 1.5_Substitution of mineral fertiliser	Production of nitrogen fertiliser as N	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	70 %	6,96	kg
		Spreading of nitrogen fertiliser, emission N2O	Dinitrogen monoxide	70 %	0,070	kg
		Spreading of nitrogen fertiliser, emission NH3	Ammonia, NO	70 %	0,066	kg
	Ref 1.6_Substitution of carbon to soil	Carbon to soil	Carbon, organic, in soil or biomass stock	70 %	27,92	kg

Sensitivity analysis for biogas scenario 1:

Process category	Simapro unit created	Description of inventory	Ecoinvent inventory name	Data quality	Value per FU	Unit
Transport and storage of substrate	Scenario 1.1_Storage manure at farm before going to biogas	Storage cattle manure at farm, NH3 emission	Ammonia, NO	70 %	0,018	kg
Transport of substrate to waste mng facility	Scenario 1.2_Transport manure from farm to HOFF biogas	Transport manure from farms to HOFF biogas	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	90 %	70,7	tkm
	Scenario 1.3_Transport potato and vegetable residues from farm to HOFF biogas	Transport veg/potato residues from farms to HOFF biogas	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	90 %	62,1	tkm
Biogas production	Scenario 1.4_Biogas production from potato stillage, manure and farm residues	Electricity for production from Norwegian electricity mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	70 %	47,07	kwh
		Biogas plant material	Anaerobic digestion plant, agricultural (RoW)| construction | Alloc Rec, U	50 %	1,61E-05	unit
Upgrading of biogas	Scenario 1.5E_CHP power transformation of biogas	CHP power conversion	Mini CHP plant, common components for heat+electricity (Arapoglou *et al.*)| market for | Alloc Rec, U	90 %	5,80E-05	units
	Scenario 1.5D_Converting biogas to transport fuel and use of biogas in buses	Electricity for pumping through pipe, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	70 %	18,01	kwh
		Biogas transport pipe, infrastructure	Pipeline, natural gas, low pressure distribution network (RoW)| construction | Alloc Rec, U	50 %	6,45E-05	km
		Electricity for upgrading biogas to transport fuel, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	70 %	90,03	kwh
		Upgrading biogas to transport fuel, CH4 emission	Methane, biogenic	70 %	1,684	kg
		Electricity for compression of upgraded biogas, Nor el mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	70 %	33,93	kwh
		Use of biogas in buses, Nox emission	Nitrogen oxides, NO	90 %	40,74	g
		Use of biogas in buses, PM emission	Particulates, < 10 um	90 %	11,41	g
		Use of biogas in buses, CO2 emission	Carbon dioxide, biogenic	70 %	0,00	g

Transport to storage and storage of digestate	Scenario 1.6_Transport digestate from HOFF biogas to farms	Transport digestate HOFF biogas to farms	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U	90 %	364,2	tkm
	Scenario 1.7_Storage of digestate at farm	Storage digestate at farm, CH4 emission	Methane, biogenic	70 %	9,237	kg
		Storage digestate at farm, NH3 emission	Ammonia, NO	70 %	0,392	kg
Transport to spreading and spreading for use	Scenario 1.8_Spreading of digestate on farm fields	Diesel use, stirring of stillage with cattle manure	Diesel (RER)| market group for | Alloc Rec, U	70 %	0,224	kg
		Diesel use, pumping from storage to field	Diesel (RER)| market group for | Alloc Rec, U	70 %	0,499	kg
		Diesel use, tractor for spreading	Diesel (RER)| market group for | Alloc Rec, U	70 %	1,396	kg
		Spreading digestate on farm fields, N2O emission	Dinitrogen monoxide	50 %	0,115	kg
		Spreading digestate on farm fields, NH3 emission	Ammonia, NO	50 %	1,845	kg
Biogas substitutes energy carrier or transport fuel	Scenario 1.9E_Substitution of electricity and heat	Norwegian electricity mix	Electricity, medium voltage (NO)| market for | Alloc Rec, U	70 %	807,31	kwh
		Heat, from district heating	Heat, district or industrial, other than natural gas (RoW)| heat production, hardwood chips from forest, at furnace 1000kW, state-of-the-art 2014 | Alloc Rec, U	50 %	1637,61	MJ
	Scenario 1.9D_Substitution of diesel fueled busses	Production and distribution of diesel to market	Diesel (RER)| market group for | Alloc Rec, U	70 %	147,95	kg
		Use of diesel in buses, Nox emission	Nitrogen oxides, NO	90 %	83,82	g
		Use of diesel in buses, PM emission	Particulates, < 10 um	90 %	7,82	g
		Use of diesel in buses, CO2 emission	Carbon dioxide, fossil	90 %	624599,31	g
Digestate substitutes mineral fertiliser or compost	Scenario 1.10_Substitution of mineral fertiliser	Production of nitrogen fertiliser as N	Nitrogen fertiliser, as N (RER)| calcium ammonium nitrate production | Alloc Rec, U	70 %	10,96	kg
		Spreading of nitrogen fertiliser, emission N2O	Dinitrogen monoxide	70 %	0,110	kg
		Spreading of nitrogen fertiliser, emission NH3	Ammonia, NO	70 %	0,104	kg
	Scenario 1.11_Substitution of carbon to soil	Carbon to soil	Carbon, organic, in soil or biomass stock	70 %	56	kg

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Assessment of environmental benefits of cooperative biogas treatment of wet organic wastes

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