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Feasibility study on the potential methane fuel production via anaerobic digestion of organic waste in Hérað

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Abstract

Due to the threats of climate change and the need to meet national and international strict environmental regulations, Iceland is currently in a transition towards a sustainable energy and waste management system. Currently, Iceland has a large fossil fuel consumption in the transport sector and relies heavily on landfill to treat organic waste. This reports intends to connect both concepts by addressing the production of methane fuel via anaerobic digestion of organic waste to provide green fuel and a sustainable waste management option to landfill. The aim of this report is to carry out a feasibility study for a potential biogas plant, taking the Icelandic eastern region of Hérað as the study area and addressing environmental and economic aspects of such plant, using AD Modeling Tool. The purpose of this thesis is to contribute to the sustainable transition of East Iceland.

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Acronyms

MSW	Municipal Solid Waste
COP	Conference of Parts
DS	Dry Solids
VS	Volatile Solids
TS	Total Solids
HRT	Hydraulic Retention Time
OLR	Organic Loading Rate
CSTR	Continuous Stirred Tank Reactor
EC	European Commission
EU	European Union
AD	Anaerobic Digestion
LCA	Life Cycle Analysis
GHG	Greenhouse Gas
TOE	unit of energy, Tons of Oil Equivalent
HTI	High Temperature Incineration
LTI	Low Temperature Incineration
IRR	Internal Rate of Return
NPV	Net Present Value
GWP	Global Warming Potential
O&M	Operation & Maintenance

1. Introduction

As climate change threats increase all over the world, the necessity to review the current energy system has become obvious. The transition from fossil fuel based energy systems to renewable energy is a crucial step for enormous environmental impacts to be avoided. Countries worldwide have compromised to act on such issue and signed treatments such as the COP21 which set binding targets on cutting down greenhouse gas emissions, or GHG. Iceland is one of the current frontrunners when it comes to renewable energy, since its power production comes mostly from renewable geothermal and hydropower sources. However, there are still huge steps for Iceland to be taken towards a 100% fossil fuel free energy system. Even though the electricity production is totally renewable, other sectors within the energy system are still very much dependant on fossil fuels. That would be the case of the transport sector, which runs mostly on imported fossil fuels (National Energy Authority, 2018).

Therefore, the focus now relies on transitioning away from fossil fuels within the transport sector. Even though most of the road vehicle grid is expected to go electric in the not so distant future, there are some areas within the transport sector which will not be able to get electrified due to technical limitations. That is the case of the heavy transport vehicles such as trucks and fishing vessels, which characteristics require liquid fuels to perform. Here is where alternative fuels play a crucial role, since they represent a sustainable alternative to fossil fuels (National Energy Authority, 2009). Moreover, another issue that the Icelandic government is addressing is the waste management system. Up until 2004 there was little estimation of the real amounts of waste that the country was handling, and most of it was landfilled or burned in an open pit, resulting on significant levels of pollution in many levels. Currently a great part of the waste generated is still being landfilled and an alternative waste management is required in order to meet the environmental goals fixed (Umhverfisstofnun, 2013).

With the objective of addressing both problems, Iceland has put major attention on methane fuel production from waste as a way to produce green fuels and to serve as a sustainable waste management system. The use of methane extracted from biogas has been established successfully in Reykjavík and Akureyri (Sorpa, 2018).

The aim of this report is to carry out a feasibility study for the methane fuel production via anaerobic digestion of organic waste in a potential biogas plant in Hérað, addressing environmental and economic aspects.

Iceland is located in the Northern Atlantic, accounting for an area of 102.775 km² and a population of 332.259 inhabitants. Hérað is a region located in the eastern part of Iceland, which conforms two municipalities: Fljótsdalshérað and Fljótsdalshreppur. The population in this region is 3.574 inhabitants and accounts for an area of 10.400 km² (City Population, 2018).

Figure 1 - Map of Hérað (Wikipedia, 2018)

1.1. Context of the problem

Biogas and methane fuel

Methane is a gas formed naturally in wetlands, marshes and the stomach of ruminants, through the biodegradation of organic matter carried out by bacteria in the absence of oxygen. This process is known as anaerobic digestion. The use of methane has been widespread around the world for heating and power purposes, proving itself as environmentally and economically sound. It is produced in large scale in facilities such as landfills, water treatment plants and biogas plants, where the gas is collected for the mentioned purposes (Metan, 2018).

Methane can be extracted from biogas, which is the waste product of anaerobic digestion of organic compounds. The composition of biogas is generally about 53-55% methane and 41-43% carbon dioxide, along with traces of other substances such as nitrogen, hydrogen sulfide, oxygen, water vapour and ammonia (Vista, V. 2013). After the collection of biogas from the anaerobic digestion facility the methane is isolated from the other gases, leaving a product with a methane purity of 95-98%. This process is known as biogas upgrading and results into a fuel-quality product, which has a better performance energy wise than raw biogas and enables its use in transportation. The main feedstock biogas is produced from is biomass, which involves organic waste and energy crops. The fact that these are considered renewable resources and that methane has a high energy content, makes it an environmentally and technically sound fuel (Schnürer, A. & Jarvis, Å, 2010).

The feedstocks used are digested in a reactor at high temperatures without the presence of oxygen. The digestion is based on microorganisms activity, which break down the biomass to simpler compounds and produces methane as an end product. The equilibrium and stability of the process is a critical point which gets most of the attention of the process design. The biogas production, and its upgrade to methane fuel, will be explained in more detail in the following chapters (Schnürer, A. & Jarvis, Å, 2010).

It is important to understand and distinguish between the terms of methane, biogas and biogas plant, since all of them will be discussed in this thesis. The outcome of anaerobic digestion is biogas, from which methane can be extracted and upgraded to fuel quality for its use in transportation. Therefore, it is important to understand that methane is extracted from the biogas produced in the biogas plants. This report will use the term 'biogas plant' when discussing the plant from which methane fuel is produced via anaerobic digestion of organic waste.

Heavy transport and the need for sustainable fuel

According to the National Energy Authority in Iceland, most of the road vehicle grid is expected to get electrified in the short term. However, heavy transport vehicles are unlikely to be able to carry out such transition, since the technical dimensions of this sector can not be met by the current technology involving electric propulsion. Many industries in Iceland rely heavily on heavy transport, such as fishing and all the other industries which involve transport of goods.

Therefore, finding sustainable fuel alternatives for these industries would be crucial in order to avoid any negative economic impacts related to penalties on GHG emissions among other issues. Methane as an alternative fuel could meet both technical dimensions and environmental aspects, which makes it a great candidate for its use in heavy transport (National Energy Authority, 2009).

Waste management

Back in the 1970s, Iceland used to carry out most of the waste management through disposal methods in burning pits. Landfill disposal of waste became the main method in the 1990s, which still represents a considerable share of the final destination for the waste generated nowadays. The legislation on waste management became more strict once Iceland joined the European Economic Area in 1994, with Iceland being obliged to implement EU regulations on the matter.

The current Icelandic legislation on waste management is in accordance to the European Union legislation, and so are their strategies and policies. The National Waste Management Plan, which has been vigent since 2004, aims at setting up more stringent demands on the Icelandic waste management system. Several regulations under the mentioned plan address the reduction of waste generated, the increment on recycling and the reduction of landfill sites (Umhverfisstofnun, 2013).

Currently, 42% of the waste still ends up in landfills while 58% is recovered by several means such as recycling, composting and energy recovery via incineration. According to the National Waste Management Plan set strategies, the final goal is to abolish landfill practice by 2021. The plan intends to increase the material recycling and recovery by promoting the production of fuel from waste (Umhverfisstofnun, 2013).

Hérað and East Iceland

The use of methane as transport fuel has been a reality in Iceland since 2003, with private cars and buses running on methane extracted from the landfills. Methane is produced in landfills close to urban areas, activities which are coordinated by the public company Sorpa. Therefore, the management of the waste disposal system of several municipalities is runned by Sorpa, along with the landfills themselves, and pushes the commercial development of methane as an alternative fuel through Metan Ltd., Sorpa's subsidiary (Askja Energy, 2018).

Sorpa is currently producing methane fuel for approximately 2.500 private cars in Iceland, which accounts for only the 3% of Iceland's fuel consumption (Hafliðason, 2013). Moreover, it is estimated that this share will increase in the coming years due to Iceland's goal to reach up to 60-70% of sustainable energy consumption. However, other green fuels such as methanol, biodiesel and ethanol, along with electricity, will take part of this increment so it will not all be covered by methane (Sorpa, 2013). Currently, there is no ongoing methane fuel production in the region of Hérað. The positive experiences from Reykjavik and Akureyri, along with other experiences from agricultural regions in several european countries, draws an encouraging scenario for potential methane fuel production in Hérað. The organic waste from livestock such as cattle, sheep and horses in Hérað accounts for the 40% of East Iceland, being one of the main feedstock resources available in the East (Matvælastofnun, 2011).

1.2. **Problem formulation**

Due to climate change threats and the ever developing strict regulations on GHG emissions, the necessity to transition away from fossil fuels has become a rather urgent matter in many countries. The heavy transport sector in Iceland has a high fossil fuel demand, which is hard to meet with electrification. Alternative fuels could represent cost effective and sustainable solutions to cut down emissions and abandon fossil fuels in the transport sector. Moreover, Iceland is also facing a waste management transition, since landfill practice is to be abolished by 2021. Therefore, a waste management alternative to landfill is also needed.

Methane has been one of the most successful alternative fuels in Iceland in the recent years, along with biodiesel. The production of methane fuel via anaerobic digestion of organic waste, a production pathway which technology has been mastered and relies on waste which otherwise could be potentially landfilled, steps out as one of the most feasible solutions to carry out. However, the design of a biogas plant for methane fuel production from organic waste purposes carries with it many difficulties and challenges, which have to be addressed through a feasibility study in a context specific scenario. This report will use Hérað, a region in East Iceland, as the scenario to carry out such study. The problem addressed can be summarized as it follows:

Iceland has a large fossil fuel demand for transportation and a significant amount of landfilled waste. The organic waste generated in Hérað could potentially be used for producing methane fuel for transportation via anaerobic digestion and act as an alternative waste management option to landfill.

1.3. **Research question**

This report focuses on carrying out a feasibility study for the construction of a biogas plant in Hérað, which would produce methane fuel via anaerobic digestion of organic waste, addressing both environmental and economic aspects. The following question summarizes such aim:

In economic and environmental terms, how feasible would be the production of methane fuel via anaerobic digestion of organic waste to provide sustainable fuel for transportation and a waste management alternative to landfill?

In order to address the research question, several sub-questions have been elaborated based on the nature of the different aspects such question encloses. These are necessary to support the research question and provide a comprehensive approach to it. Taking the context of Hérað, the following sub-questions will be taken into account;

A. What is the current situation of waste management, heavy transport and methane fuel?
B. How is methane fuel produced in a biogas plant?
C. What technology is involved in the anaerobic digestion process?
D. What design parameters would the biogas plant have?
E. What are the energy and mass balances of the biogas plant?
F. What GHG emissions does the production of methane fuel from organic waste in a biogas plant imply?
G. What are the potential revenues and costs of the biogas plant?

<u>Scope of the report</u>

The intention of this report is to address the potential methane fuel production via anaerobic digestion of organic waste in Hérað, taking into consideration context specific data for the Hérað scenario. Therefore, the results of this research might only apply to such context.

<u>Report structure and guide</u>

The figure 2 represents the structure of this report, where the flow of lecture and influence between chapters can be appreciated. The introduction, problem formulation and research question are described in the initial stages of the report, which are supported by literature review. In second place, the theoretical framework and the research design used in this report are presented and explained.

The theories influence and structure the whole research, specially the methodological approach. Such approach is explained in the methodology chapter, where the ways to collect data and the tools used in the research are described. Life Cycle Analysis and AD Modeling Tool are presented in this section. The results of the data analysis and process are addressed next, which leads to the discussion. The findings and conclusions are finally presented in the conclusion chapter. The following figure is inspired by the quantitative and qualitative research methods described by Bryman (Byriman, 2001).

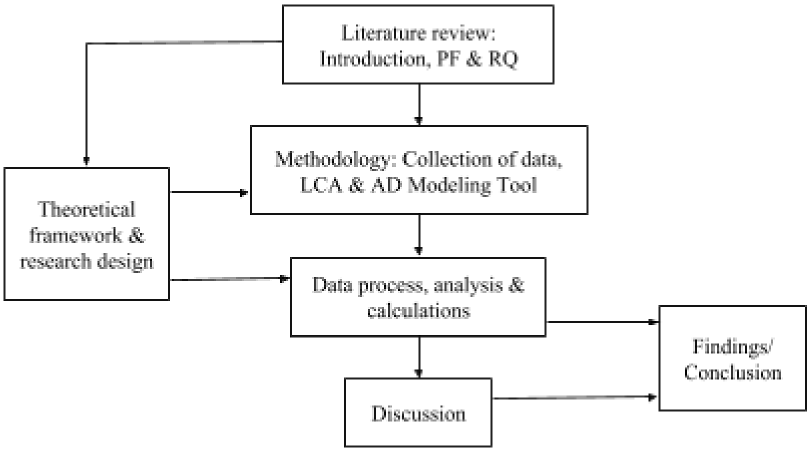

Figure 2 - Report structure (Modified based on Alonso, 2018; Bryman, 2001)

2. Theoretical framework

This chapter presents the theoretical framework which will be used to inform this research. A description of the theories used will be carried out followed by an explanation how these will be applied to the report.

2.1. Industrial Ecology Theory

Industrial Ecology basis relies on engineering and management, with a main focus on tracking the flows of substances of industrial processes aiming at reducing its impacts on the environment. The origins of Industrial Ecology theory are based on the conception that industrial production processes "require new ways of thinking" considering the environmental concerns that such activities carry with them (Duchin, F. & Hertwich, E., 2003).

The growing population and its increasing materialization demands has been putting great amounts of pressure on the environment. If these demands are to be met without damaging the environment critically, the industrial processes need to mimic the ecosystems in nature copying the closed circles of material flows with no waste generation. The term 'metabolism' regarding industrial processes had already been used by Knees, Ayres and D'Arge in 1970. Such term would be described through the material balances that get in and out of a defined production unit, which could be defined as a factory or even a city. The fate of the inputs and outputs of the production unit is also addressed, in terms of the amount of material that was actually converted to the end product and the material disposed as waste. A main pillar of Industrial Ecology is the conservation of mass (Duchin, F. & Hertwich, E., 2003).

The main objective of Industrial Ecology is to influence the decision making process in industrial operations introducing nature-inspired concepts and procedures designed to take into consideration environmental concerns (Duchin, F. & Hertwich, E., 2003).

There are different levels that can be differentiated within the aspects addressed by the theory. The 'micro level' makes reference to the physical balances, such as the substances and material flows interacting with a production unit. The 'macro level' involves the "formulation and evaluation of options for key decision makers" (Duchin, F. & Hertwich, E., 2003). However, there is a conceptual bridge between these two concepts, which need to be linked in an operational way. The suggestion of

Industrial Ecology is to use Life Cycle Analysis as the ‘meso level’ which would bridge the two concepts (Duchin, F. & Hertwich, E., 2003).

2.2. Cost-Benefit Analysis

Cost-benefit analysis is a widely used theory, which main goal is to provide a procedure for evaluating decisions in terms of their consequences or costs and benefits. Even though it might seem a theory of simple application, it is important that its methods are comprehended properly. In this chapter the basic concepts of the theory will be explained, which are the following ones: the *project, the planner, the shadow price and the project evaluation* (Stern, N. & Drèze, J., 1987).
The *project* is described by the theory as a change in the net supplies of commodities, from both the public or the private sector. The cost-benefit analysis is carried out from the perspective of the *planner* who is in charge of carrying out the projects assessments, and has a series of set preferences over states of economy of social welfare. The planner nature could be attributed to many different identities; the planner could be the government, or an agent focused on one single project. The *shadow price* is an estimated price for a commodity or good for which real cost is difficult to calculate or no market price exists. *Project evaluation* is the process where the decision on whether carrying out a project or not is examined. Within the context of project evaluation, cost benefit analysis is a decision rule which consists on either accepting or refusing projects. Only the projects which turn out to make a positive profit at shadow prices will be accepted by the theory (Stern, N. & Drèze, J., 1987).

To get an accurate result when conducting Cost-Benefit Analysis and evaluating the economic feasibility of a project, it is important to convert all future costs and benefits to present values and obtain the respective Net Present Value or NPV. To adjust such future cash flows, a discount rate is used in the calculations. A positive NPV reflects a profitable project, whether a negative NPV project accounts for a non-profitable project. The Internal Rate of Return is also used to evaluate the feasibility of projects, being the interest rate where the NPV of all the cash flows of a given project equals zero (Merritt, C. 2018).

2.3. Theories linked to this report

Industrial Ecology

Methane fuel production from organic waste is a strategy which resembles the closed circles concept within the natural ecosystems, using waste as a resource. Therefore, Industrial Ecology Theory is used by this report to inform the evaluation of such strategy.

The different layers presented in the Industrial Ecology Theory have been taken into account to carry out such evaluation. Therefore, the material balance flows which conforms the ‘micro level’ layer of the production of methane fuel via anaerobic digestion are addressed, along with the energy balances as well. LCA concepts will be applied to analyse the flows assessed in the ‘micro level’ stage in order to provide a solid basis for the ‘macro level’ layer, where the evaluation of the methane fuel production from organic waste is carried out. Therefore, LCA framework will be used as the operational bridge between the ‘micro level’ and the ‘macro level’.

This report intends to address the following concepts for the production of methane fuel from organic waste, from the Industrial Ecology Theory scope:

- Definition of the production unit
- Quantification of mass and energy balances
- Determination of the basis for the evaluation
- Link between “micro” level and “macro” level
- Industrial metabolism: “Mimic” the natural processes

Cost-Benefit Analysis

The application of the cost-benefit analysis by this report will be rather simple, making use of the theory intentionally in a broad way. Basically, the theory will be used to support the determination of whether the construction of a biogas plant for the production of methane fuel from organic waste would be economically sound, taking into account the potential revenues and costs of such project and the time value of money. Economic concepts linked to Cost-Benefit Analysis such as the NPV, discount rate and IRR will be used in the calculations.

3. Methodology

In this chapter, the methodology used to structure this report will be described. Firstly, the research techniques will be addressed through the explanation of the research design taken by this report. Secondly, the different steps of the methodology will be presented, followed by an introduction to Life Cycle Analysis methodology. LCA will be used as a tool to inform this research. Lastly, the calculations this report will be carrying out are described. The modeling tool used by this report within the analysis and calculations step will be presented as well.

3.1. Research design

The research design used by this report is Action Research design, which serves as a logic structure of inquiry to address the research question and the problem formulation set on this research (Georg, S. et al., 2016). Action Research aims at getting a deep understanding of a problem being addressed, with the objective of suggesting solutions to it an eventually checking their potential applicability. This report will use this research design to learn about the situation in Hérað regarding fuel consumption and waste management, addressing the potential shift from the fossil fuels being used by heavy transport sector to methane produced in a biogas plant, and developing a feasibility study to check on the practicability of the construction of such plant.

3.2. Steps of the methodology

In this chapter the basic approach to study the research question will be presented, distinguishing between the differents steps which structure such approach (Georg, S. et al., 2016). First, a literature review was carried out with the aim of getting a proper insight of the problematica this report is addressing and collect both qualitative and quantitative data. Secondly, an analysis of the collected data is carried out and calculations based on such data are also developed. Lastly, the outcomes from the data analysis along with the results of the calculations are addressed in the discussion, which is followed by the conclusion of this study.

This previous steps provide a solid basis for the development of the report. The analysis of the data collected is further explained, along with Life Cycle Analysis. This report has used the LCA framework in order to inform the methodology carried out, and apply key concepts of this well known tool. The discussion of the analysed data will follow, which will finally lead to the conclusion.

3.3. Data collection: Literature review

The first step of the methodology is data collection through literature review, with the objective of getting a deep understanding of the problem scenario addressed by this report in order to elaborate a proper problem formulation and research question. Both qualitative and quantitative data are collected in this step. This provides a solid basis for the whole report, since these two concepts will structure the development of the study.

A second literature review is carried out with the aim of answering the research question and the sub-questions elaborated through the first literature review. In this second step the focus relies on getting context specific data in order to approach the Hérað scenario properly, with special attention on the collection of quantitative data which will be used in the next step.

3.4. Data analysis & Calculations

The quantitative and qualitative data previously collected is then processed and analysed in this step, with the objective of addressing the sub-questions which support the research question:

A. What is the current situation of waste management, heavy transport and methane fuel?
B. How is methane fuel produced in a biogas plant?
C. What technology is involved in the anaerobic digestion process?
D. What design parameters would the biogas plant have?
E. What are the energy and mass balances of the biogas plant?
F. What GHG emissions does the production of methane fuel from organic waste in a biogas plant imply?
G. What are the potential revenues and costs of the biogas plant?

The purpose of sub-question A is to provide an insight of the current scenario for methane in Iceland, addressing its use and applications in the nordic country, with special attention on Hérað. This sub-question is answered through a description of the waste management sector and transport sector in Iceland, finally linking them with methane fuel as the common denominator. The sub-questions B and C aim at granting a basic understanding of the methane fuel production process before going deeper in the subject. These are answered via a broad description of the process, addressing the role of microorganisms and technology, along with the main operational aspects.
Sub-question D aims at providing an insight of the design parameters of the biogas plant, as the feedstock used, OLR, HRT, the volume of reactors and so on. This sub-question is answered using the AD Modeling Tool, which will be described in the next chapters. The sub-questions E and F are also

answered using AD Modeling Tool, aiming to address the energy and mass balances, as well as the GHG emissions specifically. Lastly, the purpose of sub-question G is to account for the costs and benefits the potential biogas plant would represent, based on the results of the AD Modeling Tool.

3.4.1. Life Cycle Analysis

Life Cycle Analysis, or LCA, is strongly related to engineering and industrial applications, where it is used to quantify the environmental burden caused by a product resulted from an industrial process. LCA involves quantifying mass and energy balances for all the stages of production, from the extraction of the raw materials and its processing to the use and the final disposal of the product/s. Therefore, LCA takes into account all the inputs and outputs for this given production unit or industrial process (Duchin, F. & Hertwich, E., 2003).

A critical part of LCA is the delimitation of the production unit, which involves the definition of the system's boundaries for a certain production process. The definition of the production unit facilitates the identification of the inputs and outputs to the system, which is quite a challenging procedure due to the great amount of flows that have to be considered (Duchin, F. & Hertwich, E., 2003).

The application of LCA normally consists of the following steps (Guinée et al. 2002):

- Definition of the goal of the project, definition of the system's boundaries
- Quantification of the inputs and outputs through all the stages of the production
- Identification of impacts and assessment from the previous step
- Interpretation of the impacts and significance assessment

<u>Application of LCA by this research</u>

It is important to note that this report does not intend to carry out a full LCA for the construction of a biogas plant in Hérað, since the extension of such study would be prohibitive. However, the intention of this report is to go through the LCA application steps mentioned before, and therefore use key concepts of the LCA approach to inform this report. These concepts are the following ones:

- Definition of production unit
- Definition of system boundaries
- Quantification of inputs and outputs
- Identification of environmental impacts
- Interpretation of the impacts

3.4.2. AD Modeling Tool

This report has used AD Modeling Tool to answer the following subquestions:

D. What design parameters would the biogas plant have?

E. What are the energy and mass balances of the biogas plant?

F. What GHG emissions does the production of methane fuel from organic waste in a biogas plant imply?

Therefore, the aim of using such tool was to carry out an assessment regarding the dimensions of a potential biogas plant in Hérað and its respective energy and mass balances, along with GHG emissions. The tool also provides a basis to address sub-question G "What are the potential revenues and operating costs of the plant?".

AD Modeling Tool, developed by the Biology and Organic Resources Research Group from the University of Southampton along with other entities, is able to calculate the annual potential energy and mass balances for organic feedstock treated via an anaerobic digestion system, therefore providing data for a one-year simulated biogas plant. The tool provides the user with a data pool, where default values for most of the parameters concerning the functionality of the different units in the biogas plant are provided. However, the tool enables the user to change such parameters and input data of their own, which provides a great flexibility and context specific calculations (University of Southampton, 2016).

3.5. Discussion and conclusion

The data analysed in the previous chapters, along with the results of the calculations carried out, is discussed and put into perspective. The key findings of the report are presented in this chapter, along with the conclusions to it, which will lead to the answer of the research question.

4. Background on the Icelandic scenario

In this chapter the main cores of the report will be described: waste management, heavy transport and methane fuel production. The stricts measures imposed by international agreements on waste management have Iceland looking for transitioning away from landfill practice, which has been a common method for waste management in the last decades. The abolition of such system by 2021 puts pressure on the Icelandic government to find alternative ways to manage the still significant share of waste that ends up in landfill sites, for penalties to be avoided. Methane fuel production from organic waste comes up as a solution for such waste management problem and enables the production of sustainable fuel, which also addresses the reduction of fossil fuel consumption.

Therefore, this report intends to present the link between these two concepts. The background on waste management in Iceland and the current situation of methane fuel in Iceland will be described in this chapter. The link between these concepts will be explained lastly, pointing out the relevance for this report. The sub-question A **"What is the current situation of waste management, heavy transport and methane fuel?"** is addressed in this chapter.

4.1. Waste management sector

Present situation of waste management

Waste generation in Iceland has increased steadily since 1995, going from 1482 kg of waste per capita in 1995 to 1596 kg in 2010. The amount of waste production peaked in 2008 with 2518 kg of generated waste per capita, which then dropped on the following years as a reflect of the changing economic conditions (Umhverfisstofnun, 2013).

Great advances have been done regarding waste management, and the overall picture has improved considerably as it can be appreciated in the figures 3 and 4 for the final destination of the waste in 1995 and 2011. More than half the waste generated in Iceland is currently being recycled, representing 59% of the total including composting. The share of the waste which is landfilled dropped heavily from being 79% in 1995 to 31% in 2011. Incineration of waste at low temperatures (LTI) is practically nonexistent, dropping from 6% to 0.4%, and high temperature incineration (HTI) only takes 4% of the total share. Such incineration practices are carried out with energy recovery systems, so these can be accounted as waste recovery methods (Umhverfisstofnun, 2013).

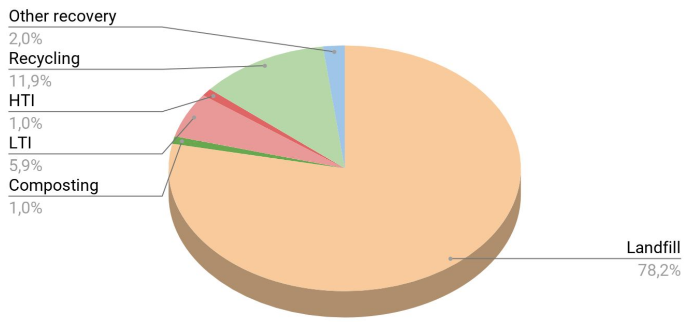

Figure 3 - Share for end-life methods for waste management in 1995 (Umhverfisstofnun, 2013)

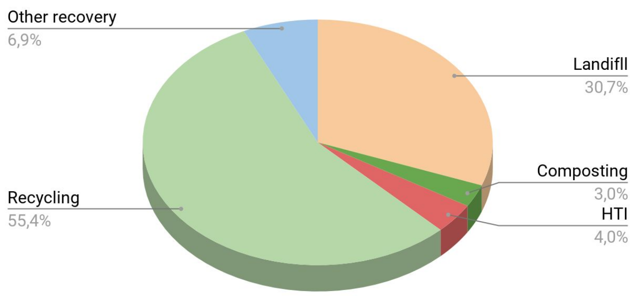

Figure 4 - Share for end-life methods for waste management in 2011 (Umhverfisstofnun, 2013)

GHG emissions from waste sector

The emissions from the waste sector represent around 5% of the total national GHG emissions, with 207 kilotons of CO_2 equivalent in 2015 (Environment Agency of Iceland, 2017). Moreover, methane emissions from solid waste disposal in landfills account for 88% of such emissions. Carbon dioxide, methane and nitrous oxide from wastewater treatment and waste incineration accounted for 5.6% and 4.5% respectively. Composting and other biological waste treatment practices represent the remaining 1.9% (Environment Agency of Iceland, 2017).

Waste sector emissions incremented steadily from 1990 to 2007 due to an increase on landfill waste disposal, peaking at over 250 kilotons of CO_2 equivalent emissions. The decrease of such emissions since 2007 is mostly due to the decline of landfill practice, which started going down considerably in 2005, along with the increment on the methane recovery methods from the very waste disposal sites.

However, the total increase on emissions from the waste sector regarding 1990 levels is over 28% for 2015 (Environment Agency of Iceland, 2017).

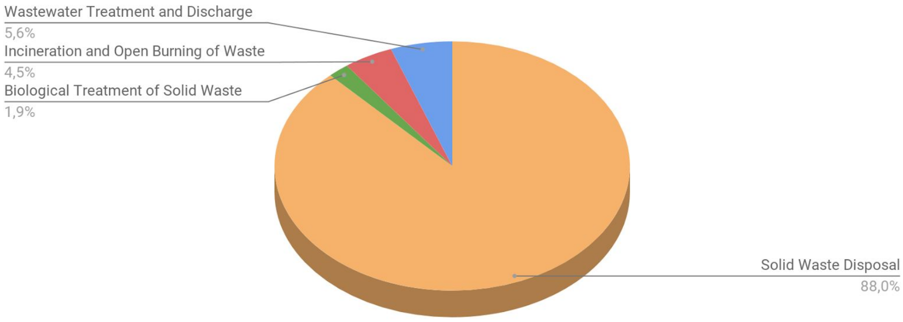

Figure 5 - GHG emissions from the waste sector from source in 2015 (Environment Agency of Iceland, 2017)

<u>Waste management national policies</u>

The basic foundations of the current waste management policies and strategies being carried out in Iceland were set in 1992, through the ratification of the Rio Declaration on environment and development (United Nations, 1992). Later in 1995, Iceland would also sign the Basel Convention, an international agreement which main focus relied on minimizing the transport of waste, as well as its volume and toxicity, along ensuring environmentally sound management procedures being carried out as close as possible from the waste generation point.

EU policy has also defined the Icelandic waste management, mostly through the EU directive on waste 2008/08/EC, since Iceland joined the European Economic Area in 1995. Significant steps have been taken on waste reduction and recycling, such as the Strategy on the Prevention and Recycling of waste of 2005. These policies laid the foundations for regulations and action plans for all EU members for the coming years (Umhverfisstofnun, 2013).

On 2011, the Roadmap to a Resource Efficient Europe strategy highlighted the importance of waste as a resource by setting objectives regarding recycling and reusing of waste by 2020 and developing a market for recycled raw materials. Moreover, this regulations also aimed at the abolition of landfills, which would no longer be an option for end-treatment of waste. As a result of the early waste management measures, Iceland currently counts with more than 30 landfill sites spreaded all over the country, seven of them of inert waste only. Landfills were first seen as a sound measure to reduce the open pit burning sites that were numerous in the 1990s, which produced many pollutants and spread toxins into the air as a result of the low temperature combustion of the waste. However, according to the more strict regulations imposed by the EU landfilling was not longer a sound practice for waste management due to its environmental burden, making a system transition necessary (Umhverfisstofnun, 2013).

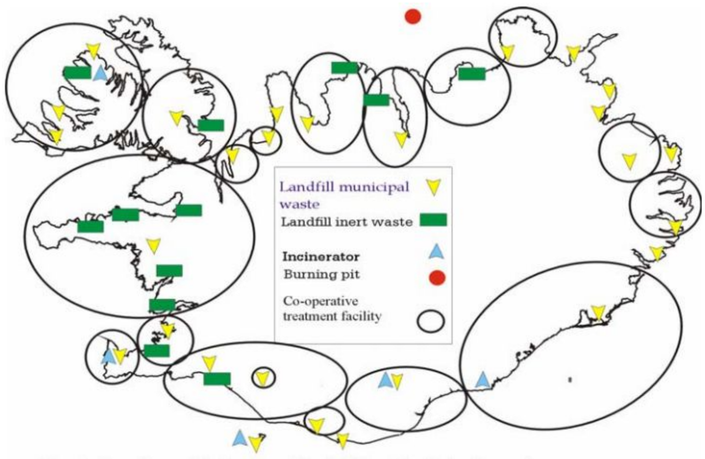

Figure 6 - Waste treatment in Iceland 2005 (Umhverfisstofnun, 2006)

The approval of the law 55/2003 on waste management lead the Icelandic environmental agency to develop the first national strategy on such matters, which was published in 2004 and had a 12 years validity until 2016. The plan was aimed at reducing the generation of waste systematically, increase recycling and reuse and decreasing the share of waste for disposal. A summary of the objectives and measures regarding organic waste are described as follows, in chronological order (Umhverfisstofnun, 2013):

- July 2013: Organic waste disposal in landfills must be maximum 50% of the total amount of organic waste produced in 1995, a maximum of 120.000 tons
- December 2015: Proportion of total landfill waste must be maximum 25%
- January 2016: Additional landfill tax, with the revenues used to promote innovative methods to manage waste
- July 2020: Organic waste to landfill must be maximum 35% of the total amount of organic waste produced in 1995, a maximum of 84.000 tons
- January 2021: Ban on landfill of organic waste

Moreover, the national plan also contemplated the constitution of regional programs on waste management, which would be developed by the local authorities of the different municipalities. These programs would aim at achieving the goals set by the national plan and elaborate specific strategies within the municipal layer. Most of the local authorities made efforts to carry out joint waste management plans for their particular area or region, adapting such strategies to their own reality, which benefits from higher efficiency and governance. Such strategies were focus on the increment of recovery and recycling of waste and the incentivisation of green energy production from waste (Umhverfisstofnun, 2013).

A number of Icelandic municipalities carried out policies for sustainable development within the local layer, including waste management, under the banner of the Agenda 21 agreement. The long term vision on waste generation prevention along with the reduction of the burden on the environment are of vital importance in such context (Umhverfisstofnun, 2013).

4.2. Heavy transport sector

Present situation of heavy transport

Fishing vessels are the heavy transport vehicles addressed by this report, which main focus will be set on them. The transport sector, including the heavy transport, is the major fossil fuel consumer in the Icelandic energy system (Environment Agency of Iceland, 2017). The industry of Iceland relies heavily on such vehicles for the transport of goods and the fishing sector, which represents a significant part of the Icelandic economy.

Most of the vehicle grid is expected to get electrified in the near future, as Iceland is transitioning away from fossil fuels towards a 100% renewable energy system, including the transport sector. The great electric production capacity installed in Iceland, based on renewable sources such as geothermal and hydropower, imply that the country could withstand the demand of power for an eventual EV national grid. Therefore, electricity represents the most sustainable option to supply road transportation due to its low cost, higher efficiency from generation to final use and its renewable source.

However, heavy transport is not likely to go through the same pathway. The dimensions and requirements of fishing vessels, for instance, demand for a large autonomy due to long periods out on the sea, demands that current technology involving batteries and electric engines cannot meet.

Alternative fuels could meet heavy transport dimensions and comply with the sustainable goals fixed by the Icelandic government, since alternative fuels represent sustainable gains to fossil fuels, especially if they are produced from waste. Moreover, alternative fuels can be locally produced, enhancing energy provision and security (Ministry of the Environment, 2007).

The consumption of oil from 1978 to 2015 from the fishing vessels is represented in figure 7. It can be observed that the oil consumption trend is decreasing since peaking in 1996, from over 250 thousand tons of oil per year to 150 thousand. Such decrease can be explained due to the improved fishing techniques using radar technology, which enables the vessels to fish more efficiency over time. Another main reason is the use of bigger fishing vessels, which can carry out the performance of several smaller ones (Orkustofnun, 2016). The fishing vessels operating in East Iceland represent the 22% of the total consumption, accounting for 1.373 tons of oil equivalent (Helgason, 2016).

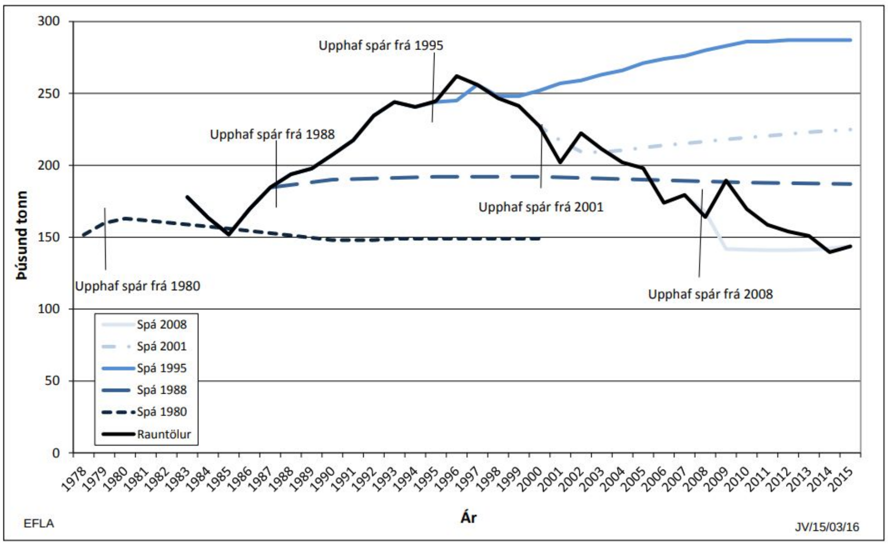

Figure 7 - Fuel consumption from fisheries in thousands of tons (Orkustofnun, 2016).

<u>GHG emissions from the heavy transport</u>

Figure 8 presents the greenhouse emissions from the energy sector in Iceland in 2015, which also includes the transport sector. As it can be appreciated in the figure, road transportation and fishing represent up to 77% of the total emissions of the energy sector. The emissions from the transport sector have increased by 43% since 1990 levels to 2015, mostly through the increase of road transport. The fishing sector experienced an emission reduction of 31% for the same year range. Road transport and fishing account for around 1200 kilotons of CO_2 equivalent per year (Environment Agency of Iceland, 2017).

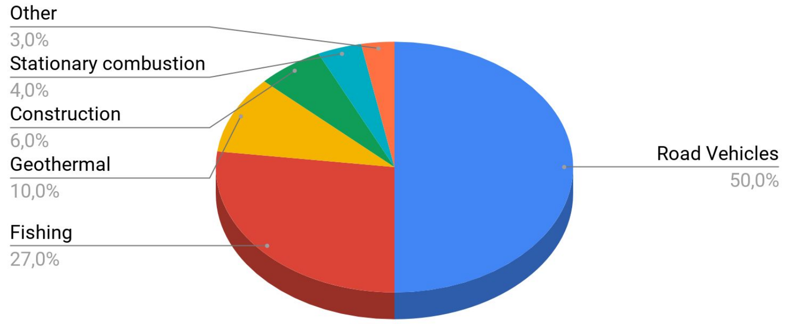

Figure 8 - Emissions by source from the energy sector (Environment Agency of Iceland, 2017)

Energy national policies

Iceland ratified in 1993 the United Nations Framework Convention on Climate Change (UNFCCC) and started carrying out national anthropogenic emissions by sectors reports since 1994, as a requirement within the Convention of Parties, along with implementing sustainable energy strategies based on UNFCCC commitments. In 2002 Iceland ratified the Kyoto Protocol, which made commitments on fixing legally binding targets for greenhouse emissions reduction for the member parties (Environment Agency of Iceland, 2017).

Some of the obligations under the Kyoto Protocol were to compromise to not increase more than 10% the greenhouse emissions regarding 1990 levels, during the first period of the protocol from 2008 to 2012. For the second period, the parties had to commit to reduce 20% of the emissions regarding 1990 levels from 2013 to 2020.

In 2007 Iceland adopted the Iceland's Climate Change Strategy, which set goals for reducing the greenhouse gas emissions by 50-75% by 2050 regarding 1990 levels. This plan also aimed at increasing carbon sequestration from the atmosphere, implement carbon taxing and trading, increment afforestation and revegetation and incentivize the production of alternative fuels, especially from biomass resources. The law No. 70/2012 on climate change passed in 2012 pushed the creation of the Climate Change Act, which aimed at the following objectives (Environment Agency of Iceland, 2017):

- Reduce greenhouse gas emissions in an efficient and effective way,
- Increase carbon sequestration from the atmosphere,
- Promote mitigation measures to climate change consequences, and

- Create conditions for the Icelandic government to fulfil the international obligations regarding climate change

4.3. Methane fuel in Iceland

There are basically two options for utilisation of biogas; the first one being its direct use for power and heating purposes, and the second one being its use as fuel followed by upgrading techniques to fuel quality methane. The first option is extended and the technology mastered, whereas the second option regarding biogas upgrading to methane fuel is more advanced and defines a new industrial scenario. Due to the characteristics of the Icelandic energy system, which runs mostly on renewable energy and accounts for low emissions, neither biogas or methane are considered to be used for power and heat production purposes. However, sound applications for biogas and methane in Iceland include the production of fuel for transport.

Sorpa has been producing methane fuel from biogas at the landfill in Álfsnes since the year 2000, being the only place in Iceland where methane fuel is produced. The composition of the biogas is monitored in real time when collected for the purification stage, which generally being about 53-55% methane, 41-43% carbon dioxide and other trace substances such as nitrogen and hydrogen sulfide. The biogas collected is upgraded to methane via scrubber water technology, resulting in a product of high quality with up to 98% methane purity (Sorpa, 2013).

Methane fuel is produced at a rate about 300 Nm^3 per hour, which is transported through a pipe 10 km long and pressurised at 10 bar to the N1 gas station in Bíldshöfða. Another gas station in Tinhellu has pressurised tanks at 250 bar and a capacity of 2000 Nm^3 of methane fuel, format which other fuel suppliers are studying to implement as well. Currently Sorpa produces methane fuel for approximately 2.500 private cars, which corresponds to 3 million liters of gasoline per year (Hafliðason, 2013).

However, current methane fuel production accounts for only 3% of the total fuel consumption of the transport sector in Iceland. Álfsnes facility aims at improving production efficiency to reach 700 m^3 of methane fuel per hour, in order to increase the share of methane fuel into the vehicle fuel grid. Iceland has set objectives on green energy production, and Sorpa’s methane production could represent up to 60-70% of Iceland’s objectives for green energy (Sorpa, 2013). Methane Energy, Sorpa’s subsidiary, is carrying out studies on the exploration of other possibilities for methane production in the country, focusing especially on the great potential of using organic waste from agriculture. One of this studies suggests the potential production of 1 million Nm^3 of methane from pig manure in Melasveit (Methane Energy Ltd, 2012).

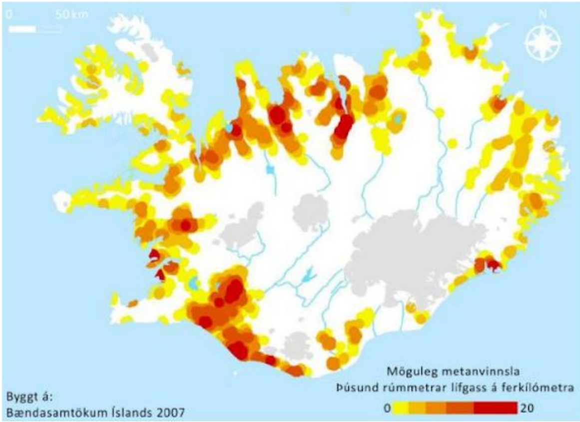

Figure 9 -. Potential methane production in Iceland (Hafliðason, 2013)

There is no current market for methane fuel in the east of Iceland, since all its production is focused in the Reykjavík area. However, the potential for methane production in the east is significant, accounting for large amounts of raw material in form of manure and other types of feedstock.

Taking into account the context of Hérað, biogas plants carrying out co-digestion of different feedstock resources are a sound idea for methane fuel production, while located close to the several biomass sources available. In agricultural communities such as Hérað, livestock waste is usually the dominating resource which is produced in the many neighboring farms in the form of manure or expired hay. Other waste available in the area which is suitable for methane production are plant residues, waste from meat or fish processing plants, household waste and sludge. The location of the co-digestion plants is of great importance to minimise the distances for transporting the required raw materials.

As seen in the figure 9, there are few areas in Iceland which have the density required to collect sufficient biomass from agriculture, cultivation and municipalities. Hérað represents over 40% of the total organic waste generation in the East, mostly due to its significant number of livestock (Matvælastofnun, 2011). Therefore, Hérað has the required density of biomass to produce methane via co-digestion plants.

Relevance to this report

The aim of this report is to study and check on the applicability of the potential production of methane fuel via anaerobic digestion of organic waste in Hérað, as a sustainable process to simultaneously provide renewable energy and treatment of organic waste. Therefore, this report intends to address waste management and sustainable energy issues in Iceland.

As explained previously, on the one hand the national waste management plan aims at abolishing landfill sites by 2021, leaving just a few years for Iceland to find an alternative way to manage about 31% of the waste that currently goes to landfills. On the other hand, Austurland energy transition is seeking for alternative fuels to transition away from fossil fuel consumption in the heavy transport sector. By using the organic waste currently being landfilled for the production of methane fuel, both problematic scenarios are addressed and a common solution is set with the following outcomes; an alternative method for managing waste in a sustainable way and a renewable green fuel for supplying the heavy transport sector.

To sum up, methane fuel production from organic waste is a sound option to manage organic waste in agricultural communities such as Hérað. The benefits of methane fuel production from waste are (Umhverfisstofnun, 2013):

- Reduction of emissions
- Production of renewable energy
- Eco-friendly recycling of organic waste
- Increased fertilizer value
- Reduction of odor
- Increased process optimization for farmers

5. Background on the methane fuel production process

In this chapter the several aspects involved in the methane fuel production process will be addressed. The scope of this report is to approach these concepts in an intentional broad way, in order to describe them in a comprehensive way the main aspects of anaerobic digestion of organic waste for methane fuel production. This will provide a solid understanding basis of the overall process, before jumping into the design of the biogas plant and the assessment of the linked energy and mass flows.

Several concepts to be taken into account will be described, such as feedstocks and substrates, pretreatment, anaerobic digestion, biogas upgrading and byproducts. The subquestion B **"How is methane fuel produced in a biogas plant?"** will be addressed in this chapter.

5.1. Feedstock and substrate

The medium from where the microorganisms involved in the biogas production process get their 'food' from is called substrate, which content several different elements: energy sources, electron acceptors, building blocks for cell crafting, along with vitamins and trace elements. The substrate is composed by different types of organic material, which contain all the necessary elements for the microorganisms to carry out metabolism and anabolism activities (Schnürer, A. & Jarvis, Å, 2010).

It is important to distinguish between the terms 'substrate' and 'feedstock', since in the coming chapters both will be addressed. On the one hand, the substrate is the medium the microorganisms use to grow, which can be proteins, fats and cellulose, among others. On the other hand, the feedstock is the material used as a resource in the biogas plants, being the material that is actually feed into the reactor. Some common feedstocks are organic waste, sludge and crops.

Commonly used feedstocks in biogas plants are organic waste products, such as sewage and the organic fraction of MSW, along with other residues such as manure from farm animals. Moreover, crops can also be used as feedstock for biogas production as well as lignocellulosic wood. Some types of feedstocks require special pretreatments in order to be used in the biogas plant, which will be explained in the next chapters.

The higher the variety of the organic material fed into the reactor the better, since more components are available for microbial growth. This translates to a higher diversity of microorganisms present in the process, which has positive effects. However, the composition of the feedstock should not vary too frequently over time since many microorganisms which are present on the biogas production process are specialist and function better on a specific substrate (Schnürer, A. & Jarvis, Å, 2010).

5.2. Pretreatment

It is common for the feedstock used in a biogas plant to go through pretreatment and sanitation stages. The main reasons for pretreatment of feedstock are (Mata-Álvarez et al., 2000; Tsao, 1987):

- Destroy potential pathogens
- Concentrate the organic material content
- Increase solubility

According to the EU Regulation EC 1069/2009 on animal by-products, pasteurization of some types of feedstock from animal and human origin which is intended to be used in a biogas plant is mandatory. Such feedstocks are the ones defined in the Category 3 of the regulation, like sewage sludge and the organic fraction of municipal solid waste. The pasteurization process consists on heating up the feedstock to 70ºC during 1 hour, in order to kill the potential pathogens present in the feedstock and sanitise it (European Commission, 2009).

Other pretreatment methods have more to do with operational technical aspects, such as increasing the solubility of the feedstock by reducing the size of its particles to facilitate pumping. The most common methods are mechanical, using mills, blenders and screws, among others. Moreover, the biogas yield of the feedstock also increases due to the reduction of the volumetric load on the digester, since the freedup volume can be used for more feedstock (Schnürer, A. & Jarvis, Å, 2010).

5.3. Anaerobic digestion

The biogas production process has four key stages. The first step is hydrolysis, where the microorganisms break down the complex organic compounds into simpler compounds, like sugar and amino acids. Afterwards, fermentation occurs where intermediate products such as alcohols, fatty acids and hydrogen are formed, followed by anaerobic oxidation. Lastly, methane is formed in the methanation step by a very specific group of microorganisms which require certain environmental aspects to function. These three main steps will be covered extendenly in the next paragraphs, and can be summed up in figure 10 (Schnürer, A. & Jarvis, Å, 2010). Before jumping to the description of the anaerobic digestion stages, the environmental factors which affect the process will be addressed.

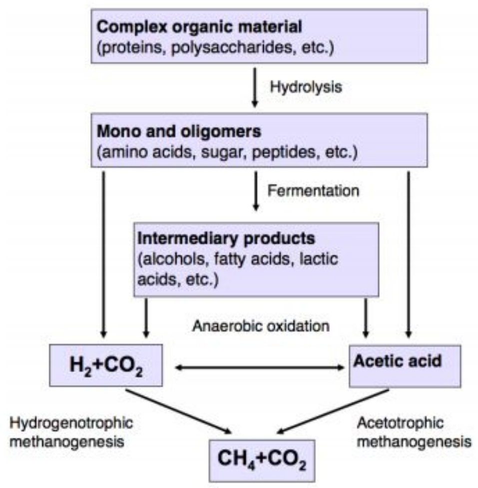

Figure 10 - Diagram of the anaerobic digestion process (Schnürer, A. & Jarvis, Å, 2010)

5.4. Environmental factors which affect the process

Microorganisms need very specific environmental conditions in order to develop and grow optimally. Due to the high variety of microorganisms in the methane production process, meeting the requirements for all of them is rather complex, so the reactor environment should tend to satisfy the needs for as many organisms as possible. The result would not be a perfect environment for each microorganism, but it would allow many to grow in an optimal way (Schnürer, A. & Jarvis, Å, 2010).

The most important environmental factors which affect the anaerobic digestion process are temperature, oxygen content, pH and salts (Apples et al., 2008). These aspects will be addressed in the coming paragraphs:

Temperature

Temperature affects the growth rate and metabolism of the present microorganisms in the reactor. The optimal temperature may vary for the different microorganism groups, since each species works best within a different range of temperature. Microorganisms can be divided into four categories regarding their optimal functional temperature: psychrophilic (4ºC), mesophilic (39ºC), thermophilic (60ºC) and extremophilic (>60ºC) (Noha & Wiegel, 2008).
The biogas process normally operates at a mesophilic temperature, around 30-40ºC or at thermophilic conditions around 50-60ºC (Nordberg, 2006). High temperatures have positive effects on the process, including the increment on the organic compounds solubility and a faster chemical and biological

reaction rate. Thermophilic conditions achieve higher biogas yields and pathogens elimination, but they are also more sensitive to changes in the environment (Kim et al. 2006).

Oxygen

The presence of oxygen has diverse effects on the different microorganisms groups present in the biogas process. For instance, methane producers cannot tolerate oxygen, therefore dying if they come in contact with it. However, there are some types of microorganisms that can indeed tolerate the presence of such gas. Depending on the relationship microorganisms have with oxygen, these can be divided into groups that go from strictly aerobic to strictly anaerobic (Schnürer, A. & Jarvis, Å, 2010).

pH: Acidity & alkalinity

The pH requirements for the different microorganisms present in the biogas process vary significantly. The ones which carry out fermentation work optimally at pH 5.0, while most of the methane producers require a neutral pH, around 7.0-7.5 (Whitman et al., 2006). However, there are cases of acidophilic methane producers which can grow at an acid pH around 4.7 (Bräuer et al., 2006) and others which grow up to alkaline conditions to 10.0 pH (Mathrani et al., 1988). Variations in the pH level can be critical for the overall process, since it is rather difficult to correct them and may lead to inhibition and even cell death for the methane producers, which would slow down the consumption of hydrogen and eventually stop the process (Schnürer, A. & Jarvis, Å, 2010).

Salts

Salts are present in the feedstock used for biogas production, which contain substances such as sodium, potassium and chlorine. These are essential components for the proper development of the microorganisms, since they act as building blocks. Nevertheless, too much salt concentration might lead to inhibition of certain microorganisms, such as the methane producers, which are the most sensitive to high levels of salt in the biogas process (Schnürer, A. & Jarvis, Å, 2010).

5.4.1. Hydrolysis

Hydrolysis represents the first stage of the biogas process, where the organic compounds in the feedstock are broken down into simpler compounds. This fact is crucial since otherwise the molecules of the feedstock would be too large to be used by the microorganisms.

The biodegradation of molecules is accomplished by enzymes secreted by certain groups of microorganisms, known as extracellular enzymes, which tear apart large molecules into smaller compounds. These smaller molecules are used by the other microorganisms as a source of energy, which they use for their own development and growth (Schnürer, A. & Jarvis, Å, 2010).

5.4.2. Fermentation

Fermentation is the second stage of the biogas process, where the resulting products from the biodegradation of large molecules carried out during hydrolysis are used as substrate by some groups of microorganisms. During fermentation the number of active microorganisms is the highest for the whole biogas process (Schnürer, A. & Jarvis, Å, 2010).

The products used by the fermenting organisms are carbon and energy sources such as sugars, amino acids and alcohols. These are converted into organic acids, ammonia, carbon dioxide, hydrogen and alcohols through several fermentation reactions. The exact amount of reactions depends on the type of substrate and the microorganisms present.
Fermentation reactions are complex, since even microorganisms within the same species can produce different outcomes from reacting the same molecular compound, due to changes within its fermentation pattern which is susceptible on the characteristics of the environment. Products of fermentation process are used during the next stages of the biogas process, and can also be used by other fermenting microorganisms (Schnürer, A. & Jarvis, Å, 2010).

5.4.3. Anaerobic oxidation

The products resulting from the fermentation process are broken down by anaerobic oxidation reactions in this stage. The coordination between microorganisms which carry out oxidation in this step and methanation in the next one is of major importance for the biogas production to be successful.

The critical link between these two types of microorganisms has much to do with hydrogen gas; organisms carrying out anaerobic oxidation produce hydrogen, and due to thermodynamic reasons these organisms can only function and keep forming hydrogen if the concentration of such gas is kept at a significant low level. Therefore, the hydrogen produced has to be constantly removed, and this is where methanation microorganisms play a big role since they consume hydrogen to produce methane. If hydrogen is not removed and its concentration increases, the process will then stop (Schnürer, A. & Jarvis, Å, 2010).

5.4.4. Methanation

This is the last step of the biogas production process, where methane and carbon dioxide are formed by microorganisms known as methanogens. The main substrates used by these microorganisms are hydrogen gas, carbon dioxide and acetate, which are produced in the previous step of anaerobic oxidation. It is important to note that, just like in all the previous processes, there are many different types of microorganisms active through the methanation step (Schnürer, A. & Jarvis, Å, 2010).

Since methane producers grow rather slowly, their growth rate becomes a limiting factor when it comes to the velocity the biogas production process carries out on. The slow growth of methanogens also affects the retention time in a continuous biogas process, where these set the limit for how short the retention time may be. There is a risk of washing out the methanogen organisms if the retention time is too short. This fact means that these organisms would not have enough time to grow at the same rate as the content is taken out of the reactor. This fact will be further explained in the coming chapters (Schnürer, A. & Jarvis, Å, 2010).

Methane producers organisms are not common bacteria, since they are part of the group Archaea which differs from the other microorganisms present in the process which are either bacteria or fungi. Archaea organisms are not as robust as other organisms in the biogas process, and they are very sensitive to pH changes and the presence of certain toxic compounds such as heavy metals. The fragility of methanogens has to be taken into account, since these are one of the most important microorganisms in the whole process and their inhibition or malfunction could lead to shutting down the whole biogas process (Schnürer, A. & Jarvis, Å, 2010).

5.5. Biogas upgrading

As explained in previous chapters, the biogas produced in the anaerobic digestion has a composition of around 55-70% methane, 30-50% carbon dioxide and traces of nitrogen, vapour water, oxygen, hydrogen sulfide and ammonia, depending on the feedstock used. It is important to note that the energy content of biogas relies mostly on the methane, so the other substances in the biogas are considered impurities that reduce its quality as a fuel. Therefore, the higher the CO_2 or N_2 levels, the lower the energy content of the biogas (Angelidaki, I. et al., 2018).

Methane fuel is subjected to quality specifications if it is intended to be used as a fuel, such as the EU regulation on methane from biomass which composition is required to be around 95% CH_4. In order to achieve such values, the biogas has to go through upgrading processes which remove the impurities present in the gas. There are several techniques to do so, involving both physical and chemical procedures. The most successful method is the water scrubber, which account for around 41% of the biogas upgrading market (Toledo-Cervantes, A. et al., 2017). This system uses water to remove CO_2 and H_2S from the biogas using their higher solubility in water in comparison to methane (Angelidaki, I. et al., 2018).

5.6. Byproducts: Digestate

The main byproduct of the methane fuel production process via anaerobic digestion of organic waste is digestate, which could be referred as the degraded organic material left after the process is carried out. If the digestion is done using feedstock from manure, organic fraction of MSW and plant residues, the digestate can be used for fertilization purposes in food production (Schnürer, A. & Jarvis, Å, 2010).

Digestate can give similar or even better results than mineral fertilizers on crop yields (Avfall Sverige, 2005; Odlare 2005; Baky et al, 2006; Johansson, 2008), and it also has beneficial effects on the chemical status of the soil (Odlare et al., 2008). The solids content of the digestate is similar to slurry manure, meaning that the same techniques can be carried out to spread it on the crop fields. The content of digestate consists mainly of nitrogen, phosphorus, potassium and magnesium, which are present in an available form for the plants. Several trace elements beneficial for plants are also found in the digestate. Moreover, farmers using digestate for fertilizing their crops are mostly reporting positive feedback, since according to them the digestate provides better nitrogen efficiency and has better characteristics regarding odour, pathogens and spreadability than slurry manure (Avfall Sverige, 2005).

In the following table the properties of different digestates are compared to cattle manure fertilizer. The values presented in the table 1 are the total content of dry solids, nitrogen, ammonia, phosphorus and potassium for each fertilizer (Avfall Sverige, 2005).

Table 1 - Nutrient values for digestates and cattle manure. Digestate 1 included substrates: manure 10%, slaughterhouse waste 75%, waste from food industry 5%. Digestate 2 included substrates: household and restaurant source-separated waste. Digestate 3 included substrates: manure 61%, 17% abattoir waste, food waste 2%, fat 11%, waste from food industry 9%. Digestate average of seven certified biogas plants in 2005 e plant nutrient content of individual samples may vary 17-35% (Avfall Sverige, 2005: Baky et al., 2006).

	DS Content %	**N (kg/m³)**	**NH_4 (kg/m³)**	**P (kg/m³)**	**K (kg/m³)**
Digestate 1	5,0	7,1	5,3	0,80	1,0
Digestate 2	1,6	3,6	2,6	0,20	1,1
Digestate 3	4,8	5,7	4,3	0,38	2,0
Digestate (avg)	3,8	4,5	3,2	0,40	1,2
Cattle manure	9,8	3,9	1,8	0,80	4,0

6. Technology of the anaerobic digestion process

The production of biogas occurs naturally in the environment, where microorganisms decompose organic matter in habitats such as wetlands, swamps and the stomachs of ruminants. It can be stated that the rumen of cows happen to be a natural biogas reactor, since all the necessary microorganisms for methane production are found there. In order to replicate such environment, technology is used to shape the working environment of microorganisms and achieve a functional and stable process with high methane production (Schnürer, A. & Jarvis, Å, 2010).

The role of technology on carrying out an artificial environment for anaerobic digestion to take place will be explained in this chapter. First, the main operating parameters of an anaerobic digestion plant will be described, following by the different process designs and finally the reactor addressed in this report will be presented. In this chapter, the sub-question C **"What technology is involved in the anaerobic digestion process?"** will be addressed.

6.1. Operating parameters of an biogas plant

In this chapter the main operating parameters to take into account when operating an anaerobic digestion plant will be addressed. These parameters are the digester temperature, the organic loading rate and the retention time.

6.1.1. Digester temperature

High temperatures have positive effects on the process, including the increment on the organic compounds solubility and a faster chemical and biological reaction rate. Thermophilic conditions achieve higher biogas yields and pathogens elimination, but they are also more sensitive to changes in the environment (Kim et al. 2006).

Methane-producers are sensitive to temperature fluctuations, so once the digestion process has started, the temperature should be kept constant and avoid variations of more than half degree celsius for optimal results. Mixing the organic content in the reactor is a common method used to maintain a stable temperature.

Mesophilic digestion

The range for mesophilic digestion is around 25-40ºC, even though the biogas production will only function if the temperature does not drop below 32ºC (Gerardi, 2003).

The most optimal temperature range for methane producers, which are the organisms which grow the slowest, lies between 35-37ºC. If the temperature drops below this range, methane producers will slow down considerably while fermentative microorganisms which are not as sensitive to temperature fluctuations would keep on their activity, producing fatty acids and alcohols. This would lead to an accumulation of fermentation products which would not be digested by methane producers, which would cause a drop on the pH and the process would therefore stop (Schnürer, A. & Jarvis, Å, 2010).

Thermophilic digestion

The thermophilic range for biogas production is around 50-60ºC, and the optimal work temperature lies between 50-55ºC. At this temperatures most of the mesophilic microorganisms inactivate or die. However, this extra heat makes the thermophilic microorganisms to be up to 25-50% more active than in mesophilic digestion, even though only around of the 10% of the microbial flora present in a mesophilic process can survive thermophilic conditions.

Advantages and disadvantages of the temperature range

Both ranges of temperature have advantages and disadvantages. For the thermophilic range, the process is faster and more methane can be produced due to the higher temperature. High temperatures tend to increase the solubility of the organic compounds, which lowers its viscosity and facilitates mixing. Moreover, high temperatures provide sanitation of the material, and pathogens are destroyed.

However, the need for heat increases energy demand, and also creates the need for cooling down the feedstock. Thermophilic process are more sensitive to temperature variations, since the microorganisms work at the maximum temperature where other microorganisms become inactivated. Toxic components such as ammonia are also produced faster, so the risk for inhibition of the whole process may increase as well. Higher temperature means more difficulties into stabilise the process, also because there are fewer microorganisms varieties compared to mesophilic process. The greater the diversity the greater the stability (Schnürer, A. & Jarvis, Å, 2010).

6.1.2. Organic loading rate

Loading makes reference to the amount of new material which is added to the biogas production process per unit of time (Schnürer, A. & Jarvis, Å, 2010). Since the process keeps on consuming material through continuous biodegradation, new material has to be added eventually in order to keep the process ongoing. Therefore, the biological conversion capacity of the process determines the sustainable loading rate, which is of great importance in continuous processes. Feeding the process above its sustainable loading rate would lead to inhibition and collapse of the process (Monnet, 2003).

Important concepts to be taken into account for loading are the dry solids (DS) and the organic matter or volatile solids (VS) content present in the substrate, since these will determine the right loading rate value. These values give a measure of the potential biogas yield and the pumping viability of the material fed into the anaerobic digestion reactor.

When a process is to be started, it is common to use a low loading rate just for the beginning and slowly increase the rate up to the desired level. Anaerobic microorganisms grow slowly, so the loading rate has to adapt to their rhythm. It can take several months to achieve the loading rate desired. If there is too much substrate at the beginning, there are simply not enough microorganisms to digest the new material. This fact leads to an accumulation of fatty acids, which results into an acidification of the material and eventually the process stops (Schnürer, A. & Jarvis, Å, 2010).

Once the process runs on the desired loading rate, it is important to keep it as constant as possible for the whole process both in the composition and the incoming rate. Microorganisms adapt the substrate, so it is important not to vary it much. Normal loading rates for thermophilic processes are 4-5 kg VS/m^3 digestion tank per day, and 2-3 kg VS/m^3 digestion tank per day for mesophilic processes. If the substrate has to be changed, it is important to do it in a gradual way in order to let the microorganisms adapt to the new conditions (Jørgensen, P., 2009).

6.1.3. Retention time

The retention time refers to the time it takes for all the material in the reactor to get eventually replaced. Due to the biodegradation of the material carried out by the microorganisms in the biogas production process, the solid hydrocarbons present in the substrate get converted to methane and carbon dioxide. Therefore, the amount of solid material gets reduced over time. New material is being added in order to keep the process constant, which will also be converted into gas. However, the amount of new material added is usually bigger than the amount of solid material removed, so it is common to remove some content from the digestion tank regularly to keep a constant volume within the digestion tank (Schnürer, A. & Jarvis, Å, 2010).

The duration of the retention time varies depending on the substrate, the digestion temperature and the process type (Monnet, 2003). Feedstocks which are hard to break down, such as crops, will take more time to be digested by the microorganisms in the hydrolysis stage. On the other hand, soluble organic matter is easily broken down so the hydrolysis would happen quickly or would not even be necessary.

In the literature retention time is also referred as hydraulic retention time (HRT) or solids retention time (SRT), which are usually the same in most cases. However, if part of the removed material from the digestion tank is recirculated to the process, SRT becomes then longer than HRT (Schnürer, A. & Jarvis, Å, 2010).

The common values for HRT are 15-30 days for mesophilic process and 12-14 days for thermophilic process (Monnet, 2003). Longer HRT can achieve higher biogas yields, but it also increases the energy demand for mixing and heating, which consequently increases the costs. However, shorter HRT values lead to overloading the process and reduce the biogas yield, since the degradation rate is not optimal (Latvala, 2009).

6.2. Process design

Biogas production takes place in a tank without oxygen, since methane producers microorganisms are anaerobic - they do not function with the presence of oxygen. However, a small leak of oxygen within the tank would not stop the process, since there are some facultative microorganisms not related to direct methane production which do tolerate oxygen. Nevertheless, the presence of oxygen would increase the growth of such microorganisms, which would consume substrate organic matter for no methane production purposes. Therefore, the efficiency of the overall process decreases, since a smaller portion of the organic matter is converted to methane (Schnürer, A. & Jarvis, Å, 2010).

Some feedstocks used in the digestion tank have to be treated previously, process which differs depending on the type of material. For instance, energy crops substrates require a pre-treatment step to increase its digestibility, due to the presence of lignin which is a compound hard to break down for the microorganisms. Substrates from animal origin such as food waste, sewage sludge and slaughterhouse waste need to go through a sanitation stage where the substrate is heated up to 70ºC for over an hour (Schnürer, A. & Jarvis, Å, 2010).

6.2.1. One-step & two-step design

The overall biogas production process may be designed in different ways, depending on the substrate and the digester steps. The biogas produced is collected from the top of the digestion tank, while the substrate is pumped in. The digested material is removed through pumps for its recirculation into the process or its storage for fertilisation purposes.

The simplest process design is the one-step digester, where all microbial decomposition activity takes place simultaneously in a single reactor. Therefore, all the stages happen at the same place at the same time: hydrolysis, fermentation, anaerobic oxidation and methanation. The most common reactor design for one-step digestion of sludge, food waste or manure is the Continuously Stirred Tank Reactor or CSTR, where the substrate is mixed continuously.

On the other hand, the two-step digester is a valid alternative which the complete microbial activity takes place in two reactors. In the first reactor hydrolysis and fermentation are carried out, where little methane is produced. This first part focuses mostly on acid formation. On the second step, the residue from the first reactor is fed to the second digester tank, specially designed for methanogenesis, where anaerobic oxidation and methanation take place (Swedish, J. et al., 2008). The two-step design is useful for substrates which are significantly easy to decompose, so the hydrolysis stage occurs quickly. Dividing these two steps translates into a higher efficiency and methane production (Schnürer, A. & Jarvis, Å, 2010).

6.2.2. Continuous or batch digestion

The substrate can be added continuously or in batches, depending on the material being used (Nyns, 1986; Sakar et al., 2009) . For instance, sewage feedstock with a dry solids content of less than 5% can be pumped into the digester tank continuously adding a constant inflow of new material through time. Feeds with a higher concentration of dry solids around 5-15% such as manure and sludge can also be fed continuously to a lower extend, through a process known as semi-continuous digestion. On the other hand, solid feedstocks with a dry solid content of 20-25% such as energy crops or food waste are usually fed into the reactor through batches, less frequently and in larger portions (Schnürer, A. & Jarvis, Å, 2010).

On the one hand, batch digestion involves all the material being digested at once in the same reactor through the entire process. Therefore, no new material is added nor residues from the digestion are removed during the process. Once the content in the digestion tank has been digested, the whole tank is emptied and a new batch is fed to the reactor. Methane production peaks in the beginning of the process, decreasing over time. Digestion by batches prevents washing out microorganisms, which is an advantage in comparison to continuous digestion. However, it may be difficult to get a high and consistent digestion rate (Kreuger and Björnsson, 2006; Nordberg & Nordberg, 2007).

On the other hand, continuous digestion may be more practical in operational terms than batch digestion since substrate is continuously fed into the reactor. That removes the necessity to empty the reactor every now and then and stopping the process several times. Continuous digestion is also advantageous for the microorganisms since they get a more uniform supply of the substrate, which favors its functionality and reduces risks of overloading the digestion tank (Schnürer, A. & Jarvis, Å, 2010).

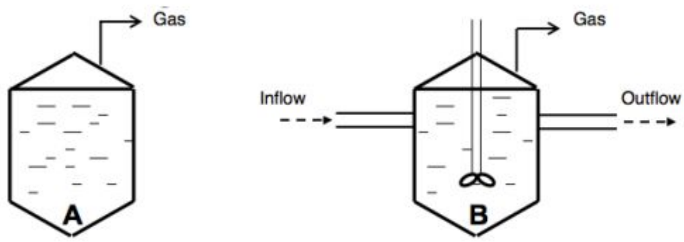

Figure 11 - Batch (A) and continuous digestion (B) (Nyns, 1986)

6.2.3. Dry and wet digestion

The most common way to break down organic matter to produce biogas is wet digestion, which consists on diluting the material with liquid so it achieves a low content of dry solids around 2-15%, making its transportation by pumping possible. An alternative to this process would be dry digestion, which focuses on high dry solids content feedstocks such as solid waste, manure and crops (Nordberg & Nordberg, 2007). During dry digestion, there is no need to add liquid to the feedstock since the digestion is adjusted for high dry solids content, which could be over 20-35%. Moreover, it is crucial to have the right microorganisms in the feedstock in order to achieve a good degree of decomposition.

Dry digestion presents several advantages in regards to wet digestion, being the low consumption of water due to the lack of necessity to water down the feedstock one of the most significant ones. The reduction of water content in the material also avoids foaming related issues, and transportation and storage procedures both for feedstock and residues are more efficient. Dry digestion is more stable to disturbances as well, meaning that methane production could be reduced but the whole process would not stop necessarily. Nevertheless, it is important to keep the water content over 65% and the dry solids content maximum at 35% to keep the process from malfunctioning (Jewell, et al. 1981).

6.3. Reactor configuration: Continuous Stirred Tank Reactor

Anaerobic reactors have been around since back 1859, when the first digester was started up in India. Since then the technology involving anaerobic digestion has been developed and extended to treat organic waste, becoming more complex and efficient over time. The core principle of anaerobic digestion is the usage of microorganisms present in the treated feedstock to convert organic matter into biogas rich in methane, in an oxygen free environment.

The chosen reactor configuration for modeling the biogas plant addressed by this report is the Continuous Stirred Tank Reactor or CSTR, since this type of digester is the one that fits best to the feedstock available in Hérað. That is because the high content of dry solids present in manure, hay, garden waste and the organic fraction of municipal solid waste, which would be co-digested along with municipal sewage. Therefore, the design being presented next refers to CSTR only.

The CSTR basically consists of a digestion tank and a stirring device, which pretty much resembles to an ordinary batch reactor. The differential factor, however, is the constant influent and effluent flows in the reactor. This description can be better appreciated in the following figure of a CSTR (Mazzotti, M. 2015):

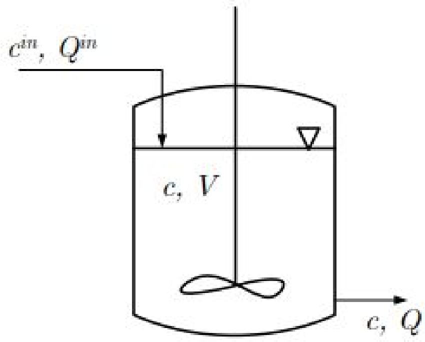

Figure 12 - Sketch of a CSTR (Mazzotti, M. 2015).

The reactor is assumed to be perfectly mixed, so the composition in every part of the tank is homogeneous. Moreover, CSTRs are assumed to run on steady-state, meaning that the continuous influent and effluent flows do not vary the composition neither the volume of the content within the tank. Therefore, there are no changes regarding the composition of the content in the tank over time, as for other parameters such as temperature, pressure and reaction rate as well. Contrary to batch reactors, CSTRs do not need to be eventually emptied and cleaned up, avoiding cooling and heating issues that this process would involve. Therefore, this fact translates to a more efficient process which the continuity aspect of the reactor enables (Mazzotti, M. 2015).

<u>Reactor design main equations</u>

The design equations which address the basic parameters in order to dimensionate a CSTR will be presented in this chapter. These refer to the calculation of total solids, volatile solids, rector volume, biogas yield, methane production, hydraulic retention time, working reactor volume and total reactor volume (Rauhala, A. 2013). These calculations will be used in coming chapters to design the biogas plant through the modeling tool used.

First, it is important to state the assumptions CSTR carries, which are the following ones:

- Reactor operates at steady-state, so there is no accumulation
- Perfectly mixed
- Homogeneous conditions

The first assumption implies that there is no accumulation, and since CSTR is a continuous process,where influent and effluent are equal over time, then (Rosen, A., 2014):

$$\textit{input - output + generation = accumulation = 0}$$

These parameters can be represented as components of the material balance in the reactor for a given substance A, with the flows being defined by the feed rate *(Q)* and the composition of the feed *(Ca)*. Therefore, the input flow would be represented such that:

$$\boldsymbol{F_{AO}}\ (mol/s) = \boldsymbol{Q}\ (m^3/s) \cdot \boldsymbol{C_{AO}}\ (mol/m^3)$$

And the output:

$$\boldsymbol{F_A}\ (mol/s) = \boldsymbol{Q}\ (m3/s) \cdot \boldsymbol{C_A}\ (mol/m^3)$$

The generation factor can be defined as the rate of reaction *(-rA)* per the system volume *(V)*. Since the reactant A is being consumed in the process, the rate of reaction must be negative. Assuming uniform system variables through the system volume, generation can be defined as (Rosen, A., 2014):

$$\boldsymbol{G_A}\ (mol/s) = \boldsymbol{rA}\ \ (mol/m^3 \cdot s)\ \boldsymbol{V}\ (m^3)$$

Then, the steady-state equation can be rewritten as:

$$\boldsymbol{F_{AO} - F_A + G_A = dN_A/dt = 0}$$

Or:

$$\boldsymbol{F_{AO} - F_A + rAV = dNA/dt = 0}$$

$$\boldsymbol{V = F_{AO} - F_A\ / -rA}$$

This equation can be stated as the main design equation for CSTR, since it is specific for this type of reactor. It can be used either for calculating the volume of the reactor or the reaction rate. Next, the equations for the calculation of important parameters which affect the biogas process design will be presented.

The total solids content (TS) and volatile solids content (VS) are basic parameters when it comes to designing the biogas plant, and they can be calculated with the following equations:

$$\text{Amount of TS (kg)} = \text{feedstock (kg)} \cdot \text{TS (\%)}$$

$$\text{Amount of VS (kg)} = \text{amount of TS (kg)} \cdot \text{VS (\% of TS)}$$

In order to calculate the biogas yield of the different feedstocks that will be used, the biogas production per reactor volume has to be calculated, as defined by the next equation:

$$\text{Biogas per reactor volume } (m^3/m^3) = \text{biogas production per day } (m^3/d) \,/\, \text{reactor volume } (m^3)$$

The methane in the biogas, which is the ultimate end-product of the process, can be as well calculated:

$$\text{Methane production } (m^3/d) = CH_4 \text{ potential } (m^3/\text{kgVS}) \cdot \text{amount of VS (kgVS/d)}$$

Another main factor to calculate is the hydraulic retention time, which is the time it takes for the content inside the digestion tank to be replaced and therefore consumed:

$$\text{HRT (d)} = \text{reactor volume } (m^3) \,/\, \text{daily feed rate } (m^3/d)$$

The volume of the reactor can be calculated with the reactor design equation previously presented, or it can also be calculated using the organic load rate and the daily feed rate of VS. Therefore, the equation used will be such that:

$$\text{Working reactor volume } (m^3) = \text{daily feed rate VS (kgVS/d)} \,/\, \text{OLR } (\text{kgVS}/m^3)$$

However, the reactor has to be designed for a bigger volume that the one calculated with the previous equation, in order to give room for possible variations on the biomass amounts and foam and gas formation in the digestion tank. This extra space represents approximately the 10-25% of the working reactor volume (Rosen, A., 2014; Rauhala, 2013).

Total reactor volume (m^3) = daily feed rate VS (kgVS/d) / OLR (kgVS /m^3/d)

7. Modeling and assumptions

The intention of this report is to model an biogas plant to address its potential feasibility regarding environmental and economic aspects, which involve diverse calculations linked to the plant design, energy and mass balances, GHG emissions and economic parameters. In order to do so, several assumptions have been taken into consideration regarding the mentioned modeling aspects. The assumptions and specific data used to carry out the modeling calculations will be explained in this chapter, in order to provide a comprehensive basis for the analysis and discussion of the results of such calculations. These assumptions will be presented in the following sections: Plant design, feedstock, energy grid, biogas use, use of digestate and production and economic analysis.

Before presenting the assumptions taken for the mentioned aspects, the system boundaries of the biogas plant will be explained. The set boundaries will determine the aspects which will be considered for the modeling scenario and the aspects which will be left out, aiming as well at providing a comprehensive approach of the aspects addressed in the following chapters.

7.1. System boundaries

In order to characterise the mass and energy balances of the biogas plant in a sound way, it is important to define system boundaries and define the production unit. Setting up 'limits' of the production system enables the determination of what flows are to be considered and what flows are to be left out of the study, concept which is informed by Industrial Ecology theory. The boundaries of the system considered by this report care defined in the figure 13 (Rauhala, 2013). There is also water consumption, but it has not been considered in the figure since it represents a flow three orders of magnitude lower than the rest.

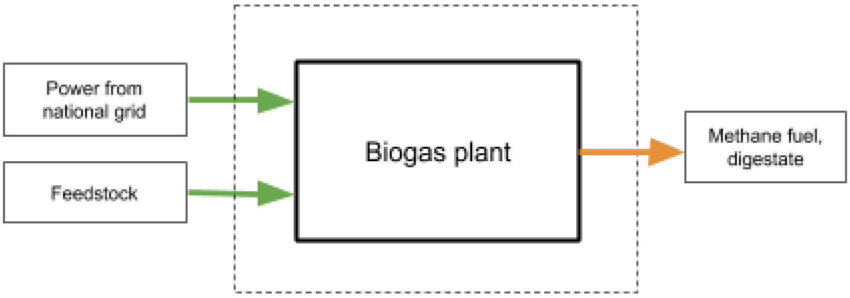

Figure 13 - Diagram representing the system boundaries of the biogas plant (Modified based on Rauhala, 2013)

Therefore, the energy and material balances that stay within the marked boundaries will be taken into account on the modeling process of the biogas plant, and balances out of the boundaries will not be considered. However, this report chose to address the potential impact of using the outcomes of the biogas plant both for methane fuel and digestate. Even though the strict use of the such products falls outside the marked boundaries, from this report's perspective it is of significant importance to address the potential economic and environmental impacts the utilization of such products might have.

7.2. Plant design

In this section, the assumptions taken regarding the strict design of the biogas plant modeled will be presented. These assumptions will address technical aspects such as the type of reactor used, operating values chosen, materials used and the very site the plant would be built on. The operational lifespan of the plant is assumed to be 30 years.

Reactor design and operating values

The reactor design chosen for the modeled scenario is a CSTR, operating in continuous one-step wet digestion conditions. As explained in the previous chapters, the CSTR is the design which fits the most to the conditions found in Hérað, specifically feedstock wise. Moreover, other reactors are more sensitive to the climate and would have some difficulties to adapt to the cold and harsh temperatures of Iceland. However, the CSTR does not have such problems, which makes it a valid option (Schnürer, A. & Jarvis, A., 2010).

The organic loading rate value considered is 3 kgSV/m^3/day, which is the recommended value for CSTR. As explained in previous chapter, higher values for the organic load rate can compromise the performance of the reactor so adjusting the OLR at 3 kgVS/m^3/day reduces the risk of technical issues (Rauhala, A., 2013). The OLR will be used as the base parameter for dimensioning the reactor capacity. Process losses are estimated to be respectively 1% and 10% for electric and heat consumption. It is also assumed that the CSTR is operated in mesophilic conditions at 37ºC. As explained in the previous chapters, the mesophilic process tends to be more stable than plants running on thermophilic temperatures, which reduces the risk of system collapse (Schnürer, A. & Jarvis, A., 2010).

The reactor will be constructed with a 10% additional capacity of the working volume and the material on which the reactor is built is concrete for all the scenarios (Rauhala, A., 2013).

Plant site and transportation

For calculations, it is assumed that the average distance between the different feedstock collecting points is 50 km for the surrounding farms and 5 km for organic MSW, garden and sewage. The transport between these points and the biogas plant is assumed to be covered by road. Apart from the methane, another end-product which will be addressed is the digestate, which can be used as a high quality fertilizer. Therefore, the digestate would be transported back to the farms from the biogas plant.

The transport of the feedstock and digestate is assumed to be done with a tractor and trailer running on fossil diesel fuel with the consumption rate shown in the table 2, taken from the standard pool data of the modeling tool. Such data will be used to calculate the total energy consumption regarding the transport of both feedstock and digestate.

Table 2 - Energy and fuel consumption for transportation (University of Southampton, 2016)

Vehicle type	**Energy consumption (MJ/ton·km)**	**Fuel consumption (L/ton·km)**
Tractor & trailer	1,91	0,053

The location of the biogas plant for the modeled scenario can be seen in the figure 14. The final site was decided upon the current system of pipelines in Egilsstaðir, being the point where the pipelines intersect the site where the biogas plant would be built on. The red circles on the map represent existing water treatment plants (Austurbrú, 2018).

The following figure shows the chosen location for the construction of the addressed anaerobic digestion plant, situated within the municipality of Egilsstaðir. The exact site is highlighted with a red spot, point where the existing pipelines system intersects.

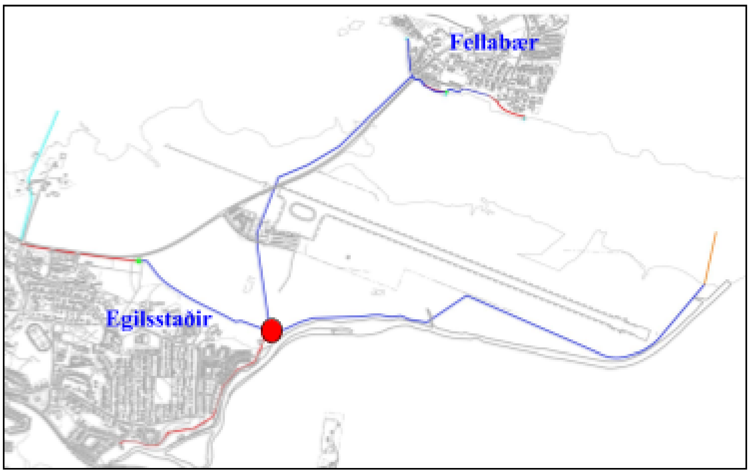

Figure 14 - Map of the construction site of the biogas plant (Austurbrú, 2018)

Process design

The following diagram represents simplification of the process design carried out in the production of methane fuel from anaerobic digestion. The intention of such diagram is to provide a comprehensive overview of the material flow of the processes which will be discussed in this report. Therefore, figure 15 intends to be a simplified explanation of the process addressed.

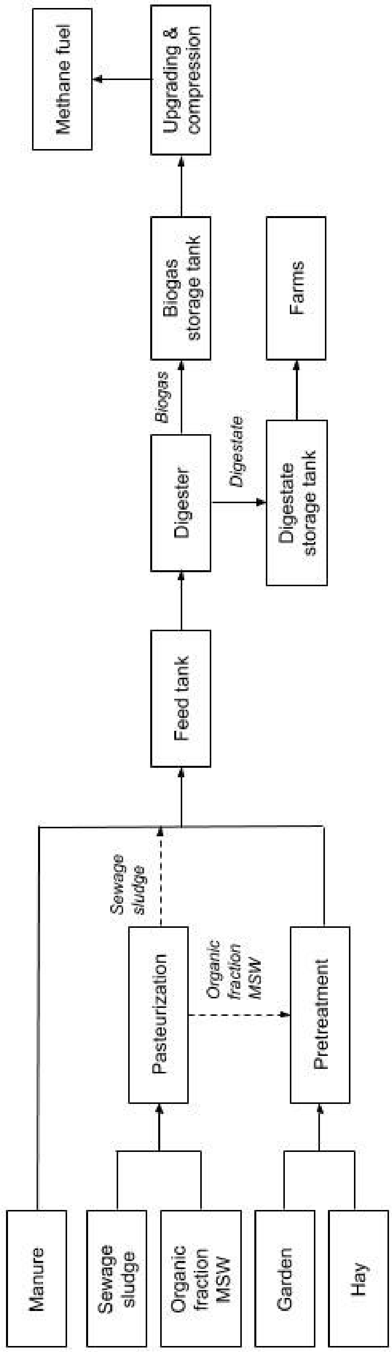

Figure 15. Diagram of the simplified process design for methane fuel production from organic waste via anaerobic digestion (Modified from Rauhala, A., 2013)

7.3. Feedstock

The feedstock used to dimensionate the biogas plant is presented in the table 3, concerning the biomass available from households, services, industries and agriculture in Hérað. The type of feedstock with more presence is manure from agriculture, accounting for over 88% of all the biomass considered. As explained in the previous chapter, the variety of the feedstock used is of crucial importance in order to guarantee a correct performance of the anaerobic digestion process, since diverse feedstocks facilitates the growth of more diverse microorganisms, enhancing the process stability (Hafliðason, Í., 2013).

Table 3 - Amounts of feedstock considered for using in the design of the biogas plant in tons per year. (Hafliðason, Í., 2013).

Households, services and industries	**Ton/year**
Organic MSW	200
Garden residues	50
Sewage	1.500
Agriculture	
Manure	39.196
Hay	2.150
Total combined	43.096

The properties of the feedstock used for biogas production are of major importance, since these define the biogas and methane yields, which are key values when dimensioning a biogas plant. Furthermore, the composition of the digestate regarding nitrogen, phosphate and potassium levels is also fixed by the properties of the feedstock.

Pretreatment and sanitation stages are also taken into account in the modeling process. Extrusion method is used to pretreat the organic fraction of MSW, hay and garden waste, which accounts for an energy consumption of 35 MJ per ton of wet feedstock (University of Southern Denmark, 2016). Moreover, pasteurization of the feedstock used is carried out as dictated by the regulation EC 1069/2009 on animal by-products and the use of organic waste (European Commission, 2009).

However, the only feedstocks that must be pasteurized are the organic fraction of municipal solid waste and the sewage sludge, which represent a low share of the total amount of feedstock used. During pasteurization, the feedstock is heated up to 70ºC during 1 hour before pumping it into the reactor in order to comply with the mentioned sanitation procedures.

In order to simplify the calculations, some generalisations have been carried out regarding the properties of the different feedstocks used. The composition of the manure used will be based on cattle manure standard values given by the modeling tool (University of Southampton, 2016). Manure properties may vary from one species to another, but for simplification purposes all the different types of manure will be assumed to be the same. Therefore, the considered manure from cattle, horse and sheep will be estimated to have the same composition.

The composition of sewage, hay and the organic fraction of MSW will be based on standard data from the modeling program as well. The main properties addressed are the total solids and volatile solids content, the methane yield and the content of nitrogen, phosphate and potassium, which are presented in the table 4. These values will be used to calculate the potential production of methane and the properties of the digestate.

Table 4 - Properties of the different feedstocks addressed (University of Southampton, 2016; Rauhala, A., 2013).

Feedstock	**TS%**	**VS%**	**Methane yield (m3/kgVS)**	**Methane yield %**	**N (g/kg TS)**	**P (g/kg TS)**	**K (g/kg TS)**
Manure	9	83	0.185	60	57	10	48
Hay	19.9	90.1	0.320	55	19	4	19
Organic MSW	24	92	0.420	58	33	5	14
Sewage	6	65	0.260	60	25	7	3
Garden	50.4	98.6	0.217	60	5.3	1.65	0.34

7.4. Energy grid

The energy consumption within the defined system’s boundaries for the biogas plant will also be taken into account, along with the emissions linked to its production. Several stages of the production of biogas are significantly energy intensive, so it is crucial to consider the energy balance for the whole production process. To address such fact, specific data regarding energy production and CO_2 equivalent emissions from Iceland has been used.

As mentioned in previous chapters, the Icelandic energy system is pretty peculiar due to its low emissions and the fact that most of its electricity and heat are produced using renewable resources. Therefore, using specific data for the Icelandic energy system is crucial to address the energy consumption and emissions of the modeled biogas plant. Moreover, it is assumed that heat supply will be covered with electricity using electric boilers.

Table 5 represents the emissions in tons of CO_2 equivalent per GJ produced for electricity and heat production in Iceland, along to the emissions linked to oil consumption. These values are used to calculate the emissions related to the energy required to run the anaerobic digestion plant and also take into account the energy needed for feedstock and digestate transportation.

Table 5 - Emissions from different energy sources in tons of CO_2 equivalent per GJ (Environment Agency of Iceland, 2016)

Energy source	**tCO_2e per GJ**
Geothermal	0,0091
Hydropower	0,00044
Weighted average	0,0028
Oil	0,07

7.5. Climate

The temperature surrounding the reactor has an influence on the overall efficiency of the process, so it is important to take into account the climate of Hérað to model the biogas plant heat losses and calculate the final efficiency (Rauhala, A., 2013). The monthly temperatures for both air in Hérað are presented in the table 6:

Table 6 - Monthly temperatures for Egilsstaðir in degrees celsius (YR, 2018)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Air temperature (ºC)	0.5	0.6	0.5	1.4	3.7	6.2	8.2	8.7	6.9	4.4	2.1	0.8

7.6. Biogas use

In this study it is assumed that all the biogas produced in the biogas plant is upgraded and compressed to methane fuel suitable for transportation. The upgrading method used is water scrubber, which has an energy demand of 1,08 MJ/m³ of biogas upgraded and a CO_2 removal efficiency of 98%. The water consumption accounts for 0,1 m³/h (Toledo-Cervantes, A. et al., 2017). The energy requirements for the compression of the upgraded methane are also accounted, which are assumed to be also 1,08 MJ/m³ of compressed methane (University of Southampton, 2016).

Furthermore, default values for the specific energy and density for some substances involved in the biogas production process are also used for the calculations carried out by this study. The density of the gases methane and carbon dioxide is assumed to be 0,717 kg/m³ and 1,965 kg/m³ respectively, and the specific energy of methane and diesel is assumed to be 35,82 MJ/m³ and 35,7 MJ/m³. The specific CO_2 emissions for methane and diesel are 0,056 and 0,07 tons of CO_2 equivalent per GJ produced, respectively (University of Southampton, 2016).

7.7. Use of digestate fertilizer and production

The intention of this report is to calculate the energy and emissions offset provoked by the use of digestate as a sustainable alternative to industrial fertilizers. In order to do so, data regarding the energy required for the production, transport and packaging of industrial fertilizers and its CO_2 equivalent emissions.

Values for the energy accounting for the production of fertilizer have been also taken from the default values in the modeling program, which are respectively 40,3 MJ/kg for nitrogen, 3.4 MJ/kg for phosphate and 7,3 MJ/kg for potash. Emissions values from the manufacturing of fertilizers were also taken into account in this study for the same substances, which are represented in the table 7. The average emissions for transport and manufacturing of the fertilizers is 4,921 kg/kg for CO_2, 0,004 kg/kg for methane and 0,47 kg/kg for N_20 (University of Southampton, 2016). These values will be used to calculate the offset emissions related to the usage of digestate as sustainable fertilizer instead of industrial fertilizers, along with the potential GHG emissions savings.

Table 7 - Emission values for different GHG for fertilizer manufacturing in kg/kg (University of Southampton, 2016)

Substance (kg/kg)	**N**	**P_2O_5**	**K_2O**
CO_2	2.24	1.59	1.66
CH_4	0.012	0.003	0.003
N_2O	0.015	0	0
CO_2e	7.01	1.665	1.735

7.8. Economic analysis

The data used to calculate the economic aspects addressed by this study are presented in this section. It is important to note that the calculations being developed in this report intend to be an insight of the economics linked to the mentioned plant, rather than a deep economic study.

As mentioned before, the Icelandic energy system is based on geothermal and hydroelectric power, which provides both power and heat in the region of Hérað. Therefore, the average cost of electricity from the energy grid mix will be used to calculate the total cost of the energy imported to run the biogas plant. Moreover, it is considered that the transport of feedstock and digestate is covered by tractors and trailers which run on diesel oil. The cost of water used in the upgrading process is also considered. Such costs will also be taken into account, which are summed up in the table 8 (Samorka, 2018; Global Petrol Prices, 2018).

Table 8 - Costs for electricity, oil and water in Iceland 2018, presented in monetary unit per kWh and monetary unit per liter (1 ISK=0,0082€) (XE Currency Converted, 2018; Smorka, 2018; Global Petrol Prices, 2018; HEF, 2018)

	ISK	**€**	**DKK**
Cost of electricity, 2018 (unit/kWh)	9,780	0,080	0,587
Cost of oil, 2018 (unit/L)	212,20	1,74	12,73
Cost of water, 2018 (unit/m³)	31	0,25	1,86

The methane fuel and digestate costs are used to calculate the total revenues of the anaerobic digestion plant, which are presented in the table 9. Such data is taken from the current price of both products in Iceland, with the aim of providing competitive selling costs. Moreover, this report also addressed potential economic savings regarding the production of methane fuel and digestate, such as the carbon tax costs avoided for the use of methane fuel instead of oil. This tax on carbon dioxide applied in Iceland is fixed on 14€ per ton emitted (OECD, 2014).

Waste disposal costs for landfilling are also avoided by using such waste in the anaerobic digestion plant, which represents economic savings as well. However, not all the waste considered by this report has a fixed disposal costs since these vary from the different regions and municipalities in Iceland. The only wastes considered by this report which have disposal costs according to Hérað regulations are sewage slurry and the organic fraction of municipal solid waste, with 0,043€/kg and 0,175€/kg respectively. These values will be used to calculate the savings from avoiding disposal costs (Hafliðason, Í.K., 2013).

Table 9. Methane and digestate costs in different monetary units per kilogram of product (Hafliðason, Í.K., 2013; CNG, 2018)

	ISK	**€**	**DKK**
Methane price (unit/kg)	160,15	1,31	9,61
Digestate price (unit/kg)	2	0,016	0,12

8. Results

In this chapter the results based on the assumptions explained in the previous chapter will be described. First, the values for the plant design will be presented, answering the subquestion D **"What design parameters would the biogas plant have?"**. Secondly, the subquestion E **"What are the energy and mass balances of the biogas plant?"** is addressed. After, GHG emissions of the biogas plant will be addressed by describing the intrinsic emissions related to its performance at maximum capacity, along with the overall impact that the production of methane fuel would have on GHG emission savings from an environmental perspective. The subquestion F **"What GHG emissions does the production of methane fuel from organic waste in a biogas plant imply?"** will be answered in this section. Sub-questions E and F aim at addressing the micro-level flows defined in the Industrial Ecology Theory. Lastly, the results concerning the economic analysis carried out will be presented, by that answering the subquestion G **"What are the potential revenues and costs of the biogas plant?".**

8.1. Mass balance and design parameters

Taking into account the several assumptions described in the previous chapter, which conforms the scenario addressed by this report, the following plant design parameters have been calculated. These calculations will involve strict design parameters and mass balance values, considering the plant to work at maximum capacity. The table 10 presents the results of such calculations, addressing the intrinsic design values of the biogas plant concerning the feedstock used, the properties of the digester feed, the organic loading rate and retention time, the volume of the reactor and lastly the potential methane and digerstate produced.

Table 10 - Mass balance and plant design values (Own table)

Mass inputs	**Unit**	**Value**
Digester input	ton/year	43.096
Manure	ton/year	39.196
Hay	ton/year	2.150
Garden	ton/year	50
Organic fraction MSW	ton/year	200
Sewage	ton/year	1.500
Water	m^3/year	876
Mass outputs		
Potential biogas	m^3/year	1.193.383
Upgraded methane	m^3/year	683.191
Digestate	ton/year	41.630
Design parameters		
Digester feed TS	%	9,6
Digester feed VS	%	83,5
Organic loading rate	kg VS/ m^3/day	3
Retention time	days	27
Digester temperature	ºC	37
Total digester capacity required	m^3	3.142
Individual capacity - single reactor	m^3	3.142
Individual capacity - two reactors	m^3	1.728
Individual capacity - three reactors	m^3	1.152

As mentioned in the previous chapter, the feedstock considered for the biogas plant is mostly composed by manure due to the significant agriculture industry in Hérað. Expired hay comes as second largest feedstock, even though the amount is considerably lower than manure. Sewage, organic municipal solid waste and garden waste represent a discreet 4% of the total feedstock used. The total feedstock used is 43.096 wet tons per year, which conforms the input to the digester.

The most important properties of the digester feed are the total solids and volatile solids content, since this will have significant impacts on the performance of the plant. On the one hand, the TS% content represents a main aspect of the feed since it determines the feasibility of pumping the biomass into the reactor. A total solids content higher than 12% would imply great pump issues and it would be required to water the biomass down to acceptable levels lower than 12%. However, the feedstock used has an acceptable value of total solids content of 9.6%, which does not require the addition of water to enable pumping. On the other hand, the volatile solids content represents the total amount of organic content which the microorganisms will use as substrate and produce methane from. The VS% resulting of the scenario studied by this report is an acceptable 83,5%.

It is possible to base the design of the plant using the organic loading rate or the retention time, dimensioning all the other parameters according to the respective desired values. This report has used an organic loading rate of 3 kg VS/m^3/day to dimensionate the biogas plant, as explained in the modeling and assumptions chapter. The resulting retention time is of 27 days.

Taking into account the described organic loading rate and the properties of the digester feed, the capacity of the anaerobic digestion reactor was calculated. The total volume required is 3.142 m^3, which could be covered with a single reactor. However, it might be desirable to build more than one reactor in case the process collapsed. A second, or even a third reactor, would represent alternatives to keep the methane production ongoing while addressing the issues occured in the malfunctioning reactor. The volume of each reactor in a two-digesters and three-digesters plant would be, respectively, 1.728 m^3 and 1.152 m^3.

The potential biogas produced per year is over 1,2 million m^3, from which 60% is methane. However, this methane is upgraded and compressed for its use as transportation fuel, which results on a final methane fuel product of approximately 700.000 m^3 per year. In energy terms, that accounts for over 584 tons of oil equivalent per year. Another key product of the biogas plant is the digestate, which represents 41 kilotons. Water consumption during the biogas upgrading process accounts for 876 m^3 per year.

8.2. Energy balance

Values for energy inputs to the biogas plant are presented in table 11. These values comprehend the energy used for transport, both for feedstock and digestate, and the energy consumption to produce the required electricity and heat to power the biogas plant. The total energy consumption for transport purposes is 189,7 toe per year, considering that the same distance is covered to bring the feedstock from the farm to the plant and to bring back the digestate to the very same farm. The specifications of the distance covered for each feedstock and the vehicle used to transport it are described in the modeling and assumptions chapter.

Table 11 - Energy inputs and output values in tones of oil equivalent per year (Own table)

Energy inputs	**Toe/year**
Total transport	189,7
Feedstock transport	94,7
Digestate transport	95
Total electricity	67,1
Electricity *(Upgrading + compressing)*	48,1
Feedstock pretreatment	2
Digester electricity	17
Total heat	62,1
Digester heat	41,4
Pasteuriser heat	11,4
Heat loss	9,3
Total energy input (no transport)	129,2
Total energy input (including transport)	318,9
Energy outputs	
Methane fuel	584,5

The electricity consumption is used for the pretreatment of the feedstock, to power the digestion reactor and to upgrade and compress the methane to fuel quality. The total energy consumption for this section is 67,1 toe per year. Most of the heat used in the plant is used to keep the temperature up to mesophilic conditions at 37ºC, followed by the heat needed for pasteurization of the feedstock, which as explained in the previous chapter is a requirement from the European Commission for the organic fraction of the municipal solid waste and sewage sludge.

There is a significant heat loss during such procedures, which brings down the overall efficiency of the process. The total energy consumption for heat supply is 62,1 toe per year. All in all, the total energy requirement for the biogas plant for the sections addressed in this report is 318,9 toe per year, including transport.

In the table 12 values for the energy net balance for the biogas plant are presented. The methane fuel produced accounts for 584,5 toe per year, being the main product energywise of the anaerobic digestion process.

Table 12 - Energy balance in tons of oil equivalent per year (Own table)

Parameter	**Toe/year**
Energy input, total	318,9
Energy output, methane fuel	584,5
Energy balance	265,6

The energy balance for the biogas plant is positive, accounting for a net value of 265,6 toe per year. Such balance takes into account the total energy inputs and outputs of the anaerobic digestion plant.

8.3. Greenhouse gas emissions

GHG emissions from the production of methane fuel will be addressed in this chapter, and the subquestion **"What GHG emissions does the production of methane fuel from organic waste in a biogas plant imply?"** will be addressed. In order to present the results in a comprehensive way, all the data will be displayed in emissions of CO_2 equivalents. The summary of the emissions linked to the methane fuel and digestate production process in the anaerobic digestion plant is presented in the table 13:

Table 13 -. Emissions released in the methane production process in tons of CO_2 equivalent per year (Own table)

Parameter	**Energy source**	**CO_2e emissions (ton/year)**
Feedstock transport	Fuel (oil)	296,5
Digestate transport	Fuel (oil)	297,3
Imported electricity	Grid mix (hydro,geo)	7,9
Imported heat	Grid mix (hydro,geo)	7,3
Total	Fuel+grid	608,9

The emissions are calculated using all the energy inputs required and the linked CO_2 equivalent emissions per toe for the energy source used for each section. Once again, the data for such values is presented in the modeling and assumptions chapter. The main contributor to the overall emissions from the production of methane fuel and the digestate is the transport sector, representing 593,8 tons of CO_2 equivalent per year. Transport is the only section of the whole production process where fossil fuels are used, since both the power and heat consumed are produced from electricity generated in geothermal and hydroelectric power plants, which are renewable sources.

However, these sustainable energy sources also have a small but considerable contribution when it comes to the GHG emissions of the process. The total emissions for the imported electricity and heat, respectively, are 7,9 and 7,3 tons of CO_2 equivalent per year. Combining both the emissions linked to transport and power, the total emissions represent 608,9 tons of CO_2 equivalent per year.

8.4. Economic analysis

A simple economic analysis is carried out in this chapter, with the aim of answering the subquestion F **"What are the potential revenues and costs of the biogas plant?"**. As explained before, all the calculations are based on the data presented in the chapter modeling and assumptions, regarding the average costs and taxes used for the following analysis. The following table sums up the results obtained by this study regarding the aspects addressed in the economic analysis:

Table 14 -. Economic analysis on electricity and costs and methane and digestate revenues per year in different monetary units. *Water costs have been considered negligible, since these were three order of magnitude smaller than the rest (Own table)

Costs per year	**ISK**	**€**	**DKK**
Electricity cost	14.700.000	120.000	900.000
Oil cost	47.000.000	380.000	2.800.000
Total costs	61.700.000	500.000	3.700.000
Revenues per year			
Revenue methane fuel	78.500.000	640.000	4.700.000
Revenue digestate	83.300.000	680.000	5.000.000
Total revenues	161.800.000	1.320.000	9.700.000

As it can be appreciated in the previous table, the total revenues from selling both products of the biogas plant, methane fuel and digestate, exceed the total costs of operating such plant including transportation. Therefore, a positive net balance is achieved when the plant is running at maximum capacity and the totality of both products is sold.

It is important to state that in the table 14 not all the costs linked to run an anaerobic digestion plant are considered, since such table only makes reference to costs for power and transport. In order to address the other costs regarding operation and maintenance of the plant, along with investment costs, the figures 16 and 17 have been taking into account.

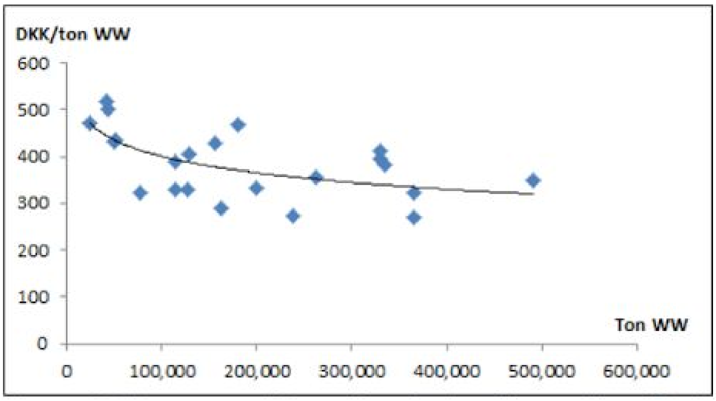

Figure 16 - Construction costs in DKK per ton wet weight per year (Y axis) as a function of the annual input of feedstock in tons wet weight (X axis) (Hethey, 2014)

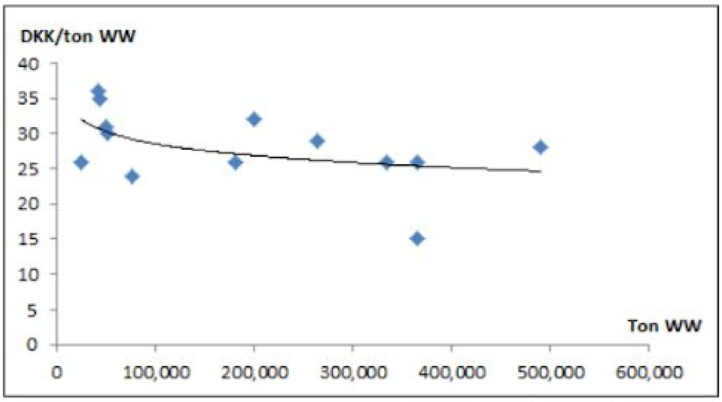

Figure 17 - Operation and maintenance costs in DKK per ton wet weight per year (Y axis) as a function of the annual input of feedstock in tons wet weight (X axis) (Hethey, 2014)

Figure 16 presents the general expenses for building a conventional biogas plant, including the construction of several units such as digesters, gas cleaning systems, gas storage, land and buildings among others. Operation and maintenance costs are presented in the figure 17, which covers the necessary expenses for the operation of the digester. However, it does not include the costs for transport of feedstock and digestate. Such graphs are based on existing and planned biogas plants (University of Southern Denmark, 2016).

Considering the size of the biogas plant this thesis is addressing, which is over 43 kilotons of mixed feedstock per year, the economic data presented in the figures 16 and 17 can be extrapolated to its context. Therefore, according to the data presented in the previous graphs, the investment, operation and maintenance costs for the biogas plant studied by this report are as follows:

Table 15 - Investment, operation and maintenance costs in different monetary units. *Transport and labour not included in the total operational costs. (Hethey, 2014)

	ISK	**€**	**DKK**
Investment cost per wet ton	7.500	60	450
Total investment cost	323.000.000	2.700.000	19.000.000
Operational costs per wet ton	530	4	32
Total operational costs*	23.000	188.000	1.400.000

The total investment cost of the plant is calculated using the function presented in the figure 16, where by knowing the size of the plant based on the annual wet feedstock input, the investment cost per wet ton can be extrapolated. Then, the investment cost per wet ton is multiplied for the total amount of annual input of wet feedstock per year, which result is the total investment cost of the plant as presented in the figure 16. The operation and maintenance costs are calculated in the same way, using the figure 17.

However, the operational and maintenance costs shown in the figure 17 do not include either transport or labour costs. Therefore, transport costs calculated by this report are added to the O&M costs shown in the graphic. Labour costs are estimated to be 200.000€ per year for plant and transport operators. Such value is also added to the final O&M costs.

In order to know if building a biogas plant to produce methane fuel and digestate is feasible, taking into consideration all the assumptions and data presented previously in the context of Hérað, the net present value and the intern rate of return of such project have been calculated. These economic terms are useful to determine how profitable a project or investment can be, therefore being a break even point to find out if such project or investment should be carried out or no. Such concepts rely on the Cost-Benefit Analysis theory.

Table 16 shows the present value of future cash flows, the net present value and the intern rate of return considering a discount rate of 6%. In order to make the calculations more realistic, it has been considered that the designed biogas plant would take three years to reach its maximum capacity performance, therefore taking into account possible issues and problems during the initial stages of the plant. The production of methane fuel and digestate during the first year is considered to be at 50% of its maximum capacity, 75% on the second year and finally 100% on the third year, keeping such rate during the rest of its operational life, which is 30 years. It is important to comprehend that these would be applied to both costs and benefits rates in the mentioned years.

Table 16 - Discount rate, present value of future cash flow, net present value and internal rate of return. Monetary results presented in € (Own table)

Parameter	**Value**
Discount rate	6%
Present value of future cash flow	7.200.000 €
Net present value	4.500.000 €
Internal rate of return	18%

The positive values for both the net present value and the intern rate of return indicate that the construction of a biogas plant in Hérað is feasible, taking into consideration all the assumptions presented in the previous chapters.

8.5. Sensitivity analysis

In a sensitivity analysis, changes are made in the data used for the calculations in order to evaluate the impact such changes have on the final results. The intention of this report is to carry out a sensitivity analysis focused on the economic viability of the anaerobic digestion plant, by setting up different scenarios where specific specific variables are changed to evaluate their impact on the overall economic feasibility of the plant.

The sensitivity analysis main focus will be on the revenue of the digestate as a byproduct of the anaerobic digestion process. In the economic analysis carried out previously, it is considered that all the digestate will be sold back to the farmers. Since the economic revenue of selling the digestate is bigger than the one for methane fuel, changes on such revenue might have a significant impact on the economic feasibility of the plant. The intention of this report is to study to what extent a significant reduction of the revenues of the biogas plant would affect its economic viability.

Therefore, three scenarios have been considered:

- Scenario 0: Reference scenario, all the digestate is sold. The revenues of the plant account for both methane fuel and digestate.
- Scenario 1: Only half of the digestate is sold. The revenues of the plant account for methane fuel and half of the digestate.
- Scenario 2: The digestate is given away at free cost. The revenues of the plant only account for methane fuel.

In order to study the viability of the difference scenarios, the net present value and internal rate of return will be calculated, as in the economic analysis. The difference between the scenarios will also be pointed out. The discount rate used is 6%.

Table 17 - Present value of future cash flow, net present value and internal rate of return. Monetary results presented in € (Own table).

Parameter	**Scenario 0**	**Scenario 1**	**Change**
Present value of future cash flow	7.200.000 €	2.700.000 €	-63%
Net present value	4.500.000 €	90.500 €	-98%
Internal rate of return	18%	6%	-67%

The effect of removing half the revenues of the digestate can be appreciated in the table 17. The change on the net present value is around a reduction of 98%, while the internal rate of return experiences a reduction of 67%. However, both values are positive for the scenario 1.

Table 18 -. Present value of future cash flow, net present value and internal rate of return. Monetary results presented in € (Own table)

Parameter	**Scenario 0**	**Scenario 2**	**Change**
Present value of future cash flow	7.200.000 €	-1.700.000 €	-123%
Net present value	4.500.000 €	-4.400.000 €	-197%
Internal rate of return	18%	-	-

In the table 18, the effect of removing all potential revenues from the digestate on the economic evaluation of the biogas plant is presented. In this case, both net present value and internal rate of return are negative. The changes for the scenario 2 regarding the reference scenario are a reduction of 181% of the net present value. Since the costs of operating the plant exceed the revenues from selling methane fuel, the annual net value for costs and revenues is negative. Therefore, the internal rate of return cannot be calculated.

8.6. Potential impact of digestate use

As explained in the modeling and assumptions chapter, the intention of this report is to address the potential impact the use of digestate as fertilizer might have in environmental and economic terms.

<u>Impact on greenhouse gas emissions</u>

This report chose to address the potential impact the use of methane fuel and digestate would represent in environmental terms, as alternatives to industrial fertilizers respectively. Even though the final consumption of the digestate is outside the system boundaries described in the modeling chapter, from this report perspective it is significant to take into account the potential benefits the use of the products from the biogas plant would carry out.

Both the production of methane fuel and digestate as sustainable fertilizer are desirable for their beneficial impact on the environment, since apart from being renewable sources the GHG emissions linked to their use are lower and represent significant emission savings.

The potential impact on using digestate instead of industrial nutrients is significant, taking into consideration the production process of both types of fertilizers. This report has carried out calculations regarding the total CO_2 equivalent emissions that would be released to produce the same amount of nutrients found in the digestate by-product of anaerobic digestion, using the table 7 in the modeling and assumptions chapter on emissions produced per kilogram of industrial nutrient. According to such values, 2.000 tons of CO_2 equivalent emissions per year would be avoided by not producing industrial nutrients and using digestate as fertilizer instead. Therefore, 2.000 tons of CO_2 equivalent per year could be potentially offset by shifting to digestate.

Potential impact on economics

To the economic results, the savings achieved per year can also be considered. These account for the savings on carbon taxes per year, along with the disposal costs avoided for landfilling the organic fraction of municipal solid waste and the sewage sludge. The following table sums up the mentioned savings:

Table 19 - Economic analysis on costs, revenues and savings per year in different monetary units (Own table)

Savings per year	**ISK**	**€**	**DKK**
Disposal cost of organic MSW	4.300.000	35.000	260.000
Disposal cost of sewage	8.000.000	65.000	480.000
Estimated carbon tax	3.000.000	25.000	180.000
Total savings	15.300.000	125.000	920.000

Only savings linked to the avoided emissions for production of industrial nutrients and the use of methane fuel instead of oil in transport are accounted in the table 19, since the emission savings for avoiding landfill practice are difficult to estimate. The emissions saved from not importing fossil fuels have not been considered as well. The results from the table 19 are considered costs prevented, and are not taken into account as direct benefits or revenues for the anaerobic digestion plant by this report. The intention of this report is to carry out a simple feasibility study by considering the direct costs and benefits of running the plant, so that is the reason why these values will be left out of following calculations. Nevertheless, such fact does not mean that the values presented above regarding the savings achieved by using waste to produce sustainable fuel are not significant, but that this report has chose to not consider them in order to get a better insight of the economics of the very anaerobic digestion plant.

9. Discussion

The main points of the results presented in the previous chapter will be discussed in the following paragraphs, focusing in the following topics: Energy and mass balances, GHG emissions, economic analysis, sensitivity analysis, heavy transport fuel demand and the link between waste management and fuel production.

9.1. Energy and mass balances

The energy balance of the overall processes in the anaerobic digestion plant is positive, meaning that the energy outcomes exceed the energy inputs. Therefore, more energy is produced than it is consumed to produce methane fuel via anaerobic digestion process in the context of Hérað. Electricity imported from the national grid is used to meet both the heat and electric requirements to run the different units in the anaerobic digestion plant. The only fossil fuels used in the process have to do with the transportation of feedstock and digestate.

None of the biogas produced in the plant is used on-site, since the totality of the biogas produced is upgraded to methane fuel to maximise its production quantity. Moreover, the average emissions released per unit of energy produced from the national grid are lower than the CO_2 equivalent emissions produced by using biogas, meaning that is more environmentally sound to use electricity from the national grid than to use biogas to power the plant. That is another main reason to not use biogas or methane to produce electricity in Iceland but to produce fuel.

The main energy input is for transportation of feedstock and digestate, due to the 50 kilometers average distance from farms to the plant. Transport represents 59% of the total energy input of the process. Biogas upgrading and compression to methane fuel is the most energy intensive process in the plant, followed by the heat requirements of the digester.
Methane fuel represents the main energy output of the process. The energy return per energy investment is around 1,7 considering all the energy inputs and the outcome of methane fuel alone.

As mentioned before, the heat needed for the plant is produced using electricity from the national grid. However, the region of Hérað has some geothermal activity which could have been also used for heating purposes. In fact, there is a 76ºC water spring of geothermal source in the surroundings of Egilsstaðir which could be used to heat up the digester to mesophilic temperatures using a heat exchanger. Nevertheless, to use such spring to provide the necessary heat for the pasteurizer unit would be difficult. There is little knowledge about how such spring would be exploited and what costs would represent, so for simplification purposes this report chose to obviate such heat resource.

The conservation of mass is an underlying concept within the Industrial Ecology Theory, which is also addressed in this report. The mass conversion from the feedstock tons to methane fuel is rather low, accounting for only 1% of the total weight of the feedstock converted into methane fuel. It can be stated that such conversion rate is normal taking into account than the total content of solids and organic volatile solids, which is the content of the feedstock that is actually used to produce the methane, is also significantly low in comparison to the total weight of the feedstock. The mass conversion from feedstock to digestate is way higher, accounting for a 96% of the total weight. Considering both products, the total conservation of mass is 97%.

9.2. GHG emissions

Overall, the direct energy consumption of the biogas plant accounts for low emissions, since all the power is met by importing electricity from the national energy grid. As mentioned in previous chapters, the Icelandic energy grid has significant lower emissions of GHG per unit of energy produced compared to any other country from the european context, since the electricity is generated using geothermal and hydroelectric power.

Most of the emissions come from the transportation of the feedstock to the anaerobic digestion plant as well as for the transport of the digestate back to the farms, accounting for 97% of the total emissions released during the methane fuel production process. Such fact points out that there might be a distance limit turnpoint where the emissions produced for transporting such products are greater than the emissions saved by using methane fuel and digestate produced in the plant, turning the GHG emissions balance of the overall process positive. Therefore, in order to maximize emission savings, it is important to focus on the local resources even within a regional level. The GHG emissions from transport are the main impact of the methane fuel production process, which falls under GWP impact according to LCA impact categories (Danish Ministry of the Environment, 2005).

The calculations of this report take into account that all transport is carried out using diesel tractors and trailers, which do most of the heavy transport in the region. In the period of 30 years of operational lifespan of the biogas plant addressed, it could be argued that at some point these vehicles would have to be replaced or upgraded. Therefore, the future introduction of tractors and trailers running on more sustainable fuels, such as the very methane produced in the plant, could also be considered. Such fact would mean that the emissions regarding the transport of feedstock and digestate in the future could be considerably lower, even though such estimation has not been considered in the calculations.

As it can be seen in the results, the use of digestate as fertilizer offsets over 2.000 tons of CO_2 equivalent emissions per year, meaning that to produce the same quantity of fertilizer by industrial nutrients 2.000 tons of CO_2 equivalent would be emitted per year. Moreover, the use of digestate instead of raw manure as fertilizer also avoids CH_4 emissions to the atmosphere. Methane is a GHG gas with 21 times the warming potential of CO_2, so it is way more harmful to the environment than carbon dioxide. Even though it is hard to estimate the total savings on CH_4 emissions from the use of manure in the fields, it is important to take such fact into account.

The use of methane fuel instead of oil in transportation has proved to be advantageous in terms of GHG emission savings, due to the lower specific CO_2 equivalent emissions for methane fuel compared to fossil diesel. Therefore, such fact implies that less GHG are emitted by using methane fuel instead of oil to produce the same amount of energy. If all the methane fuel produced in the modeled plant replaces oil in transportation, 457 tons of CO_2 equivalent can be avoided per year.
Taking into account the emissions linked to methane fuel production and the emissions prevented by the use of digestate and methane fuel replacing industrial fertilizers and oil, 1.848 tons of CO_2 equivalent emissions can be potentially saved per year. Moreover, methane fuel can be locally produced using resources available in the region, instead of importing fossil fuels from abroad. Therefore, the GHG emission savings for using methane as transportation fuel are much greater if the extraction, transport and distribution of fossil fuels to Iceland is taken into account. Such estimation has been left out the scope of this report since the main focus was to assess the GHG emissions linked to the biogas plant processes and the savings on the use of digestate instead of industrial fertilizers.

9.3. Economic analysis

The economic analysis carried out by this report intends to be a sound framework for the economic aspects that a potential biogas plant in Hérað would represent, so the economic feasibility of the plant can be determined. Operation and maintenance costs, investment costs and transport costs have been taken into account in order to provide a solid economic analysis. Moreover, economic savings linked to the avoidance of CO_2 emissions and the disposal costs of some waste products are also taken into account.

As it can be seen in the results chapter, the costs for transporting the feedstock and the digestate are higher than the operation and maintenance costs of the biogas plant itself, which might be a context specific situation for Hérað. The main reason behind such fact is the long distances feedstock has to be transported, since the farms are spread out the region and the digestate is transported back to the very same farms. Therefore, road transportation of feedstock and digestate has a great impact on the economics of the biogas plant.

The digestate has a great influence on the revenues of the biogas plant, accounting for a higher revenue than the one for methane fuel. Therefore, the degree of profitability of the plant relies heavily on the capacity to sell the digestate back to the farmers. Such matter will be addressed more deeply in the sensitivity analysis section in the discussion.

As mentioned before, the potential benefits linked to savings on CO_2 emissions and disposal costs of waste are also addressed in the economic analysis. Such savings can be considered as external benefits, since these are not strictly produced in the plant itself, but are produced in consequence of its activities. Moreover, these savings benefit directly the municipalities of Fljótsdalshérað and Fljótsdalshreppur, which conform the region of Hérað. As it can be appreciated in the results chapter, the savings for avoiding the disposal costs for landfilling the organic fraction of municipal solid waste and sewage sludge are bigger than the savings related to the carbon tax costs avoided by the reduction of CO_2 emissions.

Both the investment costs and the operational and maintenance costs for the modeled plant have been estimated, using the figures 16 and 17 presented in the results chapter. Such estimations addressed more costs and were more complete than the calculations this report could carry out with the available data, so for such reasons such estimations were used for the final calculations on the economic viability of the plant. However, the estimation for operational and maintenance costs did not include transport costs so these were added from the transport costs calculated by this report. Therefore, the overall estimation is slightly more contextual for the Hérað scenario.

As it can be appreciated in the figures 16 and 17, there appear to be economy of scale benefits for larger plants for both investment and O&M costs. Therefore, larger plants have lower costs than smaller plants regarding the capital costs per unit of wet ton of feedstock. The anaerobic digestion plant addressed by this report is considerably small, regarding the annually amount of feedstock input, so its investment and operation and maintenance costs per wet ton of feedstock are relatively high. To put the size of the plant into context, in the same figures there is data for plants with a size of 500 kilotons of wet feedstock per year, in contrast of the 40 kilotons for the plant this report is addressing.

The net present value and the internal rate of return of the anaerobic digestion plant have positive values, as it can be seen in the table 16. According to such results and the Cost-Benefit Analysis theory, the anaerobic digestion plant considered by this report is profitable and could be constructed. Nevertheless, it must be stated that such claims carry uncertainties that might have not be taken into consideration by this report. Moreover, these results are certain considering the assumptions taken during the calculations. A deeper economic analysis should be carried out to know the exact feasibility for an anaerobic digestion plant in Hérað.

9.4. Sensitivity analysis

As explained in the results chapter, the sensitivity analysis carried out by this report was aimed at addressing the impact specific variables had on the overall feasibility of the anaerobic digestion plant in economic terms. The variable addressed was the revenue of the digestate.

According to the perspective of this report, it was important to evaluate the viability of the anaerobic digestion plant in a scenario where the digestate could not be sold. The fact that the potential revenue from the digestate is even higher than the one for methane fuel puts the economics of the anaerobic digestion plant in a sensitive situation, since failing to sell the digestate back to the farmers would considerably affect the economic analysis carried out by this report. Farmers use most of the raw manure their farms produce to fertilize their fields and add up industrial nutrients to meet up with the desired nutritional levels, since raw manure alone is not enough.

Digestate has a better performance in comparison to industrial nutrients which Icelandic farmers currently use since all the necessary nutrients are found in it, and the price of digestate is significantly lower than industrial nutrients, with 2 ISK/kg and 50 ISK/kg respectively (Hafliðason, 2013). Because of such reasons, farmers should be willing to give away the manure they currently use to fertilize their fields for methane fuel production purposes, and accept to buy it back in form of digestate. Nevertheless, even though the digestate has better performance and a more competitive price than industrial fertilizers, the scope of this report found necessary to address such assumption carefully since the perspective of the farmers on the matter is yet unknown. That is the reason why this report chose to carry out a sensitivity analysis focused on the potential revenues of the digestate.

According to the sensitivity analysis presented in the results chapter the anaerobic digestion plant would be feasible in the scenario 1, with positive net present value and internal rate of return. Such fact means that the biogas plant would still be profitable in a scenario where half the digestate would not be sold, taking into consideration the Cost-Benefit Analysis theory. However, the net present value and internal rate of return drop considerably, making the scenario 1 much less profitable than the reference scenario 0.

On the scenario 2, no revenue is made by the production of digestate and it is given away free of cost to the farmers. The results of the sensitivity analysis point out that the net present value for such scenario would have negative values, meaning that the plant would not be feasible. Therefore, in the scenario 2 the plant is not profitable and should not be constructed.

9.5. Heavy transport fuel demand

One of the main aspects this thesis addressed was the necessity for sustainable fuel for heavy transport, as an alternative to fossil fuels. Methane fuel properties make it a sound alternative due to its high specific energy when compressed and its consideration as a CO_2 neutral fuel when produced via anaerobic digestion of biomass. Therefore, the production of methane fuel using the waste biomass available in the east region of Hérað was considered.

However, the amount of methane fuel that could potentially be produced using the feedstock addressed by this report is not close to be sufficient to meet the fuel demands of the heavy transport sector in the east of Iceland. In the results chapter, the total methane fuel energy output is 265,5 toe, which lies way behind the potential benchmark of 1.373 toe for the total fuel consumption by the fishing vessels operating in the east. Therefore, with the waste biomass addressed by this report it would only be possible to meet 2% of the total demand. Nevertheless, it must be stated that the fuel consumption of the fishing industry is one of the main consumers of fossil fuels in the Icelandic energy system, so the numbers it deals with are rather gigantic in comparison to other sectors.

9.6. Waste management and methane fuel

As it can be seen in the results carried out by this report, using organic waste to produce methane fuel via anaerobic digestion has proven to be advantageous in economic and environmental terms.

Using organic waste as a resource to produce fuel falls within the scope of circular economy, enlarging the life cycle of products previously considered as waste. Moreover, unsustainable practices such as landfill can be avoided as the anaerobic digestion of waste is shown as an eco-friendly alternative for the current waste management methods, while profit can be made out of the products produced in the anaerobic digestion plant.

Producing methane from waste contributes to the ultimate goal of abandoning landfill practice by 2021, when it will become banned according the Icelandic legislation, along producing sustainable fuel for transport locally and avoiding GHG emissions from solid waste disposal. Therefore, it is possible to link waste management and fuel production under a sustainable alternative, as anaerobic digestion of waste for fuel production purposes has proved.

9.7. Limitations

- The lack of available context specific data for East Iceland and Hérað regarding solid disposal in landfills and emissions was a limitation for this report.
- The early stage of methane fuel production process in the East of Iceland represents a limitation. The amount of available data regarding such matter is limited.

10. Conclusion

The intention of this report was to determine the feasibility of a potential anaerobic digestion plant in Hérað for the production of methane fuel from organic waste, regarding economical and environmental terms. Such aim was approached using the following research question:

In economic and environmental terms, how feasible would be the production of methane fuel via anaerobic digestion of organic waste to provide sustainable fuel for transportation and a waste management alternative to landfill?

By answering this research question, this report intends to contribute to the body of knowledge regarding alternative fuels in Hérað and East Iceland, as a step to transition away from fossil fuels in the transport sector and produce renewable energy locally.

10.1. Key findings

<u>According to the aspects addressed and the assumptions considered by this report, the production of methane fuel via anaerobic digestion of organic waste in Hérað is environmentally and economically feasible</u>

In the biogas plant modeled by this report, the energy balance of the methane fuel production process is positive, accounting for a net value of 265,6 tones of oil equivalent per year. Transportation of feedstock and digestate represents the main energy input of the overall process, with 59% of the total energy investment. Moreover, transport accounts for 97% of the total emissions released in the methane fuel production process.

Considering the potential emissions avoided by using methane fuel instead of oil in transportation and preventing the production of industrial fertilizers by using digestate, the estimated GHG balance of the overall process is 1.848 tons of CO_2 equivalent saved per year. This balance does not include the estimated prevented emissions for avoiding landfill practice, fossil fuel imports and the use of raw manure in agricultural soils, so the GHG balance is estimated to be significantly bigger. However, in order to make such claim properly, a full Life Cycle Analysis of the biogas plant and the use of its products should be carried out.

The production of methane fuel from organic waste represents a sustainable alternative to landfill waste management, using waste as a resource to produce renewable energy. Such fact resembles the natural ecosystems described by Industrial Ecology Theory, with an industrial process which generates no waste.

Moreover, the biogas plant has proved to be economically feasible according to the assumptions taken by this report. However, the feasibility of the plant in economic terms is highly dependant on the potential revenue generated by the by-products of the methane fuel production process. According to the data used by this report, the digestate accounts for more than half the potential revenue the biogas plant could generate. For the plant to be economically feasible, it is crucial to get a positive revenue in economic terms for the digestate.

<u>The potential amount of methane fuel produced by the modeled biogas plant would not meet the fuel demand for heavy transport</u>

The amount of energy produced in form of methane fuel in the biogas plant would cover around only 2% of the total energy demand by the fishing vessels operating in East Iceland. Therefore, it is not possible to meet the energy demand of the heavy transport sector by the methane fuel produced in the modeled biogas plant.

Nevertheless, according to the results presented by this report it is technically and economically sound to produce sustainable fuel from local waste resources in Hérað. Such possibility should not be overlooked in the future energy system of Hérað, and the integration of alternative fuels along electricity as means of power for transportation should be considered, even for heavy transport vehicles.

10.2. Further research

<u>Integration of methane fuel in the future energy system</u>

The integration of methane fuel within the future energy system of Iceland, and specifically East Iceland and Hérað, should be approached in further research. As mentioned in the introduction chapter, most of the road transport grid is expected to be electrified but alternative fuels should not be overlooked in the future energy system, especially the ones produced from waste.

<u>Elaboration of a full LCA</u>

In order to determine the environmental feasibility of the biogas plant in a precise way, a full environmental study on its impacts should be carried out, such as a Life Cycle Analysis.

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