Feedstock research

Feasibility of importing feedstock to the Netherlands

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Student
Erik Groot Koerkamp
S2401835
e.grootkoerkamp@student.utwente.nl
BSc Industrial engineering and management

Supervisor University of Twente
Dr. P.B. Rogetzer
Assistant professor
Faculty of Behavioral, Management and
Social Sciences (BMS),
Industrial Engineering & Business Information
Systems (IEBIS)

Second supervisor
Renata Guizzardi
Assistant professor
Faculty of Behavioral, Management and
Social Sciences (BMS),
Industrial Engineering & Business Information
Systems (IEBIS)

Company
HoSt Group | Bioenergy Systems
Thermen 10
7521PS Enschede

Company supervisor
Jesse Buiteveld
Project developer

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Preface

In front of you lies the thesis "Feasibility of importing feedstock to the Netherlands". This is a thesis for Industrial Engineering and Management This assignment was given by the company HoSt located in Enschede.

First of all, I want to thank everybody from HoSt that helped me during the research. Especially Jesse Buiteveld, who was my company supervisor. Their feedback helped me in doing this research in the best way possible. Everyone was always open to answering questions, which helped a lot during the research.

Secondly, I want to thank the UT supervisors, especially Patricia Rogetzer. The constant support during the research contributed to the quality of the research.

I hope you enjoy reading this thesis!

Erik Groot Koerkamp

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Management summary

This aim of this thesis is to investigate the feasibility of importing feedstock from Romania and Poland to the Netherlands. It has to be feasible from a financial and environmental perspective for HoSt.

Problem definition

HoSt, a company in the waste-to-energy sector that specializes in transforming biomass to biogas, has the goal that 40% of the revenue comes from installation in own management, this means that HoSt has to build more installations to have in own management. Installations in own management are installations that are operated by HoSt itself and not by a third party. The biggest problem with this is that there is not enough feedstock available in the Netherlands to build more installations. So the core problem that HoSt encounters is that there is **not enough feedstock available in the Netherlands.** Therefore, HoSt wants to know the feasibility of importing feedstock to process it here in the Netherlands, specifically the newly proposed site in Waalwijk, known as Wabico 2.0. The main research question answered in this thesis is: **How financially and environmentally feasible is it for HoSt to import feedstock streams from Poland and Romania to Waalwijk?**

Research approach

To solve the main research question seven steps are taken. We started with finding out what the aspects are of a life-cycle analysis, an LCA is necessary to find out the environmental feasibility. The inputs for anaerobic digestion were researched, to look for what types of feedstock need to be researched. AD is an technique which processes biomass to biogas and digestate. Then the regions where feedstock is available were found in Romania and Poland. These regions were used to set-up transportation networks, these transportation networks were used in the LCA. When the transportation networks were found, a LCA was conducted. The results of the LCA were used in drawing conclusions. After the LCA was done the costs of the whole process were found, from this the internal rate of return of the proposed new site was found. Both the LCA and the IRR are used in the conclusion.

Results

The outcomes of the LCA and the IRR are the main results found in this thesis. The LCA shows the environmental feasibility of importing the feedstock. The CI-score of the feedstock must be below 28.53 gCO_2/MJ. This is 70% lower than the CI-score of diesel production. The IRR of the proposed new site should be 15% or higher. For the results of the IRR a sensitivity analysis was conducted. In this sensitivity analysis the feedstock prices and gas prices were analysed.

Conclusion

Importing feedstock is feasible if the feedstock streams pass two tests, CI-score below 28.53 gCO_2/MJ and the IRR over 15%. All the feedstock streams that were selected for LCA were below 28.53 gCO_2/MJ, so from an environmental point of view it is feasible. The financial feasibility depends on three main factors, transportation costs, feedstock price and gas prices. Transportation prices are high at the moment, this influences the feasibility. Importing with the trucks that return empty from Poland is a good option of importing feedstock. For big quantities it can be feasible in the right circumstances. This means that either the feedstock price and transportation prices are lower, or when locally sourced feedstock prices go up.

In summary, from an environmental perspective it is feasible. From a financial perspective it is feasible under the right circumstances.

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Contents

Preface 3
Management summary 4
List of tables 8
List of figures 9
Glossary 10
1. Introduction 11
1.1 Company introduction 11
1.2 Main problem 11
1.3 Problem identification 11
1.3.1 Action problem 12
1.3.2 Problem cluster 12
1.3.3 Core problem 12
1.4 Theoretical framework 13
1.5 Problem solving approach 13
1.6 Research questions 14
1.7 Outline of thesis 15
2. Literature review 16
2.1 Systematic literature review 16
2.2 Life-cycle-assessment 16
2.3 Waste pyramid 18
2.4 Butterfly diagram 18
2.5 Generations of biofuel 19
2.6 Availability and localizing feedstock 19
2.7 Modes of transport 20
2.7.1 Transport by boat 20
2.7.2 Transport by train 20
2.7.3 Transport by truck 21
2.7.4 Intermodal transportation 21
2.8 Conclusion 21
3. Anaerobic digestion process of HoSt 23
3.1 AD process 23
3.2 Inputs of AD 24
3.3 Outputs of AD 24
3.4 Conclusion 25
4. Localizing and availability of feedstock in Poland and Romania 26
4.1 Country selection 26
4.1.1 Romania 27

4.1.2 Poland ... 28
4.2 Conclusion ... 29
5. Transportation of feedstock ... 31
5.1 Destination of feedstock ... 31
5.2 Departure ... 32
5.2.1 Romania ... 32
5.2.2 Poland ... 33
5.3 Storage ... 33
5.4 Collection ... 33
5.5 Distances ... 34
5.6 Emissions per mode of transportation ... 34
5.7 Costs per mode of transportation ... 34
5.7.1 Truck ... 34
5.7.2 Train ... 34
5.7.3 Transport over sea ... 34
5.7.4 Inland waterways ... 35
5.8 Set-up of transportation network ... 35
5.9 Conclusion ... 35
6. Performing the LCA ... 36
6.1 LCA set-up ... 36
6.1.1 The goal and scope definition phase ... 36
6.1.2 The inventory analysis phase ... 36
6.1.3 The impact assessment phase ... 36
6.1.4 The interpretation phase ... 37
6.2 Emissions from pelletizing ... 37
6.3 Emissions from the process ... 38
6.4 Outcomes the LCA ... 38
6.5 Results of the LCA ... 38
6.6 Conclusion ... 39
7. Internal rate of return of HoSt ... 40
7.1 Costs of the process ... 40
7.2 Revenue ... 40
7.3 Case study ... 40
7.4 Conclusion ... 42
8. Conclusion, recommendations and limitations ... 43
8.1 Conclusion ... 43
8.2 Discussion ... 44
8.3 Future research ... 45

References 46
Appendices 51
Appendix A – Elements of LCA 51
Appendix B – AD potentials 2030 EU countries 52
Appendix C – Biogas production EU countries 53
Appendix D – Min and max values produced residues Romania 54
Appendix E – Min and max values produced residues Poland 55
Appendix F – Middle point approximation Romania 56
Appendix G – Middle point approximation Poland 56
Appendix H – transportation networks scenarios Romania 57
Appendix I – transportation networks scenarios Poland 58
Appendix J – Visual representation scenario Poznan - Moerdijk 59
Appendix K – LCA calculation excel glycerine Romania 60
Appendix L – LCA calculation excel straw pellets Romania 61
Appendix M – LCA calculation excel straw Romania 62
Appendix N – LCA calculation excel sunflower husk pellets Romania 63
Appendix O – Costs and revenues current situation 64
Appendix P – Data residues Romania 65
Appendix Q– Data residues Poland 66
Appendix R – Example of transport cost calculation 67
Appendix S – Example calculation CI-score 68
Appendix T – Distances to Wabico from Poland/Romania 70
Romania 70
Poland 70

List of tables

Table 1: Distances to port areas 32
Table 2: Distances to ports in Rotterdam port area 32
Table 3: Distances to ports in Amsterdam port area 32
Table 4: Distances to ports in Zeeland port area 32
Table 5: energy usage for pelleting 38
Table 6: Biogas returns of selected feedstock 38
Table 7: CI-scores Poland for different feedstock 39
Table 8: CI-scores Romania for different feedstock 39
Table 9:CI-score straw pellets case study 42
Table 10: Residue-to-crop ratio for different crops in Romania 65
Table 11: Availability for energy purposes in % for Romania 65
Table 12: Average available residues for different cereals in 1,000 tonnes Romania with biogas potential 65
Table 13: Residue-to-crop ratio for different crops in Poland 66
Table 14: Availability for energy purposes in % for Poland 66
Table 15: Average available residues for different cereals in 1,000 tonnes in Poland with biogas potential 66
Table 16: on road distances from Romania to Wabico in Km 70
Table 17: Waterway distances from Romania to Netherlands in Km 70
Table 18: Rail distances from Romania to Netherlands in Km 70
Table 19: Distances from Ploiesti to Constanta in Km 70
Table 20: Road distances in Km 70
Table 21: Waterway distances in Km 70
Table 22: Rail distances in Km 70
Table 23: Distances from Kutno/Poznan to Gdynia in Km 70

List of figures

Figure 1: Problem cluster HoSt 13
Figure 2: Problem solving approach 14
Figure 3: Butterfly diagram 19
Figure 4: Flow diagram of AD process 24
Figure 5: NUTS 2 regions Romania with highest residues available 28
Figure 6: NUTS 2 regions Poland with highest residues available 29
Figure 7: Location of Wabico with the plot of land 31
Figure 8: System boundary 37
Figure 9: Pellets 37
Figure 10: Cash flow HoSt with related IRR 41
Figure 11: Sensitivity analysis feedstock- and gas prices 41
Figure 12: Elements of a LCA 51
Figure 13: Biomethane potential 2030 52
Figure 14: Biogas and biomethane production in the EU 53
Figure 15: Min and max values of the residues produced for Romania 54
Figure 16:: Min and max values of the residues produced for Poland 55
Figure 17: NUTS map of Romania with middlepoin 56
Figure 18: NUTS map of Poland with middlepoint 56
Figure 19: Scenarios transportation network Romania 57
Figure 20: Scenarios transportation network Poland 58
Figure 21: Visual representation of transport network 59
Figure 22: LCA calculation glycerine Romania 60
Figure 23: LCA calculation straw pellets Romania 61
Figure 24: LCA calculation straw Romania 62
Figure 25: LCA calculation sunflower husk pellets Romania 63
Figure 26: Life cycle HoSt 64

Glossary

Abbreviation	Definition or meaning
AD	Anaerobic digestion
BCM	Billion cubic metres
BMP tests	Biomethane potential tests
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxide
EU	European Union
IRR	Internal rate of return
KPI	Key performance indicator
LCA	Life cycle assessment
LNG	Liquefied natural gas
Nm^3/h	Normal cubic meter per hour
NUTS	Nomenclature of territorial units for statistics

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

1. Introduction

In this first chapter the company and the problem given by the company is introduced. The problem is introduced, in this the core problem, problem cluster and problem solving approach are discussed.

1.1 Company introduction

HoSt is one of the leading companies in the bioenergy industry, the headquarters are located in Enschede. HoSt has over 200 engineers and a big service team all over the world. HoSt specializes in waste-to-energy systems, these systems provide a sustainable way to transform biomass and waste streams into biogas and bioenergy. HoSt is a technology provider, but also owner and operator of multiple bio-energy plants, such as in Waalwijk (HoSt Bioenergy systems, 2019).

The site in Waalwijk is known as WABICO and is a biogas installation. In this installation biomass and waste streams are processed to biogas. On the site there is a biogas upgrading unit to upgrade the biogas to natural gas quality. The capacity of the installation is 1,900 normal cubic meter per hour (Nm^3/h) biogas that is upgraded to 1,200 Nm^3/h biomethane. Normal cubic meter per hour means the Nm^3 is the standard value of volume occupied by matter under normal conditions (LawInsider, n.d.). When the gas is processed to biomethane with natural gas quality it is injected in the gas grid or processed to Liquefied Natural Gas (LNG) or compressed to compressed natural gas (CNG).

1.2 Main problem

HoSt transforms organic waste streams and biomass into renewable energy and biogas. Most of the waste streams and biomass are collected locally and processed there. However, there are many waste streams around the world which are not utilised right now. The best solution would be to process these streams locally, but it is not possible to build a plant at every location. Right now there are streams which are unused or even burned on the land. This is a waste of energy and this leads to more greenhouse emissions. To transform biomass to biogas is a more sustainable way (Ellen MacArthur foundation, n.d.). There is no short-term solution for these organic waste streams, so HoSt wants to investigate the sustainable feasibility of transporting these streams to the Netherlands.

At the moment HoSt has a biomethane production facility in Waalwijk with a biogas installation, biogas upgrading system and CO_2 capture and liquefaction installation. This installation processes streams such as vegetable waste, flotation sludge and supermarket waste. These streams are also known as feedstock (Stahl, n.d.). After the biomass is processed to biogas, the biogas is upgraded to green gas with the quality of natural gas. Right now there is only one installation at the site in Waalwijk, but there is an option for HoSt to buy another plot of land. The location in Waalwijk is located at the river Maas, which is a logistically strategic position. This is interesting since the organic waste streams needs to be imported from different parts of the world. HoSt wants to know whether it is feasible to get the streams to the Netherlands. This needs to be feasible from a sustainable perspective. A sustainable perspective consists of three pillars: economic-, social, and environmental pillar (Investopedia, 2022). This means that an sustainable perspective also covers the financial part, which HoSt is interested in. The social perspective has been covered in philosophy of science and business ethics. HoSt wants to know whether it is feasible to get the feedstock streams to Waalwijk and process them here in the proposed new facility.

1.3 Problem identification

The principal problem is very broad and needs to be defined to a manageable project. For that we need to find out what the problems are the company encountered and why they have not started to import these feedstock streams already. To find out why these feedstock streams are not utilised yet we need to conduct research within the company and talk to the employees. HoSt knows of the existence of these feedstock streams, but does not know where they are located exactly and what is done with them. HoSt does not know how to get the feedstock to the Netherlands, so a transportation network has to be set up. This means that HoSt does not know if importing these streams is feasible for them from an economic and sustainable point of view.

Another aspect that the company does not know is the quality of these feedstock streams, so the return in energy of these streams cannot be calculated. With a sample of the feedstock this can be resolved, getting a sample would help in calculating the returns and the carbon intensity. Analysing samples takes around 40 days, because they have to be digested. That might form a problem for the outcome of the research.

1.3.1 Action problem

It became clear why HoSt wants to find out more about these feedstock streams. The goal for HoSt is that 40% of revenue should come from own sites, so not the sales projects, but from the installations owned and operated by HoSt. This is now about 20% which is far off the goal they set for themselves. One could say that HoSt could simply built new installations and run these until the goal of 40% is reached. Right now in the Netherlands there is not enough feedstock for HoSt to build and run all these installations. That is why HoSt are looking for new feedstock streams to run these new plants on. Right now HoSt is developing seven new projects in Poland, since there is a lot feedstock available there. These are installations which are owned and operated by HoSt. The development of these project take time and this means that these feedstock streams are not utilised right now. Even after these installations are built there, there is a lot of feedstock still unused.

1.3.2 Problem cluster

The company wants to know whether importing feedstock streams to Waalwijk from abroad is feasible. The feedstock streams need to be processed in the plant and the quality is important in the process. When there is, for instance, a lot of sand in a batch of feedstock it is less efficient to process this and gives a lower return than a stream without sand in it. This would also mean that the plant needs to be cleaned out.

HoSt already has specific guidelines for the costs of these streams. According to HoSt a plant is viable when the internal rate of return (IRR) is 15% or higher, this is a very interesting Key Performance Indicator (KPI). These costs consist of purchase price of the feedstock and transportation costs. Since the location of feedstock streams are not exactly known and therefor the transportation network is not known, this makes it hard for HoSt to determine the cost of these feedstock streams. Another goal and KPI for HoSt is that the carbon intensity of the produced gas should be at least 70% lower than a fossil fuel alternative. This 70% includes all forms of CO_2 emission, so the emissions from transportation and the processing of these streams and so forth.

This assignment is not merely to find out the feasibility of the site in Waalwijk, but it has a broader scope than that. HoSt is interested in these feedstock streams, because some of these streams remain unused. These streams are not used in some countries, which is bad for circular economy(Ellen MacArthur foundation, n.d.). The goal of 40% revenue from installations in own management will not be achieved with just the new site in Waalwijk, so the problem is not fixed completely after this project.

1.3.3 Core problem

The core problem can be formulated as: "The problem that will have the greatest impact at the lowest amount of costs" (Heerkens & Van Winden, 2017). Another characteristic for the core problem is that it can be influenced. For example some countries have not developed a way to inject the green gas back in the natural gas network, this is something that cannot be influenced by HoSt. Another problem that is very hard for HoSt to influence is getting permits, so this is not considered as core problem. problems which cannot be influenced does not need researching. And another characteristic of a core problem is that it does not have a cause itself. The core problem here is: **Not enough feedstock available in the Netherlands.**

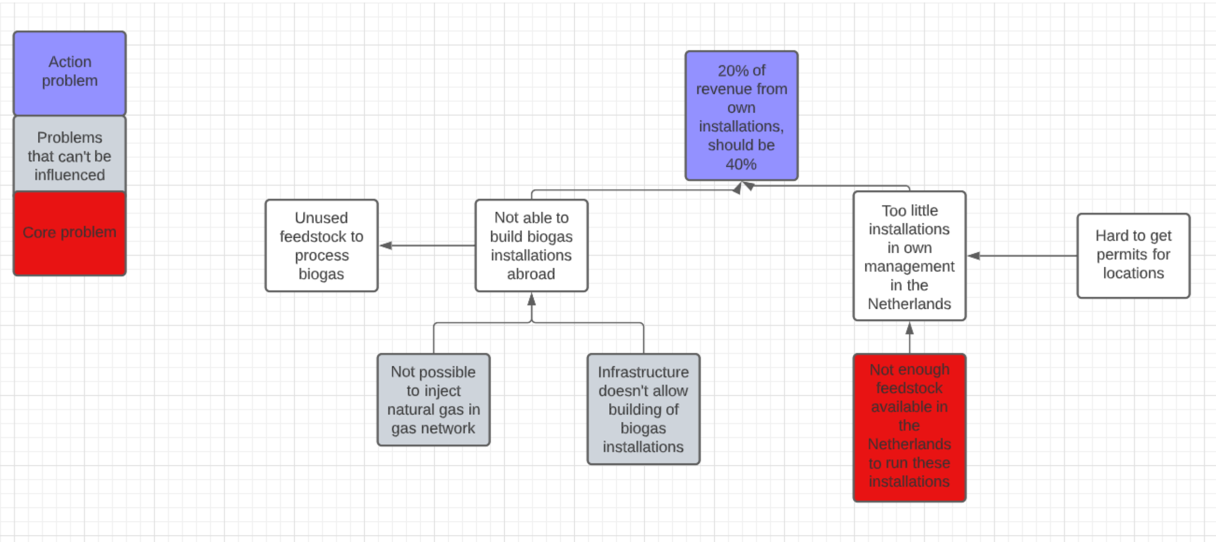

Figure 1: Problem cluster HoSt

1.4 Theoretical framework

A vital aspect for HoSt is the carbon intensity of the whole process, this includes collection, transportation and processing, to find out if this goal is achieved a Life Cycle Assessment (LCA) needs to be conducted. LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences (International Organization for Standardization, 2006a). HoSt uses LCA a lot, these are not as elaborate as the LCA's found in literature.

LCA can help decisionmakers in making the right decisions (Yu, 2021). In the case of HoSt it helps determining if the goals of carbon intensities are achieved, if this is not the case waste streams are not interesting anymore. The LCA alone does not give the final decision on what stream should be imported, like mentioned before HoSt has some guidelines which needs to be achieved. Importing the feedstock streams have to be sustainable, so this means that carbon intensity goals are accomplished as well as the financial aspect.

To find out more about how LCA works a literature review was conducted. After reading the literature and getting to know everything that needs to be known an LCA was conducted to find out what the environmental impact is of the different feedstock streams.

1.5 Problem solving approach

To make sure the research is conducted properly, a problem solving approach needs to be established. In order to do this, the D3 principle was used. D3 stands for Do, Discover and Decide (Heerkens & Van Winden, 2017). All the activities that needs to be done have been mentioned and explained, this varies from simple to harder tasks. The next step is asking the right questions, this helps solving the core problem. Then we have to decide on who and what to involve for the research.

The problem has to be mapped, we have to know what the problem exactly is and why HoSt wants this fixed, that is done already in the problem identification stage. The second step is to find out how to do an LCA. To find out what feedstock streams can be imported, the kind of feedstock that can be processed needs to be identified. With this the returns of these streams can be calculated.

After that the streams in Poland and Romania needs to be identified and located. When it is known where feedstock is available, transportation networks can be set-up.

After this LCA can be performed to see if the 70% lower carbon intensity compared to fossil fuel alternatives is achieved, if this is not achieved a stream was not considered anymore. Selected streams were analysed by means of an LCA. The last aspect HoSt wants to know is if it is financially feasible to get the streams to Waalwijk, for this a case study was set-up. When all this was done conclusions were drawn up and recommendations were given. From all this a flowchart can be created to give a clear and visual overview of what needs to be done. Now research questions can be drawn up.

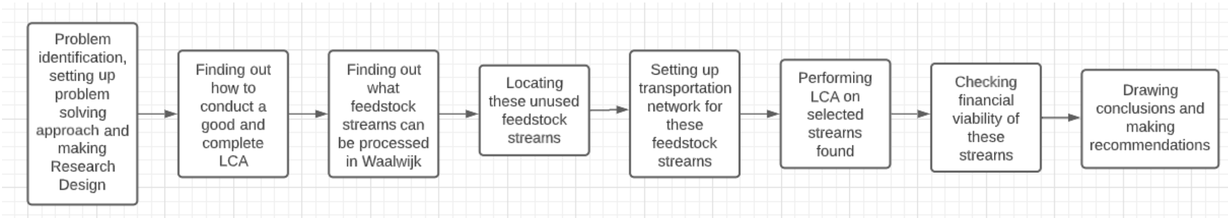

Figure 2: Problem solving approach

1.6 Research questions

Now that the problem is defined and the problem solving approach is known research questions can be drawn up.

The main research question for this research is: **How financially and environmentally feasible is it for HoSt to import feedstock streams from Poland and Romania to Waalwijk?**

To answer this main research question sub-questions need to be set-up which helps guide towards the final answer.

Sub research question 1: What are the aspects to perform an LCA?

This sub-question is needed, because HoSt wants to know what the CO_2 intensity is for the whole process. This process includes, collection, transportation and processing. Like mentioned before HoSt wants the carbon intensity of the produced gas to be at least 70% lower than a fossil fuel alternative. This sub research question was answered by means of a systematic literature review, which is part of this project plan.

Sub research question 2: What feedstock can be processed in a biogas installation?

The feedstock that can be processed was researched, this was needed to see what types of feedstock needed to be researched.

Sub research question 3: Where are these feedstock streams available in Poland and Romania?

After researching what feedstock can be processed they need to be located in Poland and Romania. A sample of feedstock makes it possible to give accurate calculations about the returns and make the best LCA possible.

Sub research question 4: What do the transportation network of these feedstock streams look like?

This question is the most relevant for HoSt. This question influences the next two sub-questions. It is also important because this is shows HoSt how to get the different streams to the Netherlands.

Sub research question 5: What is the carbon intensity on selected streams?

To answer this question, LCA was used. HoSt has the guideline that the carbon intensity of the produced gas should be at least 70% lower than a fossil fuel alternative, otherwise the stream should not be considered. This is HoSt policy and a hard constraint for every stream of feedstock. For this the process as a whole should be mapped to find the right inputs and outputs. This process includes collection, transportation and processing of the feedstock.

Sub research question 6: What is the internal rate of return for the streams?

HoSt makes choices of building plants based on the internal rate of return (IRR). This IRR should be higher than 15% to even consider the option. This 15% is high, but there are risks involved for HoSt. There risks are, changes in gas price, changes in feedstock price and the plant to shut down at times.

From all the sub research questions the main research questions was answered and conclusions were drawn. After all sub questions are answered recommendations on different streams can be made to HoSt.

1.7 Outline of thesis

In this section the outline of the thesis is discussed chapter by chapter. In Chapter 2 the literature review part can be found. Chapter 2 can help in understanding the contents of the report. Chapter 3 shows the process of AD of HoSt and the inputs and outputs of AD. The inputs found in Chapter 3 helps in Chapter 4. Chapter 4 is about the availability of feedstock and where the feedstock is available. Chapter 5 shows the way of transportation for feedstock, multiple scenarios have been analysed and used in this chapter, to eventually come up with the cheapest route to get the feedstock to the Netherlands. The results in Chapter 5 will be used in Chapter 6, where the LCA is performed. To perform the complete LCA transporting routes were needed. Chapter 6 provides the CI-scores which are important to analyse if importing feedstock is feasible. Chapter 7 goes further into depth of the costs of the whole process of HoSt. All the information gathered from Chapters 2 to 7 will be used in Chapter 8, the concluding chapter.

2. Literature review

In this chapter the relevant literature for this research is discussed, this chapter helps in understanding the concepts used in the research. A systematic literature review was conducted to answer the first sub-question.

2.1 Systematic literature review

One research question was answered by means of a systematic literature review. The research question that was answered is: **What are the aspects to perform a good and complete LCA?**

This question needs to be answered in order to answer the main research question at the end of the research. This LCA gives the carbon intensity of the different streams, this is a very important aspect. That is the main reason for answering this research question in this section.

2.2 Life-cycle-assessment

LCA have many applications in many different fields. LCA helps decision makers in making decisions, it gives insight in the environmental impacts of processes and it can help with marketing of products. (International Organization for Standardization, 2006a) There is a framework and methodology for doing a LCA.

A LCA consists of four phases:

- The goal and scope definition phase
- The inventory analysis phase
- The impact assessment phase
- The interpretation phase

Every phase has its own goal and way of working, these are explained more elaborately. All the phases are related and complement each other.

The goal and scope definition phase

The goal and scope must be clearly defined to do a good LCA (Chiaramonti, 2010). The goal should include: the reason for doing an LCA, for whom the LCA is intended and for what the LCA will be used. The scope is a very broad defined phase of the LCA. The scope should mention what technologies are reviewed and what their functions are. The assumptions made for the LCA should be mentioned here and the limitations of the LCA as well.

Impact categories need to be determined in the scope. Different wastes and emissions come from a process and these all impact something else, for example global warming or ozone depletion. There are 15 different impact categories, which are not all mentioned, these impact categories all have their own units in which it can be measured (Hillege, 2022). So in the scope the impact categories which are under review are mentioned.

The system boundary has to be defined in the scope. The system boundary is the boundary of what should be considered from the process in the LCA, think about the different life cycle stages of a product. To get a good view on what should and should not be considered, a good view of the whole process must be present. To get a good view a process flow diagram can be used and from this the system boundary can be set up (International Organization for Standardization, 2006a).

The inventory analysis phase
The inventory analysis phase consists of data collection and how one calculates the inputs and outputs of the system boundary. Data inputs and outputs should be mapped for all the different processes within the system boundary, this also involves waste and by-products. This can become very extensive, therefor constraints should be put on what and what not to consider. The researcher has to explain the assumptions made for leaving out data. The data that has been collected has to be validated and should be related to different unit processes. When processes are performed energy is used and sometimes energy or heat is used, this is important to keep in mind during the inventory analysis phase.

LCA usually consists of three stages: raw material acquisition, product manufacturing and end use and disposal (Wang, 2021). All these stages should be kept in mind during the inventory analysis, keep these stages in mind to make it easier to get a good view of all the inputs and outputs.

The impact assessment phase
In this phase the results from the inventory analysis phase are evaluated. The data from inputs and outputs found will be linked to different impact categories. This assessment is also linked back to the goal and the scope of the LCA, in this phase one can check if the goals of the research are accomplished. To make sure this phase is conducted properly it should be separated into different elements (International Organization for Standardization, 2006b). There are some mandatory and optional elements for the impact assessment phase, these can be found in appendix A.

Life cycle interpretation phase
In this last phase the findings of all the phases which are mentioned are combined. This phase should give results which align with the goal and the scope of the research. From this interpretation the researcher should be able to make recommendations and give conclusions. After this an easy to understand representation of the results of the LCA should be given. This makes it easier for the researcher to give recommendations and draw conclusions.

LCA tools
There are multiple LCA tools, we have to decide which tool to use during the research. Some of the LCA tools available are discussed.

OpenLCA
OpenLCA offers a free to use LCA tool, it is fast and reliable and user friendly. The tool gives a reliable and detailed insight in the calculations that are done (OpenLCA, n.d.). Life cycle costing and social assessment is also integrated in this tool. Life cycle costing can be useful, the social aspect was already done in the project plan. OpenLCA can be used in many different fields of industry, such as bike sharing, renovations and copper mine operations.

Ecochain
Ecochain is a LCA tool which has to be paid for, but there is a free trial for two weeks. Ecochain offers two different types of tools. One is called Helix, this measures the impact on the environment for products. The other is Mobius, which helps in designing sustainable products (Ecochain, 2023). For this research Helix is the best option, since HoSt is interested in the carbon footprint. It has many different applications, but the main is in the manufacturing industry.

Biograce 2
Biograce 2 offers a free to use LCA tool. This tool is specifically designed for calculations of greenhouse gas for electricity, heat and cooling from biomass (Biograce, n.d.). Biograce 2 offers a big database, with input values for different countries in Europe. It also offers data emissions of multiple ways of transport.

For this research Biograce 2 was used, because this is a tool specialized in electricity, heating and cooling from biomass. HoSt makes biogas from biomass, so this tool fits the case.

2.3 Waste pyramid

The waste pyramid, sometimes referred to as waste hierarchy, is a simple ranking system which ranks the different waste management options from best to worse (ISM, 2021).

Prevention

This means preventing waste at all costs. When there is no waste in the first place it does not have to recycled or landfilled. This can be done by designing and manufacturing with less materials. If this is not possible, go one step down in the waste pyramid.

Re-use

When prevention is not possible re-use is the next best option. This means reusing whole products or reusing certain parts of the product. Many products can be reused after being cleaned, repaired or refurbished. This option does not dispose of the wastes yet.

Recycling

From this option on the waste is disposed of. In recycling raw materials are retrieved from the products. These raw materials can then be used as raw materials for the next product or the recycled material can be turned into a new product.

(Energy) recovery

The next option is (energy) recovery, also known as waste-to-energy. For waste that cannot be recycled energy recovery is the best option. This option helps in reducing society’s reliance on fossil fuels.

Disposal

The last and least favourable option is disposal of waste, this means landfilling or burning the wastes. Often this option costs a lot of money, this is to drive companies to use one of the other options mentioned.

2.4 Butterfly diagram

The butterfly diagram, also known as the circular economy system diagram, shows the flows of materials in a circular economy (Ellen MacArthur foundation, n.d.). In this diagram there are two cycles, the technical cycle and the biological cycle. The technical cycle is closely related to the waste pyramid, it shows the best way of managing waste. The ways also mentioned in the waste pyramid are re-use, recycling and refurbish. The biological cycle is about saving nutrients and giving these back to earth (Ellen MacArthur foundation, n.d.). Figure 3 shows of the butterfly diagram. The smaller the loop in the figure, the better option it is in terms if circularity. So re-use is better than recycling, the waste pyramid also shows this.

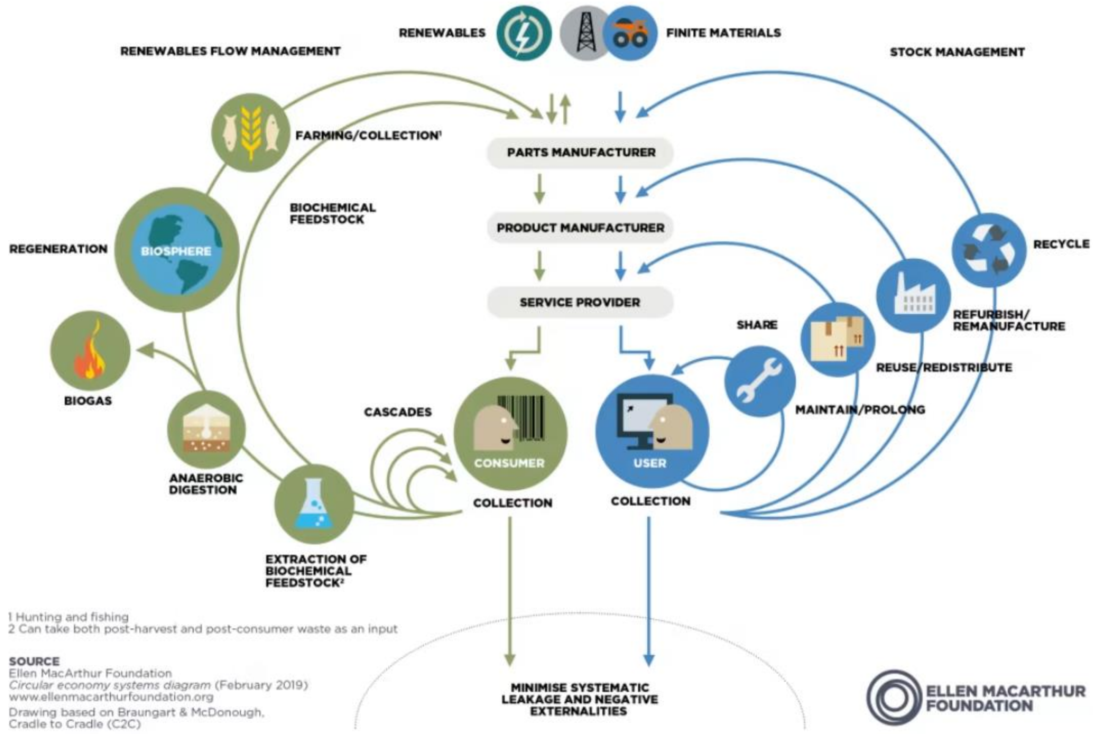

Figure 3: Butterfly diagram, Source: https://ellenmacarthurfoundation.org/circular-economy-diagram

2.5 Generations of biofuel

The two main generations of biofuel are first and second generation biofuels. There are differences in what kind of feedstock both generations use. There are third generation biofuels, this has to do with algae, third generation biofuels are not discussed.

First generation biofuel

First generation biofuels are produced from crops straight from the field. The most used crops for this are maize, cereals and sugar beet (Biofuel Express, n.d.). This is in battle with food production, this brings up the fuel vs food discussion. This means that the area of land which is used for fuel can also be used to cultivate food (ETIP, n.d.).

Second generation biofuel

Second generation biofuels are produced from residues from agriculture and residual food streams, like straw from the fields and used frying oils from restaurants (Biofuel Express, n.d.). There are many more residual streams which can be used as a feedstock.

2.6 Availability and localizing feedstock

There is enough feedstock available in the European Union (EU) to reach the goals that are set within the EU (Gas for Climate, 2022). Today only three billion cubic metres (BCM) green gas has been produced in the EU and the goal set for 2030 is 35 BCM (Guidehouse, 2022). The production of this green gas should be expanded with 32 BCM, which is about eleven times the green gas produced now. This means that rapid development in the field of green gas production is absolutely necessary. There is enough feedstock to produce this gas, so there are a lot of opportunities to get feedstock within Europe. One of the ways to work towards to this goal is to import the streams from the countries where there are no biogas installations yet and transport to countries where there are biogas installations. Development in these countries can take time and the short term solution would be to process it in places where there are biogas installations.

The availability and location of feedstock have been determined. First a country selection was made, for this multiple sources of literature are used. To check in what countries there is feedstock available the report: “Biomethane production potentials in the EU (2022)” is used. This report shows biomethane potentials for countries in the EU. This was used to check where a lot of feedstock is produced. The next step is to check whether this feedstock is not used yet, to do this the biomethane and biogas that is produced in these countries have to be evaluated. This was reported by the IFEU (2022), in this report the biomethane and biogas production per country in the EU is reported. From these two reports availability of feedstock in the countries can be deduced.

The next aspect is to check in what regions in the countries there is feedstock available. Scarlat shows a way to do this. Scarlat take into account some country and crop specific characteristics. These characteristics have to do with the residue produced per crop. Residues are produced from crops, but every crop produces different amounts of residues. The so-called residue-to-crop ratio determines the residues produced per crop. EUROSTAT reports data on how much crops are produced, per region in a country. This data in combination with the crop-to-residue ratio is used to check the produced residues in specific regions. Scarlat et al. takes into account the competitive uses of the residues, like soil enrichment.

2.7 Modes of transport

Transportation means moving a product from one location to another (Chopra, 2019). For setting up transportation networks the book, supply chain management by Chopra (2019) is used. Different modes of transport have been discussed.

Grain is mainly transported by sea, road and rail. Often various transportation modes are used to get the grain to the location where it needs to go (Miller Refereed, 2022). This is not a research into grain, but the way to transport feedstock is the same. Grain is transported mostly in bulk, so are the residues. Often bulk is not packaged when it is transported, sometimes it is packaged. When transporting big quantities it is better to transport the material unpackaged. In this case it is better to transport it while it is not packaged, because that safes costs and wastes. Also the material goes into the digester unpackaged.

2.7.1 Transport by boat

For the transportation of bulk cargo over water there are so-called bulk-carrier boats. Bulk carriers transport raw material that need to be processed elsewhere. Typical cargo transported by bulk carriers are ores, coal and grains (International Chamber of Shipping, n.d.). These are all unpackaged material which are shipped in large quantities. These bulk carriers come in all kind of different sizes, ranging from 10,000 tonnes up to 200,000+ tonnes (USDA, n.d.). Transport over sea is the most carbon-efficient way of moving cargo. Another positive aspect about sea shipping are the costs, it is most cases the cheapest way of moving cargo (Chopra, 2019). A challenge for transportation by boat is the accessibility to specific sites. When it is delivered to a port, the cargo has to move from the port to another location, which has to be done by trucks and/or trains.

2.7.2 Transport by train

Transport by train offers a relatively sustainable and cost-effective way of transporting large amounts of cargo, because of the heavy load capabilities (Chopra, 2019). Many destinations in Europe can be reached by train in a fast way, comparing it to truck and sea transport (Chopra, 2019). Train transport is more fuel efficient and it is cheaper, compared to truck transport. Train transport is about three to four times cheaper and fuel efficient (Freight course, n.d.). That is mainly due to the fact that a train can transport as much as 300 trucks can (Union Pacific, 2022). The challenge, however is that the trains can only travel on the rail network, whereas trucks can move on the roads, which makes that trucks can access more places. Again in this case the cargo has to be shipped from a train station to the specific location.

2.7.3 Transport by truck

Truck transportation has the unique characteristic that it offers door-to-door delivery (Chopra, 2019). It is, like mentioned before, more expensive than trains and by sea. Mainly due to the fact that a truck cannot carry as much cargo as a train or a boat. Another cost is the fuel for trucks, a truck needs much more fuel per tonne transported, than train and boat. The biggest advantage for a truck is that it can deliver directly to the customer and does not need any other action or alternative transportation mode.

2.7.4 Intermodal transportation

"Intermodal transportation is the use of more than one mode of transportation to move a shipment to its destination" (Chopra, 2019). There are several ways of intermodal transportation. For example a boat arrives in a port and trucks have to get the products from the ports to the manufacturer. Intermodal transportation has gained increased attention over the past few years. Intermodal transportation also comes with challenges, because there are multiple transporting companies involved. This means that there are more transfers of information, which can lead to disturbances in the supply chain (Chopra, 2019).

2.8 Conclusion

The four phases of the LCA are defined and explained. The four phases are: The goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase. All the phases do not look very big and ambiguous. A process can have many different aspects and sub-processes. There are many factors which have to be taken into account. To get a good view of all the inputs and outputs one should have a good view on the process which is researched.

Multiple LCA tools are evaluated, the tools all consider different types of industries. Biograce 2 is used for the research, since this tool is specifically made for calculations of greenhouse gas for electricity, heat and cooling from biomass (Biograce, n.d.).

The waste pyramid is a ranking system that shows the most to least favourable way of waste management (ISM, 2021). The order is: Prevention, re-use, recycling, (energy) recovery and disposal.

The butterfly diagram represents the circular economy. This diagram consists of two cycles: the technical cycle and the biological cycle (Ellen MacArthur foundation, n.d.). The smaller the loop in the butterfly diagram, the better the option is. This diagram is all about closing the loop in a circular economy.

Two generations of biofuels are discussed and the differences are mentioned. First generation biofuels are biofuels made from crops specifically cultivated for energy production. Second generation biofuels are made from residues and wastes (Biofuel Express, n.d.). First generation biofuels bring up the food vs fuel discussion, this is not the case for second generation biofuels.

There is enough feedstock in Europe to reach the goals set for 2030 (Gas for climate, 2022). Rapid development in the production of green gas is needed to reach the goals. One of the ways of reaching the goal is to transport available feedstock to places where it can be processed to green gas. The biomethane potential in different countries have been analysed along with the biogas and biomethane produced in different countries in the EU. This helps in determining availability of in different countries in the EU.

Scarlat shows a way to localize feedstock per region in a country. To do this multiple aspects have to be kept in mind. Some country and crop specific characteristic have to kept in mind while localizing feedstock. The residue-to-crop ratio determines the residues produced for a specific crop. EUROSTAT shows the data on where and how much crops are cultivated in specific regions. The crop-to-residue ratios are then used to see how much residues are produced in the regions. There are competitive uses for the residues, so these have to be accounted for. From this a availability for energy purposes can be deduced.

Different modes of transportation are analysed and the advantages and disadvantages of the modes are discussed. Transport by truck, train and boat have been discussed. Truck offer a door-to-door way of transporting, but is more expensive and have a big carbon footprint compared to train and boat. Train is relatively fast way of transporting big quantities. It is cheaper and emit less CO_2 than trucks, but the disadvantage is that the product has to be moved from the train station to the buyer. Sea transport is the most carbon-efficient and cheapest way of moving cargo (Chopra, 2019). From the port the cargo still has to be moved to the specific sites, this a challenge.

The literature for the research is discussed in this chapter and can be helpful in understanding the research that has been conducted.

3. Anaerobic digestion process of HoSt

Anaerobic digestion (AD) helps closing the loop and this is better for the environment and makes sure that all the products are used as efficient as possible (Ellen MacArthur Foundation, n.d.). The process which produces biogas from biomass is called AD, HoSt is specialized in this process. HoSt wants to know if importing feedstock for AD is feasible. To have a good understanding of the process, it is discussed here first. After the process is discussed the inputs and outputs are analysed. The inputs of the process have been looked at, since this is the feedstock that needs to be imported. The outputs are discussed and what value the outputs have. The inputs found in this chapter will help in chapter 4 with selecting at what type of feedstock will be looked at.

3.1 AD process

This part is partly done specifically for HoSt sites. HoSt has patents and unique innovations, these innovations come through continuous R&D (HoSt Group, 2023). An overall description of the AD process is given.

When the feedstock arrives at a biogas plant it is put into a tank for liquid materials or into so-called solid feeding system for solid materials. After that the feedstock is put into the first digester, called the primary digester. In this digester there are bacteria which break down the organic material in the digester. The organic materials in the digester are continuously mixed, to make sure that all the organic material is processed and to prevent a floating layer. If there is a floating layer not all the material are affected by the bacteria in the tank, which reduces the return. These mixers result in maximum organic matter degradation and gas production per tonne feedstock (HoSt Group, 2023). After the first digester the organic material is pumped into the second digester. This second digester makes sure that the returns are even higher than just using the first digester. When this process is done there are two materials that come out of the digesters, biogas and digestate. Digestate comes from the bottom of the digesters and the gas comes from the top side. CO_2 comes from the process, also the use of CO_2 is discussed.

HoSt offers several ways of using the biogas obtained from AD. One of the most used ways is biogas upgrading. A biogas upgrading plant is designed to upgrade the biogas to biomethane, which can be used as a substitute of natural gas. This upgrading goes through patented membranes, where the CO_2 and the methane are separated very efficiently. In this way over 99% of the methane can be recovered from the biogas. The biomethane can be injected directly into to gas grid, it can be compressed to CNG and it can be liquefied to LNG. The last two options can be used as a sustainable transport fuel. Another application of the obtained biogas is producing renewable electricity and heat in a so-called combined heat and power unit (CHP). In these CHP units electricity and heat is generated with the biogas. The last and least favourable is burning the biogas with a biogas flare, this is least favourable since this is disposal of waste (ISM, 2021). This is only done when there are irregularities, when for some reason the gas cannot be injected back into the gas grid or the CHP unit is undergoing maintenance (HoSt Group, 2023).

HoSt is against wastes and this means that they try to use every output of the process. Even the CO_2 that comes from the process has useful purposes and it generates income. The CO_2 can be upgraded to food-grade CO_2 (HoSt Group, 2023). This CO_2 has several uses, for example the air that is in a bag of crisps. Figure 4 shows the flow diagram of the process.

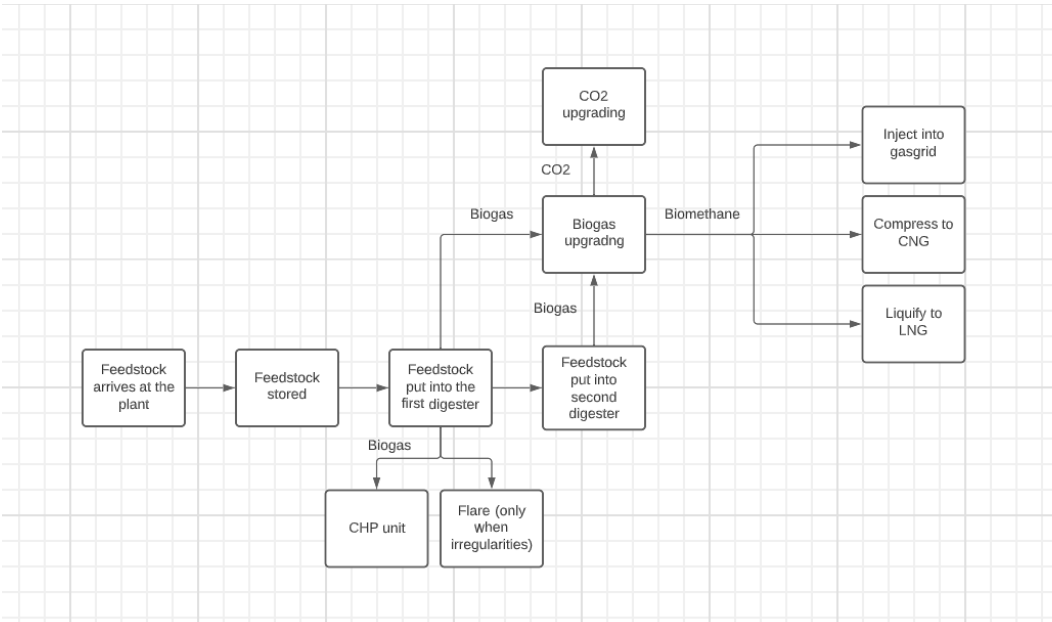

Figure 4: Flow diagram of AD process

3.2 Inputs of AD

Almost all organic matter can be used as feedstock for AD. "Input streams for the digester can be manure, expired food, straw, chaff, grass cuttings, slaughterhouse waste, sludge, fats, and many more (HoSt, 2023)."

HoSt is mainly interested in agricultural residues, since these are often burned on the field. This is a bad option for managing waste, since this means the wastes are disposed (ISM, 2021). Also wate streams of industry are interesting, one of the waste streams that has a very high return and HoSt is always interested in is glycerine. So the residues from industry are limited to glycerine. Glycerine comes as a by-product in for example animal- and plant fats (e.g. sunflower oil production) and from the production of biodiesel (Santhakumar, 2021).

The agricultural residues are limited to residues of cereals, rapeseed and sunflower. Cereals are the most cultivated crops in the world (Sadhukhan, 2022). Since cereals are the most produced crops in the world there are lots of residues. Residues from rapeseed and sunflower are discussed, because these are so-called oil crops, these have high returns on average (Biogas calculator, n.d.). These are the main inputs that are considered during this research.

3.3 Outputs of AD

AD gives two outputs: biogas and digestate (AGSTAR, 2022). The biogas that comes from AD consists primarily of methane, carbon dioxide and hydrogen sulphide. Methane is the component which is in natural gas. Natural gas is used every day in modern society and is a fossil fuel (AFDC, n.d.). Biogas can be used as a substitute of natural gas. The percentage of methane in biogas differs a lot, but it is often in between 50-75%. This biogas has multiple applications, it can be used for heating and generating electricity, using a CHP unit (AGSTAR, 2022). The biogas can also be worked up to natural gas quality, after that the gas is called green gas, this once again comes with different ways of using it. The green gas can be injected into the gas grid, where it is mixed with the natural gas which is already in the gas grid. One cannot distinguish between natural gas and green gas. Biogas and green gas have countless other uses which are not discussed, the applications mentioned before are the main applications used by HoSt.

CO_2 and digestate are the main residues that come from the AD process. Digestate consists of a solid fraction and a liquid fraction. These are treated separately, since both have different uses.

Solid digestate is mainly used as a fertilizer. During AD no nutrients are lost and this means that the fertilizer is nutrient rich. Using the digestate as a fertilizer closes the loop for these valuable nutrients (Ellen MacArthur Foundation, n.d.).

Another good aspect about using the digestate as a fertilizer is that it poses a lower risk to nature compared to a traditional fertilizer. The nitrogen stored in common fertilizers come out very quickly, which sometimes means the ground and plants cannot absorb it. Whereas digestate as fertilizers releases it to the ground and plants slowly over a period of 3 years (European Biogas Association, n.d.). Another feature about using digestate as fertilizers are the energy and water savings, compared to artificial fertilizers. One tonne of artificial fertiliser replaced with digestate saves one tonne of oil, 108 tonnes of water and 7 tonnes of CO_2 emissions (European Biogas Association, n.d.). This shows that the use of digestate as a fertilizer is very promising. The farmers that use digestate instead of artificial fertilizers save money. Artificial fertilizers are a large expense in for farmers, sometimes even the biggest expense (European Biogas Association, n.d.). Using digestate saves money, especially when a farmer has an own AD plant. HoSt offers specialized ways of separating the liquid and solid fraction, this increases efficiency in the plants build by HoSt (HoSt Group, 2023).

The liquid fraction of digestate can also be used as a fertilizer, since there are valuable nutrients in the liquid fraction. Then there are three other ways for HoSt to treat the liquid fraction. The first option is that the liquid fraction is send to a water purification site. The liquid fraction is treated there and a sludge is a by-product from this process (CAMBI, n.d.). This sludge can be treated again by AD to get biogas. This is a favourable way, because the liquid fraction is used to its full potential. Using the liquid fraction in this way helps closing the loop (Ellen MacArthur foundation, n.d.).

The second way of using the liquid fraction is using it as a ‘water’ supply in AD. For AD water is needed, so the feedstock can be circulated continuously. For example when straw is treated, water is needed to make sure it can be circulated. Instead of using clean water every time, the liquid fraction can be used to pump around the digesters. This lowers the water usage and once again helps towards a circular economy (Ellen MacArthur Foundation, n.d.).

The last and least favourable way for HoSt to treat the liquid fraction is to have it disposed of. Sometimes liquid fraction cannot be used in the aforementioned ways. Sometimes the liquid fraction does not have other uses. This means that HoSt has to dispose of the liquid fraction. To have it disposed of HoSt has to pay money for it (ISM, 2021). This also means that the liquid fraction does not have other uses, which means that the liquid fraction becomes a waste. This is the least favourable option since this does not close the loop (Ellen MacArthur Foundation, n.d.).

3.4 Conclusion

AD offers a promising way in managing agri-cultural residues and turning the residues in valuable outputs namely: digestate and biogas. There are several different uses for both of these outputs. In AD bacteria slowly break down organic matter. Almost all organic matter can be processed in an AD site, so choices had to be made on what to look at. Glycerine is a very promising waste product from industries and has been looked at. The biogas can be worked up to natural gas quality and injected into the gas grad, liquefied to LNG or compressed to CNG. The inputs and outputs will be used during the LCA.

4. Localizing and availability of feedstock in Poland and Romania

In chapter 3 the AD process of HoSt was researched, also the inputs and outputs are mentioned there. Especially the inputs will help in this chapter. In this chapter sub-question 3 is answered. This question is formulated as following: **Where are organic feedstock streams available in Romania and Poland?** This chapter is important mainly to find out where feedstock is available. This is helpful for setting up the transportation networks in chapter 5.

The goal of HoSt is to build more installations to keep in own management, but there is not enough feedstock available in the Netherlands. This is to increase the revenue from installations in own management, which is too low in the current situation. That is the main reason for this research. HoSt wants to find out if it is feasible to import feedstock from abroad to the Netherlands to process the feedstock in the Netherlands. Right now there are many unused feedstock streams in the world and this has to do with bad disposal, utilisation and management practices (Tripathi, 2019). Since there is an increasing demand for food and other resources these waste streams get bigger, digesting these streams to biogas is a sustainable solution for the wastes. AD helps closing the loop, which is good for a circular economy (Ellen MacArthur foundation, n.d.). Many crop residues are burned on the land and this has a very big impact on global warming. Burning these crop residues is responsible for about 18% of the global emission of CO_2 (Tripathi, 2019). This indicates how important it is that these waste streams are utilised and how bad it is to leave these streams unused**.** There is a lot of feedstock available in Europe, but it is important to take a look at where there is a lot of unused feedstock. When the feedstock has no uses it is cheaper to buy it and this helps in achieving the economic goals of this research.

4.1 Country selection

When looking for potential feedstock to process in the Netherlands, one has to keep in mind the other uses of the feedstock. Some feedstock can be suitable for biogas production, but if this feedstock has already other purposes this cannot be considered. The feedstock really needs to be a residue or waste, it does not have other vital uses. HoSt is only interested in wastes and residues, since this is a second generation biofuel. When looking at the potential methane produced from AD in 2030 there are some big countries: Germany France, Italy, Spain, Poland, Romania, the Netherlands, United Kingdom and Hungary (Guidehouse, 2022). The United Kingdom is not considered, since they are not in the EU, this means that there are more challenges to get it from the UK to the Netherlands. The Netherlands is not considered, since the research is outside the Netherlands. The list with biomethane potentials can be found in Appendix B. This list is based on feedstock available in the different countries. The most interesting countries to look at are the countries where there is not much biogas and biomethane produced, since the feedstock is then mostly unused.

Right now Germany is the leading country in the production of biomethane and biogas. (IFEU, 2022) Germany is also the country with the highest potential, because so much is used already this makes it less interesting to look at. In appendix C, a picture can be found on the biogas and biomethane production per country. All the other countries mentioned before as the biggest potential countries do not produce much biogas and biomethane. This makes these countries interesting to look at, since much of the feedstock is not yet used in these countries. This would also mean that there is less competition that want to buy the feedstock. If there is more competition it would mean that the prices of feedstock would rise. It is important to look at what kind of feedstock is available in these countries. The countries which seem most interesting are: France, Italy, Spain, Poland, Romania and Hungary.

The main bottleneck for importing feedstock are the transporting costs of the feedstock. This means that it is best to transport feedstock which give a high return. Some of the organic waste streams contain a lot of water, which do not give high returns. This was analysed by inhouse biomethane potential tests (BMP tests) and the inhouse biogas calculator.

Another aspect that is important is that the waste streams should be close together, this makes it easier and cheaper to collect them. Another important feedstock stream to consider are the waste streams that come from industry, for example biodiesel plants (which produce glycerine as a by-product).

It is very hard to determine which feedstock has the biggest returns, since it also depends on the quality of the feedstock that is delivered. If there is a lot of water or a lot of sand in a batch the return is lower. HoSt has some historical data on a lot of feedstock, which have been analysed in the lab.

The two countries that were analysed for the research are Poland and Romania. Both Poland and Romania do not produce much biogas and biomethane, so there is less competition for the feedstock. HoSt is interested in Poland, since they are planning on opening some installations there. Now both countries are analysed separately.

4.1.1 Romania

To find out what waste-streams are available in Romania we have to look at what is cultivated in Romania. This was done by using EUROSTAT, they have data on how much crops are cultivated in different regions of the country. The most recent data on EUROSTAT was used to analyse this. Since HoSt is only interested in residues it is important to make sure that there are residues available. There are so-called residue-to-crop rates which gives an indication on how much residues are available with a given amount of crops harvested. Residue-to-crop ratio means: the ratio of the amount of residue generated to the amount of the main product of the crop (e.g. ratio of straw and grain in the case of cereals) (FAO, 2014). These productions are given in production per 1,000 tonnes. Romania was analysed on NUTS 2 level. The nomenclature of territorial units for statistics (NUTS) is a geographical system, according to which the territory of the European Union is divided into hierarchical levels (DEStatis, n.d.). The higher the level, the smaller the regions. NUTS 1 regions are bigger than NUTS 2 regions. The last aspect that has to be checked is the availability of these residues. This availability has to do with the other uses of the residues, such as soil enrichment.

First the production of different types of cereal were found. After this the crop-to-residue ration are used to find out how much residues come from the crops. The crop-to-residues ratio are found in literature by Scarlat. These crop-to-residue ratios are in min and max values. These min and max values are used to calculate the min and max values of the residues produced in 1,000 tonnes. The min and max values of the residues can be found in Appendix D. The average of the min and max values are used in the rest of the research. The crop-to-residue ratios are specifically for Romania. The residues are calculated by multiplying the produced amount of crops by the residue-to-crop ratio. The residue-to-crop ratios can be found in Appendix P.

For Sunflower and Rapeseed no data could be found on the production in NUTS 2 regions, but the overall production was found. For sunflower this was 2.200.000 tonnes (Our World in Data, n.d.).The national production for rapeseed in 2020 was: 780.160 tonnes (Our World in Data, n.d.). The highest yield of rape- and sunflower seeds are in the NUTS 2 regions RO31, RO32 and RO22, this is in tonnes/km^2 (Eurostat, 2014).

Now the average produced residues for different cereals, sunflower and rapeseed are known, the other uses of the residues was kept in mind. Like mentioned before the biogas production cannot disturb other uses of the residues, such as feed for animals and if the residues are used to plough under to make sure the land stays fertile. The average produced residues need to be multiplied by the availability for energy purposes to find the overall available residues. The availability for energy purposes can be found in Appendix P.

All the crops that were analysed give straw as a by-product, except from sunflower, these give husk. The return of straw is: 295 M^3 biogas per tonne. And from sunflower husk is: 243 M^3 biogas per tonne. The available residues for energy purposes, with the biogas potential can be found in appendix P.

For rapeseed the available amount of residue left for energy purposes would be: 620,227.2 tonnes
For sunflower the available amount of residue left for energy purposes would be: 3,135,000 tonnes

Biogas potential for Rapeseed: $1.830*10^8$ M^3 biogas
Biogas potential for Sunflower: $7.618*10^8$ M^3 biogas

Most of the cereal residues are located in RO31, RO41 and RO42. And for the sunflower seeds and rapeseed most RO31, RO32 and RO22. Al these regions are the most south regions of the country, this makes it easier to collect the residues. Like mentioned before it is necessary that the residues are located closely together, in the case for Romania they are close together in the south. So looking at the southern regions of Romania is best. In picture 4 the selected regions can be found, they are all located in the south of Romania. The regions highlighted in red are the regions with the highest availability.

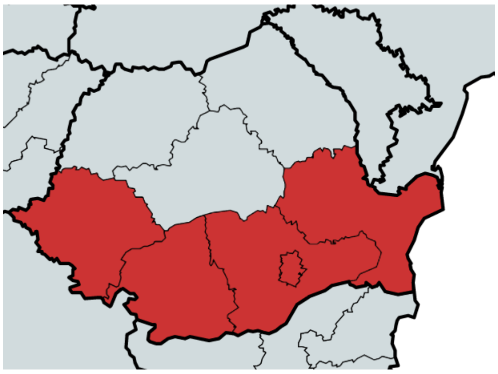

Figure 5: NUTS 2 regions Romania with highest residues available, Source: https://www.mapchart.net/europe-nuts2.html

4.1.2 Poland

The same method for finding the agricultural residues in Poland is used. To do this first the production was found in EUROSTAT with the most recent data available. After that the residue-to-crop ratio were found and used to calculate the residues. Again this was done in NUTS 2 regions. This gives indications on where agricultural residues are available.

Romania and Poland are different countries and have different weather, that is why there is a difference in the cereals produced. Some crops produced in Poland are not produced in Romania, this works the other way around as well. This means the list of residues is different for Poland compared to Romania.

The data was extracted from EUROSTAT. The residues that are released from this production are calculated, for this the Residue-to-crop ratio were found. For this the same ratios cannot be used that were used for Romania, because these ratios differ. These ratios are not the same for every country, that has to do with the differences in techniques and uses of residues. Another aspect that really influenced the residues left in the field is the drought, this changes each year, that makes it hard to determine one stable residue-to-crop ratio (Havrysh, 2021). Not for every crop data could be found on the residue-to-crop ratio for Poland specifically, for these the ratio for the EU is used. The crop-to-residue ratios can be found in appendix Q.

Min and Max values are given again for the residues, the average of the two was for the rest of the research. These averages are calculated in Excel. The Min and Max values can be found in Appendix E.

Poland produced about 14,850 tonnes of sunflower seed (Our World in Data, n.d.). This number is so small when comparing it to production of other crops that this is not worth considering. The production of rapeseed was 2.99 million tonnes (Our World in Data, n.d.). Once again the specific regions for the production could not be found, but the yields were found. The three regions with the highest yields are PL42, PL52 and PL51, with a yield of over 24 tonnes/km^2.

In appendix Q the availability for energy purposes can be found along with the average residues available for energy purposes.

Average produced residues for rapeseed: 5.083.000 tonnes.
For rapeseed the available amount of residue left for energy purposes is: 2,541,500 tonnes
Biogas potential for Rapeseed: 7.497*10^8 M^3 biogas

PL41, PL42, PL51, PL52, PL61, PL71, PL81, PL92 are the biggest producers of residues in Poland. PL41, PL61, PL71 and PL92 are located next to each other, this is all in Central-Poland. These regions would be best to look at for HoSt, since they are all close to each other. This makes it easier to collect residues. In picture 5 the regions can be seen, they are highlighted in red. These are the regions that will be used during the research.

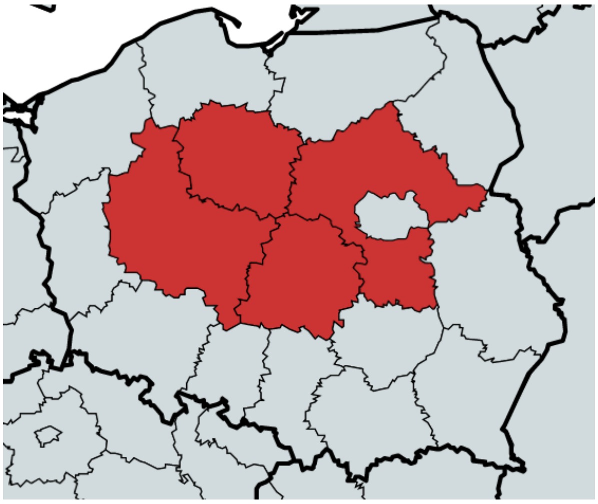

Figure 6: NUTS 2 regions Poland with highest residues available, Source: https://www.mapchart.net/europe-nuts2.html

4.2 Conclusion

In this chapter the regions where most residues are available have been determined for Poland and Romania. This is important to know, so transportation networks can be set-up from the regions found. This was done by finding the production of cereals, rapeseed and sunflowers. The production was found in NUTS 2 level on EUROSTAT. NUTS 2 level are regions within a country, every region has its own number and helps localizing the residues. There are so-called residue-to-crop ratios, this ratio give the residues produced from crops. These ratios are different per country and per crop type. After combining produced crops with the residue-to-crop ratio, the residues produced were found per region. The other uses of the residues have been kept in mind, from this an availability for energy purposes was found. Multiplying the produced residues with the availability for energy purposes give the residues available for energy purposes.

The regions in Romania with the biggest available residues for energy purposes are: RO22, RO31, RO32, RO41 and RO42. These regions are located in the south of Romania. For Poland the regions with the most residues available for energy purposes are: PL41, PL42, PL51, PL52, PL61, PL71, PL81, PL92. These regions are located all across the country, but it is better that the regions are close together for easier collection. Regions PL41, PL61, PL71 and PL92 are located close together in central-Poland, so these are the best regions when looking for residues to collect.

5. Transportation of feedstock

In chapter 4 the availability and locations of feedstock were found, the results from chapter 4 were used in this chapter to help answer the next sub-question. This is the fourth sub-research question: **What do the transportation network of these streams look like?** In this chapter several ways of transportation are researched and options are given. To find out how to get the feedstock to Wabico, information on how to transport organic material was needed. Possible transportation routes are necessary to estimate the costs from the transport. The transportation routes are based on the results of chapter 4. The modes of transportation mentioned in the literature review are used for the research. This chapter gives insight in multiple ways of transportation and eventually the cheapest route was found. This route was used in chapter 6, where the LCA was done for different feedstock types.

5.1 Destination of feedstock

HoSt is interested in ways to get the feedstock to the Netherlands from Poland and Romania, for this Waalwijk was used as a reference point. In Waalwijk HoSt has an option to buy a new plot of land, this can be used to build a new installation. At the moment HoSt have enough feedstock for the existing locations, so the new location was used as reference point. The new plot of land in Waalwijk is strategically located, the Bergsche Maas is very close to the plot of land in Waalwijk. Another positive aspect about the plot of land is that is located next to another site HoSt already owns, known as Wabico BV. In figure 7 the plot of land which is available can be seen, it is outlined in red. The Bergsche Maas can be seen on the left side of the picture. At the moment there is no way for HoSt to unload at the Bergsche Maas, so other possibilities have to be researched.

Figure 7: Location of Wabico with the plot of land, Source: https://www.google.nl/maps

Different ports and places to onload and tranship the bulk material are researched. It is necessary that a port has the possibility to onload bulk cargo, since that is the way the residues are shipped. The ports must be as close as possible to Wabico, Shipping by truck is relatively expensive. If residues are imported in great volumes, lots of trucks need to commute to and from Wabico. The distances for different ports are analysed here, the distances are found by using Google maps. The ports were analysed per port area. There are four port areas: Rotterdam (Moerdijk, Dordrecht, Vlaardingen), Amsterdam (IJmuiden, Beverwijk, Zaanstad), Groningen (Delfzijl, Eemshaven) and Zeeland (Vlissingen, Terneuzen) (Centraal Bureau voor de Statistiek, 2022). There is another interesting port to look at. The port of Waalwijk, this port does not have the possibility to tranship bulk goods now. However, this port is on the verge of being expanded (Gemeente Waalwijk, n.d.). It looks like it will only be able to tranship containers, even after the expansion, but because of its strategic location this was analysed. Nothing is mentioned about train rails being added to the port, so it does not allow for train transport.

Port area	Distance to Wabico (KM)
Waalwijk	4
Rotterdam	94
Amsterdam	114
Zeeland	139
Groningen	291

Table 1: Distances to port areas, Source: https://www.google.nl/maps

From this Groningen can be eliminated immediately, since this distance is far greater than the other port areas. For Amsterdam, Rotterdam and Zeeland port areas the distances are not too far apart, so for these port areas, the ports were analysed separately. Here the possibility for transhipping dry bulk were also analysed, since this is needed to tranship the residues to the trucks.

Rotterdam port area	Dry bulk transhipment	Distance (Km)
Rotterdam	Yes (Port of Rotterdam, n.d.)	94
Moerdijk	Yes (Port of Moerdijk, n.d.)	43
Dordrecht	Yes (Port of Rotterdam, n.d.)	52
Vlaardingen	Yes (World Port Source, n.d.)	79

Table 2: Distances to ports in Rotterdam port area, Source: https://www.google.nl/maps

Amsterdam port area	Dry bulk transhipment	Distance (Km)
Amsterdam	Yes (Port of Amsterdam, 2020)	114
Ijmuiden	Yes (IJmuiden Port, n.d.)	131
Beverwijk	Yes (ANP, 2021)	127
Zaanstad	Yes (ANP, 2021)	118

Table 3: Distances to ports in Amsterdam port area, Source: https://www.google.nl/maps

Zeeland port area	Dry bulk transhipment	Distance (Km)
Vlissingen	Yes (North Sea Port, n.d.)	123
Terneuzen	Yes (North Sea Port, n.d.)	143

Table 4: Distances to ports in Zeeland port area, Source: https://www.google.nl/maps

Moerdijk and Dordrecht are the ports which are closest to Wabico, for transport over road. These distances are taken from terminals where dry bulk can be transhipped, the distances are different for different companies that do this. This gives an indication of the distances from the different ports the Wabico. All the ports of the port area Rotterdam were considered during the research, since these are all closest to Wabico. The port of Rotterdam is one of the biggest ports in the World and have many connections with many ports. Rotterdam, Moerdijk and Dordrecht have possibilities for cargo trains to arrive (ProRail, 2022).

5.2 Departure

There are multiple points of departure in Romania and Poland. The choice for ports were based on the results of chapter 4. It is best if the ports are closest to the places where there are a lot of residues available, the transportation costs of the residues to the port are less in that way.

5.2.1 Romania

Most of the residues are located on the south side of Romania, in the regions RO22, RO31, RO32, RO41 and RO42. This means that ports in the south is best. The train station needs to have the possibility to load bulk cargo onto the train.

The port of Constanta is the biggest and most important port of Romania. The port of located south-east in Romania. This is very convenient, since most of the residues are available in the southern regions of Romania. Another interesting place is Ploiești, this is a rail station where cargo can be transported. Rotterdam and Moerdijk can be reached from Ploiești with certainty (Papatolios, 2021). These are the two location that were used for the research. Like mentioned before the inland waterways are limited. The other way is all the way around Portugal and Spain to get the residues to Waalwijk.

For both the options trucks are not discussed, because trucks can reach anything on the mainland on Europe. Trucks have the door-to-door delivery characteristic (Chopra, 2019). This means that the trucks can take the residues from the supplier straight to Wabico.

Inland waterways from Romania to the Netherlands are limited. There is a bottleneck where the river Danube cannot handle big ships and there are limits in the amount of tonnes that can be transported. Other restrictions are the maximum height and the maximum draught. This bottleneck starts at Regensburg and ends near Frankfurt. Because of this restriction only one type of ship is able to navigate through these waters, CEMT class 3 (Map of the European Inland Waterway Network, 2018). This means a maximum tonnage of 1,000-1,200 can be transported, since these are the restrictions for this type of ship.

5.2.2 Poland

For Poland most of the residues located close to each other are in PL41, PL61, PL71 and PL92. This is in central-Poland, so ports and train stations in this region were considered. The port that was considered is Gdynia. This port has the possibility to handle bulk (Port of Gdynia, 2022). Gdynia also has the possibility to handle train cargo (Papatolios, 2022). For Poland it is not possible to transport through inland waterways (Map of the European Inland Waterway Network, 2018).

Poznan and Kutno are the most central located train stations in Poland, these two are closest to the available residues. These stations can be reached according to the European map of intermodal rail terminals (n.d.). These are the 3 locations which were analysed during the research.

5.3 Storage

Storage is another aspect that has to be considered. HoSt stores the feedstock at the sites in storage facilities build and owned by themselves. Because the feedstock is stored at the sites itself, the digesters can run 24/7. However it can be the case that feedstock have to be stored at the ports before shipping. This is the case when there is not enough feedstock available directly and some more need to be delivered to the port. For example when there is not enough to fill a bulk carrier completely, it can be best to wait for some more to arrive and transport all the feedstock at once. Especially when looking at transporting very big amounts, the ports have facilities to store dry bulk. There is no need to look at how long residues can be stored, since the residues do not perish for a very long time (Wittker, 2022).

5.4 Collection

The residues have to be collected and needs to be shipped to a transhipping point, from there it has to be loaded onto a boat or train. Since there are no suppliers found yet assumptions need to be made about the distances for collection in Romania and Poland. This is important, because the costs and emissions during the whole process are very important to HoSt. For every different location of departure a different distance for collection was taken. An estimation of the middle point of the different area was found, this is an approximation made by hand. This approximation is made with the most northern and southern point, and the most eastern and western point. A line from the most northern to the most southern point is drawn and the middle point is taken the same has been done for the most eastern and western point. From these middle points a perpendicular line has been drawn and the intersection was used for the middle point of the areas. From this the distance to the locations are made up. This can be found in appendices F and G.

From this Mioveni was found as collection point for Romania and Zychlin for Poland. The distances to the ports are mentioned below.

Mioveni – Constanta: 357 Km
Mioveni – Ploiesti: 144 Km

Zychlin – Gdynia: 306 Km
Zychlin – Kutno: 20 Km
Zychlin – Poznan: 208 Km

5.5 Distances
Different ports and train stations are known, this means that we can look at the transportation networks itself. There are different options on how to get the feedstock to the Netherlands. Intermodal transportation is the mode which most commonly used (Chopra, 2019). The relative distances from Poland and Romania to Wabico can be found in Appendix T.

5.6 Emissions per mode of transportation
The emissions of the whole process are discussed in the LCA. The LCA method which is used is Biograce 2. Biograce 2 already has numbers for transportation and these are used for the LCA.

5.7 Costs per mode of transportation
The costs are given in Tonne Kilometres again, this is convenient since the emissions are also calculated per Tonne Kilometer. The costs were found in Cost Figures for Freight Transport – final report (2020), this is a report of Netherlands Institute for Transport Policy Analysis. The cheapest route to Wabico is used during the research.

5.7.1 Truck
There are several configurations for trucks, (e.g. truck or truck with trailer). Trucks (without trailer) are mainly used for the transportation agricultural products.
Costs for truck: €0.366 per tonkm

5.7.2 Train
Once again a distinction is made for the type of cargo that has been shipped, dry bulk was used.
Costs per TonKm: €0.012

5.7.3 Transport over sea
For transport over sea there are several modes of transportation, bulk carriers, tankers and big container ships. For this research the bulk carriers are only interesting, since bulk carriers are used to ship dry bulk.
Costs per TonKm: €0.0032

5.7.4 Inland waterways

For this mode of transport differences are made for small, medium and big ships. The costs for transport vary per type of boat. The prices of dry bulk are used, since residues are dry bulk. For this mode of transport distinctions were made for different lengths of boats, once again the average for this number is taken.

$$(0.033+0.020+0.017)/3=0.0233$$

Costs per TonKm: €0.0233

5.8 Set-up of transportation network

The distances between different ports and different modes of transport, the costs of different modes of transportation are known. Now different scenarios are analysed to see what the best options are for transportation. An excel file was made, in this file the data can be filled in and from this the overall costs were found. Because the costs depend on the amount of tonnes being transported, the amount of tonnes are equal for all the scenarios. For these scenarios 2,000 tonnes was used. Waalwijk is included, because of the strategic position. But Waalwijk does not have options to unload dry bulk yet, so for now this cannot be seen as an option. One scenario is worked in appendix R.

5.9 Conclusion

In this section different ways of transporting feedstock are discussed. The ones that were discussed are: transportation by truck, by train and over sea and combinations of these modes. Costs for the different ways of transporting were found, this was used to analyse the costs. Different scenarios were set up and the tonnage and distances for every mode of transport were used to calculate the costs. At the end of the chapter one example is worked out to show how it was done.

The cheapest way for Poland is: from Kutno by Train to Gdynia and by boat to Moerdijk, this costs 31.96 euro per tonne. The cheapest way for Romania is: from Ploiesti by train to Constanta and by boat to Moerdijk, this costs 93.23 euro per tonne. The costs of the transportation networks are needed to answer the last sub-question. So these are the routes that were used during the rest of the research. The distances found in this chapter can be used in the LCA, since the distances are important for tonnes kilometres travelled for the feedstock.

6. Performing the LCA

Multiple transportation networks have been set up and analysed in Chapter 5, from this the cheapest way was found from Poland and Romania to Wabico. This route was used for the LCA, which was performed in this chapter. The distances travelled are important for the LCA and will be used. This chapter answers the fifth sub-question: **What is the carbon intensity on selected streams?** The LCA was performed on internal documents from HoSt, called the biogas calculator. There are some standard values that need to be used, for this Biograce 2 is used. Biograce 2 is an Excel-based tool for the calculation of greenhouse gas (GHG) emissions (BIOGRACE, n.d.). The results from this chapter were used in Chapter 8 for the conclusion.

6.1 LCA set-up

To find out the emissions of the whole process an LCA was carried out. First a short introduction to the framework and methodology of LCA is presented. LCA consists of four phases, the four phases are discussed more elaborately in the literature review:

- The goal and scope definition phase
- The inventory analysis phase
- The impact assessment phase
- The interpretation phase

All these phases are interrelated and complement each other, these phases have been used to carry out the LCA.

6.1.1 The goal and scope definition phase

This LCA was conducted to gain insight in the CO_{2eq} emitted during the whole process of AD and transportation. This LCA gives HoSt insight if importing feedstock is feasible from an environmental perspective. This LCA helps determining if feedstock can be imported from Poland and Romania. The technology of AD is reviewed in this LCA, since this is used by HoSt to process the feedstock. The impact category used is climate change, this is in gCO_{2eq}. HoSt is interested in gCO_{2eq}/MJ, so this is the appropriate impact category. The system boundary gives the processes which are included in the LCA (International Organization for Standardization, 2006a). The main limitation is that there are no suppliers and no actual distances can be used to calculate the emissions from transport. The system boundary can be found in Figure 7. The transportation of digestate and liquid CO_2 is not included in this LCA, since these are completely new products that came from the process.

6.1.2 The inventory analysis phase

In this phase the data collection is discussed, the way it is collected and how the calculations are done (International Organization for Standardization, 2006b). The data for transportation was calculated by hand and the inputs for this were mentioned in Chapter 5. Data for processing feedstock is found by internal documents from HoSt. Also calculating methods are provided by HoSt, these are approved ways of calculating the CI-score. In this way HoSt can get ‘green’ labels for the gas that is produced. The values used for the LCA were found in Biograce 2.

6.1.3 The impact assessment phase

In the impact assessment phase the results of the inventory analysis phase are evaluated. In this phase the data from the inventory analysis phase are linked to impact categories (International Organization for Standardization, 2006b). So in this case the results are linked to climate change. So gCO_{2eq} emitted from the process and after that it is linked to gCO_{2eq}/MJ.

6.1.4 The interpretation phase

In this phase the results found in the inventory analysis phase and the impact assessment phase are considered together. Here the results of the LCA should be clearly presented and related to the goals that were mentioned in the goal and scope definition phase. In this phase conclusions and recommendations can be made (International Organization for Standardization, 2006a). In this case if importing feedstock is feasible or not.

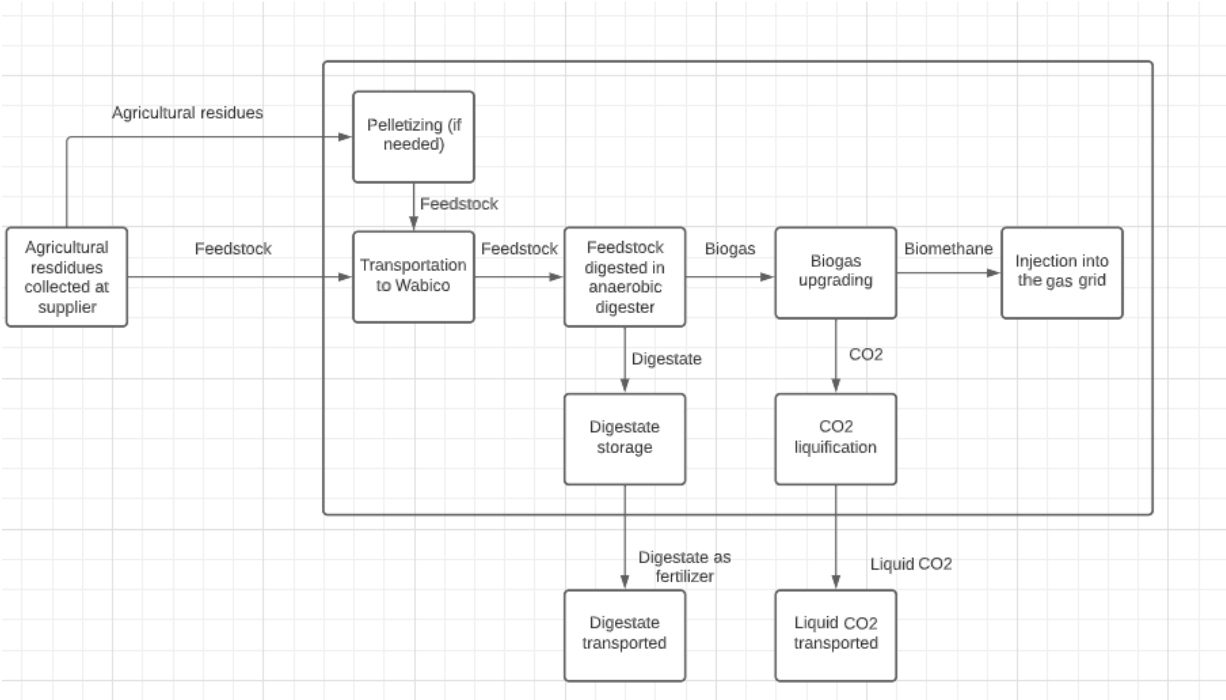

Figure 8: System boundary

6.2 Emissions from pelletizing

Energy density of a transported product is important if it is transported over a long distance. When there is a higher energy density the overall impact of the transport is lower per tonne transported. A very promising way of doing this is pelletizing the raw materials into pellets. Pellets are small compressed granules. The raw material go in as straw or husk in the and come out as pellets. The advantages of these pellets are that they have a higher (energy) density and therefor more of the product can be transported at once. Another advantage is that more biogas comes from a tonne of pellets compared to a tonne of raw material of the pellet. Pellets are made of milled very compressed raw material, such as straw. Because the material is milled there is a higher return of biogas, because of a bigger overall surface area. There is technical explanation for this, which is not discussed further. However for the production of pellets energy is used, this was taken into account when looking at the emissions from the process.

Figure 9: Pellets, Source: https://www.ecopedia.be/pagina/pellets

Energy consumption of pelletizing

There are two main processes in the pelleting process, these are milling and pelleting. In table 23 are the energy consumptions for milling and pelletizing

Process	Energy consumption (kWh/tonne)
Milling	13.81
Pelleting	140.75
Total	154.56

Table 5: energy usage for pelleting, Source: (Wilson, 2014)

6.3 Emissions from the process

There are several emissions involved in the whole process. The emission for transportation, for processing the feedstock at the plant and for some cases pelletizing. Now cases were set up to run the whole plant on four kinds of feedstock. The kinds of feedstock that were used are: Sunflower husk pellets, glycerine, straw and straw pellets. For the cases 15,500,000 M^3 of biogas is used as reference point. For the analysis the cheapest routes from the last chapter are used.

Some emissions are involved in processing feedstock, also CO_2 is captured. CO_2 capturing is positive for the emissions in the whole process, since these CO_2 emissions do not go into the air. HoSt even sell this CO_2 in liquid form. The main emission that is used is the electricity used by the process. This used electricity comes from several processes: Biogas production, Biogas upgrading to biomethane, CO_2 recovery and heating up the digesters to the right temperature. For calculating this the biogas calculator from the company is used. This is used as the LCA tool, with the values found in Biograce 2.

6.4 Outcomes the LCA

Eight scenarios are studied with four different kinds of feedstock: sunflower husk pellets, glycerine, straw and straw pellets. For these scenarios the cheapest route found in the last section was used. From this the LCA was done and determined if the different feedstock make environmental goals set by HoSt. The goal is at least 70% CO_2 reduction comparing it to fossil fuels, specifically diesel. This is important, because HoSt sells bio-LNG, when this goal is achieved the bio-LNG gets a 'green' label. The CO_2 emissions of bio-LNG should be 70% lower than fossil fuels alternatives.

In Biograce 2 the values for diesel production was found, this is 95.1 gCO_2/MJ. This means that the so-called carbon intensity of the whole process should be lower than 28.53 gCO_2/MJ.

Four scenarios were made for both Romania and Poland, on these LCA were done, these are analysed and compared. Four types of feedstock were analysed, these were glycerine, straw pellets, straw and sunflower husk pellets. These types of feedstock have different returns, these can be seen in Table 6.

Feedstock	M^3 biogas/tonne
Glycerine	545
Straw pellets	474
Straw	288
Sunflower husk pellets	213

Table 6: Biogas returns of selected feedstock, Source Biogas calculator, 2018

6.5 Results of the LCA

In Tables 7 and 8 the results of the performed LCA can be seen.

Feedstock (from Poland)	CI-score (gCO_2/MJ)	Reduction compared to diesel
Glycerine	-23,86	125.09%
Straw pellets	-11,32	111.90%

Straw	-15.45	116.25%
Sunflower husk pellets	24.12	74.64%

Table 7: CI-scores Poland for different feedstock

Feedstock (from Romania)	**CI-score (gCO_2/MJ)**	**Reduction compared to diesel**
Glycerine	-18.65	119.61%
Straw pellets	-13.60	114.30%
Straw	8.63	90.92%
Sunflower husk pellets	19.47	79.53%

Table 8: CI-scores Romania for different feedstock

It can be seen from this that all the feedstock pass the first goal. It means that even for feedstock with low returns the goal of 70% CO_2 reduction compared to fossil fuels alternatives is achieved.

Looking at the outcomes of the different countries some counter-intuitive results can be seen, for example the CO_2 reduction compared to diesel for straw pellets from Poland and Romania. For Romania the reduction is bigger than for Poland, but the distances travelled are smaller from Poland. This has to do with the emissions from electricity. In Poland the emissions from electricity are bigger than for Romania, that is why the reduction is bigger for Romania than for Poland. Appendices K, L and M show the other feedstock for Romania, in these appendices the different values can be seen. The values are for different types of transport, mostly boats, and the difference in emissions from electricity can be seen in appendix N. Not all the biogas calculators are shown. Also there is difference for straw pellets and straw for both countries, this again comes from the emissions from electricity.

6.6 Conclusion

In this chapter the emissions from the process have been calculated and analysed, by means of an LCA. The different phases of LCA are discussed. To do the LCA internal documents from HoSt and Biograce 2 were used. A system boundary was set-up to see what processes were included during the LCA. Also the emission for pelletizing were researched and some of the positive aspects of pelletizing are mentioned. These results are used to see if importing feedstock is environmentally feasible. CO_2 capturing plays a big role in the process, this has to be used to make it feasible. From the results it can be seen that importing is feasible when looking at CO_2 reduction compared to diesel production, even for feedstock with relatively low returns.

The first goal for importing is achieved for the selected feedstock and this will be used in Chapter 8. In Chapter 7 the costs are analysed to see if it is financially feasible to import feedstock.

7. Internal rate of return of HoSt

The last sub-question will be answered in this chapter: **What is the internal rate of return for importing the streams?** Whether HoSt is building a plant is based on the IRR, if it is over 15% than HoSt considers it. In this chapter a case study was set-up for straw pellets. This is done specifically for the straw pellets, since a supplier was found for these. This means that actual numbers can be used for the price of the feedstock. Also the route provided by transporting company X is used in this chapter. The case study is made in the biogas calculator, this automatically calculates the costs and IRR for the plant. The results found in this chapter were used in Chapter 8 to conclude this research. The numbers found in this chapter were found using the biogas calculator, due to confidentiality the screenshots cannot be shared.

7.1 Costs of the process

The biggest costs that are involved in the process are the feedstock costs and electricity and heat costs (biogas calculator, n.d.). This can be seen in Appendix O. The feedstock costs also includes the transportation costs, e.g. feedstock costs are €100 and transportation costs are €80, the total is filled in as €180.

The case study is set up for the straw pellets found in Poland, purchasing price for the straw pellets are known to be around €170 per tonne and this means an actual case study can be set up. The straw pellets have relatively high returns, this was mentioned in the last chapter. It was important for the feedstock to have a high return and for these straw pellets this is the case.

Transportation costs were calculated based on literature in Chapter 5. Also transportation companies were contacted, these mentioned that train transport is the easiest and cheapest at the moment for Poland and Romania. transporting company X, told the costs to be around €60 per tonne from Poland and €150 per tonne for Romania. These costs are without the collection of feedstock and transportation to Wabico, this is for train from Ploiesti to Rotterdam. This means that the costs come in even higher. The costs that were calculated based on literature were €31.96 per tonne for Poland and €93.23 for Romania.

The digestate that comes from the process can be used as a fertilizer. Part of the digestate is transported to Poland by trucks and the trucks return empty to the Netherlands, this is an opportunity to combine this with import of the feedstock. These are 4-5 trucks per week, so this is around 100-125 tonnes per week. This was reported to be around €10 per tonne transported. This is a situation that was analysed as well.

7.2 Revenue

The main income for HoSt is selling the green gas (biomethane), bioLNG, bioCO_2 and digestate. In the case study that was used green gas, bioCO_2 and digestate are the revenue streams. The price of gas changes all the time and that makes it uncertain for HoSt how much money they make for the gas they produce. Therefor sensitivity analysis was done on the results of the case study. Also a sensitivity analysis was done on the feedstock price, since these can change over time.

7.3 Case study

The case study is based on the straw pellets that were found in Poland and the whole plant runs on the straw pellets. The assumption is made that the whole plant runs on the straw pellets. The purchase price of these straw pellets are €170 per tonne, at Supplier Y. For the process water is used and the purchase price of water is €1.50 per tonne. The total investment for building the site comes in at around €24,500,000. There are many more operational costs, such as maintenance, electricity and heat. Not all the costs are mentioned. The revenue from green gas is €1.065, bioCO_2 can be sold for

€131 per tonne and the digestate can be sold for €5. These values are filled in the biogas calculator and automatically calculates the revenue and costs.

The case study describes building a new plant, Wabico 2.0. In the proposed new plant around 33,500,000 M^3 biogas can processed, this comes in at a little over 17,000,000 M^3 biomethane. For this 65,000 tonnes of straw pellets are needed.

For this situation multiple feedstock prices have been analysed, the results can be seen below in the picture. This means that it is feasible for HoSt to import the feedstock if the transporting costs stay under €50 per tonne, since this is the last transporting price for which the IRR is over 15%. This also means that importing from Romania is not feasible. The transporting costs calculated from literature was €31.96 for Poland, so from this perspective it is feasible to import the straw pellets to Wabico. However transporting prices for transporting company X are over €50, since these are actual prices it means that it is not feasible to import at the current situation. Importing with the trucks that return empty to the Netherlands gives a good IRR, this means that it is feasible.

* This has been left out due to confidentiality*

Figure 10: Cash flow HoSt with related IRR

Another aspect that needs to be taken into account is the fluctuations in the gas prices and feedstock prices, a sensitivity analysis was done to analyse this. In the columns the feedstock prices can be seen and in the row the revenue from green gas. Below the sensitivity analysis can be seen. From this it can be seen that differences in the revenue from the green gas has a big impact on the IRR. Fluctuating gas prices involve a great risk in the feasibility of importing feedstock. Importing with the trucks that return empty to the Netherlands looks like a great way of importing, but these do not transport big quantities. When looking at the costs based on literature it is also feasible for the situation now. Looking at the prices transporting company X sent it is feasible for a gas price of 1.15/M^3.

IRR	0,95	1	1,05	1,1	1,15	1,2	1,25	1,3
160	22,66%	27,87%	33,04%	38,21%	43,38%	48,55%	53,73%	58,91%
170	19,02%	24,27%	29,46%	34,63%	39,80%	44,97%	50,14%	55,32%
180	15,30%	20,64%	25,87%	31,05%	36,22%	41,39%	46,56%	51,73%
190	11,46%	16,96%	22,25%	27,46%	32,64%	37,81%	42,97%	48,15%
200	7,22%	13,18%	18,60%	23,86%	29,05%	34,23%	39,39%	44,56%
210	2,10%	<-5%	14,88%	20,23%	25,46%	30,64%	35,81%	40,98%
220	-5,00%	<-5%	11,01%	16,54%	21,84%	27,06%	32,23%	37,40%
230	<-5%	<-5%	6,69%	12,75%	18,19%	23,45%	28,65%	33,82%
240	<-5%	<-5%	<-5%	8,71%	14,45%	19,82%	25,05%	30,24%

Figure 11: Sensitivity analysis feedstock- and gas prices

When gas prices go up electricity prices also go up (Shaw, 2022). Electricity is one of the biggest operational costs, after feeding costs. This means that the IRR of the system would go down, so IRR close to 15% go down even more. This is not discussed further, but it has an impact on the IRR.

For this case study a separate LCA was done to evaluate the CI-score for this specific case transporting company X has terminals from Ploiesti to Rotterdam, for train transport. This route is used to evaluate the LCA for this case study, to give a realistic view on the LCA. Table 9 shows the results of the LCA. This shows that it is feasible from a environmental perspective.

Feedstock (from Poland)	CI-score (gCO_2/MJ)	Reduction compared to diesel
Straw pellets	-7.74	107.86%

Table 9:CI-score straw pellets case study

7.4 Conclusion

In this chapter the biogas calculator was used to set-up a case study and calculate the IRR of the process and another LCA was done specifically for this situation. HoSt only builds a new site if the IRR is at least over 15%. The revenue and costs of HoSt have been analysed and this was used to look at the IRR. Multiple prices were used to look at the IRR of the process, by means of a sensitivity analysis. A sensitivity analysis was conducted on the price of gas, the feedstock prices and the transportation prices. Importing with the trucks that return empty looks like a good option, but this is just for 100-125 tonnes per week. Prices at transporting company X are around €60 per tonne, as the situation currently is this is not a good option. The IRR of the process will be used in chapter 8.

8. Conclusion, recommendations and limitations

In this last chapter the conclusion, recommendations and limitations are discussed for the decisions makers at HoSt. In this last chapter the main research question is answered. The main research question is: **How financially and environmentally feasible is it for HoSt to import feedstock streams from Poland and Romania to Waalwijk?** This research was to look into importing biomass waste streams to the Netherlands to process it to biogas and biomethane, specifically importing in large quantities. After that the limitations of the research are discussed. The IRR in this chapter has been changed by a random factor X, due to confidentiality.

8.1 Conclusion

The feedstock streams should pass two goals, namely 70% CO_2 reduction compared to fossil fuel alternative, specifically diesel, and the internal rate of return should be 15% or higher. To see if the first goal is achieved research was done on how to do an LCA, this was done by means of an systematic literature review. Different LCA tools have been compared and the choice was made to use Biograce 2 as LCA tool.

To see at what countries to look at, biogas potentials were used to see where a lot of feedstock is available. These biogas potentials were compared to the biogas- and biomethane production in countries. After comparing these two aspects the choice was made to look at Poland and Romania. These are countries with high biogas potentials and low biogas- and biomethane production.

Biomass is processed to biogas and digestate in a process called anaerobic digestion. The second aspect that was researched was what kind of inputs can be used during AD. This was done by looking at the process of AD at HoSt. Almost all the organic material can be processed in AD process, so choices on this had to be made. The choice was made on cereals, rapeseed and sunflower residues. This choice was made because these are the most cultivated type of crops. The inputs and outputs of the process were eventually used in the LCA.

After selecting Poland and Romania as countries, the residues had to be located. This was done by using EUROSTAT (2022) and Our World in Data (n.d.). EUROSTAT publishes data on how much cereals are produced in different regions. Our World in Data give national production of rapeseed and sunflower. After this the residue-to-crop ratio are used to determine the residues that are produced. After the amount of residues are determined, the availability for energy purposes had to be checked. This availability keeps in mind the other uses of the residues. After the availability was used to determine the amount of residues available for energy purposes some regions were selected to look at. The regions in Romania are: RO22, RO31, RO32, RO41 and RO42. These regions are located in the south of Romania. The regions selected for Poland are: PL41, PL61, PL71 and PL92. The regions in Poland are located in central-Poland.

The regions to look at have been selected and from this transportation networks were set-up. Three modes of transport have been evaluated during this research: boat, train and truck. The modes of transport can be combined, this is called intermodal transport. Ports and train stations in Romania, Poland and the Netherlands have been researched. Choices were made on what ports and train stations to look at. The distances from the ports to Wabico were found. Also the distances from port to port were researched. From this multiple scenarios have been set-up and costs have been calculated. The cheapest route and way to transport were found, this is used for the LCA.

The next step was doing the LCA, this was used to see if the first goal of HoSt is achieved. The inputs and outputs of the process have been analysed and mapped in a system boundary. Four different types of feedstock have been used for the LCA, these all have different returns. In total eight different scenarios are used. The carbon intensity of the process was calculated and compared to the carbon intensity of diesel production. It can be seen that in all eight scenarios the 70% CO_2 reduction compared to diesel have been achieved. This means the first goal of HoSt has been achieved, for feedstock with low and high returns, from both Romania and Poland.

The next step was to analyse the revenue and costs and determine the IRR. To determine this the biogas calculator of HoSt (Biogas calculator, n.d.) is used which calculates the IRR automatically. Different costs and revenues can be filled in . The biggest costs involved in the process are: heat and electricity costs, feedstock costs and transportation costs. The biggest revenue is green gas. To analyse the IRR a case study was used. For this case study the straw pellets from Supplier Y were used. The price of these straw pellets are €170 per tonne. In the current situation it is only feasible if the transport costs are €40 or lower. A sensitivity analysis was done to evaluate what gas price and feedstock price changes due to the IRR. This is used to check if the second goal of HoSt is achieved, which is at least 15% IRR on installations.

The financial and environmental feasibility of importing feedstock depends on several factors, the cost of feedstock, transportation costs and the carbon intensity.

The environmental feasibility of importing from Poland and Romania depends on the way it is transported and the processes to get the feedstock. It can be seen that pelletizing can have a big impact on the carbon intensity of the feedstock. Transportation also has a big impact on the carbon intensity, it is best to transport with low-carbon transport such as trains and boats. From the LCA in Chapter 6 it can be seen that a 70% CO_2 reduction compared to diesel production is achieved in all cases, from both Romania and Poland, for low and high return feedstock. It seems that this will not be a problem when importing feedstock in great quantities from both Poland and Romania. So from a environmental perspective it is feasible to import feedstock from Poland and Romania.

The financial feasibility depends on three main aspects, transportation costs, feedstock price and gas prices. Transportation costs were first calculated using literature and some price indications were given by transporting company X. The costs that were calculated were around €30 per tonne for Poland and around €90 per tonne from Romania. Transporting company X reported these prices to be around €60 per tonne from Poland and around €150 per tonne from Romania. In both situations the transportation costs from Romania are huge and this makes it unfeasible from Romania. From Poland the prices are on the high side as well. The prices of feedstock are hard to determine, only one supplier was found and the prices of the straw pellets were €170 per tonne. This gives an indication of the market price of feedstock. This means that it can be financially feasible if both transportation and feedstock are the right price.

In summary, from a environmental perspective it feasible for both Romania and Poland. From a financial perspective importing feedstock from Romania is not feasible due to the high transportation costs. From Poland it can be feasible under the right circumstances, when transporting costs and feedstock prices are right. When looking to import feedstock from abroad HoSt has to keep in mind the prices of locally sourced feedstock. When prices of locally sourced feedstock increase it becomes more interesting to look at Poland.

8.2 Discussion

In this section the choices made in the research are discussed. The first big choice that was made was the country selection. In this country selection Romania and Poland were selected. The research assignment given by HoSt was for Europe, however this is too big to analyse. The choice for Romania and Poland was made together with the company supervisor and R&D of the company. This mainly due to the fact that these are low income countries and therefore the thought was that feedstock and labour costs would be cheaper there.

The costs of transportation were calculated. This was done, because transportation companies did not give price indications. Later transporting company X gave price indications and these were used in the analyses of the costs in chapter 7.

For the LCA the reference point was 15,500,000 M^3 biogas this might look like a random number. The decision to do this was made because some guidelines had to be achieved in the biogas calculator. The nitrogen value of digestate cannot be too high, due to regulations. For sunflower husk pellets it was hard to get this value right and it was best at 15,500,000 M^3 biogas produced. That is why this was used as a reference point for all the feedstock. Overall it is not realistic that a plant completely runs on one type of feedstock, the feedstock is mostly co-digested with other products. In this research the choice was made to run one installation completely on one type of feedstock, this was done to give an indication on the CI-scores of selected streams.

In the final case-study other route for transporting was used to do the LCA of the process. At this point a transporting company gave price indications and multiple routes. One of the routes was actually in the list of scenarios that was made in chapter 5, this scenario has been used to evaluate the LCA for the last case study.

After the final presentation for the company a discussion came up on how to use this thesis within the company. The main outcome from this was that processing feedstock locally is a better option. Also some ideas about starting an own pelletizing factory in the regions with the most residues available. From this came that Poland is not the best option for this since the emissions from electricity are high there and it would be best to have a factory like that in a country with lower emissions from electricity

8.3 Future research

In this section possible future research is mentioned. For now only one supplier was found, this supplier gave a price indication. From one supplier it is hard to determine what the market price of the feedstock is. So for further research more suppliers can be contacted to get a good view on the prices of feedstock.

Secondly, not much information was found on glycerine. HoSt see glycerine as a very interesting feedstock, therefor it can be good to do more research in glycerine production in Poland. Since the CI-scores of glycerine are very good and achieve the 70% reduction to diesel production. More research in this can give more insight in the glycerine production in Poland and possibly suppliers can come from that.

The last thing HoSt can look into is the costs of building a pelletizing factory, since this came up in the discussion after the presentation. HoSt is interested in this, especially in great quantities. For great quantities it might be more interesting to have a pelletizing site than to buy it from a pelletizing company.

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Appendices

Appendix A – Elements of LCA

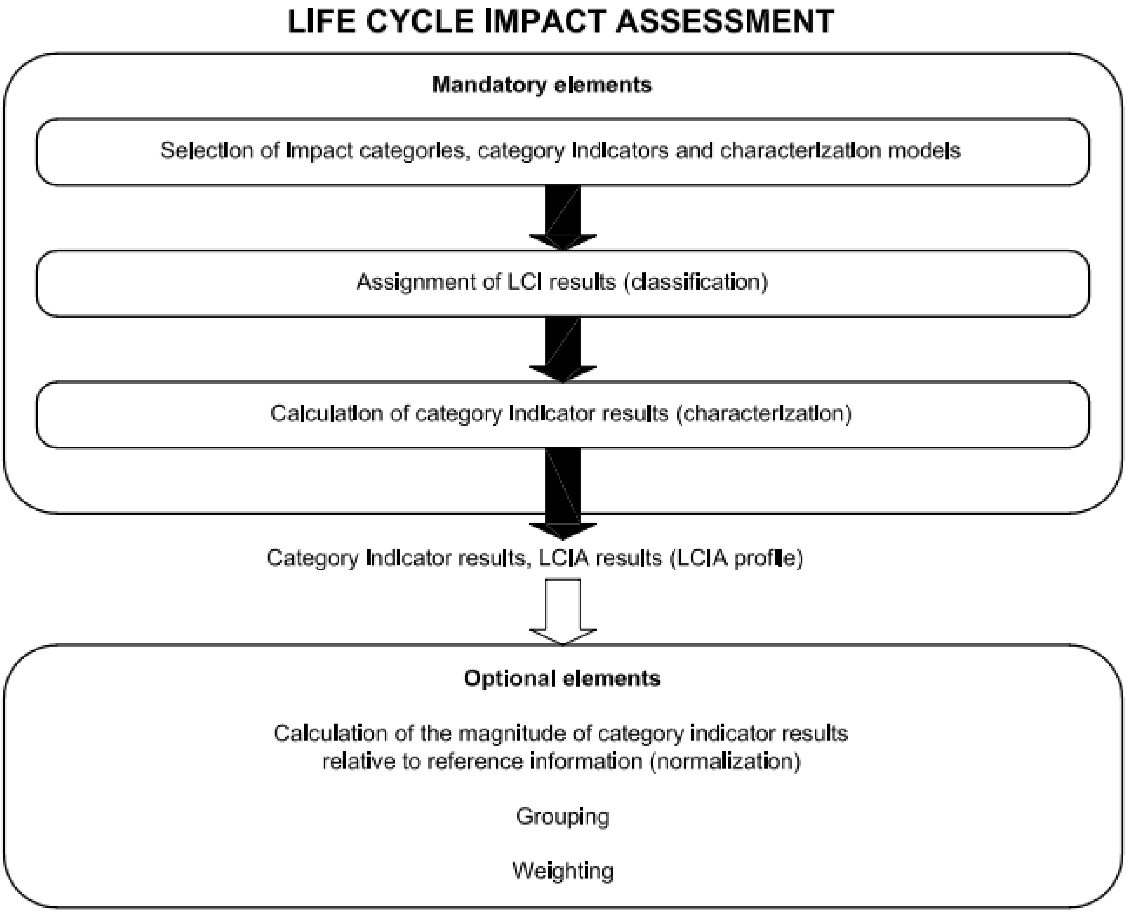


Figure 12: Elements of a LCA, Source: (International Organization for Standardization, 2006a)

Appendix B – AD potentials 2030 EU countries

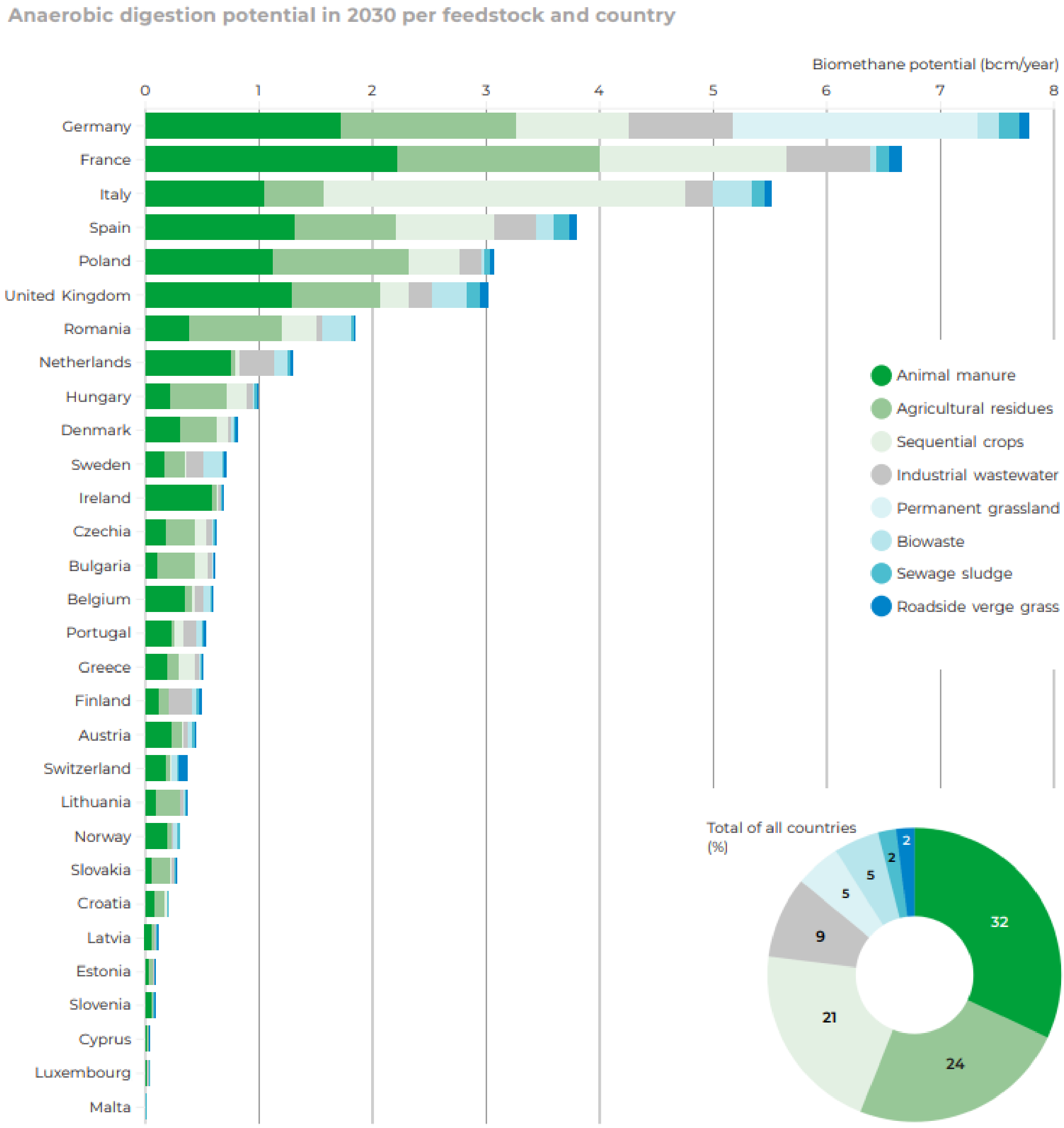
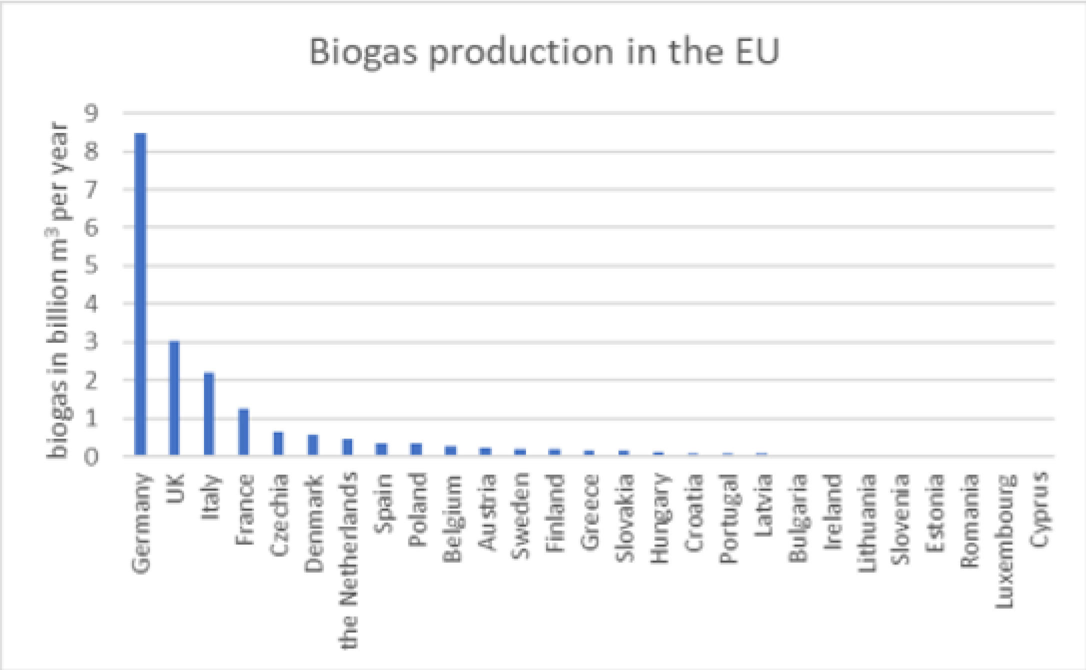


Figure 13: Biomethane potential 2030, Source: (Guidehouse, 2022)

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Appendix C – Biogas production EU countries



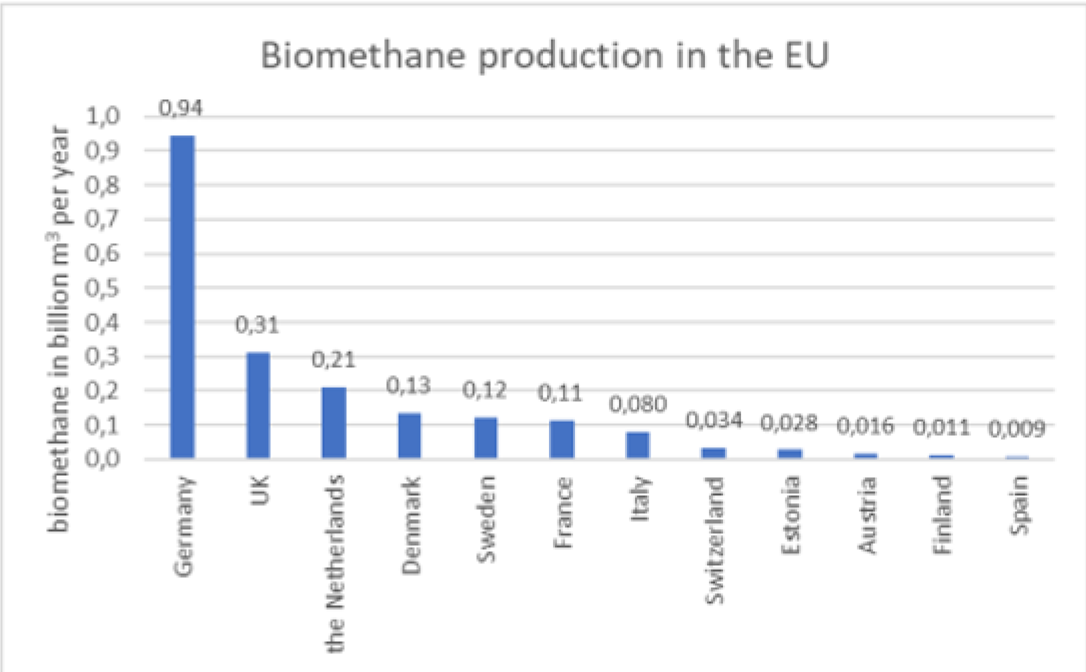


Figure 14: Biogas and biomethane production in the EU, Source: (IFEU, 2022)

Appendix D – Min and max values produced residues Romania

NUTS 2 regions	Common wheat and spelt		Grain maize and corn-cob mix		Barley		Durum wheat		Rye	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
RO11	625.49	1060.35	1709.45	2498.42	102.06	173.02	1.79	3.03	3.02	3.98
RO12	358.05	606.98	1044.26	1526.23	71.40	121.04	0.63	1.07	5.72	7.53
RO21	541.49	917.95	1702.79	2488.70	62.69	106.27	0.11	0.18	12.20	16.05
RO22	676.41	1146.68	1057.47	1545.54	236.04	400.14	1.58	2.67	0.32	0.43
RO31	1848.10	3132.98	1846.31	2698.46	380.00	644.18	0	0	1.94	2.56
RO32	63.95	108.40	46.80	68.40	10.82	18.33	0	0	0.11	0.14
RO41	1533.95	2600.40	1514.34	2213.27	211.47	358.49	1.47	2.49	6.91	9.09
RO42	1053.26	1785.52	1579.24	2308.12	123.59	209.51	5.67	9.61	0.54	0.71

Figure 15: Min and max values of the residues produced for Romania

Appendix E – Min and max values produced residues Poland

NUTS 2 regions	Common wheat and spelt		Grain maize and corn-cob mix		Barley		triticale		Oats		Rye and winter cere	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
PL21	352,48	704,96	224,7	299,64	72,9	118,43	62	70,06	41,314	49,032	22,86	40,64
PL22	280,56	561,12	183,7	244,92	81,1	131,82	177,1	200,123	47,047	55,836	77,13	137,12
PL41	997,6	1995,2	1218	1624,3	438	711,75	1094,1	1236,33	122,031	144,828	576,09	1024,16
PL42	627,12	1254,24	183,8	245,04	176	285,74	363	410,19	103,467	122,796	284,31	505,44
PL43	184,56	369,12	138,4	184,56	81,6	132,6	219,4	247,922	28,301	33,588	111,69	198,56
PL51	1128,96	2257,92	642,2	856,32	255	413,66	232,5	262,725	64,701	76,788	86,58	153,92
PL52	745,36	1490,72	460,1	613,44	251	408,2	168,3	190,179	24,206	28,728	57,51	102,24
PL61	977,28	1954,56	832,9	1110,5	210	340,47	452,1	510,873	39,676	47,088	212,85	378,4
PL62	661,52	1323,04	181	241,32	84,6	137,54	372,1	420,473	85,54	101,52	121,41	215,84
PL63	795,68	1591,36	110,4	147,24	90,2	146,51	258,7	292,331	74,62	88,56	173,7	308,8
PL71	448,4	896,8	316,1	421,44	134	217,1	697,7	788,401	157,885	187,38	392,31	697,44
PL72	271,28	542,56	52,65	70,2	84,2	136,76	170,4	192,552	31,213	37,044	40,95	72,8
PL81	1467,76	2935,52	254,8	339,72	208	337,35	585,9	662,067	207,48	246,24	152,19	270,56
PL82	324,24	648,48	363,7	484,92	48,9	79,43	75,5	85,315	58,877	69,876	28,98	51,52
PL84	167,12	334,24	251,1	334,8	43,4	70,59	325,6	367,928	158,704	188,352	195,3	347,2
PL91	83,76	167,52	100,9	134,52	10	16,25	78,8	89,044	44,408	52,704	62,37	110,88
PL92	505,76	1011,52	509,6	679,44	91,5	148,72	754,3	852,359	209,027	248,076	419,58	745,92

Figure 16:: Min and max values of the residues produced for Poland

Appendix F – Middle point approximation Romania

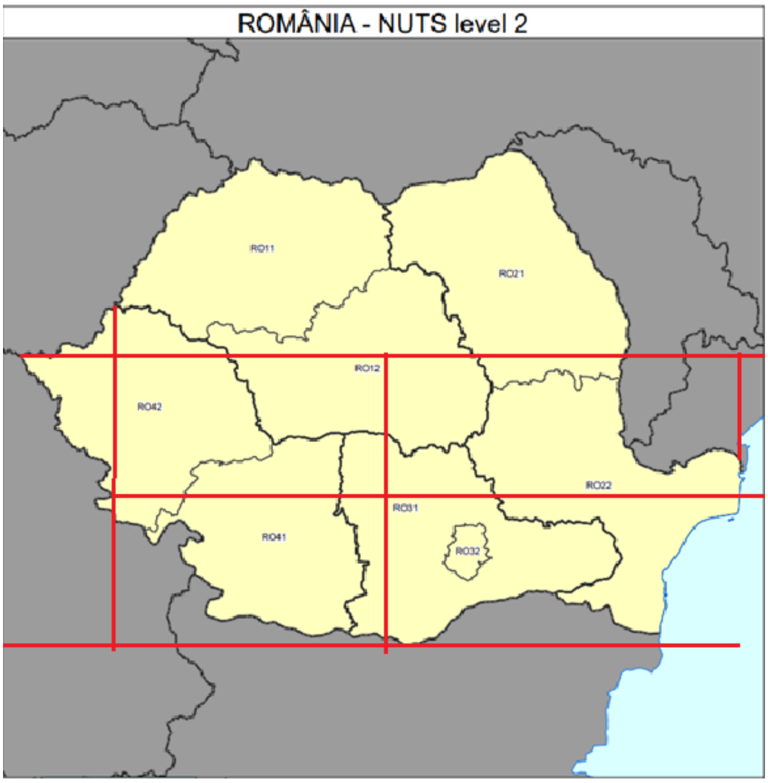


Figure 17: NUTS map of Romania with middlepoint, Source: https://ec.europa.eu/eurostat/web/nuts/nuts-maps

Appendix G – Middle point approximation Poland

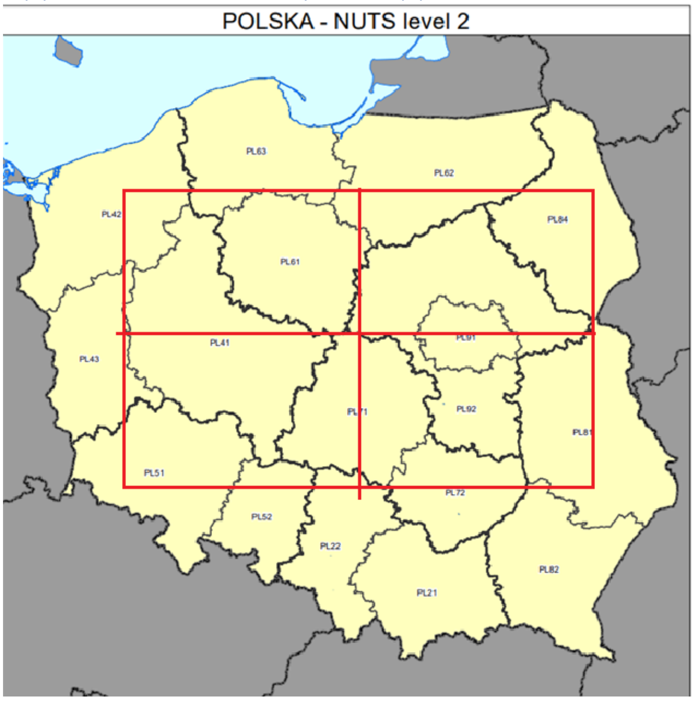


Figure 18: NUTS map of Poland with middlepoint, Source: https://ec.europa.eu/eurostat/web/nuts/nuts-maps

Appendix H – transportation networks scenarios Romania

Romania
From Romania there are several options which are analysed, the scenarios are listed below.

Transportation by train from Constanta
Constanta – Moerdijk: distance for collection: 357 km, distance on rail: 2824 km, distance to Wabico: 43 km
Constanta – Rotterdam: distance for collection: 357 km, distance on rail: 2851 km, distance to Wabico: 94 km
Constanta – Dordrecht: distance for collection: 357 km, distance on rail: 2842 km, distance to Wabico: 52 km

Transportation by train from Ploiesti
Ploiesti – Moerdijk: distance for collection: 144 km, distance on rail: 2309 km, distance to Wabico: 43 km
Ploiesti – rotterdam: distance for collection: 144 km, distance on rail: 2285 km, distance to Wabico: 94 km
Ploiesti – Dordrecht: distance for collection: 144 km, distance on rail: 2571 km, distance to Wabico: 52 km

Transportation over sea from Constanta
Constanta – Moerdijk: distance for collection: 357 km, distance over sea: 6409 km, distance to Wabico: 43 km
Constanta – Rotterdam: distance for collection: 357 km, distance over sea: 6381 km, distance to Wabico 94 km
Constanta – waalwijk: distance for collection: 357 km, distance over sea: 6452 km, distance to Wabico: 4 km
Constanta- Dordrecht: distance for collection: 357 km, distance over sea: 6413 km, distance to Wabico 52 km

Transportation by truck
Constanta – wabico: distance on road 2399 km
Ploiesti wabico: distance on road 2144 km

Ploiesti to Constanta by train, from Constanta over sea
Ploiesti – Rotterdam: distance for collection: 144 km, distance on rail: 271 km, distance over sea: 6381 km, distance to Wabico: 94 km
Ploiesti – Moerdijk: distance for collection: 144 km, distance on rail: 271 km, distance over sea: 6409 km, distance to Wabico: 43 km
Ploiesti – Dordrecht: distance for collection: 144 km, distance on rail: 271 km, distance over sea: 6413 km, distance to Wabico: 52 km
Ploiesti – Waalwijk: distance for collection: 144 km, distance on rail: 271 km, distance over sea 6452 km, distance to Wabico: 4 km

Inland waterway:
Constanta – Moerdijk: distance for collection: 357 km, distance inland waterway, distance to Wabico: 43 km

Figure 19: Scenarios transportation network Romania

Appendix I – transportation networks scenarios Poland

Transportation by truck
Gdynia – Wabico: distance on road: 1237 km
Poznan – Wabico: distance on road: 913 km
Kutno – Wabico: distance on road 1090 km

Transportation over sea from Gdynia
Gdynia – Moerdijk: distance for collection: 306 km, distance over sea: 1369 km, distance to Wabico: 43 km
Gdynia – Rotterdam: distance for collection: 306, distance over sea: 1335 km, distance to Wabico: 94 km
Gdynia – Dordrecht: distance for collection: 306 km, distance over sea: 1361 km, distance to Wabico: 52 km
Gdynia – Waalwijk: distance for collection: 306 km, distance over sea: 1406 km, distance to Wabico: 4 km

Kutno to Gdynia by train, from Gdynia over sea
Kutno – Moerdijk: distance for collection: 20 km, distance on rail: 348 km, distance over sea: 1369 km, distance to Wabico: 43 km
Kutno – Rotterdam: distance for collection: 20 km, distance on rail: 348 km, distance over sea: 1335 km, distance to Wabico 94 km
Kutno – Dordrecht: distance for collection: 20 km, distance on rail: 348 km, distance over sea: 1361 km, distance to Wabico: 52 km
Kutno – Waalwijk: distance for collection: 20 km, distance on rail: 348 km, distance over sea: 1406 km, distance to Wabico: 4 km

Poznan to Gdynia by train, from Gdynia over sea
Poznan – Moerdijk: distance for collection: 208 km, distance on rail: 340 km, distance over sea: 1369 km, distance to Wabico: 43 km
Poznan – Rotterdam: distance for collection: 208 km, distance on rail: 340 km, Distance over sea: 1335 km, distance to Wabico: 94 km
Poznan – Dordrecht: distance for collection: 208 km, distance on rail: 340 km, distance over sea: 1361 km, distance to Wabico 52 km
Poznan – Waalwijk: distance for collection: 208 km, distance on rail: 340 km, distance over sea: 1406 km, distance to Wabico 4 km

Transportation by train from Poznan
Poznan – Moerdijk: distance for collection: 208 km, distance on rail: 1158 km, distance to Wabico: 43 km
Poznan – Rotterdam: distance for collection: 208 km, distance on rail: 955 km, distance to Wabico: 94 km
Poznan – Dordrecht: distance for collection: 208 km, distance on rail: 977 km, distance to Wabico: 52 km

Transportation by train from Kutno
Kutno - Moerdijk: distance for collection: 20 km, distance on rail: 1172 km, distance to Wabico: 43 km
Kutno – Rotterdam: distance for collection: 20 km, distance on rail: 1128 km, distance to Wabico: 94 km
Kutno – Dordrecht: distance for collection: 20 km, distance on rail: 1155 km, distance to Wabico: 52 km

Transportation by train from Gdynia
Gdynia - Moerdijk: distance for collection: 306 km, distance on rail: 1170 km, distance on road: 52 km
Gdynia – Rotterdam: distance for collection: 306 km, distance on rail: 1159 km, distance to Wabico: 94 km
Gdynia – Dordrecht: distance for collection: 306 km, distance on rail: 1141 km, distance to Wabico: 52 km

Figure 20: Scenarios transportation network Poland

Appendix J – Visual representation scenario Poznan - Moerdijk

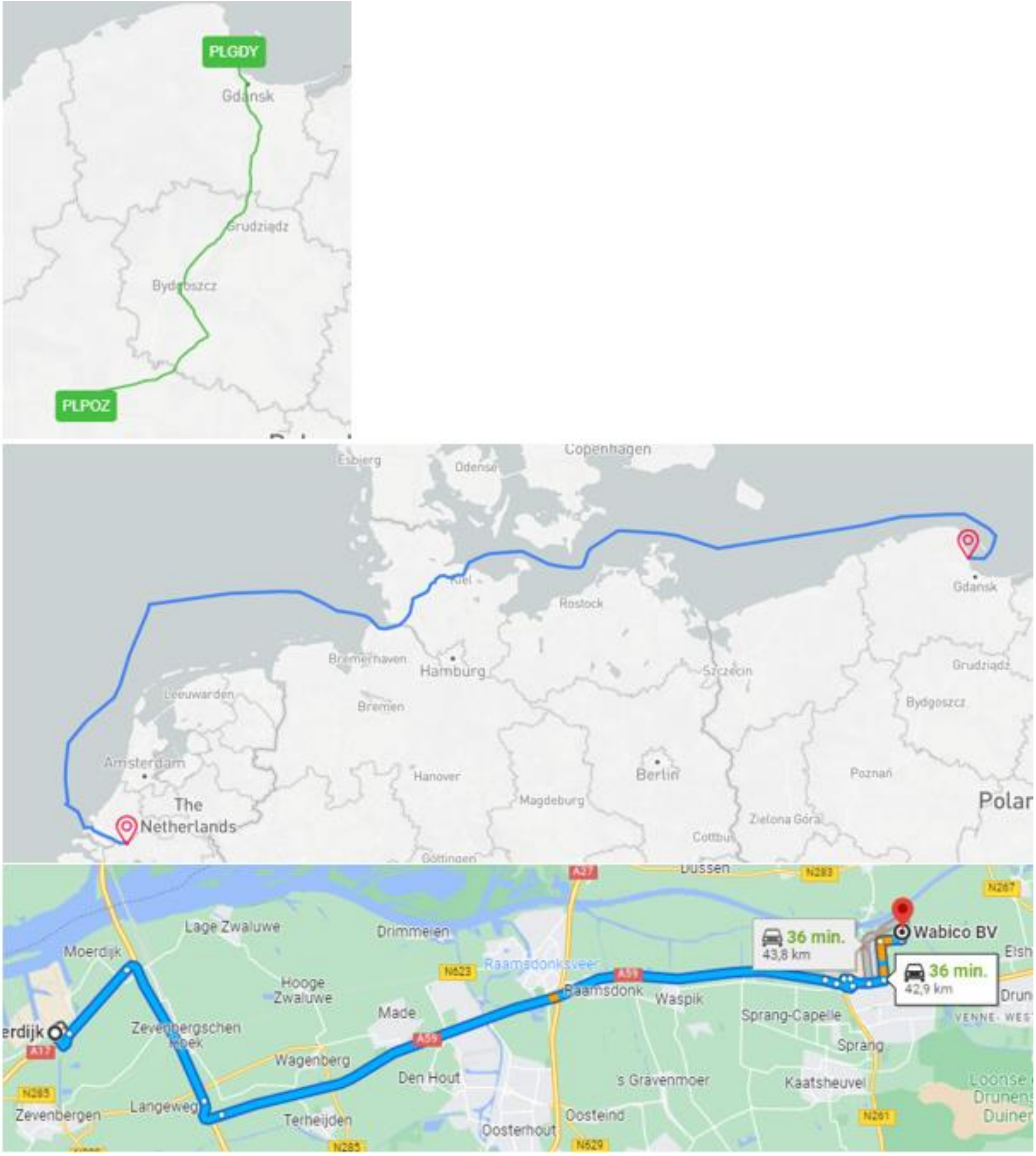


Figure 21: Visual representation of transport network, Sources: app.searoutes.com, https://www.google.nl/maps, https://www.routescanner.com/

Appendix K – LCA calculation excel glycerine Romania

Transportation emissions to plant				
Kilometers by train	271	Km/Km		
Kilometers by truck	187	Km/Km		
Kilometers over sea	6409	Km/Km		
TonneKm by train	7,72E+06	TonneKm/Tonnekm		
TonneKm by truck	5,33E+06	TonneKm/Tonnekm		
TonneKm over sea	1,83E+08	TonneKm/Tonnekm		
Biograce 2 road transport				
Total TonneKm road	5,33E+06	TonneKm/Tonnekm		
Diesel consumption	0,87	MJ/ton.km	Biograce 2	Truck (40 ton) for liquids and pellets (Diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to	4,41E+08	g CO2/y		
Relative CO2 emmissions t	**1,44**	**g CO2/MJ**		
Biograce 2 train transport				
Total TonneKm train	7,72E+06	TonneKm/Tonnekm		
Diesel consumption	0,25	MJ/ton.km	Biograce 2	Freight train USA (diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to	1,84E+08	g CO2/y		
Relative CO2 emmissions t	**0,60**	**g CO2/MJ**		
Biograce 2 boat transport				
Total TonneKm boat	1,83E+08	TonneKm/Tonnekm		
Fuel oil consumption	0,10	MJ/ton.km	Biograce 2	Chemical/product tanker 22.56 kt (Fuel oil)
Fuel oil emissions	94,2	grCO2eq/MJ	Biograce 2	Emission coefficient fuel oil
Total CO2 emissions transport to	1,72E+09	g CO2/y		
Relative CO2 emmissions t	**5,62**	**g CO2/MJ**		
Methane produced per year	8,54E+06	M3 per year		
Methane energetic value	35,81	Mj/M3	LHV	Lower heating value
Total energetic value	**3,06E+08**	**MJ**		
Electricity consumption plant				
Required electricity	1,04E+04	MWh/y		
Emissions from electricity	1,47E+02	gCO2eq/MJ	For the Netherlands	
Total emissions electricity	**5,50E+09**	**gCO2eq/y**		
CO2 liquification				
Ammount of tons CO2 captured	13.552	ton CO2/y		
Annual CO2 emissions capt	**1,36E+10**	**gCO2/y**		
Pelletizing energy consumption				
Tonnes pelletized				
Energy for pelletizing		MWh/tonne		
Overall energy for pelletizin	**0,00E+00**	**MWh/y**		
CO2 emissions from electricity	176,6	gCO2eq/MWh	For Romania	
CO2 emissions pelletizing	0,00E+00	gCo2eq/y		
Relative CO2 emissions				
Transport	7,67	gCO2/MJ		
Electricity	17,99	gCO2/MJ		
Pelletizing	0,00	gCO2/MJ		
CO2 capture	-44,30	gCO2/MJ		
Overall	-18,65	gCO2/MJ		

Impact per mode of transport (%)	
Truck	18,80
Train	7,83
Boat	73,37

CO2 reduction compared to diesel	
Overall relative CO2 emissions	-18,65
Emission coefficient diesel	95,1
CO2 reduction (%)	-119,611

Figure 22: LCA calculation glycerine Romania

Appendix L – LCA calculation excel straw pellets Romania

Transportation emissions to plant				
Kilometers by train	271	Km/Km		
Kilometers by truck	187	Km/Km		
Kilometers over sea	6409	Km/Km		
TonneKm by train	8,86E+06	TonneKm/Tonnekm		
TonneKm by truck	6,11E+06	TonneKm/Tonnekm		
TonneKm over sea	2,10E+08	TonneKm/Tonnekm		

Impact per mode of transport (%)	
Truck	24,11
Train	10,04
Boat	65,85

Biograce 2 road transport				
Total TonneKm road	6,11E+06	TonneKm/Tonnekm		
Diesel consumption	0,87	MJ/ton.km	Biograce 2	Truck (40 ton) for liquids and pellets (Diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to	5,06E+08	g CO2/y		
Relative CO2 emmissions t	**1,79**	**g CO2/MJ**		

Biograce 2 train transport				
Total TonneKm train	8,86E+06	TonneKm/Tonnekm		
Diesel consumption	0,25	MJ/ton.km	Biograce 2	Freight train USA (diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to	2,11E+08	g CO2/y		
Relative CO2 emmissions t	**0,74**	**g CO2/MJ**		

Biograce 2 boat transport				
Total TonneKm boat	2,10E+08	TonneKm/Tonnekm		
Fuel oil consumption	0,07	MJ/ton.km	Biograce 2	Bulk Carrier "Supramax" (Fuel oil) - pellets with bulk density 650 kg/m3
Fuel oil emissions	94,2	grCO2eq/MJ	Biograce 2	Emission coefficient fuel oil
Total CO2 emissions transport to	1,38E+09	g CO2/y		
Relative CO2 emmissions t	**4,88**	**g CO2/MJ**		

Methane produced per year	7,90E+06	M3 per year		
Methane energetic value	35,81	MJ/M3	LHV	Lower heating value
Total energetic value	**2,83E+08**	**MJ**		

Electricity consumption plant			
Required electricity	1,05E+04	MWh/y	
Emissions from electricity	146,70	gCO2eq/MJ	For the Netherlands
Total emissions electricity	**5,56E+09**	**gCO2eq/y**	

CO2 liquification		
Ammount of tons CO2 captured	14.726	ton CO2/y
Annual CO2 emissions capt	**1,47E+10**	**gCO2/y**

Pelletizing energy consumption			
Tonnes pelletized	32.700		
Energy for pelletizing	0,15	MWh/tonne	
Overall energy for pelletizin	**5,05E+03**	**MWh/y**	
CO2 emissions from electricity	176,6	gCO2eq/MWh	For Romania
CO2 emissions pelletizing	**3,21E+09**	gCo2eq/y	

Impact pelletizing	
Overall CO2 emissions	1,09E+10
CO2 emissions pelletizing	3,21E+09
Impact pelletizing (%)	29,54

Relative CO2 emissions		
Transport	7,41	gCO2/MJ
Electricity	19,66	gCO2/MJ
Pelletizing	11,35	gCO2/MJ
CO2 capture	-52,02	gCO2/MJ
Overall	-13,60	gCO2/MJ

CO2 reduction compared to diesel	
Overall relative CO2 emis	-13,60
Emission coefficient dies	95,1
CO2 reduction (%)	-114,301

Figure 23: LCA calculation straw pellets Romania

Appendix M – LCA calculation excel straw Romania

Transportation emissions to plant				
Kilometers by train	271	Km/Km		
Kilometers by truck	187	Km/Km		
Kilometers over sea	6409	Km/Km		
TonneKm by train	1,46E+07	TonneKm/Tonnekm		
TonneKm by truck	1,01E+07	TonneKm/Tonnekm		
TonneKm over sea	3,45E+08	TonneKm/Tonnekm		
Biograce 2 road transport				
Total TonneKm road	1,01E+07	TonneKm/Tonnekm		
Diesel consumption	0,87	MJ/ton.km	Biograce 2	Truck (40 ton) for liquids and pellets (Diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to	8,32E+08	g CO2/y		
Relative CO2 emmissions tr	**2,73**	**g CO2/MJ**		
Biograce 2 train transport				
Total TonneKm train	1,46E+07	TonneKm/Tonnekm		
Diesel consumption	0,25	MJ/ton.km	Biograce 2	Freight train USA (diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to	3,47E+08	g CO2/y		
Relative CO2 emmissions tr	**1,14**	**g CO2/MJ**		
Biograce 2 boat transport				
Total TonneKm boat	3,45E+08	TonneKm/Tonnekm		
Fuel oil consumption	0,27	MJ/ton.km	Biograce 2	Bulk Carrier "Supramax" (Fuel oil) - agri-residues with low bulk density (125 kg/m3)
Fuel oil emissions	94,2	grCO2eq/MJ	Biograce 2	Emission coefficient fuel oil
Total CO2 emissions transport to	8,77E+09	g CO2/y		
Relative CO2 emmissions tr	**28,74**	**g CO2/MJ**		
Methane produced per year	8,52E+06	M3 per year		
Methane energetic value	35,8078648	Mj/M3	LHV	Lower heating value
Total energetic value	**3,05E+08**	**MJ**		
Electricity consumption plant				
Required electricity	1,17E+04	MWh/y		
Emissions from electricity	1,47E+02	gCO2eq/MJ	For the Netherlands	
Total emissions electricity	**6,20E+09**	**gCO2eq/y**		
CO2 liquification				
Ammount of tons CO2 captured	13.519	ton CO2/y		
Annual CO2 emissions capt	**1,35E+10**	**gCO2/y**		
Pelletizing energy consumption				
Tonnes pelletized	0			
Energy for pelletizing	1,55E-01	MWh/tonne		
Overall energy for pelletizin	**0,00E+00**	**MWh/y**		
CO2 emissions from electricity	176,6	gCO2eq/MWh	For Romania	
CO2 emissions pelletizing	0,00E+00	gCo2eq/y		
Relative CO2 emissions				
Transport	32,60	gCO2/MJ		
Electricity	20,33	gCO2/MJ		
Pelletizing	0,00	gCO2/MJ		
CO2 capture	-44,30	gCO2/MJ		
Overall	8,63	gCO2/MJ		

Impact per mode of transport (%)	
Truck	8,37
Train	3,48
Boat	88,15

CO2 reduction compared to diesel	
Overall relative CO2 emis	8,63
Emission coefficient dies	95,1
CO2 reduction (%)	-90,92209

Figure 24: LCA calculation straw Romania

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Appendix N – LCA calculation excel sunflower husk pellets Romania

Transportation emissions to plant				
Kilometers by train	348	Km/Km		
Kilometers by truck	63	Km/Km		
Kilometers over sea	1369	Km/Km		
TonneKm by train	2,68E+07	TonneKm/Tonnekm		
TonneKm by truck	4,85E+06	TonneKm/Tonnekm		
TonneKm over sea	1,05E+08	TonneKm/Tonnekm		
Biograce 2 road transport				
Total TonneKm road	4,85E+06	TonneKm/Tonnekm		
Diesel consumption	0,87	MJ/ton.km	Biograce 2	Truck (40 ton) for liquids and pellets (Diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to pl	4,01E+08	g CO2/y		
Relative CO2 emmissions tra	**1,23**	**g CO2/MJ**		
Biograce 2 train transport				
Total TonneKm train	2,68E+07	TonneKm/Tonnekm		
Diesel consumption	0,25	MJ/ton.km	Biograce 2	Freight train USA (diesel)
Diesel emissions	95,1	grCO2eq/MJ	Biograce 2	Emission coefficient diesel
Total CO2 emissions transport to pl	6,37E+08	g CO2/y		
Relative CO2 emmissions tra	**1,95**	**g CO2/MJ**		
Biograce 2 boat transport				
Total TonneKm boat	1,05E+08	TonneKm/Tonnekm		
Fuel oil consumption	0,07	MJ/ton.km	Biograce 2	Bulk Carrier "Supramax" (Fuel oil) - pellets with bulk density 650 kg/m3
Fuel oil emissions	94,2	grCO2eq/MJ	Biograce 2	Emission coefficient fuel oil
Total CO2 emissions transport to pl	6,95E+08	g CO2/y		
Relative CO2 emmissions tra	**2,12**	**g CO2/MJ**		
Methane produced per year	9,14E+06	M3 per year		
Methane energetic value	35,8078648	Mj/M3	LHV	Lower heating value
Total energetic value	**3,27E+08**	**MJ**		
Electricity consumption plant				
Required electricity	1,17E+04	MWh/y		
Emissions from electricity	1,47E+02	gCO2eq/MJ	For the Netherlands	
Total emissions electricity	**6,18E+09**	**gCO2eq/y**		
CO2 liquification				
Ammount of tons CO2 captured	12.317	ton CO2/y		
Annual CO2 emissions captu	**1,23E+10**	**gCO2/y**		
Pelletizing energy consumption				
Tonnes pelletized	77.000			
Energy for pelletizing	1,55E-01	MWh/tonne		
Overall energy for pelletizing	**1,19E+04**	**MWh/y**		
CO2 emissions from electricity	287	gCO2eq/MWh	For Poland	
CO2 emissions pelletizing	1,23E+10	gCo2eq/y		
Relative CO2 emissions				
Transport	5,30	gCO2/MJ		
Electricity	18,89	gCO2/MJ		
Pelletizing	37,56	gCO2/MJ		
CO2 capture	-37,63	gCO2/MJ		
Overall	24,12	gCO2/MJ		

Impact per mode of transport (%)	
Truck	23,15
Train	36,75
Boat	40,10

CO2 reduction compared to diesel	
Overall relative CO2 emissions	24,12
Emission coefficient diesel	95,1
CO2 reduction (%)	-74,6389

Figure 25: LCA calculation sunflower husk pellets Romania

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Appendix O – Costs and revenues current situation

* This has been left out due to confidentiality*

Figure 26: Life cycle HoSt

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Appendix P – Data residues Romania

Crops	Common wheat and spelt	Grain maize and corn-cob mix	Barley	Durum wheat	Rye	Sunflower	rapeseed
Residue-to-crop ratio	1.05-1.78	1.04-1.52	1.05-1.78	1.05-1.78	1.08-1.42	2.20-3.50	1.20-1.98

Table 10: Residue-to-crop ratio for different crops in Romania (Scarlat, 2011)

Crops	Common wheat and spelt	Grain maize and corn-cob mix	Barley	Durum wheat	Rye	Sunflower	Rapeseed
Available for energy purpose (%)	40	50	40	40	40	50	50

Table 11: Availability for energy purposes in % for Romania (Scarlat, 2011)

NUTS 2 regions	Common wheat and spelt	Grain maize and corn-cob mix	Barley	Durum wheat	Rye	Total
RO11	337.17	1051.97	55.02	0.96	1.4	1446.52
RO12	193.01	642.62	38.49	0.34	2.65	877.11
RO21	291.89	1047.87	33.79	0.06	5.65	1379.26
RO22	364.62	650.75	127.24	0.85	0.15	1143.61
RO31	996.22	1136.19	204.84	0	0.9	2338.15
RO32	34.47	28.8	5.83	0	0.05	69.15
RO41	826.87	931.90	113.99	0.79	3.2	1876.75
RO42	567.76	971.84	66.62	7.64	0.25	1614.11
Total	3612.01	6461.94	645.82	10.64	14.25	-
M^3 biogas	$1.065 * 10^9$	$1.906*10^9$	$1.905*10^8$	$3.139*10^6$	$4.204*10^6$	

Table 12: Average available residues for different cereals in 1,000 tonnes Romania with biogas potential

Appendix Q– Data residues Poland

Crops	Common wheat and spelt	Grain maize and corn-cob mix	Barley	Triticale	Rye and winter cereal	Oats	Sunflower	Rapeseed
Residue-to-crop ratio	0.8–1.6 (Scarlat, 2010)	0.9–1.2 (Scarlat, 2010)	0.8-1.3 (Scarlat, 2010)	1.00-1.13 (Havrysh, 2021)	0.9-1.6 (Scarlat., 2010)	0.91-1.08 (Havrysh, 2021)	2.2–3.2 (Scarlat, 2010)	1.4-2.0 (Scarlat, 2010)

Table 13: Residue-to-crop ratio for different crops in Poland

Crops	Common wheat and spelt	Grain maize and corn-cob mix	Barley	Triticale	Oats	Rye and winter cereal	Rapeseed	Sunflower seed
Available for energy purpose (%)	40 (scarlat, 2010)	50 (scarlat, 2010)	40 (scarlat, 2010)	75 (Dassanayake, 2012)	40 (scarlat, 2010)	40 (scarlat, 2010)	50 (Scarlat, 2010)	50 (Scarlat, 2010)

Table 14: Availability for energy purposes in % for Poland

Nuts 2 regions	Common Wheat and Spelt	Grain Maize and Corn cob mix	Barley	Triticale	Oats	Rye and winter cereal	Total
PL21	211.49	131.09	38.26	49.53	18.07	12.7	461.14
PL22	168.34	107.15	42.59	141.46	20.58	42.85	522.97
PL41	598.56	710.64	229.95	873.91	53.37	320.05	2786.48
PL42	376.27	107.21	92.32	289.95	45.25	157.95	1068.95
PL43	110.74	80.75	42.84	175.25	12.38	62.05	484.01
PL51	677.38	374.64	133.64	185.71	28.30	48.10	1447.77
PL52	447.22	268.38	131.88	134.43	10.59	31.95	1024.45
PL61	586.39	485.84	110.00	361.11	17.35	118.25	1678.94
PL62	396.91	105.58	44.44	297.21	37.41	67.45	949
PL63	477.41	64.42	47.33	206.64	32.64	96.50	924.94
PL71	269.04	184.38	70.14	557.29	69.05	217.95	1367.85
PL72	162.77	30.71	44.18	136.11	13.65	22.75	410.17
PL81	880.66	148.63	108.99	467.99	90.74	84.55	1781.56
PL82	194.54	212.15	25.66	60.31	25.75	16.10	534.51
PL84	100.27	146.48	22.81	260.07	69.41	108.50	707.54
PL91	50.26	58.85	5.25	62.94	19.42	34.65	231.37
PL92	303.46	297.26	48.05	602.50	91.42	233.10	1575.79
Total	6011.71	3514.16	1238.33	4862.41	655.38	1675.45	-
M^3 biomethane	$1.773*10^9$	$1.037*10^9$	$3.653*10^8$	$1.434*10^9$	$1.933*10^8$	$4.941*10^8$	-

Table 15: Average available residues for different cereals in 1,000 tonnes in Poland with biogas potential

Erik Groot Koerkamp
e.grootkoerkamp@student.utwente.nl
S2401835
Datum

Appendix R – Example of transport cost calculation

All the scenarios can be found in appendix H and I, now an example is worked out. This example uses exactly the same method as the excel file. The scenario that is worked out is from Poznan to Moerdijk. First the feedstock has to be collected, from Poznan by train to Gdynia, Gdynia to Moerdijk by boat and from Moerdijk to Wabico. The distances for are listed below.

Poznan – Moerdijk: distance for collection: 208 km, distance on rail: 340 km, distance over sea: 1,369 km, distance to Wabico: 43 km

For this scenario 2,000 tonnes is used as baseline. The costs are given in tonne kilometer (tkm). Tkm = total distance (in km) * total weight (in tonnes). (Poel, n.d.) Also a density of 1 kg/liter is used. The densities matter, since the costs change for different densities.
For every mode of transport the tkm is calculated, this is done because every mode has different costs per tkm.
First the tkm for the trucks is calculated. A truck has a limited capacity, in this case 35 tonnes is used. First the number of truckloads is calculated: 2,000/35 = 57.14… After rounding this up there are 58 truckloads.
208*58 = 12,064 km
43*58 = 2,494 km
The total amount of km travelled by truck: 12,064 + 2,494 = 14,558 km

Tkm per mode
Amount of tkm truck = 35*14,558 = 509,530.
Amount of tkm train: 340 * 2,000 = 680,000
Amount of tkm sea = 1369 * 2,000 = 2,738,000
The tkm per mode is known, so now the costs can be calculated.

Costs per mode
The costs are given in euro.
Costs for truck: 509,530*0.366 = 186,487.98
Costs for train: 680,000*0.012 = 8,160.00
Costs for sea: 2,738,000*0.0032 = 8,761.60
Total costs: 203,409.58
The overall costs are calculated, now this is calculated per tonne of product.
Costs per tonne: €101.70

In this way the costs and are calculated. To make sure that all the scenarios can be analysed in an efficient way, an excel file was made where the values can be filled in and the costs come out of it in this way. In appendices: the routes can be found for this scenario. The route for collection is not included.

Appendix S – Example calculation CI-score

One calculation of a the LCA is shown, for the other calculations a screenshot are added in the appendix. The scenario that is shown is sunflower husk pellets from Romania. Values for the emissions were found in the Biograce 2 tool. The calculation itself was done in an internal document from HoSt called: Biogas calculator. In this biogas calculator some values needed to be achieved for the plant to stay within the regulations. For this 77,000 tonnes of sunflower husk and 200,000 tonnes of water was needed. This gave a return of around 15,500,000 M^3 biogas and 9,200,000 M^3 methane. These returns are used for all the feedstock.

For this calculation TonneKm are used again, since that is how the values are given by Biograce 2. The cheapest way from Romania to Wabico was: from Ploiesti by train to Constanta and from there to Moerdijk. This was 271 km by train, 187 km by truck and 6409 km by boat.

Like mentioned before 77,000 tonnes of sunflower husk was used.

TonneKm per mode of transport.

TonneKm road: 77,000*187 = 14,399,000 TonneKm for trucks
TonneKm train: 77,000*271 = 20,867,000 TonneKm for train
TonneKm boat: 77,000*6409 = 493,493,000 TonneKm for boat

Every mode of transport has different emissions, these were found in Biograce 2

Truck

Diesel consumption truck (40 ton, pellets and liquids): 0.87 MJ/TonneKm
Diesel emissions: 95.1 $grCO_{2eq}$/MJ
Total emissions: 0.87*95.1*14,399,000 = $1.19*10^9$ gCO_2

Train

Diesel consumption train (freight train USA): 0.25 MJ/TonneKm
Diesel emissions: 95.1 $grCO_{2eq}$/MJ
Total emissions: 0.25*95.1*20,867,000= $4.96*10^8$ gCO_2

Boat

Fuel oil consumption (Bulk carrier, Supramax, pellets): 0.07 MJ/TonneKm
Fuel oil emissions: 94.2 $grCO_{2eq}$/MJ
Total emissions: 0.07*94.2*493,493,000 = $3.25*10^9$ gCO_2

Electricity

The feedstock needs to be processed at the plant, for this electricity is used.

Required electricity: $1.17*10^4$ MWh/y (Biogas calculator, n.d.)
Emissions from electricity (Netherlands): 146.7 gCO_{2eq}/MJ (Biograce, 2018)
1 MWh = 3,600 MJ (Biogas calculator, n.d.)
Total emissions electricity: $1.17*10^4$*3,600*146.7 = $6.18*10^9$ gCO_2

CO_2 liquification

Another step in the process is capturing CO_2, after this it liquified and has other uses. This has a positive effect on the LCA.

12,317 tonnes CO_2/y is captured.

Overall emissions CO_2 liquification = $-1.23*10^{10}$

Pelletizing

In this case the feedstock is pelletized first, so this has to be taken into account for the LCA.

Tonnes pelletized: 77,000
Electricity for pelletizing: $1.55*10^{-1}$ MWh/tonne (Wilson, 2014)
Overall energy for pelletizing: $77{,}000*1.55*10^{-1} = 1.19*10^{4}$ MWh/y
Emissions from electricity (Romania): 176.6 gCO_2/MJ (Biograce, 2018)
Overall emissions pelletizing: $1.19*10^{4}*3600*176.6 = 7.57*10^{9}$ gCO_2

Methane produced

HoSt is interested in gCO_2/MJ. This means that the energy produced in terms of methane should be looked at as well.

M^3 Methane produced: $9.14*10^{6}$ (Biogas calculator, n.d.)
Methane energetic value: 35.81 MJ/M^3 (Biogas calculator, n.d.)
Total energetic value: $9.14*10^{6}*35.81 = 3.27*10^{8}$ MJ

Now all the emissions and energetic value of methane are known. So the relative emissions are calculated, in gCO_2/MJ.

Relative emissions

Truck transport relative emissions: $1.19*10^{9} / 3.27*10^{8} = 3.64$ gCO_2/MJ
Train transport = 1.52 gCO_2/MJ
Boat transport = 9.94 gCO_2/MJ
Electricity consumption = 18.89 gCO_2/MJ
Pelletizing = 23.11 gCO_2/MJ
CO_2 capture = -37.63 gCO_2/MJ

Overall relative emissions: 19.47 gCO_2/MJ

This value was compared to the value of diesel emissions to see if the 70% CO_2 reduction compared to fossil fuel alternative was achieved.

(19.47-95.1)/95.1 = -79.53%

For this situation the 70% CO_2 reduction compared to diesel was achieved, so it passes this goal.

Appendix T – Distances to Wabico from Poland/Romania

Romania

The distances on road from the aforementioned locations in Romania to Wabico are given.

From/To	Wabico
Constanta	2,399
Ploiesti	2,144

Table 16: on road distances from Romania to Wabico in Km, Source: https://www.google.nl/maps

From/To	Moerdijk	Rotterdam	Dordrecht	Waalwijk
Constanta	6,409	6,381	6,413	6,452

Table 17: Waterway distances from Romania to Netherlands in Km, Source: app.searoutes.com

From/To	Moerdijk	Rotterdam	Dordrecht
Constanta	2,824	2,851	2,842
Ploiesti	2,309	2,285	2,571

Table 18: Rail distances from Romania to Netherlands in Km, source: https://www.routescanner.com/

From/To	Constanta
Ploiesti (Rail)	271
Ploiesti (Road)	290

Table 19: Distances from Ploiesti to Constanta in Km, Source: https://www.google.nl/maps, https://www.routescanner.com

Poland

From/To	Wabico
Gdynia	1,237
Poznan	913
Kutno	1,090

Table 20: Road distances in Km, Source: https://www.google.nl/maps

From/To	Moerdijk	Rotterdam	Dordrecht	Waalwijk
Gdynia	1,369	1,335	1,361	1,406

Table 21: Waterway distances in Km, Source: app.searoutes.com

From/To	Moerdijk	Rotterdam	Dordrecht
Gdynia	1,170	1,159	1,141
Poznan	1,004	955	977
Kutno	1,172	1,128	1,155

Table 22: Rail distances in Km, Source: https://www.routescanner.com/

From/ To	Gdynia
Poznan (Rail)	335
Poznan (Road)	340
Kutno (Rail)	348
Kutno (Road)	293

Table 23: Distances from Kutno/Poznan to Gdynia in Km, Source: https://www.google.nl/maps, https://www.routescanner.com/