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# GRASS SILAGE AS A FEEDSTOCK FOR A BIOGAS PLANT-

## A feasibility study and development of a cost calculation tool

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Abstract

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Abstract

This study was commissioned by Envitecpolis Oy to investigate the cost structure of grass silage used as feedstock for a biogas plant in order to determine the factors affecting it, and to assess its profitability from the biogas plant and the producer's point of view.

Three different types of harvesting chains were included in the study, which were assumed to be suitable for different situations. The input data and calculation criteria for the calculator were based on a literature review, on time consumption analysis carried out between 2021 and 2022, actual costs incurred at the time, as well as on the available statistical costs of contracting.

During the study, an Excel-based calculation tool was developed. The calculator could be used to calculate feedstock production costs in terms of yield, transporting distance, and the average field size. The calculator was used to examine the production costs in general, and in two separately defined cases; one for a farm-scale wet digester with a procurement radius of about 15 km, and one for an industrial-scale dry digester with a procurement radius of about 50 km. In the future, the same calculation tool can be utilized to estimate the costs of feedstock procurement, e.g., in the pre-feasibility phase of a biogas plant project.

In the study it was found out that if used for the feedstock, the production cost of grass silage is a significant factor in the total cost of biogas production. Due to the high production costs (so-called plant price) from an inefficient supply chain, grass silage may not be a viable feedstock for the biogas process. But if organized efficiently, grass feed can be used to produce biomethane profitably. However, profitability demands high efficiency in the supply chain and that the sustainability criteria targets are met.

The most important factors affecting production costs are the yield per hectare and the moisture content of the material. The size of the field also had a significant impact on the cost and varied considerably between the harvesting chains. Bale-based chains were better suited for smaller fields and lower yields, but forage harvester-chain provided the lowest costs in case the average field size was over 1.5 ha. At its lowest, the plant cost of the grass feedstock was around 100 € /t-DM (~30 €/MWh-CH4). As the yield levels dropped, or another harvest efficiency variable was unfavorable, the production cost quickly reached 200 €/t-DM (~60 €/MWh-CH4), a level that could be considered approximately the upper limit of profitability at the current biomethane selling prices.



Keywords

biogas, feedstock, silage, grass, supply chain, production cost

PREFACE

Many thanks go to Toni and Mika of Envitecpolis Oy, who made this work possible by being very flexible in defining the research topic, and above all, setting a very reasonable schedule for a part-time student. I hope that this work will help you at least a little in the great work you are doing as pioneers in the biogas sector in Finland.

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The biggest thanks, however, go to the great crew at home, who put up with the student hiding in his office in the evenings and wandering around in his thoughts - and who, now that the work is finally finished, can hopefully be more of a father and husband. Thank you, Pirjo, Miska, and Pyry; and of course, Martta, the foot-warmer-dachshund - you are the best!

Kiuruvedellä 20.11.2022
Mikko Jauhiainen

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# ABBREVIATIONS AND DEFINITIONS

| | |
|---|---|
| AD | anaerobic digestion |
| CH4 | methane |
| CHP | combined heat and power |
| CBG | compressed biogas |
| CNG | compressed natural gas |
| C:N | A carbon-to-nitrogen ratio; is a ratio of the mass of carbon to the mass of nitrogen. |
| CSTR | continuously stirred tank reactor |
| DEC | dedicated energy crops |
| DM | dry matter |
| EU | European union |
| GHG | greenhouse gas |
| GWh | gigawatt hour |
| HRT | hydraulic retention time |
| kWh | kilowatt hour |
| L-AD | liquid anaerobic digestion process (wet process) |
| LBG | liquefied biogas |
| LNG | liquefied natural gas |
| Nm3 | normal cubic meter. A quantity of gas which at 0 °C and at an absolute pressure of 1.01325 bar occupies the volume of 1 cubic meter. |
| P2G | power-to-gas |
| SRT | solids retention time |
| SS-AD | solid state anaerobic digestion process (dry process) |
| TS | total solids |
| VAT | value-added tax |
| VS | volatile solids |

# 1 INTRODUCTION

Awakening to the problems caused by the rapid climate change has been the biggest concern of the industrialized world during the last decade. In order to mitigate the problem and slow down climate warming, the EU commission has stated at the European Green deal roadmap in 2021 that the EU´s objective is to be climate neutral by 2050 (European Commission 2019 and 2021).

On its way to climate neutrality, the EU is committed to reducing greenhouse gas emissions by at least 55% of the 1990 level by 2030. In July 2021, the European Commission presented the EU climate package, the so-called Fit for 55 Package, which will help the EU reach its emissions reduction target for 2030 (European Commission 2021). The European Climate Law was enforced in the summer of 2021, making the climate neutrality target for 2050 and the emissions reduction target for 2030 legally binding. Prime Minister Sanna Marin's Government set Finland's goal even higher, as it outlined in its government program that Finland was anticipated to be carbon-neutral in 2019 and the first fossil-free welfare society by 2035 (Programme of Prime Minister Sanna Marin's Government 2019, 35-41). This ambitious goal obviously requires very fast emissions reductions and stronger carbon sinks in all sectors of the Finnish society.

The need to meet these goals has promoted an increasing demand for innovation and development among all the environmentally sustainable energy production. Biogas is recognized as one of the biggest unutilized and readily technically available sustainable energy resources in Finland. A national biogas program was drawn up in 2019, when the Ministry of Economic Affairs and Employment appointed a working group to prepare a national biogas program with the goal of promoting the production potential of biogas and driving the achievement of our climate targets. The working group was tasked with describing the current state of biogas production, the most significant factors slowing down or preventing large-scale production and utilizing biogas, measures for resolving these issues, and implementing the measures included in the Government Program regarding biogas. The working group was asked to pay particular attention to measures that would promote decentralized and small-scale biogas production (Työ- ja elinkeinoministeriö 2020. 9-10).

In its final report, the working group described the current state of the biogas sector in Finland. The report also comprehensively outlined the most effective development measures to utilize the unused biogas potential. In particular, the development of the production and the biogas supply used as transport fuel was found to be important, as it can directly reduce transport greenhouse gas emissions, which are otherwise difficult to reduce (Työ- ja elinkeinoministeriö 2020, 23-28). The means presented in the working group's report have already been put into use at the time of writing this paper, e.g., by accepting biogas under the distribution obligation (HE 48/2021), and by promoting the development of a comprehensive distribution infrastructure and biogas plant investments with an increased investment subsidy.

Alongside with the energy sector, the agriculture and food production sectors also seem to be going towards a significant turning point. In addition to the goals set for the energy sector, it can be seen that in the near future, consumers and politicians will address increasing demands towards farmers, and the agricultural production sector as a whole, to reduce emissions to the atmosphere and the overall carbon footprint from food production. Those requirements may appear hard to meet and even unfair in a situation, where the whole agriculture sector has been struggling with rising costs and rapid restructuration. Biogas production can be seen as one promising industry that makes it possible to fulfill the demands and challenges coming from outside the agricultural sector.

Biogas production has been seen as a new business and source of income, and it has been expected to bring profitable business opportunities to rural areas and increase the vitality of the regions. Rural bioenergy production creates positive effects on the social, economic, and environmental aspects. Like Huttunen (2013) states in her dissertation: "Local bioenergy production has the potential to increase rural sustainability…" and "… can have important positive developmental effects that ameliorate and sustain livelihoods in remote areas."

The Russian invasion into Ukraine, which started while writing this thesis, has revolutionized the European energy market and further emphasized the importance of utilizing local energy sources. It has also awakened decision-makers and citizens to pay more attention to national self-sufficiency in energy production, food production, and for securing a supply of materials and fertilizers. As we can learn from the present situation in Ukraine, that is struggling under the attack of Russia, decentralized energy production is a good strategic decision in the unpredictable geopolitical situation we suddenly found ourselves living in.

## 1.1 The importance of biogas as part of the renewable energy palette

The energy and climate policies in the EU, and the introduction of various support schemes for promoting the utilization of renewable resources have encouraged the development of biogas plants for energy production (Scarlat, Dallemand & Fahl 2018).

The roadmap for fossil-free transport published by the Finish government in 2021 sets a target of around 130,000 compressed biogas (CBG) or compresses natural gas (CNG) -powered cars and vans, and around 6,200 liquefied biogas (LBG) or liquefied natural gas (LNG)-powered trucks and buses in Finland before 2030 (Valtioneuvosto 2021, 15). Although many passenger car manufacturers have announced that they will not develop their gas car models in the future, and the risk of gas as a passenger car fuel will become marginal with the development of electric cars, it is expected that the use of biogas in transportation will continue to grow, driven by heavy road- and shipping transportation.

However, it is possible to state that the importance of biogas production in Finland's and Europe's energy palette may be greater than what could be deduced from the share of energy produced alone. This view is addressed in the report prepared by Gaia consulting Oy (2021, 8-9) for the biogas working group of the Ministry of Employment and the Economy. It states that gas (both biogas and natural gas) can play a significant role in the smart energy system of the future. The existing gas infrastructure in Finland and the versatile utilization possibilities of biogas in transport, shipping, and as a fuel for industries, and regulating power will support the use of gas in the future. Gas is easier to store than electricity, so it is possible to use gas as an energy storage. In addition to the biological process, methane can be produced by the so-called Power-to-Gas technology (P2G), where water is split into oxygen and hydrogen with electrical energy, which can be used as is or further refined into methane by means of methanation, i.e., combining hydrogen and carbon dioxide. With Power-to-Gas technology, electrical energy can be stored as gas in the gas network. This is necessary because the production of renewable electrical energy is fluctuating and strongly dependent on the weather. The production of biogas and methane produced with electricity complement each other in Finland's energy system. Natural gas could therefore be replaced by biogas and synthetic methane in the future.

Due to its already quite limited production potential, biogas production cannot be an all-encompassing solution to the energy challenges of the future. Rather, it should be seen as one part of a versatile array of tools that can be used to achieve the set goals. In this thesis' work, the attempt was not so much to describe the big picture, but to find and address solutions that can lower the economic obstacles that are now slowing down the development of the biogas industry.

## 1.2 Other benefits of biogas use

In addition to the positive climate effects of biogas energy usage, there are many other benefits of biogas production. The use of wastewater treatment sludges and organic material of the municipal waste disposal as feedstock for biogas plants provides waste management organizations a cheap and safe way of processing their wastes into a hygienic product (Scarlat, Dallemand, & Fahl. 2018).

In agriculture, a large volume of organic waste and leftovers is generated from the processing of crops and from growing livestock. These wastes have traditionally been composted, but this can often lead to undesirable environmental impacts, such as odors, leaching nutrients into the groundwater and the potential eutrophication of water sources, pests, and even risks to human health from pathogenic exposure (Melville et al 2014). However, these materials are excellent feedstocks for biogas plants, and when used as such, unwanted impacts can be mitigated or even made non-existent.

Traditionally in agriculture, manure and slurry are used directly as a fertilizer for cultivation. Especially in areas with high livestock density, the extensive use of manure can cause environmental problems like groundwater contamination and the eutrophication of surface waters.  The odor from manure handling and spreading it to fields is an unpleasant nuisance, and the resulting opposition from neighbors may, e.g., prevent the granting of environmental permits for expanding livestock farms (Kymäläinen ja Pakarinen 2015). Anaerobic digestion contributes to mitigating odors associated with manure storage, handling, and spreading (Scarlat, Dallemand & Fahl 2018).

Digestate from biogas production can be used as fertilizer, just like manure, having the same content of nutrients, but often in a more soluble compound that plants can utilize easier. This brings additional economic benefits by reducing the use of chemical fertilizers in farms, reducing nutrient runoff, and avoiding methane emissions (Scarlat et al. 2018). Using grass as a feedstock for a biogas plant offers a good way to support a circular economy by allowing the recycling of nutrients collected by grassy vegetation and nitrogen-fixing plants to cereal crops, thus allowing grassland to be included in plant rotation even in areas where livestock farming is not practiced.

### 1.3 Envitecpolis Oy as a client

This thesis work was commissioned and partly supervised by Envitecpolis Oy. Envitecpolis provides counting and professional services to food chain operators to support their decision-making in energy, economic, and environmental areas. Envitecpolis Oy provides detailed information for their customers, including financial and investment profitability calculations, as well as various environmental assessments, such as looking at the carbon footprint or biodiversity. They offer support and assistance for all stages of the investment process of a biogas plant and solar photovoltaic (PV) system with long-term experience and know-how in reviewing the profitability of biogas plant investments. This company is a pioneer in the field; within their 15-year history, this company has made more assessments than any other company in Finland. Their customers are individual farms, farm groups, and the food industry (Envitecpolis 2022).

The topic of this thesis was chosen to serve both the needs of the client and theme of the energy engineering studies. The contact persons on the client's side were Senior Specialist Toni Taavitsainen and Mika Arffman, the Managing Director of Envitecpolis Oy. During the initial discussion to develop a work plan, the client presented some real-life research needs as a basis for the work. Finally, based on those suggestions and the discussion, a suitable entity was selected for the scope and research topics of this final work.

# 2 BIOGAS AS A SOURCE OF ENERGY

Biogas is a mixture of gaseous components produced when anaerobic organisms degrade organic matter in an anaerobic environment. Typically, biogas consists mainly of methane $CH_4$ (50-70% by volume) and carbon dioxide $CO_2$, (25-45%). Moreover, biogas also contains small amounts of nitrogen $N_2$, hydrogen $H_2$, Oxygen $O_2$, ammonia $NH_3$, and carbon monoxide CO (Lianhua 2017, 145-146). Usually, biogas also contains some trace elements that are often unwanted or even harmful for humans, materials, or machines. Hydrogen sulfides $H_2S$ and siloxanes are the most common harmful molecules that should be removed from the biogas before its final utilization. Nitrogen is not harmful, but it is unwanted due to the difficulty in removing it from the biogas, and as an inert gas, it will lower the calorific value of the gas mixture.

The energy content of biogas depends on the concentration of combustible gases (mainly methane) that it contains. Table 1. shows the main physical and chemical properties of CH4 and biogas. For example, the level of explosive concentration range of the biogas and methane is higher than diesel (0.6-7.5%) or gasoline (1.4-7.6%). The ignition of biogas and methane requires a higher concentration than liquid fuels, but the range of the explosive mixture is wider.

TABLE 1: Physicochemical properties of the CH4 and biogas. Source: Lianhua 2017, 146

| Characteristics | $CH_4$ | Standard biogas ($CH_4$ = 60 %, $CO_2$ < 40 %) |
|---|---|---|
| Volume percentage (%) | 54–80 | 100 |
| Calorific value (kJ/L) | 35.82 | 21.52 |
| Explosive range (%) | 5–15 | 8.33–25 |
| Density (g/L) | 0.72 | 1.22 |
| Relative density (g/L) | 0.55 | 0.94 |
| Critical temperature (°C) | −82.5 | −25.7 to 48.42 |
| Critical pressure (× $10^5$ Pa) | 46.4 | 53.93–59.35 |
| Odor | Odorless | Slight odor |

Notes: (1) Explosive range: the concentration range of flammable gas for establishing a detonation wave in the air or oxidation. (2) Critical temperature and critical pressure: the temperature and pressure of the gas beginning where it becomes a liquid, respectively.

The "Standard biogas" described in the table is a commonly used generalization of biogas properties, which could be used in physical calculations. The actual composition of biogas may differ significantly from this.

## 2.1 Applications of biogas and biomethane

The majority of biogas produced is currently used in energy production. In developing countries, biogas is often produced in small, domestic-scale digesters which provide fuel for cooking or lighting. In the developed countries, biogas production is going towards a larger scale, often in farm-based or industrial-scale biomethane- or electricity and heat-producing facilities. In Finland, and Europe in general, most of the anaerobic digesters provide biogas for combustion engines in Combined Heat and Power (CHP) plants (Scarlat, Dallemand & Fahl, 2018).

Biogas using CHP plants consist of a piston engine or turbine engine that drives an electric generator. The heat from the engine's exhaust gases and coolant is recovered and either recycled or dissipated into the air. Normally, no $CO_2$ is removed from the raw biogas before the CHP engine, but it is always necessary to remove hydrogen sulfide and siloxanes, e.g., by activated carbon filtration. The CHP plant's electrical capacity ranges from tens of kilowatts up to a few megawatts. Electricity is either used locally or fed to the distribution grid. Generated heat can be used to meet the local heat demand on a farm or community or deliver it to the external users via district heating network.

Part of the heat generated in a CHP plant is used for heating the AD digester process. Nevertheless, there is almost always surplus heat available in case of electricity production. Every so often, there is not enough economically viable utilization for all the heat generated, in which case, it can also be disposed through condensers into the air or water.

The universal problem of low demand for the heat generated in CHP production has promoted upgrading biogas to biomethane, as dissipating the surplus heat is considered a waste of energy. Biomethane is a collective term for a mix of flammable gases produced from biological material, which is mostly methane (more than 95%). Biomethane has properties similar to natural gas, which is also mostly methane. Biomethane is produced from raw biogas by removing unwanted gases, such as $CO_2$, water vapor, and harmful trace contaminants such as sulfur, $H_2S$ and siloxanes. This purification process is called biogas upgrading.

Biogas can be upgraded to biomethane through several different technologies that are readily available. Commonly used processing methods include water scrubbing, Pressure Swing Absorption (PSA), amine scrubbing, and membrane separation. When choosing a processing method, attention should be paid to the energy and consumables used among other things. According to Kaparaju, Rasi, and Rintala (2018, 167-175), the energy consumption of processing can vary between 0.3-0.9 kWh/$m^3$ biomethane. Based on various studies, the total cost of refining is estimated at 0.12 - 0.30 €/$m^3$ methane.

After upgrading, biomethane is often compressed and can then be used as a fuel in gas-powered vehicles, such as cars, buses, and light trucks. Compressed biogas (CBG) is used, which means that methane is compressed to a maximum pressure of about 300 bar, and it is in a gaseous state at a normal ambient temperature. Biogas can also be used in a liquefied form, known as Liquefied Biogas (LBG). LBG is at the moment a relatively under-utilized fuel in road transport, but its applications are constantly growing. LBG is particularly useful for heavy transport because it can be stored efficiently in a smaller space than CBG. By liquefying biogas, the volume is up to 600 times smaller, allowing large volumes of gas to be stored and transported efficiently. LBG can substitute liquified natural gas LNG in the shipping industry, where gas-driven engines are getting more and more common.

Biomethane can also be injected into the natural gas network, allowing it to be used at any point of use within reach of the gas network. The characteristics of the gas injected into the network are determined by the network owner. In general, the requirements are similar to those for gas-refined transporting purposes, i.e., the methane content must be above 96% (Gasgrid 2022).

Given the low GHG emissions over the whole supply chain, and from utilizing biomethane as fuel in vehicles, it is among the best options as renewable fuel in transport, thus contributing to the renewable energy targets in this sector. The largest market for utilizing biomethane as a transport fuel is the European Union, with a combined 160 million m3 of biomethane in 2015 (Scarlat, Dallemand & Fahl 2018).

## 2.2 Anaerobic digestion as a biological process

Anaerobic digestion (AD) is a four-stage process; hydrolysis, acidogenesis (acidification), acetogenesis, and methanogenesis (methanation), whereby organic material, such as manure, food waste or plant biomass, is broken down by the interaction of complex microorganisms in the absence of oxygen to produce biogas and digestate (Argypolous, Varzakas and Benzie 2012, 262 and Lianhua et al. 2017).

This chapter describes the biology and chemistry of the AD process to the extent necessary for the context of this work, and in order to understand the constraints on the use of different feed materials for the biological AD process. The different stages of the anaerobic digestion process are illustrated in Figure 1.

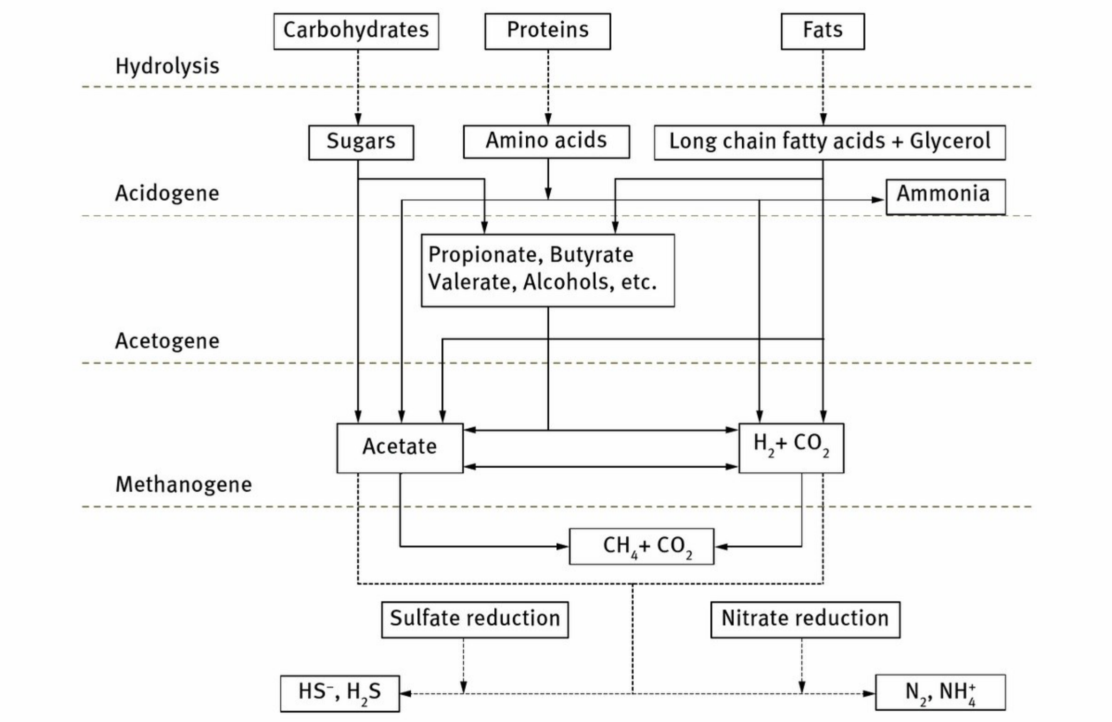


FIGURE 1. Biochemical process of biogas fermentation according to Lianhua et al. (2017)

Lianhua et al. (2017) and Al Saedi et al. (2008) described the four biogas fermentation phases as follows:

**Hydrolysis** is the first step of the AD. Feedstock consists of macromolecules, which microorganisms cannot directly consume. Therefore, these macromolecules are first degraded into small water-soluble molecules by the exoenzymes of facultative (an organism that is capable for aerobic respiration if oxygen is present but is capable of switching to fermentation if oxygen is absent) and obligatory (anaerobic) bacteria. Carbohydrates are hydrolyzed into simple sugars like glucose, proteins are degraded into amino acids, and lipids are cracked into glycerol and fatty acids. These small molecules can pass through microbial cells and are therefore used by microorganisms.

In **acidification** (or acitogenesis), the hydrolysis products are converted by anaerobic (fermentative) bacteria to methanogenic substrates, like short-chain organic acids (acetates), alcohols, carbon dioxide $CO_2$, ammonia NH3 and volatile fatty acids (VFA). Because volatile organic acids are the main products, this phase is called acidification.

During **acetogenesis**, the products from acidogenesis, which cannot be directly converted to methane by methanogenic bacteria, are converted into methanogenic substrates. VFA with carbon chains longer than two units and alcohols, with carbon chains longer than one unit, are oxidized into methanogenic substrates like acetate, hydrogen, and carbon dioxide. The production of hydrogen increases the hydrogen partial pressure. This inhibits the metabolism of the acetogenic bacteria. Later during methanogenesis, hydrogen is converted into methane. Acetogenesis and methanogenesis usually run parallel as the symbiosis of two groups of organisms.

The last stage of the AD process is **methanation** or methanogenesis. Methanogenic bacteria use acetic acid, carbon dioxide, and hydrogen to form methane $CH_4$. The production of methane and carbon dioxide from intermediate products is carried out by methanogenic bacteria. 70% of the formed methane originates from acetate, while the remaining 30% is produced from the conversion of hydrogen and carbon dioxide.

Methanogenesis is the slowest biochemical reaction of the process. That’s why it is a critical step in the entire anaerobic digestion process. The composition of feedstock, feeding rate, temperature, and pH are examples of factors influencing the methanogenesis process severely. Overloaded digesters, temperature changes, or a large entry of oxygen can result in the termination of methane production.

## 2.3 AD digester types

The AD process can be categorized as either liquid (L-AD), also known as a wet process or solid-state (SS-AD), (also dry process), depending on the total solids (TS) content of the substrate that is being digested. According to Williams et al. (2017), L-AD typically contains 0.5–14.0% TS and is usually used for liquid feedstock like animal manures; whereas SS-AD contains 15–40% of total solids and is used for the treatment of lignocellulosic biomass and organic fraction of the municipal solid waste. (Williams et al. 2017, 125)

According to Kymäläinen and Pakarinen (2015, 23), the TS content in L-AD ranges from 5% to 12%, and according to Latvala (2009), it can be as high as 15%. Despite its name, the SS-AD process also requires a lot of moisture, with the dry matter content averaging around 30–40%; at most, around 45% (Latvala 2009, 26, 87).

Slurry-based manure fed L-AD processes are considered to be mature technology. The most common process for digesting manure is a continuously stirred tank reactor (CSTR) with continuous feeding and simultaneous withdrawal of digestate. Raw materials with high total solids content can be used as co-substrates also in wet processes. However, the total solids content in the feed mixture should not be higher than 14% (Luostarinen et al. 2011a). In some studies, much lower solids contents have been found to be feasible: Mykkänen's (2008) study suggested that a CSTR reactor plant designed for processing the cow manure can (depending on plant technology) process a mixture of silage and manure with a maximum TS of 8–10%. In the said mixture, silage made about 5% of the total weight of the mixture, and the volatile solids (VS) proportion of the silage in the VS of the whole mixture was 10-18%.

It is advantageous to operate the reactor at a TS concentration as high as it is technically possible because the higher the TS concentration is, the better the utilization of the total reactor volume is.

SS-AD digesters can be divided into two separate groups according to their operation principle. The SS-AD process can be a continuous or batch-type reactor. In a continuous reactor, material is continuously fed into and removed from the reactor. A batch-type reactor is loaded with feedstock, after which the AD process is allowed to take place. In some cases, the leachate is circulated in the reactor or led to a separate tank for further digestion. After a predetermined time, the reactor is emptied, and a new feed charge is added.

The dry (solid state) process is not as widely used in Finland as the wet process. However, it could be a suitable processing method for grass-based feedstock. For example, Metener Oy has developed a batch-type silo digester for solid materials and it has already proven to work well. There are five of them in use in Finland (Metener Oy. 2022). Several continuous-type dry digestion reactors have been built in Finland in recent years but getting them up and running has been challenging due to technical problems and eventually due to the bankruptcy of the plant supplier (Saarinen 2018).

## 2.4 Process parameters of the anaerobic digester

In addition to recognizing the main characteristics and differences of the digester types, it is important to know and adopt the main parameters of the digestion process in order to understand the effect of the chosen feedstock on the biogas yield and the process itself.

### 2.4.1 Temperature

Temperature is the most important parameter in biogas production. Bacteria involved in anaerobic digestion can operate at a temperature between 8 and 65 °C, in which biogas can be generally produced. The higher the temperature is, the higher the gas production rate is, and the shorter the retention time is required for AD.

Anaerobic microorganisms can be grouped according to the temperature needed for functioning optimally. The optimal temperature for psychrophilic organisms is 12-18 °C; for mesophilic organisms, 25-40 °C; and for thermophilic organisms, 50-55 °C. The reactor’s temperature has a major impact on the growth and survival of microorganisms. Traditionally, anaerobic digesters have been designed to operate in the mesophilic zone, although in recent years, there has been an increasing interest in the use of thermophilic conditions. The use of thermophilic conditions has several advantages, including faster reactions, improved decomposition of organic matter, and better hygienization of the digestate. However, in northern climates, the heat losses of a thermophilic reactor can reduce its viability when choosing the type of plant.

### 2.4.2 pH and Carbon-Nitrogen ratio

The optimal pH value for microbes in anaerobic digestion is 6.8-7.5. Generally, when the pH is below 6 or above 8, the anaerobic digestion process slows down or even stops. Manure, for example, is an ideal feed material because of its neutral pH and high buffering capacity. The pH of the raw material used as an AD substrate is therefore an important parameter to consider, as a substrate that is too acidic will limit methane production and reduce the efficiency of the AD process. Ensiling makes the feedstock more acidic, and the addition of a neutral or alkaline feedstock as a buffer is often required. The pH can also be affected by the amount of volatile fatty acids (VFA) formed in the first steps of the AD process (Korres and Nizami 2013, 210).

Another important consideration for the substrate selection is the carbon-to-nitrogen ratio (C:N) to reduce ammonia inhibition. Ammonia is a nutrient essential for microbial growth and is produced as a result of the decomposition of nitrogenous matter. Ammonia inhibition occurs when ammonia concentrations exceed the tolerance of the micro-organisms in the digester. The C:N ratio varies from feedstock to feedstock, e.g., lignocellulosic biomass can have a C:N ratio of 40-130:1. This leads to a C:N imbalance, which in turn can lead to inhibition by limiting the amount of nitrogen available for microbial growth and thus inhibiting biogas production. The ideal C:N ratio is 20-30:1 (Williams et al.2017, 129).

### 2.4.3 Organic loading

In order to effectively break down the organic material to an acceptable level, the substrates require sufficient contact time with the microbes within the digester. The rate of breakdown will be dependent upon the characteristics of the feedstock, the bacterial population, and the reactor conditions (Melville et al. 2014).

The construction and operation of a biogas plant is a combination of economical and technical considerations. Obtaining the maximum biogas yield, by the complete digestion of the biogas substrate, would require a long retention time of the substrate inside the digester and a correspondingly large digester tank size. In practice, the choice of a system design (digester size and type) or an applicable retention time is always based on a compromise between getting the highest possible biogas yield and having a justifiable plant economy. In this respect, the organic load is an important operational parameter, which indicates how much organic dry matter can be fed into the digester per the volume and time unit. (Al Saedi et al. 2008, 27)

Organic loading is calculated as follows (formula 1):

$$B_R = m \times \frac{c}{V_R} \qquad (1)$$

where: $B_R$ is organic loading [kg/d*m$^3$], m is mass of substrate fed per time unit [kg/d], c is concentration of organic matter [%], $V_R$ is digester volume [m$^3$]

### 2.4.4 Hydraulic Retention Time (HRT)

Another important parameter for dimensioning the biogas digester is the hydraulic retention time (HRT). HRT is the average time for the liquid sludge to remain in the digester. In order to effectively break down the organic material to an acceptable level, the substrates require sufficient contact time with the microbes within the digester. The rate of breakdown will be dependent upon the characteristics of the feedstock, the bacterial population, and the reactor conditions. (Al Saedi et al. 2008, 27-28 and Melville et al. 2014).

As stated by Al Saedi et al. (2008, 27-28), HRT is correlated to the digester volume and the volume of substrate fed per time unit, according to the following equation (formula 2):

$$HRT = \frac{V_R}{V} \tag{2}$$

where: HRT is hydraulic retention time [days], $V_R$ is digester volume [$m^3$], V is volume of substrate fed per time unit [$m^3/d$]

According to the equations above, increasing the organic load reduces the HRT. The retention time must be long enough to ensure that the number of microorganisms leaving with the digestate does not exceed the number of microorganisms multiplying. The multiplication rate for anaerobic bacteria is usually over 10 days. A short HRT time may lead to a low gas yield. It is therefore important to adapt the HRT time to the specific degradation rate of the substrates used. By knowing the target HRT time, the daily feedstock to be fed, and the substrate degradation rate, the required digester volume can be calculated. (Al Saedi et al. 2008, 27-28)

### 2.4.5 Mixing or stirring of substrate

Mixing of the substrate is very important in anaerobic digestion. Biochemical reactions depend on the metabolic activity of microorganisms. Mixing ensures that the microbes are in constant contact with the new substrate. Without mixing, a stratification of the digester may happen, forming layers of foam, liquid, and sludge. Stratification leads to uneven fermentation of solids, "dead spots" with inefficient digestion, and difficulties in releasing the biogas produced. Therefore, the feedstock must be evenly distributed by stirring to break up the stratification, increasing the opportunities for microorganisms to come into contact with the feedstocks, thus accelerating the fermentation and increasing biogas production. (Lianhua et al. 2017)

Most commonly, reactor mixing is carried out by different types of paddle mixers or propeller mixers that agitate the substrate inside the reactor. This type of mixing is commonly used in Finland by plant suppliers, such as Demeca and Doranova (Doranova Oy 2022 and Demeca Oy 2022). Another common mixing method is substrate recycling, where the material is mixed by pumping it from one part of the reactor into another. Generally, the reactor is simultaneously heated by heating the recycled material through a heat exchanger. Among the common plant suppliers in Finland, Sauter biogas Oy uses substrate pumping and high-pressure spraying for the reactor mixing process (Sauter Oy 2022).

## 2.5 Feedstock options / Possible feedstocks

A wide range of biomass types can be used as substrates (feedstock) to produce biogas from AD. Al Saedi et al. (2008) lists the most common biomass categories used in European biogas production:

- Animal manure and slurry
- Agricultural residues and by-products
- Digestible organic wastes from food and agro industry (vegetable and animal origin)
- Organic fraction of municipal waste
- Sewage sludge
- Dedicated energy crops (DEC)

The most important characteristics of the different feedstock, in terms of viability, are the methane production potential of the feedstock dry matter and its volatile solids (VS) content, which describes the fraction of the feed dry matter (DM) that can decompose in the reactor and form biogas.

Scarlat, Dallemand & Fahl (2018, 464) list the potential biomethane yields of common feedstocks in Table 2. The table shows that the dry matter content of the feed has a significant influence on the amount of methane it potentially yields.

TABLE 2: Methane yields and the dry-mater contents of some common biogas feedstocks. Source: (Scarlat, Dallemand & Fahl 2018, 464)

| | DM | VS | methane yield | methane yield |
|---|---|---|---|---|
| | % | % Of DM | l $CH_4$/kg VS | l $CH_4$/kg fresh |
| pig slurry | 3-8% | 70-80% | 250–350 | 6–22 |
| cattle slurry | 6-12% | 70-85% | 200–250 | 8–25 |
| poultry manure | 10-30% | 70-80% | 300–350 | 21–84 |
| maize sillage | 30-40% | 90-95% | 250–450 | 68–170 |
| grass | 20-30% | 90-95% | 300–450 | 55–128 |
| alfaalfa | 20-25% | 90-95% | 300–500 | 57–118 |
| potatoes | 20-30% | 90-95% | 280–400 | 54–128 |
| sugar beet | 15-20% | 90-95% | 230–380 | 31–72 |
| straw | 85-90% | 80-90% | 200–250 | 136–202 |
| vegetable waste | 85-90% | 80-90% | 200–251 | 136–203 |
| organic waste | 10-40% | 75-90% | 350–450 | 26–180 |
| slaughterhouse residues | 35% | 90-95% | 550–650 | 173–216 |
| sewage sludge | 5-10% | 75% | 300–400 | 11–30 |

In this thesis, the feedstocks that were categorized as wastes were left out of the scope; the focus was on manure-based inputs and residues from agriculture, and above all, on dedicated energy crops (DEC). DEC can be herbaceous crops (grass, clover, maize, raps) andwoody crops (willow, poplar, oak), although the woody crops need a special delignification pretreatment before AD. Like waste feedstocks, woody crops are also left outside from this work.

Williams (2017) divides the feedstock crops into generations: first-generation feedstock, which includes food crops such as vegetable oils and grains; and second-generation feedstocks, which are primarily lignocellulosic and consist of agricultural residues, such as wheat straw, maize stover, oat, rye, barley and wheat straw, sorghum forage, oilseed canola straw, grass silage, non-herbaceous and herbaceous phytomass; as well as energy crops, such as miscanthus, reed canary grass, switchgrass, and willow (Williams 2017).

According to Lehtomäki (2006, 10-11), the most important parameter when choosing crops for biogas production is the *net* energy yield achievable from hectare. That net energy is defined by the biomass yield and its convertibility to methane, as well as the inputs put into cultivation. The methane production potential of plants has been examined in several studies, but they mainly dealt with convertibility of the biomass into methane, rather than an evaluation with regard to the energy potentials per hectare.

Sewage sludges and animal manures are preferred as a feedstock over dedicated energy crops because they are considered wastes and thus more sustainable. However, the methane yield potential of cattle manure is low, which is why it is frequently co-digested with energy crops that have the greatest methane yield potential. Williams (2017, 129) suggests that the optimum methane yield is achieved when different feedstocks with complementary qualities are homogenized and co-digested to enhance the digestibility of the substrate. Energy crops yield the best results when combined with other feedstocks; for example, together with manure, which contains macro and micronutrients, resulting in improved microorganism performance in the digester.

## 2.6 Digestate

In addition to biogas, the AD process produces digestate. The amount of digestate produced is roughly the same as the amount of feed fed into the reactor, although part of the dry matter is converted into biogas. The digestate is an excellent fertilizer, as it contains all the nutrients of the feedstock; rich in organic matter, and both micronutrients and macronutrients.  It consists of the same substances that have been fed into the reactor, so if the feedstock contains some harmful compounds, they can also be found in the digestate.  Only part of the organic matter is converted into biogas and other organic compounds, but in general, the dry matter content of the digestate is significantly lower than the feedstock (Paavola ja Kapuinen 2015, 95). The value of nitrogen is improved because a part of organic nitrogen is solubilized into ammonia, which is immediately available for plants (Marttinen et al. 2015).

Digestate can be used as fertilizer in agricultural fields as such, but some kind of a post-treatment is often done in order to decrease the water content of the digestate, or to separate nitrogen (N) and phosphorus (P) to different fractions. The reason behind these is lowering the transportation costs of the digestate. Especially in intensive animal production areas, where large amounts of manure are produced, the past and present manure inputs may have raised the soluble P level in field soils, meaning that addition of P is not allowed. Separating the digestate into liquid and solid fractions allows the P-rich solid fraction to be transported to areas with an actual need for P (Christensen et al. 2013, chapter 7).

For farm-scale, simple technical solutions for digestate handling are needed, while in larger biogas plants, more sophisticated post-processing technologies may become feasible. For example, liquid fractions may be processed in a stripping unit, where nitrogen is separated and collected as concentrated ammonium sulfate, which have uses in both agriculture and the industry. Solid fraction may be processed, e.g., in thermal processes to dry pellets with a high phosphorus content.

Although nutrients in the digestate obviously have value and can be used to replace mineral fertilizers, no significant revenues are currently available from selling digestate-based products for fertilizer usage. Organic digestate-based fertilizers need more storage capacity than mineral fertilizers, and their spreading is more time-consuming with the current machinery in addition to being less precise and not necessarily in the nutrient ratios that the crop requires. This may decrease farmers´ interest in using such fertilizers.

Digestate is allowed to be used as an organic fertilizer for organic production if it meets requirements stated in the legislation. Usually, the manure- and crops feedstocks -based digestates are approved for the organic fertilizers. This may increase the monetary value of the digestate, as it can be sold to be used at ecological production farms that cannot use industrial mineral fertilizers. Some digestate-based products, e.g., concentrated nitrogen rich liquid fertilizer, may also be used in industrial purposes. However, these applications usually require that the digestate is further processed, which is technically challenging and costly. At this moment, the driver for postprocessing the digestate is usually the need to transport nutrients further distances from the biogas plant, not the revenues obtained from the product. However, it's commonly expected that in the future, the digestate will have a higher role in biogas plant revenues (Marttinen et al. 2013). This will be the case especially now and in the near future, when the price of the industrial nitrogen fertilizer has risen due to the skyrocketing natural gas prices.

The biogas process also sanitizes raw materials, reduces the number of animal and plant pathogens, and destroys most of the seed germination of weeds. Hygienization is more effective when a higher temperature is used. For example, the complete destruction of salmonella typically requires using a separate hygienization unit (70°C, 1 hour). The biogas process also effectively reduces the manure scent, and thereby reduces odors from manure application.

In addition to replacing fossil fuels, the anaerobic digestion of manure contributes to GHG emission reductions by avoiding methane, nitrous oxide, and carbon dioxide emissions released into the atmosphere from natural decomposition during storage (Scarlat, Dallemand and Fahl 2018).

## 2.7 Biogas in Finland now and in the near future

Several calculations about the total biogas potential in Finland have been made during the last decade. Potential can be estimated as a theoretical potential, which takes into account all the available feedstocks without considering any technical or economic variables that limit their possible utilization for biogas production. A more realistic way to calculate the available potential is to define the existing techno-economical constraints, which rule out a part of the feedstocks and the estimate of the available potential taking those constraints into account.

Marttinen et al. (2015) calculated the theoretical biogas potential in Finland to be approximately 24 TWh and the techno-economical potential to be 10 TWh. Agriculture was the biggest contribution, as it held 86% of the techno-economical potential, more precisely 1.5 TWh in manure and 7.3 TWh in energy crops and crop residues. So far, the poor profitability of the plants has made it difficult to use cultivated grass silage in biogas production on a large scale in Finland. In addition, profitability may have been limited due to the long transportation distances of raw materials. The sustainability criteria for renewable energy may also place restrictions on the energy usage of cultivated biomass (Työ- ja elinkeinoministeriö 2020, 13).

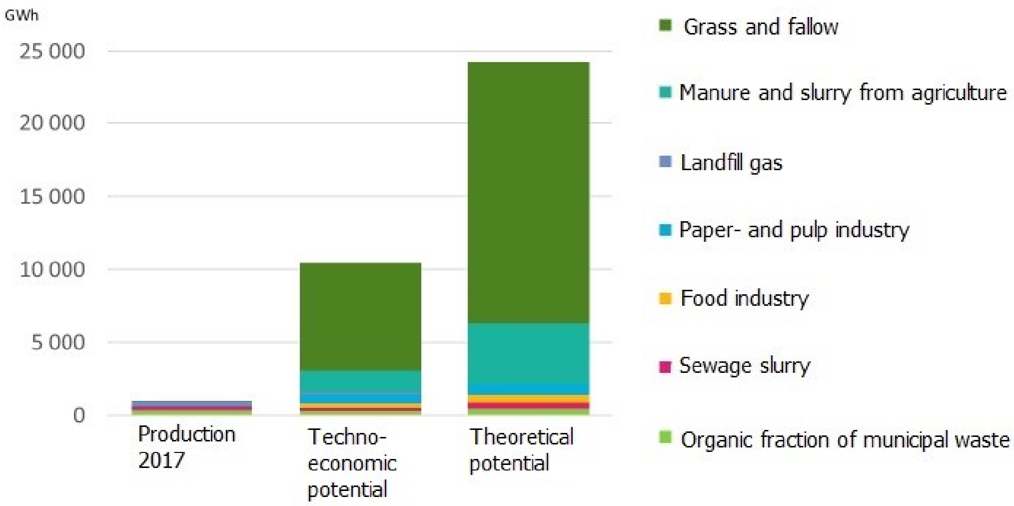


FIGURE 2. Biogas production in 2017, and production potentials in GWh. Figure include only AD-based biogas, not produced by gasification of power-2-gas. Source (Virolainen-Hynnä 2020, Marttinen et al. 2015)

Only a small portion of the estimated total potential is currently utilized. Figure 2. shows the big difference between the utilized and un-utilized biogas potential.  Finland's biogas production in 2019 was about 1 TWh and has remained stable to this day. That 1 TWh covered about 0.5 percent of Finland's total renewable energy production. There were a total of 69 biogas reactor plants in Finland, in addition to the 33 landfill gas pumping plants. Biomethane was produced at 17 plants in 2019 (Virolainen-Hynnä 2020, 9).

The future of biogas in Finland has been assessed in a workshop organized by Suomen Biokierto ja Biokaasu ry in 2020. In its final report, the working group predicted that biogas production could be 4-7 TWh in 2030. Production would be particularly based on the utilization of agricultural-based by-products, but new technologies and feeds would also play a role (e.g., gasification). For the year 2035, biogas production has been envisioned to be 6-15 TWh. It was also estimated in the workshop that in 2030, there would be a demand for biogas and biomethane of 4-11 TWh. A significant part of the demand would be for biomethane, of which heavy vehicles could consume 2.5-4 TWh, passenger cars 0.5-1 TWh, buses 0.5 TWh, industry 0.5-4 TWh, and ships 0.85-4 TWh. It was also estimated that 0.4-2 TWh of biogas would be consumed in heat and electricity production. (Virolainen-Hynnä 2020, 8)

The Finnish government has set a biogas production target of 4 TWh in 2030, in connection with the budget and climate negotiations in the autumn of 2021. This aims to reduce carbon dioxide emissions in the transport, agricultural and waste sectors, to improve security of supply, and increase national energy- and nutrient self-sufficiency. The production of four terawatt hours of biogas requires more than 100 new biogas plant investments in different parts of Finland in the 2020s (Suomen biokierto ja biokaasu 2022 a).

According to Statistics Finland's preliminary data, biomethane production in 2021 was about 156 GWh, and biogas production was about 750 GWh. In 2022, the total production of biogas and biomethane is expected to clearly exceed one TWh. In the years 2023-2025, it is expected that larger-scale processing plants for agricultural waste, residues, and manure will start up. If all the announced investment plans come true, the total production of biogas and biomethane in 2025 could approach 2 TWh. (Suomen biokierto ja biokaasu 2022 b)

When estimating the growth of biogas production, Finnish Biocycle and Biogas Association predicts that if the to date- announced investment plans materialize, the new annual domestic biomethane production capacity of about 740 GWh will be built and commissioned between 2023 and 2025. Similarly, a new CHP capacity of about 145 GWh/a is expected, of which a significant part is planned to be used by the producers in their own facilities. In total, 6 new biogas plants and 18 biomethane plants are planned and under construction between 2023 and 2025, and biomethane processing units are planned to be installed in some existing biogas plants. In 2023, some additional biogas capacities will be built for the treatment of municipal and sewage sludge. Between 2024 and 2025, the new production capacity is expected to be created specifically for the processing of agricultural waste, residues, and manure. Many of those are medium- and large-scale centralized plants, which have been eagerly awaited for the last few years.

At the time of writing (November 2022), several players have announced the launch of major industrial-scale or LBG producing biogas projects designed to use agricultural fractions as feedstock. Such projects that have been already announced (just to mention some) are:

- The project of Suomen Lantakaasu Oy, a joint venture between Valio Oy and ST1 Oy, to set up a biogas plant producing 150 GWh liquefied biogas (LBG) in Kiuruvesi. The plant will be fed mainly with cattle slurry and dry manure, agricultural residues, grass feed, and by-products of the food industry (Suomen Lantakaasu Oy 2022).
- Wega Group Oy´s and Riikinvoima Oy's biogas plant project in Leppävirta, which, if realized, will process the organic fraction separated from municipal waste at Riikinvoima Oy's eco-power plant, and use agricultural side streams and grass feed coming from the Central-Savo region. The aim is to produce at least 50 GWh of renewable LBG per year (Riikinvoima Oy 2022). The availability, logistics, and practical solutions for agricultural biomasses related to the project have been investigated partly on the basis of this thesis during the preliminary study phase of the project (Taavitsainen 2021).
- Dairy company Arla Finland, energy services provider One1, and the Finnish Energy Cooperative (SEO) have agreed to start the production and distribution of liquefied biogas at the Tikka Farm in Kurikka. This will create a new kind of innovative ecosystem combining agriculture and energy production. The biogas will be produced by BioMuu Oy, a company linked to Tikan Maatila Oy. One1 processes the gas into liquefied biogas in the immediate vicinity of the farm and SEO distributes it. The plant has a capacity of about 6 GWh.

In the future, biogas and biomethane can also be produced in other ways than by AD, e.g., with the thermal gasification of woody biomass and with Power-to-Gas (P2G) technology. In P2G, water is split into oxygen and hydrogen using electrolysis, which can be used as is or further refined into methane using methanation. Technology can be used to store electricity and wind energy in gaseous form. The advantage of methane is that it is much easier to handle and transport than hydrogen. The Power-to-Gas method has attracted interest among methane users and producers, but the method is still in the research and development phase. (Virolainen-Hynnä 2020, 9)

However, one of the key challenges for farm-scale biogas production remains the issue of farm-specific profitability. In addition to electricity, a significant amount of heat is generated, for which finding an use that can be converted into euros is a challenge in many cases (Arffman and Taavitsainen 2019).

# 3 GRASS SILAGE AS A BIOGAS PRODUCTION FEEDSTOCK

Plant species suitable for energy crops should produce a high amount of biomass with the lowest possible inputs. In addition, the plants should be as easy as possible to cultivate, harvest, and store. They should also be able to yield well with low fertilization, and perennial plants should be good overwinterers (Lehtomäki et al. 2007, 19). Also, McEniry (2013) highlights the meaning of a high $CH_4$ yield per cultivated area, which does not always come together with a high DM yield, especially outside temperate and northern climates, where some grassy plants yield high amounts of DM, but the digestibility of DM may be poor.

The growth rhythm of grass in Finnish conditions varies considerably at different stages of the growing season. In Finland, the amount of radiation is unevenly distributed over the growing season due to the northern latitude. Grass is able to take advantage of the long days of a northern summer, unlike, e.g., maize, which is a short-day crop. The flowering rhythm of grass plants is controlled by the length of the photoperiod and its changes. Grass plants grow vigorously in long-day conditions; conversely, as the day shortens, they slow down their growth and begin to prepare for winter. These grasses, which are well adapted to long-day conditions, include timothy (Phleum pratense), the most common species in Finnish grasslands (Atria 2022). Grasses are also highly tolerant in the variable conditions of the north compared to maize, which is a common energy crop in central Europe, but maize's growing reliability and yield is limited in Finnish conditions not only by the light cycle, but also by the length of the growing season.

In general, grasses produce good yields regardless of the soil type. They are well suited for growing on peat soils, where long-term grassland cultivation can be a good solution for reducing soil-based carbon dioxide emissions. Seppälä et al. (2014) lists the many benefits of promoting grass- based biogas production: Grass is a good crop for diversifying plant rotation. An AD process would allow a rational transfer of nitrogen fixed by legumes to cereal crops and support the ecological nutrient circulation. A biogas production could smooth out the peaks in grass production between the years and contribute to the trade and contract production of grass. AD process is a good way to handle potential excess or spoiled silage, which would otherwise need to be composted and then spread separately on the field. Co-digestion of grass with manure also contributes significantly to the improvement of the digestion process, the improvement of biogas yields, and biogas plant performance. In the future, it improves the competitiveness of a closed nutrient cycle via the biogas grassland cultivation compared to cereal crops if oil and fertilizer prices rise further from current levels

This work went into the details of the different cultivation or harvesting methods to the extent necessary to establish the cost calculations and compare the different options. The methods selected for the study were derived from previous studies, and generally known to be the most competitive and commonly used.

## 3.1 Physical properties and methane yield

Compiled from previous literature, McEniry (2013, 51) has presented the methane potentials of perennial grasses and gross methane yields per hectare in Table 3. The dry matter yields and methane yields per hectare shown in the table should be treated with caution in Finnish growing conditions. Although grass can take advantage of a long day, the short growing season in the north still has a negative impact on yields, compared to conditions in central Europe. In practice, in the case of northern climates, the yields are obviously at the lower end of the figures provided.

TABLE 3. Perennial grasses and red clover as feedstock for anaerobic digestion. (Source: McEniry 2013, 15)

| *Common name* | *Botanical name* | *Photo-synthetic pathway* | *Biomass yield[1] (t DM $ha^{-1}$ $a^{-1}$)* | *Specific $CH_4$ yield[2] ($m^3$ $t^{-1}$ VS)* | *Area specific $CH_4$ yield[3] ($m^3$ $ha^{-1}$)* |
|---|---|---|---|---|---|
| Perennial ryegrass | *Lolium perenne* | $C_3$ | 9–20 | 198–410 | 1,639–7,544 |
| Timothy | *Phleum pratense* | $C_3$ | 9–18 | 308–365 | 2,550–6,044 |
| Tall fescue | *Festuca arundinacea* | $C_3$ | 8–14 | 296–394 | 2,179–5,075 |
| Cocksfoot | *Dactylis glomerata* | $C_3$ | 8–10 | 308–382 | 2,267–3,514 |
| Reed canary grass | *Phalaris arundinacea* | $C_3$ | 7–13 | 340–430 | 2,190–5,143 |
| Giant reed | *Arundo donax* | $C_3$ | 3–37 | – | – |
| Miscanthus | *Miscanthus x giganteus* | $C_4$ | 5–44 | 179–218 | 823–8,825 |
| Switchgrass | *Panicum virgatum* | $C_4$ | 5–23 | 191–309 | 879–6,538 |
| Red clover | *Trifolium pratense* | $C_3$ | 7–13 | 300–350 | 1,932–4,186 |

[1] DM = dry matter; data adapted from Lewandowski et al. (2003) and Peeters and Kopec (1996) Peeters et al. (2006).
[2] VS = volatile solids; data adapted from Murphy et al. (2011), Masse et al. (2010), Seppala et al. (2009) and Kaiser and Gronauer (2007).
[3] Assuming 0.92 VS in grasses and red clover; not accounting for any field, harvesting or storage losses.

Mäenpää (2010) has presented, based on Lehtomäki, Lampinen, and Rintala, more probable methane yields per hectare under Finnish conditions. As seen in the comparison from Table 4, grass mixture compares well with other field-grown biomass plants. As a pure crop, only reed canary grass achieves better yields on average. However, McEniry (2013, 50) questions the usefulness of reed canary grass as a biogas plant feedstock due to its poor digestibility.

TABLE 4. Potential DM and CH4 yields for some plants that can be grown for biogas feedstock in the Nordic climate. Source: Mäenpää (2010) based on Lehtomäki, Lampinen and Rintala

| **Plant** | **Yield** | **Methane yield** | **Energy yield** |
|---|---|---|---|
| | ( t DM / ha) | (m3 CH4 / ha) | (MWh / ha) |
| *Grass mixture* | 7-8 | 2490-2840 | 24-28 |
| *Red clover* | 4-5 | 1070-1340 | 10-13 |
| *Forage Beet* | 6-8 | 1730-2300 | 17-22 |
| *Lupine* | 4-6 | 1150-1720 | 11-17 |
| *Reed canary grass* | 9-10 | 2970-3300 | 29-32 |
| *Sugar beet tops* | 4-6 | 1180-1770 | 11-17 |
| *Oats straw* | 2 | 580 | 6 |
| *Rye straw* | 2 | 440 | 4 |

## 3.2 General description of the supply chain of grass feedstock silage

There is a wide range of viable grass silage cultivation and production methods, and the cultivation of grass for biogas feedstock is not any different from the production of silage for animal feed. In this analysis, only the most appropriate and cost-effective methods, derived from practical experience, were selected to be included in the cost calculation tool. A large number of variables were set as a constant for the sake of simplicity.

Many studies on the productivity and methods of grass silage production in the Finnish environment have been published, e.g., by LUKE, MTT, and TTS (e.g., Seppälä et al. 2014; Lätti et al. 2014), but they were examined and referred to a limited extent due to the limitations of the scope of the work. Descriptions of farming methods are based on the authors' common knowledge of farming, and scientific sources are not always cited unless the method is deviant in some way or controversial compared to the general practices.

Figure 3 shows, based on Lehtomäki (2006, 10), the simplified production chain of a grass silage from the field to the biogas plant. The supply chain is universal for all field crops. In the box marked with number one in the figure, size reduction and pre-treatment refer to the treatment of grass in the field during harvesting (chopper or conditioner of the harvest equipment). Pre-treatment, marked with the number two, refers to the treatment of the material just before it enters the biogas digester, such as maceration or other particle size reduction. In addition to the steps presented, the feedstock supply chain may include, e.g., intermediate storing phases, depending on how the supply chain is organized.

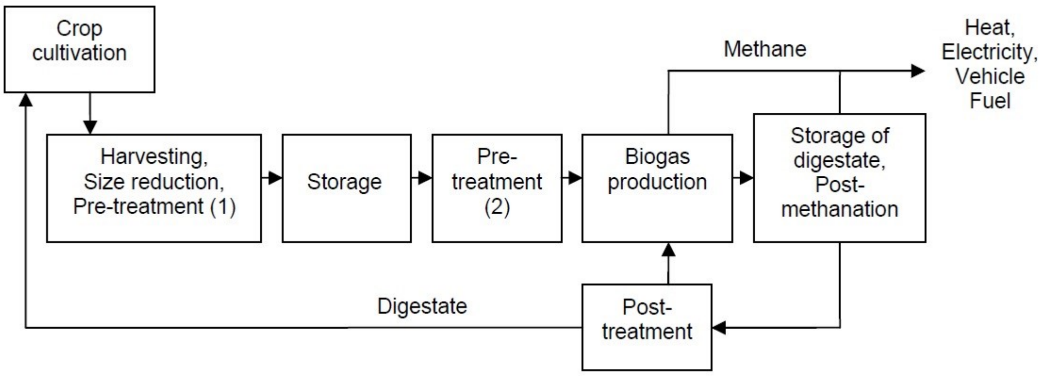


FIGURE 3. Grass silage feedstock supply chain. Source: Lehtomäki (2006, 10)

### 3.2.1 Establishment of grass vegetation

In Finland, grass is most commonly cultivated as a perennial vegetation. This means that the grass vegetation is not re-sown in the field every year, but the crop is harvested from the same vegetation several years in a row. Generally, the number of harvest years varies from three (timothy, clovers) to up to eight years (reed canary grass).

Grass vegetation is usually established in combination with cover crops. This means that grass plant seeds are sown in the spring at the same time, or at least during the same growing season, with a cereal plant seed. A faster-growing cereal plant prevents the development of weeds, and thus "protects" the slower-growing grass seedlings from competition. At the same time, a nearly normal yield of cereal crops can be harvested in the founding year, while the amount of grass crops sown in the same year alone would remain small. However, grass vegetation can also be established without cover crops; in which case, fast-growing grass species, such as ryegrass, are generally used in the seed mixture to help in the competition against weeds. (Hopkins 2000)

Grass vegetation can be established as a single-species or mixed vegetation. Nowadays, multi-species mixed crops are preferred in grass cultivation. The goal is to create a plantation where several different grass species and varieties, and for example nitrogen-binding clover plants grow at the same time (Marttinen et al. 2010, 43-45). This is useful in terms of yield potential, among other things, because different species can utilize and withstand soil nutrient and moisture fluctuations in different ways and benefit from each other's nutrient uptake. According to Tiainen et al. 2020 and Mattila et al. 2022, the diversity of the grassy species also improves the fauna diversity and e.g., carbon sequestration in the soil and the crop harvested.

In order to be able to produce a good grass harvest in the coming years, the establishment of a grass crop must be accompanied by basic fertilization and liming, field leveling and cultivation, and weed control, etc. When calculating the annual production cost, those once-in-a rotation costs have to be divided by rotation years and added for all the years of cultivation rotation.

### 3.2.2 Study variables: Establishment

In this study, the grass vegetation establishment method was standardized, i.e., it was not included as a variable in the analysis. The Excel spreadsheet default values and the calculation basis for both case studies were defined by the assumption that the establishment of the grass vegetation was done with the cover crops. The grass was assumed to be grown on a four-year rotation, which is the usual rotation length in Finland. In the first year, the cover crop is harvested for animal fodder or human consumption. In the following three years, one harvest per year would be harvested from the grass crop for the biogas plant’s feedstock.

The following costs were calculated as establishment costs: plowing, basic tillage and leveling of the field, maintenance liming and basic fertilization with the separated dry fraction of digestate, grass seed sowing, grass seed cost, and weed control. The costs listed were divided equally between the rotation years (four in this study). The year of establishment was included as a divisor in these four years, even though no biogas feedstock material was harvested then.

### 3.2.3 Fertilizing

After climatic factors, like the temperature and water availability, soil nutrients are the next limiting factor regarding the productivity of grass vegetation. Plants obtain their C, H and O (and nitrogen in some cases, like clover and leguminous plants) needs from air and water, but other nutrients (like N, P, K, Ca Mg, and S) come from the soil or added fertilizer inputs. Nitrogen (N) is the most limiting element for grass production, but Phosphorous (P) and Potassium (K) levels also must be maintained for good crops (McEniry 2013, 56). Also, a regular liming is essential for most of the Finnish soils to keep the pH level at its proper state and maintain the availability of Calcium (Ca) and Magnesia (Mg).

The nutrients needed by the plants can be applied in the form of mineral fertilizers or organic fertilizers, such as manure or digestate. Growing legumes or clover in a mixture allows the nitrogen fixed by the *Rhizobia*-bacteria living in their root systems to be used by grasses.

The appropriate level of fertilization must be determined on the basis of the soil type and the desired yield, avoiding excessive fertilization for economic and environmental reasons. The conditions of the environmental subsidy scheme and the nitrates regulation also set an upper limit for nitrogen and phosphorus fertilization (Ympäristökorvauksen sitoumusehdot 2022 and Valtioneuvoston asetus eräiden maa- ja puutarhataloudesta peräisin olevien päästöjen rajoittamisesta 18.12.2014/1250, 11 §).

### 3.2.4 Study variables: Fertilizing

The fertilization variables of the calculator are handled in its "Cultivation" tab. The fertilization is divided into two parts: for the establishment year, and for the input crop years separately. The basic fertilization for the establishment year is assumed to be applied with an organic fertilizer, such as livestock manure or the dry fraction of separated digestate, and its cost is divided evenly for all years of the crop cycle. Any mineral fertilizer applied in the year of establishment is assumed to be allocated for the cost of the cover crop and has not been taken into account in the calculation. For the grass crop years, it is possible to enter the cost of mineral fertilizers and the cost of organic fertilizer on separate lines in the calculator. In the current version, the calculator does not automatically calculate the fertilizer level based on the target yield level, but the user must enter the appropriate fertilizer rates according to the pursued yield level.

Fertilization is closely related to the main variable affecting production costs identified in the study: the level of per hectare yields. The interactions between the yield level and fertilization rates and methods are so complex that it was not possible to set them as variables in this work. Thus, for the case studies and for the general cost analysis, it was decided to standardize the annual fertilization to be done with mineral fertilizer at the rate required for the rather high (~5000 kg-DM) yield level. This would probably not be the most economical solution, but by default, it brings an upper limit to the fertilization cost in the calculation.

### 3.2.5 Harvesting

In Finland's climate, it is generally possible to harvest 2–4 crops of grass silage per year, depending on the location of the field, the chosen crop and variety, and the type of soil. The most important factor guiding the choice of biogas feedstock harvesting method is the production cost of the dry matter produced.

This objective differs from the production of grass silage for animal feed, where it is often necessary to schedule harvesting so that the protein digestibility of the harvested feed, the so-called D-value, remains optimal for animal digestion. The D-value of grass forage decreases as the crop ages, and the animal's digestive system is no longer able to utilize all the organic matter as well. Therefore, the primary objective in harvesting animal feed is to optimize the D-value of the feed before maximizing the yield (Kajan & Pasanen 2009). In practice, this means that the crop must be cut relatively early and often in the middle of the fastest growth phase of the grass, when the most rapid increase in dry matter occurs. According to Vanhanen (2009, 49), among others, the harvesting time of silage has a major impact on the dry matter yield. The highest dry matter yield is obtained by harvesting grass at a late stage of growth.

Literature gives conflicting information about the effect of harvest time on digestibility of the feedstock crops, e.g., Lehtomäki et al. (2007, 21) states that for the production of biogas feedstock, harvesting should be carried out at a fairly early stage, so that the decomposition of the biomass in the biogas reactor is at its best. However, that study apparently did not consider the effect of the increasing biomass on the biogas yield per hectare if the harvesting was delayed. According to Lehtomäki´s doctoral thesis (2006, 12-13) and McEniry (2013, 53), several conflicting results have been reported in the literature about the dependence between the harvesting time and the methane potentials of, e.g., clover and barley harvested as a whole grain.

For example, the results of a calculation by Seppälä et al. (2014, 15) show that the harvesting of grass used as feedstock for a biogas plant can be timed flexibly, as the reduced digestibility due to late harvesting is compensated by an increase in yield. These results suggest that the biogas plant and the dairy farm can share the same machinery, so that the feed required by the biogas plant would be harvested later than the feed for the cows. El Bassam (2010, 429) suggests that the methane potentials per hectare increased with most crops as the crops matured.

Based on the above sources, the D-value of grass forage harvested for biogas is not such a significant factor, as the gas yield per hectare does not change much during the harvesting period; what is lost in terms of digestibility deterioration is mainly compensated by an increase in dry matter content. One reason for this may be that the longer residence time regarding the biogas reactor compared to animal digestion also allows for the degradation of material with lower digestibility. Thus, the digestibility of grass for the biogas feed does not seem to be as important as in the production of animal grass feed. Therefore, the choice of cultivation methods for biogas-feed grass makes it possible to optimize the amount of dry matter produced during the growing season, while decreasing the harvesting costs by reducing the number of harvests (Seppälä et al. 2013).

In this study, the initial assumption was that only one crop per year is harvested from the grass produced to feed the biogas plant, which was assumed by practical experience and derived from literature to be the most economical option in optimizing the production cost for the dry matter produced. This assumption could not be fully confirmed by the literature, but it was however chosen as the basic assumption for the calculation of the case study. That was because of simplicity, and because it would have been impossible to determine the profitability of multiple harvests in this context. Using the single-harvest tactics bring forth cost savings. It also reduces the weather dependency of the logistics chain, and improves the utilization of harvesting equipment.

### 3.2.6 Study variables: Harvesting

Determining the most economical harvesting method was one of the main objectives of the study. There are numerous factors that influence the choice of harvesting method, but the definition of the research problem led to the identification of a few variables, of which were changed in order to carry out the sensitivity analyses and rank the different types of harvesting chains in order of preference.

The main variable influencing the production cost, and guiding the choice of a suitable harvesting method was assumed to be the transporting distance of the feedstock from the field to the biogas plant, i.e., in practice, the average location of the fields in relation to the plant. The effect of the field's average size on the harvesting cost was also a variable of interest, and was therefore included in the calculator.

In addition to the operations in the field, the harvesting method affects the downstream steps in the chain, such as storage and possible long-distance transportation. The transporting distance was considered in two parts: short-distance transportation and long-distance transportation. The effect of field structure was examined through the variables of field size and the distance between them. The impact of the choice of harvesting chains, e.g., on the cost of long-distance transportation, was also taken into account.

Three different grass harvesting chains were selected for the calculator, all of which were assumed to be competitive in varying circumstances.

#### 3.2.7 Ensiling

In a Nordic climate, the use of field biomass as a feedstock for biogas plants all year round requires storing and ensiling (Seppälä et al. 2014). Ensiling ensures predictable quality and year-round security regarding the supply for the biogas plant (McEniry 2013, 56).

In the case of a biogas plant, the most important criterion is to minimize dry matter losses during storage. This differs, for example, from the situation in cattle feeding, where palatableness (tastiness) also matters. According to Seppälä, differences in the potential methane yields of feeds preserved with different preservatives have been found to be small or insignificant in studies (Nussbaum, 2009, Pieper and Korn, 2010, Seppälä et al. 2013).

The cost of ensiling consists of acquiring the additives, along with the time and effort required for handling and applying it to the material. Utilizing an ensiling additive is profitable if the cost of its usage is lower than the loss during ensiling if the additive is not used. Based on Seppälä et al. (2014), the use of an additive is definitely profitable. According to McEniry (2013), several studies have found that ensiling the feedstock material has caused an increase in the $CH_4$ potential of the original material due to the formation of fermentation products that are beneficial to biogas yields during ensiling. Ensiling has also been found to have some accelerating effects on the rate of the AD process.

El Bassam (2010, 429) states in his literature review, mainly with a reference to Lehtomäki 2006, that ensiling without additives resulted in minor losses (0–13%) in the methane potential of sugar beet tops, but there were more substantial losses (17–39%) in the methane potential of grass; meanwhile, ensiling with additives was shown to have potential in improving the methane potentials of these substrates by up to 22%.

### 3.2.8 Study variables: Ensiling

In the calculation sheet, the variables related to preservation are the price and quantity of the ensiling additive used, the price and amount of the plastic films needed for ensiling. In the case of pile or bunker ensiling, the capital cost of the asphalt slab for the pile was added.

## 3.3 Description of studied grass silage supply chains

Silage used both as animal feed and as a biogas feedstock is mostly harvested and stored as a pre-dried silage nowadays. This method is currently the absolute mainstream in Finland, mainly because of its cost-effectiveness and relatively low dependence on weather. Other harvesting alternatives include fresh harvesting with a straight cutting forage harvester (self-propelled or tractor-driven), and a method based on preserving the material by drying it in the field or dryer. The latter is commonly used for harvesting and preserving straw or hay for horses. Fresh harvesting is normally used for harvesting the maize silage.

The upper limit of the targeted dry matter content of the silage is influenced by the constraints set by the chosen harvesting method. For example, excessively dry material can lead to harvesting losses and preservation failures. On the other hand, the AD process may also set limits on the dry matter content of the feedstock material. In general, the desired DM content of grass silage harvested for biogas feedstock ranges from 35 to 60%, depending on the chosen process and conditions.

This study focused exclusively on pre-dried silage harvesting, as it is by far the most common method in Finnish conditions. The advantages of pre-drying are mainly technical.  It is practically the only method, for which contracting services are widely available. In the literature, it is also widely referred to be the most cost-effective method. Pre-dried silage is mainly harvested using precision choppers or short cut pick-up wagons and round balers. The method does not offer significant advantages on the $CH_4$ yield or nutrition over fresh silage, but its advantages are in more efficient harvesting and transportation, as part of the water is evaporated in the field. In addition, machines for harvesting pre-dried silage are much more efficient than those used for fresh harvesting (Farmit.net 2010).

Several different harvesting methods are currently used to harvest grass forage.  The technical and economic superiority of the harvesting chains depends on the prevailing conditions, and the best method cannot be recommended without knowing all the factors influencing the whole. One of the starting assumptions of the study was that the biogas plant would aim to harvest grass from the vicinity of the plant in an efficient, cost-effective way. It was generally known that on the largest livestock farms handling large quantities of silage, the precision chopper-harvester-based harvesting chain and silage silos are used for harvesting when the aim is to produce a large quantity of low-cost, high-quality forage and the fields are located nearby (Seppälä et al 2015). When the transporting distance increases, and the average field size gets smaller, other harvesting methods also come into play when searching for a profitable harvesting method.

The particle size and chaff length affect the usability of the feed in a biogas plant. According to Mykkänen (2008, 44-45), higher methane yields could be obtained by shredding feed into a smaller particle size, as energy crops (such as wheat and rice straw) have shown 4-10% higher methane yields with a particle size of 0.088-0.40 mm compared to a particle size of 1-30 mm. In addition to crushing in the biogas plant, the particle size can also be reduced during the harvesting of the crop. The choice of harvesting method can also influence the amount of work required at the biogas plant, which is lower for precision-chopped silage stored in a silo or pile than grass stored in a bale. At the same time, the amount of plastic waste can be reduced.

Of the methods studied, the forage harvester-chain produces the smallest chaff length, and is therefore the most cost-effective for the biogas plant when it comes to costs involved in handling the feedstock at the plant. Those in-plant operational costs were not included in this calculator, although they have to be taken into account when designing the supply chain for the plant feedstock.

### 3.3.1 Mowing

In the pre-drying method, the harvested forage material is mown as a separate operation and left lying on the field for pre-drying. The mown material is dried in the field from a few hours to a few days, depending on the weather and desired dry-matter content of the silage. The aim is to evaporate the water contained in the mown material, and to increase the dry matter content of the harvested raw material as much as possible to avoid the need for transporting and storing water that is unnecessary for the biogas process, thus saving costs.

Mowing can be done with a rotary disc mower-conditioner, which - in addition to cutting the vegetation - pre-treats the mown grass by breaking the surface layer to promote drying. Recently, mowers without conditioner equipment, which simply cut the vegetation without conditioning it, are increasingly being used as they are more cost efficient and lighter. The mower may be equipped with a swath-combining unit, allowing several swaths to be combined in a single pass and potentially avoiding a separate windrowing operation.

### 3.3.2 Windrowing/merging

After mowing and drying, the material is collected and transported out of the field. This operation is nowadays very often preceded by a windrowing or swath merging operation, which involves gathering the mown material into a bigger windrow for the next harvesting stage. This is done by combining several swaths made by mowers into a single windrow with a raking machine. This reduces the number of passes the harvesting equipment is needed to travel during the next work phase. Additionally, windowing can be used to regulate the drying speed of the cut grass. When harvesting from a combined windrow, the harvester’s or baler´s capacity can be fully utilized without increasing the driving speed too much. Depending on the crop yield and harvesting method used, the suitable windrowing width for the harvesting equipment is between 5 and 20 meters.

In some cases, it is worth not windrowing but rather collecting the mown material directly from the mower's swaths. This is sometimes the case when baling is used on very plentiful growth or plants that are susceptible to harvest losses. On the other hand, the mower can be equipped with a merging device, so that the mower swaths are merged during mowing in the same pass.

### 3.3.3 Harvesting and storing

After the drying period, the mown and windrowed grass is collected from the field for transport and storage. This operation can be carried out using a number of different methods. It was not possible to cover all of them in this review. Three different harvesting chains were selected for comparison, each of which was assumed to have its own profitable area of operation within the framework of the main variables under interest (transport distance, field size, annual harvesting volume). The comparison did not include the pick-up wagon chain, which was known to be a cost-effective method, but it was not available for the study in this context. The square baling method, where bales are rectangular instead of a round, was also excluded for the same reasons, although its advantages, especially for longer long-distance transportation, are undisputed based on the literature.

Three methods chosen to be included in the calculator were:

1. Loose harvesting method with a Self-Propelled Forage Harvester, also known as Forage Harvester or Forage Chopper, and a distance-dependent amount of tractor-trailer units for transporting. Ensiling is done by compacting and covering the collected material hermetically in the pile or silo/bunker within the immediate vicinity of the biogas plant or further away, in which case a separate long-distance transporting stage by the truck was also required.
2. Bale harvesting method with a Combi-Baler, which bales and wraps the baled silage on a single pass. There is short-distance hauling needed for wrapped bales to intermediate storage or directly to the biogas plant.
3. Bale harvesting method with a baler, short distance hauling from the field, and separate tube wrapping at the intermediate storage area.

In the first of these methods, the grass is collected from the windrow by a forage harvester, which chops the material to an average length of about 3 cm and blows it into the tractor-drawn transport wagons running alongside the harvester. A preservative is added to the blown material stream. These loads are transported to a storage site where they are emptied. At the storage site, the material is spread into a thin layer on top of the storage pile and carefully compacted with a separate compactor, which can be a tractor, wheel loader, or even an excavator. Once the storage pile is completed, it is covered with an airtight membrane and weighted down with a suitable material, such as sand, sawdust, or used car tires. At a minimum, the chain includes a harvester, two transport units, and a pile compactor, but the number of transport units required depends on the transporting distance and the capacity of the harvester. The method is the most efficient of the three harvesting methods, but it also requires the most equipment and personnel. Its efficiency suffers in small and distant fields where the harvester's capacity cannot be fully utilized. In addition, if long-distance transportation is necessary, the transport of loose material by truck is less efficient compared to the bale method.

The two baling methods included in the calculator differ in the way the bales are wrapped after baling. In the combi-baler method, a single tractor-drawn machine (combined baler-wrapper) bales the grass, applies the preservative, and wraps the round bales hermetically with plastic film. The wrapped bales are then transported as a separate operation to an intermediate storage site or directly to the biogas plant. This method is well suited for smaller fields and is not logistically very complex, as the steps in the chain are not fully dependent on each other in terms of time. The disadvantage of this method is the high consumption of plastic wrapping material, which increases handling costs and plastic waste at the biogas plant.

In the second baling chain, the bales are not wrapped in the field immediately during baling, but they are transported by the tractor and trailer to an intermediate storage area where they are wrapped in a separate wrapping machine in one continuous line called "tube". In this way, the ends of the bales are not wrapped with plastic but are placed tightly in a line against each other, which saves a considerable amount of wrapping plastic. From the intermediate storage area, the bales can be transported to the biogas plant using a suitable long-distance transporting method. This method requires at least one transport unit in addition to the baling unit, as the unwrapped bales must be transported for wrapping as soon as possible after baling to prevent the material from deteriorating before the airtight wrapping process starts.  The efficiency of balers is not up to that of harvesters, so they do not achieve the corresponding daily yields. However, more flexible baling methods have their place in the supply chain if the transporting distance and field factors do not favor the use of more efficient methods.

### 3.3.4 Long-distance transport

One of the main objectives of the study was to determine the distance, over which the feedstock should be transported to the biogas plant, and which transporting method or combination of methods is the most profitable. The long-distance transporting method included in the calculator is as follows: long-distance transporting is carried out by a full trailer truck originally designed for the transport of stumps and other loose forest residues (Fig. 4). They are equipped with a large, enclosed load compartment and a long-reach crane with grapple for loading. The unit can load and unload bales or loose silage independently. The vehicles suitable for the job are currently 3-4 axle trucks with a 4-5 axle trailer. The gross weight of the vehicles can range from 60 to 76 tons and the load capacity from 30 to 47 tons. The trucks are mostly heavy trucks with a 6x4 or 8x4 chassis designed for forest road usage. Those are suitable for transporting in difficult conditions on unpaved roads and field roads. An example of a suitable truck-trailer unit can be seen in Figure 4.


FIGURE 4. Truck-trailer combination suitable for the long-haul transportation of bales and loose silage. Source: (Riiko oy 2022).

In long-distance transportation, the truck loads the bales or bulk silage from the intermediate storage area where they were transported in the previous operation. The storage site is chosen so that it is accessible at the planned time of long-distance transportation. Outside the wintertime when the ground is thawed, the storage site must be load-bearing and spacious enough to allow the trailer combination to turn around and load the material. The calculator defaults to the input data of an 8-axle 37-ton truck-trailer combination, but can also be used to calculate long-distance transportation by other types of combinations or by a tractor, where the hourly costs, the driving speeds, and load capacities are adjusted to match the characteristics of the transport unit.

## 3.4 Potential availability of the grass feedstock

The conclusion of the final report by the working group preparing the national biogas program states that within Finland's biogas production sector, a significant share of the potential of energy production and nutrient cycling is in the agricultural mass, although the share of renewable energy produced from agricultural raw materials in our total renewable energy production is very small so far. Only 1.4% of the manure is used for biogas production and the use of grass silage is close to neglectable (Työ- ja elinkeinoministeriö 2020, 15).

The energy potential of grass can be calculated in several ways. In the Biogas Working Groups report, the energy potential of grass silage shown in Table 5 was calculated by multiplying the estimated area of land available for biogas production by an average yield of 17 t/ha fresh weight. The grass available from fallows, fertilizing grasses, and buffer zones were estimated by converting the dry hay yield (85% DM) derived from the statistical data of the Biomass Atlas into freshly harvested silage (40% DM). The total energy potential of grass feedstock as biogas is then 4.51 TWh /a. (Työ- ja elinkeinoministeriö 2020, 60)

As an example of comparison, Helenius et al. (2017, 39) estimated the energy potential of the entire grassland sector at 7.45 TWh, taking into account the additional yield that could be obtained by improving the efficiency of current production. The working group's assessment did not assume any efficiency improvements or other possibilities for increasing the grassland cultivation. The amount of straw was calculated using the yield statistics and crop-specific yield coefficients. The straw volume has been calculated net of its use for drying, which is estimated to account for 20% of the straw produced.

TABLE 5. Annual agricultural biomass suitable for biogas production and nutrient recycling in Finland. Based on the Finnish national biogas program.

| **Biomass** | **Available amount** ( t/a, wet basis) | **Biogas production potential** (TWh/a) |
|---|---|---|
| *Manure (domestic animal, incl. horses 2017)* | 15 500 000 | 3,94 |
| *Grass silage (205 000 ha, 17 t/ha, wet basis 27% VS)* | 3 485 000 | 3,29 |
| *Grass from ecological area* | 1 210 600 | 1,22 |
| *Straw (20 % excluded for used as a bedding material)* | 2 840 400 | 6,76 |
| ***TOTAL*** | | 15,21 |

During their workshop in 2020, Finnish Biocycle and Biogas Association estimated that Finland's biogas production could be 4-7 TWh before 2030, and 6-15 TWh by 2035. Production would be based mainly on the utilization of agricultural-based by-products. The final report by the biogas working group proposes a current techno-economically exploitable potential of 10 TWh, including manure-based feedstocks (Virolainen-Hynnä. 2020).

Previous studies have estimated the theoretical biogas potential of field biomass at 17.8 TWh, and the techno-economically exploitable potential at 5.8 TWh (Tähti and Rintala 2010, 29; Kymäläinen and Pakarinen 2015, 37).

### 3.5 Sustainability of grass silage for energy production

There have been many, sometimes contradictory calculations in the literature regarding the ecological and social sustainability of biogas produced from field crops. For example, in transport, biogas is seen as a better alternative than first-generation liquid biofuels. Achievable savings in greenhouse gas emissions are heavily dependent on the feedstock used. The comparison in the Smyths' (2010) article shows that the greenhouse gas (GHG) savings of using biomethane as a transport fuel compares well to conventional biofuels. For example, biomethane produced from field crops can provide 75% GHG savings compared to fossil fuel. Manure-based biomethane performs even better with 85% savings. Those are significantly higher than rapeseed biodiesel (45%) or corn/maize ethanol (56%). Williams (2017, 122-123) suggests that when comparing the same feedstocks, the AD could be more economical than bioethanol production, as AD uses less energy in the processes to produce biogas than what is used in the production of alcohol-based transport fuels (such as ethanol), and the output energy ratio for methane is higher than that of alcohol-based biofuels.

During the last 20 years, the use of energy crops has increased in several European countries, such as Germany, Netherlands, and Austria. Maize silage has been especially used more frequently due to its high methane yields, which increased the profitability of biogas production. However, the sustainability of utilizing energy crops and the impact on land-use changes and food security has been debated, leading to local limitations on the share of energy crops used for biogas production in Germany, Austria, and Denmark (Scarlat et al. 2018).

At the EU level today, the calculation of the sustainability of biomass for energy usage is governed by the Renewable Energy Directive (RED II), published in December 2018. It defines the criteria for calculating the emission reductions, and sets the binding EU-level sustainability criteria for using biomass to produce energy. The sustainability criteria aim to ensure that the increasing use of bioenergy in the EU will generate significant greenhouse gas emission reductions compared to fossil fuels. Member states had to transpose national legislation in line with the Directive by the end of June 2021. In Finland, the sustainability criteria have been introduced by the law (604/2021); Laki biopolttoaineista ja bionesteistä annetun lain muuttamisesta, based on the government proposal for amending the Act on biofuels (HE 70/2020).

Not only does the sustainability criteria apply to the origin of the biomass, but it also concerns the life-cycle emissions of biomass and bioenergy, which must represent a certain reduction compared to fossil fuels. For the installations that started in 2021 or later, the emission reduction requirement for electricity, heating, and cooling is 70%, and 80% for plants starting up in 2026 or later. For biogas used for transport fuel, the emission reduction is 65% (Rasi et al. 2019). Meeting the sustainability criteria is a condition for national support regarding the use of biofuels for electricity, heat, and transportation from biomass. The criteria must also be met for bioenergy to count towards the national renewable energy quota. According to the current interpretation, only bioenergy that meets the criteria is arithmetically zero-emission in the EU Emission Trade System (ETS) and in the non-ETS sectors (MMM 2022).

The Finnish Natural Resources Institute (LUKE) has published a report in 2019 (Rasi et al. 2019), in which the sustainability of grass silage and compliance with the emission reduction targets have been calculated using the RED II calculation criteria. The report shows that if grass feedstock is grown solely for energy production based on the assumptions used in the analysis, it is a challenge to achieve the emission reductions required by the directive. This is particularly true for electricity and heat production, where the emission reduction requirements are higher than for transportation fuel production. However, it would be possible to achieve emission reductions if, for example, the soil fertilizer grass or surplus third crop grass is used for feedstock, or if grass silage is used as an additional feedstock, e.g., with manure. Despite the challenges posed by the sustainability criteria, the report recommends that in order to achieve the objectives of nutrient recycling and renewable fuels for transportation, it would be important to promote manure processing, and that the use of grass as an additional feedstock would contribute to these objectives; the additional energy from grass improves the economic viability of the biogas plant.

On July 14, 2021, the Commission published a proposal to update the RED II Directive (RED III) as a part of the so-called "Fit For 55" package. The key objective of the commitment package is to increase the EU's 2030 emission reduction target from 40% to at least 55%. The renewable energy target is proposed to be increased from 32% to 40% (MMM 2022).

The Commission has proposed changes to the Renewable Energy Directive, particularly in the areas of transportation, heat, and power generation. The Commission's proposal would extend the scope of the sustainability criteria to cover installations of 5 MW or more, and would extend the emission reduction requirements from new installations to all bioenergy installations. The European Parliament committees have discussed the proposed amendments, and the Parliament's plenary voted its position on the Directive on September 14, 2022 (MMM 2022). However, at the time of writing, there is no clear information on the impact of the proposed amendment on the criteria for calculating the sustainability of the biogas sector's feedstocks. Thus, it is expected that the usage of energy crops and their potential in the future biogas production in the EU will be increasingly limited due to the sustainability considerations and increased support toward the cascade use of materials and resources and the use of waste and residues.

# 4 RESEARCH IMPLEMENTATION

The reference framework of this study combines approaches from different research fields. In the literature part, many of such were covered: engineering sciences, economics, and natural sciences like biology and agriculture.

Literature research formed the basis for formulating the thesis question and methodology, and contributed to the knowledge base for the hypothesis and research framework.

Both quantitative and qualitative research methods were utilized during the study. For example, the time study of the road transportation and the cost calculations and time consumption calculations were used with purely quantitative methods; thus, interviews with the contractors and farmers were more on the qualitative side.

In addition to being based on the literature study, some of the chosen research methods were also based on the author's experiential knowledge of the available silage harvesting methods and assumed best methods to include in a closer time study. However, efforts were made to verify the validity of those subjective assumptions with more scientific methods.

The contracting costs used for baseline values in the calculator were obtained from the company's accounting system in accordance with the actual costs incurred. They were compared with the statistical contracting costs published by TTS (TTS 2020).

## 4.1 Research goals, scope of the study and initial assumptions

The primary goal in planning the thesis topic was that the subject and results should be practical and beneficial in a real-life business environment. Moreover, the primary goal of the research was to find out the economic profitability of using grass silage as an input for biogas production in the Finnish operating environment in general, and in the two cases in particular.

From the client's side, the goal of the work was to find out the procurement cost (a plant price) of grass silage feedstock for two biogas plants of different sizes and study the general technical-economic profitability of using the grass silage as a feedstock in those cases. There was particular interest in the cost of long-distance transportation of the biogas plant's grass feed, and the effect of transporting distances on profitability, as it was found to be quite an unexplored topic during the preliminary study.

The projects behind the Case study and their starting assumptions and background information were based on real biogas plant pre-assessment projects located in Finland. The projects subject to the case study were not precisely identified due to business secrecy, although the project identities were irrelevant in the study results.

The two specifically examined Case-scenarios and their background information were given by the client as follows (Taavitsainen, 2020):

1. **A small-scale wet fermentation plant or "A Farm-plant":**

Grass silage is harvested from a maximum of 15 km radius from the plant, and it is used as an additional feedstock for the mainly manure and slurry-based substrate. A long-term storage of the feedstock material takes place in the immediate vicinity of the facility.

2. **Big scale dry fermentation plant, or "Industrial-plant":**

The silage procurement radius was assumed to be approximately 50 km from the plant due to the estimated need for an industrial-scale plant's procurement area. Grass silage is the main feedstock of the biogas plant. The feedstock silage is transported to the plant at the pace of its consumption, so only a small buffer stock can be stored on site. During the year, the feedstock material is temporarily stored at intermediate storages near the fields where it was produced.

The simplified research question was:

***"Is grass silage a technically and economically possible feedstock for a biogas plant in Finland conditions?"***

and as a follow-up question:

***"Is it profitable for a farm to produce grass silage for raw material for a biogas plant?"***

Based on the preliminary research, grass silage was known to be available and technically potential input for a biogas plant. It was also known that the grass feedstock delivered to the biogas plant had a limit-price based on the possible $CH_4$ yield obtained from it, along with the income obtained from the energy products sold to the markets.

Basically, it was assumed that the production cost of any feedstock couldn't exceed the limit price determined by that profitable business. However, prior to the study questions, it was known that in a practical situation, the economic benefit from improving the farm's nutrient cycle and balance and the efficiency of manure logistics might nevertheless be a reason to exceed that limit price. In this context and in the scope of the study, these variables were not considered in the economic analysis, as their definition was impossible and unnecessary due to the big variation among the diversity in farms and biogas production facilities.

The secondary research goal, if the above-mentioned technical-economic baseline analysis indicated the need for further examination, was to find out the order of preference in some potential procurement chains identified based on the literature study.

Due to the limitation of the study and the scope of the phenomenon under investigation, efforts were made to standardize as many variables as possible in order to achieve generalizable results that can be used in practical profitability calculations. For example, the harvest times (once a year), fertilization level, and method were set as standard variables, but were identified as a necessary topic for further research. Probable values obtained from literature sources and determined based on practical experience were used as default values for the fixed variables.

Variables chosen for the comparative study were transporting distance regarding the feedstock material and transport equipment used for road transportation. Also, a comparison between harvesting methods, two bale-based supply chains compared to the self-propelled forage harvester-based chain, was included to the study.

In addition to the case specific results, the results of the study needed to be generalizable and usable in future biogas projects' feasibility studies.

During the preliminary study and preparation of the research plan, it was found that based on the data and experiences collected for the research, it seemed to be possible to create an Excel-based calculator that could be used as a tool in general and in various real-life circumstances. Therefore, the goal to create the above-mentioned Excel-calculator was added to the study plan. It later turned out that the creation of the calculator was the biggest effort of the work, but also the most useful output.

The grass silage supply chains to be examined in the study were selected by familiarizing with the previous studies conducted on the production costs of grass silage, and by interviewing farmers and contractors who produce grass silage on a scale similar to the cases under review. Based on these studies, it was decided to include three different harvesting chains and ensiling methods in the study.

A self-propelled forage harvester (SPF) chain and two round baler chains were selected for the comparative study. The harvesting methods chosen are described in more detail in Chapter 3.3.

## 4.2 Literature study

For this thesis work, I initially tried to find and go through the available basic literature written about the subject. After that, I conducted a comprehensive review of the recently published studies. Some of the sources used for the review and background research did not directly deal with the production of biogas, but they referred to the production of grass fodder used for the livestock feed. However, this was not considered to hinder the usability of the sources in this context, as the same principles often apply regardless of the final use of grass fodder.

Due to the special nature of the agricultural production and its operating environment in Finland and the framework set by our northern climate, the reference literature used as a source mainly consisted of reports and studies published in Finland. A comprehensive and updated list (in Finnish) of these reports of Finnish educational institutions and research institutes can be found, e.g., as an attachment to the final report of the FarmGas-PS 1 -project (Pyykkönen et al 2021, 30-42).

Studies and theses dealing with the topic were searched using the databases available at the Savonia-Finna and Theseus. Some of the basic keywords used for searches were biogas, silage, manure, supply chain, and transport cost calculation, etc. The reference lists of the sources found in the additional searches helped to find basic literature and studies covering the field.

A lot of the usable current information related to the topic has also been published on the websites of, e.g., biogas plant suppliers, advocacy organizations, and the state administration. These sources were used, among other things, to acquire up-to-date information related to law preparation, plant technology, and the current situation of the biogas sector.

In the background investigation of the final thesis, an effort was made to find a balance between practical knowledge and theoretical knowledge. However, in accordance with the objective of the thesis, the emphasis was placed on comparing the knowledge acquired in practice with the research knowledge, and applying this knowledge to practical problem-solving in order to achieve the set research goals.

The variation in reporting methods between the different research fields and schools of thoughts turned out to be significant. This required precision, e.g., in being consistent with the units, abbreviations, and concepts used while writing this thesis.

## 4.3 Real life time-study

Simple time studies about different phases of the grass silage supply chain were carried out during the harvest season of 2021. Results were used as the basis for the Excel calculation sheet regarding time consumption models, and for the default values used in the calculator. Time consumptions were measured for the harvesting of grass forage on the Ollinaho Oy cattle farm, and on the author's own crop farm.

The time-use studies measured the total time consumption of the work phases at a general level in order to verify the accuracy of the information found from the literature, and to find real-life values to serve as a baseline for the Excel calculation sheet. In this context, more detailed measurements and modeling were not pursued, as it was not considered necessary for the scope and purpose of the work, nor were the resources available to carry them out.

### 4.3.1 Ollinaho oy

Ollinaho Oy is a cattle farm located in Kiuruvesi, North Savo. The farm grows and harvests grass silage from its own fields and those of partner farms, covering a total area of about 300 ha in the vicinity of the farm. The harvested silage is used as a feed for more than 800 heads of beef cattle. In 2021 and 2022, the mowing and compaction of silage bunkers was carried out with the farm's own equipment and personnel. Windrowing and forage harvesting with a driven forage harvester and tractor trailer units were carried out by a contractor. For some of the smaller fields, where a silage harvester chain is inappropriate to use, a contractor with a combi-baler (baling and wrapping round bales) was also utilized. The same also applied to the fields that were too far away from the farm to be harvested with a forage harvester.

The time consumptions of mowing, windrowing, harvesting chain, and silage compacting and covering were studied on the Ollinaho Oy farm during the summer of 2021. Later on, based on the experience gained, the preliminary results and the calculation basis of the Excel calculation tool was reviewed and improved based on the experience of the 2022 harvest. The contractor who harvested in 2022 had a more efficient harvesting chain, whose performance was compared with that of the contractor who harvested in 2021 and adjusted the calculation tool respectively.

### 4.3.2 Lepola farm

Lepola farm is a crop farm owned by the undersigned. Currently, it grows mainly grass silage for the above-mentioned Ollinaho Oy farm. About half of the farm's arable land is located 50 km away from the farm center. The fields close to the farm are harvested at the same time using the same methods as Ollinaho oy, but the silage from the remote field further north is harvested a little later using the Combi-baler method. Silage bales are transported from the remote field to the farm by a truck-trailer combination.

At the Lepola farm, supply chain variables were examined, e.g., in the context of long-distance transportation from a remote field, including the time needed to load and unload round bales from and to the truck. The logistics of transporting round bales from the field to the place suitable for truck-loading were also examined.

## 4.4 Excel calculation sheet

Excel was chosen as the program to implement the calculation spreadsheet because it is the most commonly used spreadsheet program, and its use in such contexts is a common standard. Other options for the software to be used as the basis for the calculator were not explored at this time, as it was believed that Excel could be used to implement a suitable package with ease.

The design of the calculator's structure was based on the objective that it should be easy to use for the pre-feasibility phase of various biogas projects. Also, its usability should allow simple sensitivity analyses to be carried out for selected variables. The initial aim of developing the tool was to find an answer to the questions whether it is economically feasible to feed a biogas plant with grass, and if so, under what conditions.

Structurally, the solution was to use the main page (Results and Variables-tab) to enter the main variables and to display the main results.  The actual calculation was done on tabs, which are divided according to the separate supply chain operations and processes.

The tabs include separate calculation modules to calculate the values of smaller sub-operations that act as intermediate results for the calculation of final results, and they also provide information for the user of the calculator. For the spreadsheet developer, those visible intermediate results allow the examination and checking of the calculated operations. The cells were color-coded based on their operation as follows:

| |
|---|
| Input data fed by user → green |
| Values fetched from the sub-calculation tabs→ orange |
| Values fetched from the input data sheet→ light red |
| Calculated results, locked cells → yellow |

Decimals shown in the final results are usually limited to full euros, or a maximum of one decimal for easier readability and the universal nature of the calculation basis. The use and operation of the tabs and modules are described in the following sections, which are titled according to the tab headings.

The calculator produced as a result of the study is also suitable (at least partly and with certain reservations) for determining the costs of harvesting straw or maize silage, but in this case, more research is needed, e.g., on the productivity of harvesting straw.

Tabs at the Excel spreadsheet are as follows:

### 4.4.1 Results and Variables

This tab is the main view of the calculation tool, a starting page, where you can enter the main variables and see the main results. The most important figure on the tab is the production cost of grass silage dry-matter. It is presented both in unit € / t-DM and cents/kg-DM, which is a more common unit in agriculture. The last row returns the cost of feedstock production divided by the methane production potential of the dry matter harvested, which is a good figure for evaluating the overall feasibility of the feedstock under examination.

The Results-side shows the cost structure of three different harvesting chains with adjacent columns. The fourth column is for entering user-defined values if wanted. The harvest chains selected for the calculator were determined by the scope of the work, and it does not include all possible options. For example, based on a preliminary analysis, a self-loading wagon was known to be a good option for short-hauling distance operations, but it was excluded from the analysis for resource reasons.

**RESULTS PAGE: €/DM-t** | **Example CASE**

*Cost calculation of the silage feedstock* | © Mikko Jauhiainen 26.1.2020

| | | |
|---|---|---|
| **Grass, vegetation esteblishment** | 23 | €/ t DM |
| **Grass, annual fertilization and weed control** | 25 | €/ t DM |

| | BALING | | LOOSE | | |
|---|---|---|---|---|---|
| **Harvesting cost based on chosen method** | Combi baler | Tube wrapping | Harvester chain | Own values | |
| Mowing | 6,0 | 6,0 | 6,0 | N/A | |
| Windrowing | 3,6 | 3,6 | 3,0 | N/A | |
| Baling+neting+wrapping OR Harvester costs | 28,2 | 25,8 | 11,2 | N/A | |
| Ensiling costs | 13,3 | 13,3 | 13,3 | N/A | |
| Short distance hauling directly to plant or intermediate storage | 10,6 | 16,6 | 9,9 | N/A | |
| Compacting of the pile or silo | | | 0,4 | N/A | |
| Cost of plastic films | 8,6 | 4,3 | 0,9 | N/A | |
| Storage slab or silo | | | 6,4 | N/A | |
| Additional costs: (snow removal, pile weighting, etc) | 1,0 | 1,0 | 0,9 | | |
| **Cost of harvesting and ensiling before long-distance transportation** | **71,3** | **70,7** | **51,9** | **0,0** | |
| **Long-distance transportation** | 10,4 | 10,4 | 11,7 | N/A | |
| **Cost of the feedstock, at the biogas plant (€/t of DM)** | **131** | **130** | **112** | **#ARVO!** | €/t DM |
| | 13,1 | 13,0 | 11,2 | #ARVO! | cent/kg DM |
| **Cost of the feedstock at the plant / CH4 potential** | 0,40 | 0,39 | 0,34 | #ARVO! | €/m3 CH4-pot |

FIGURE 5. RESULTS and VARIABLES-tab is the "homepage" of the calculation tool, where basic input variables are given, and main results shown. The Results-side collects the calculated costs to one table.

The Input data-side is for applying the basic input variables. The most important values are the DM content of the harvested material and the DM yield of the crop. These variables were expected to have the greatest impact on the feedstock production costs under consideration. In addition to these main variables, the option to enter transporting distances and variables related to the field size and remoteness was added to the starting page, as these are significant variables in the pre-feasibility phase of the biogas plant design. These values are used for calculations in several different tabs, so it was logical to enter them all in one place (Fig. 5).

Some variables for ensiling films and additives are also placed there, as they are changing costs from time to time and from one project to another.

### 4.4.2 Cultivation

The costs for annual cultivation and the establishment of grass vegetation once per rotation are calculated under this tab (Fig. 6). The spreadsheet is based on calculations originally made for grass feedstock by Paavilainen (2021), who works as a consultant for the ProAgria- advisory organization and participated in this project in the beginning. It has since been modified further to suit this purpose.

**ANNUAL CULTIVATION COST FOR THE BIOGAS FEEDSTOCK GRASS**

**Example CASE**

© Mikko Jauhiainen 26.1.2020

| | | |
|---|---|---|
| Yield, kg of DM | 5500 | kg DM |
| crop harvests | 1 | per year |
| year rotation | 4 | years |

| | | Establishment cost, first year | Annual cost, divided for rotation years | |
|---|---|---|---|---|
| **Entablishment costs per hectare:** | | € | € | basis for cost: |
| | Basic fertilization , establishment year | 90 | 22,5 | *solid fragment 30 tn /ha* |
| | Ploughing or other basic cultivation | 100 | 25 | |
| | Tillage, (soil preparation before sowing) | 45 | 11,25 | |
| | Sowing of grass seeds | 25 | 6,25 | *roller+pneumatic drill* |
| | Basic liming | 144 | 36 | *36 € /t; 4 t/ha* |
| | Grass seed cost | 108 | 27 | *27 kg; 4€/kg* |
| | Weed control, establishment year | 50 | 12,5 | *Ariane S* |
| | **TOTAL** | 472 | 140,5 | |
| **Annual costs** | | | | |
| Fertilization: | Manure/digestate | 0 | 0 | *30 m3, free of charge* |
| | spreading | 90 | 90 | *3 €/m3* |
| | Mineral fertilizer | 135 | 135 | *150 kg/ha; 0,9 €/kg* |
| | spreading | 17 | 17 | |
| Weed control | Herbicide | | 0 | |
| if needed | spreading | | 0 | |
| | **TOTAL** | | 152 | |
| **Entablishmen costs and annual costs in TOTAL per a:** | | | 292,5 | €/ha |
| | €/kg DM | | 0,053 | |
| | €/t DM | | 53 | |

FIGURE 6. CULTIVATION-tab is used for estimating the annual cost for the grass feedstock cultivation. Values shown in the picture do not refer to any particular case.

Cost calculation is divided into two groups for the establishment year costs and annual costs. The establishment year costs are divided equally for all years of cultivation rotation. The calculation is based on the idea that in the first year of the crop rotation, a grass vegetation is established with a cover crop; this first year's crop is not harvested to feed the biogas plant, but is used, e.g., as animal feed. However, the cost of establishing the perennial grass will be calculated equally for all the years of the cycle, including the first so-called cereal-crop year. The default calculation assumptions about the cultivation rotation are in line with the input data for grassland sustainability calculations based on the RED II Directive published by Rasi et al. (2019).

### 4.4.3 Mowing and windrowing

The costs of mowing and windrowing are calculated on the same tab since they are operations that are closely related in terms of their calculation basis, and are sequential operations in the grass supply chain.

There is good information available in the literature about the time needed for mowing and windrowing. In principle, it would have been possible to determine the cost of these operations based solely on contractors' charges or on time-cost equations derived from the literature. However, in the initial review of the study task, it was noted that the effect of field size on harvesting costs would be useful information to determine the costs under various geographical conditions. In silage harvests, unfavorable field sizes and shapes have a negative impact on the working efficiency. The increase in harvesting costs is largely due to turning times in the fields (Klemola, Karttunen, Kaila, Laaksonen & Kirkkari 2002, 44).

Thus, it was decided to develop a simple model to describe the working efficiency due to the so-called field factors. To estimate this variation, I developed a calculation module to determine an efficiency ratio for tractor work in the field, which could be used to estimate the work output as a function of the field size. The calculator computes the theoretical ratio between turning on a headland and the actual effective work so the time when a baler is collecting grass is compared to the total time spent on the field, including headland turns when no material collecting is happening. The input parameters required for calculating the baling efficiency factor are shown in Figure 7.

| **Eff. ratio calculator for baler; square field** | | |
|---|---|---|
| Driving speed when baling | 4 | km/h |
| Driving speed at headland | 7 | km/h |
| Size of the field | 5 | ha |
| Width of the headland | 3 | times the working width |
| Theoretical lenghth of the A-B line | 182 | meters |
| Working width | 7 | meters |
| Driving distance on headland per turn | 24,5 | m |
| Time needed for bale drop | 15 | sec |
| | | |
| Time spent on headland turn | 10 | sec |
| Time spent baling | 126 | sec |
| | | |
| Efficiency ratio; baling/headland turning | **93** | % |

FIGURE 7. The efficiency ratio calculator module shows the results of the percentage of efficient work. In this particular case described in the picture, 93 % of the time is used for efficient work on a 5-ha field.

The eff. ratio calculator module is based on the assumption that the field is square and free of obstacles. It geometrically calculates the machine's driving path in a rectangular manner, although the actual path is more or less round. Thus, the model is rather coarse and only suitable for general-level analyses, but it does illustrate the effect of the field size on harvesting efficiency. The time required for a headland turn is calculated by assuming that the headland is driven to its halfway point, and then a single driving line (A-B line) is left in between before turning back. This corresponds well to the way that the current tractors with GPS guidance and headland automation operate in practice. The same module is also used on other tabs to calculate the efficiency of the operations.

The efficiency factor is used to calculate the hourly productivity of a machine unit, which is converted into the cost per hectare by dividing the hourly cost per unit by its productivity per hour. Some other variables, like moving from one field to another and additional time needed for the machine to be operational after entering the field, were also considered in the calculation. Value inputs for the tab are green in Figure 8. Different windrowing costs are calculated for the baler and harvester chains because their requirements for windrowing and costs differ from each other.

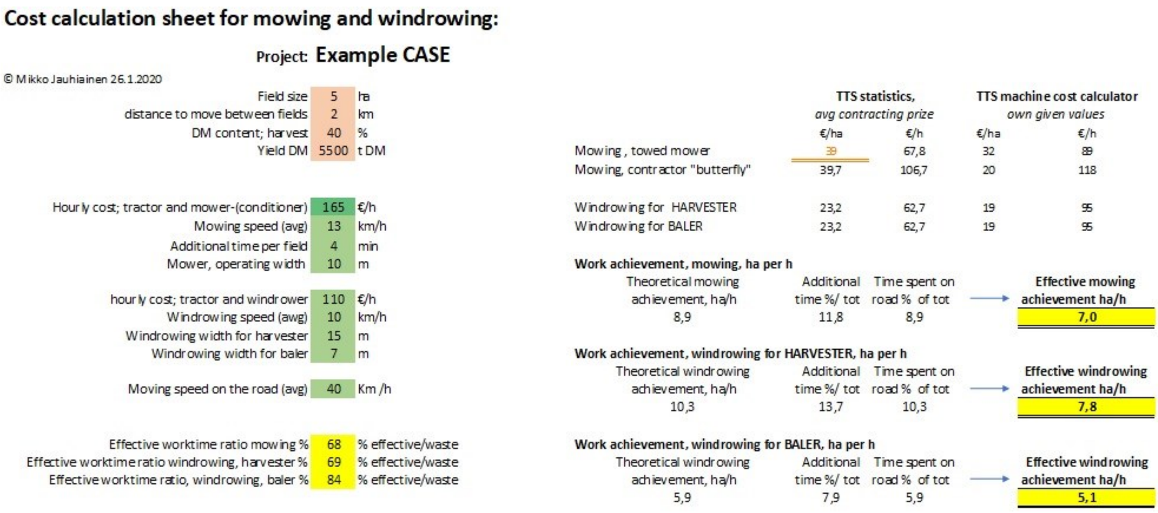


FIGURE 8. Cost calculation tab for mowing and windrowing. The calculation tab is used for estimating the hourly work achievement of the chosen machine unit.

The undersigned tested the theoretical work efficiencies given by the calculator in practice while mowing about 700 hectares during the summer of 2022, and as a conclusion, the results derived from the calculation model were surprisingly similar to those observed in practice.

The hourly costs used as a basis for calculation were determined on the basis of practical data, or by calculating them with the TTS machine cost calculator. TTS is a Finnish research and educational organization, which studies, e.g., work efficiency-related topics (Työtehoseura 2022). The calculated values were compared with the statistical contracting prices, also published by TTS (Työtehoseura 2021, 3-7). The tables of contracting prices collected from different sources were created on the tabs, from which the calculator user can choose the suitable baseline value for calculation if no actual numbers are available.

### 4.4.4 Self-Propellent Harvester (SPH)/ Forage harvester

The productivity of the harvester is calculated in the same way for mowers, by correcting the theoretical maximum harvesting capacity of the machine with an efficiency coefficient, depending on the field variables and taking into consideration the time needed for field changes and additional time needed for preparing the harvester upon arrival to the field. The efficiency coefficient is calculated geometrically on the same principle as it is for mowing, assuming that the field is square, and that harvesting is interrupted during the headland turn.

The hourly cost of harvesting and transporting is divided by the hourly productivity to obtain the cost per hectare, which is further calculated into the costs per the harvested DM tons. Figure 9 shows the variables that can be entered into the calculator. The variables depend on the conditions and the equipment in use, and must always be estimated on a case-by-case basis, according to a pre-estimate of the contractors' available equipment.

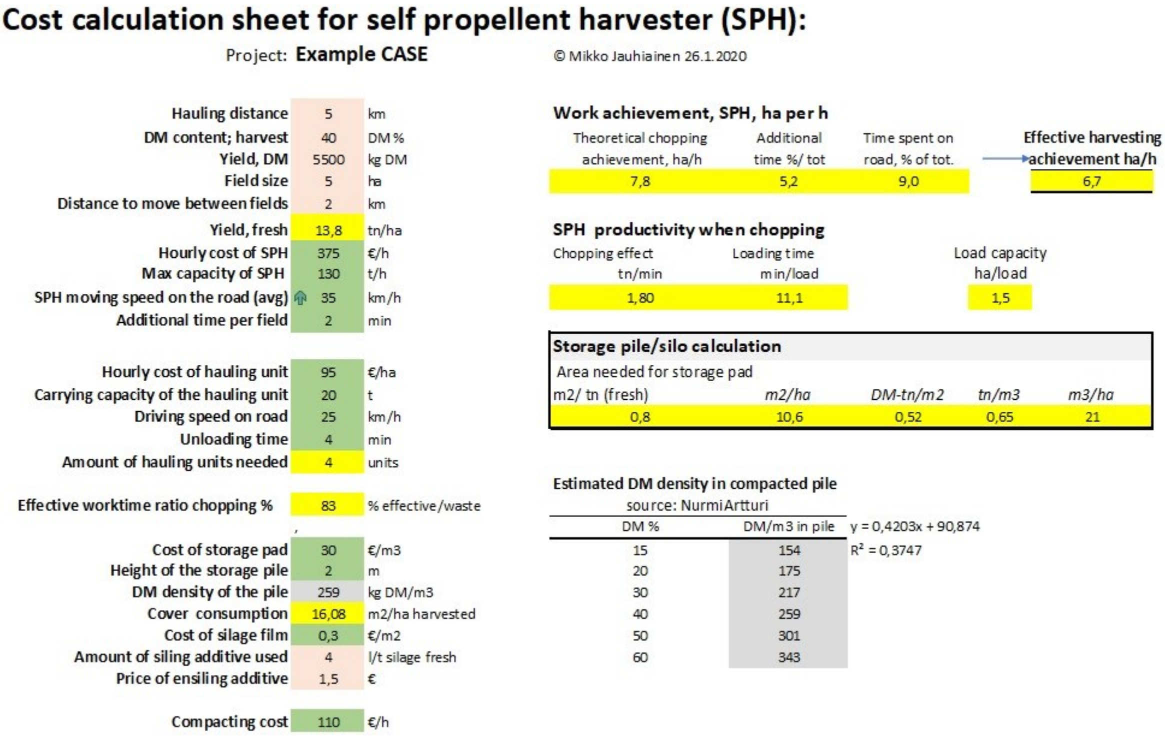


FIGURE 9. Cost calculation tab for forage harvester and hauling units (Harvester chain) is used for estimating the hourly work achievement of the chosen machine unit. Also, the costs and space needed for ensiling storage can also be calculated there.

The capacity of the transport units is determined by the carrying capacity of the trailer and their average speed of traveling. The loading time is determined by the effective capacity of the harvester, and the unloading time is given as a standard value based on experience. The calculator does not take into account the situation where the volume of the load compartment limits the load size, but assumes that the load is always a 'full carrying capacity' load. This may be a false assumption in a situation regarding a crop with very high DM content when, due to low density of collected material, the load space (volume of the load) limits the load rather than load carrying capacity (mass of the load). In this study, this error source was neglected as it was considered as a rare occasion in practice. The number of transport units required is determined by calculating the time required for one transport unit to make one round trip by adding the time required for loading (trailer carrying capacity divided by the theoretical trough-put capacity of the harvester corrected by the effectivity factor), the time spent on the road (hauling distance multiplied by two and divided by the average hauling speed), and the unloading time. This "round trip time" is divided by the loading time of the harvester, and the figure is rounded up to the next whole number. The resulting number is the theoretical amount of hauling units needed for the whole harvester capacity to be utilized, so the harvester does not have to wait for the transport units. The calculator's figures could be compared with the results presented by Lätti et al. (2014), for example, and they were found to be almost identical. Similarly, practical experience supported the finding that the calculator was reliable.

Compacting is assumed to be happening at the same time as harvesting, and its cost is calculated simply by dividing the compactor units' hourly cost by the amount of DM arriving to the storage area per hour. In reality, compacting should be continued about one hour after the harvesting is completed, but it is neglected as a nuance in this case. The default cost for the compactor unit is a cost of a 15-ton bucket loader operating at its maximum capacity, which provides the minimum compacting capacity needed to cover the harvesting capacity of an efficient harvester.

This tab can also be used to calculate the cost of storing silage in a pile on the asphalt pad. For the calculation, the Storage Pile/ Silo calculation-module defines the space required for the silage and the amount of plastic used for covering. As an assumption, only one layer of covering film is used only on the top and sides of the pile, and 10% extra is added for the overlapping.

The module also gives intermediate results, such as the storage area and volume required for a hectare of crop, which can be useful information when planning a supply chain. The cubic weight of the stored silage depends on the dry matter content of the material and the compaction method used. In the calculation basis, the density of the feed cubic is predicted by the linear equation (3):

$$Y = 0{,}4203\,X + 90{,}874 \qquad (3)$$

where X is the dry matter content [g DM/kg] and Y is the silage density [kg DM/ m3], based on the DM content of the material.

The equation is derived from the dry matter cubic weights measured in the NurmiArtturi-project. The explanatory power of the model is 0.375, so only about 37.5% of the tightness of the stockpile can be explained by the dry matter content of the material. The rest of the variation can be explained by factors, such as compaction method, compaction time, and other characteristics of the grass material, such as the length of the chaff (NurmiArtturi 2014, Palva 2017). The results of the equation are only used to calculate the surface area and plastic costs required for the stockpile, so its impact on the final calculated production costs of feedstock is negligible. Thus, it can be considered that despite the uncertainty, the use of the model provides added value compared to, e.g., using a constant value for the pile density.

The calculator also calculates the cost of the asphalt or concrete slab needed under the pile. Its cost is calculated by adding 10% to the required storage area, and multiplying it by the construction cost of the pad per square meter entered in the spreadsheet (35 €/$m^2$ by default, value is case specific, and depending on site characteristics). The resulting construction cost is then divided by the ten-year depreciation period as the estimated lifespan of the surface layer.

### 4.4.5 Baling chains: combi-baler and tube wrapping

In principle, the time required for the baling stage is calculated using the same methods from the previously described stages. For example, the efficiency ratio calculator-module is used to determine the effect of field variables. Difference between combi baler -tab and tube wrapping -tab are in the hauling variables and wrapping film consumption calculation. The time expenditure is calculated separately for baling and transporting the bales. By default, in the Combi chain calculator (Fig. 10), the wrapped bales are collected from the field 3 pcs. at a time (one in a front loader and two in a rear implement) and transported to an intermediate storage area. The transporting distance for both methods is entered on the variables tab. In the tube-wrapping method, short-distance transportation is assumed to take place with a tractor-trailer unit, where the unwrapped bales are loaded by a crane and transported to the waiting wrapper-machine in the intermediate storage area. The default load size is 18 bales. In both cases, it is possible to change the variables to match the working method used in this particular case. Figure 10 shows the input section of the baling tab. The green cells are the input variables, and the yellow cells are calculated values. Pink values are fetched from the Variables and Results tabs.

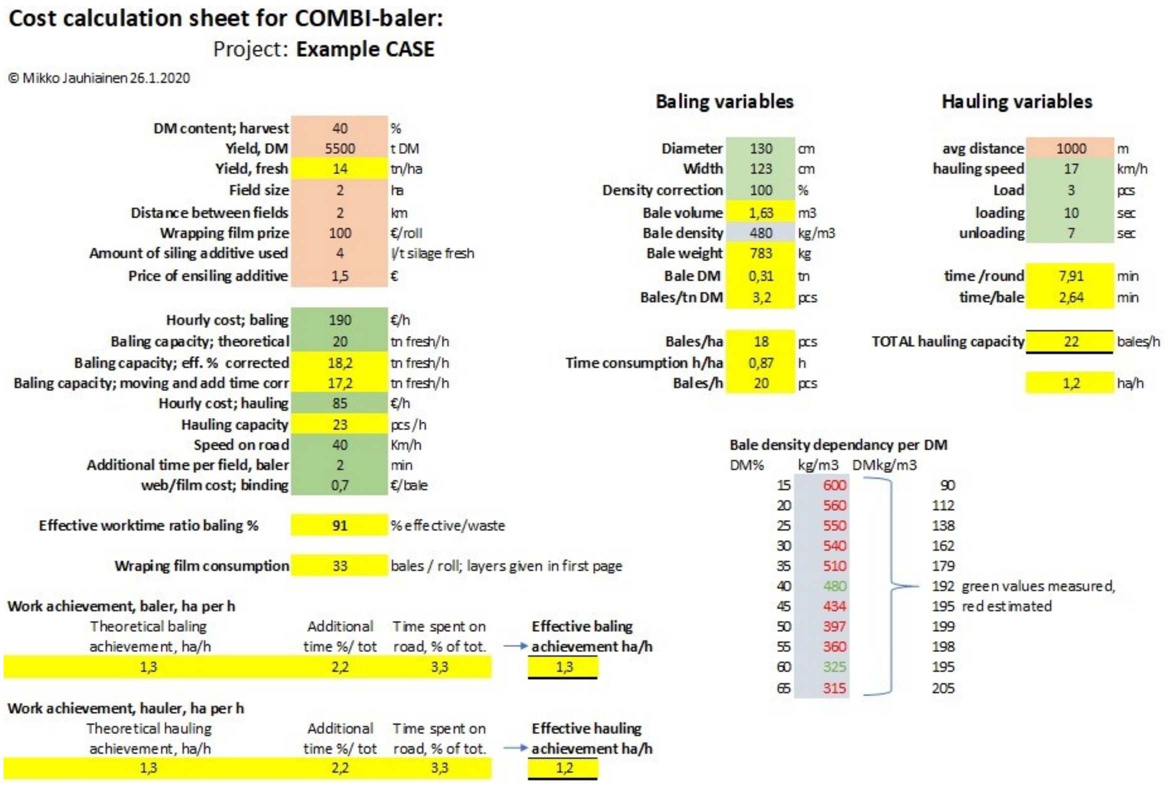


FIGURE 10. Baling costs are calculated on separate tabs for combi-balers and tube wrapping chains.

The number of bales per hectare is the most important factor when determining the cost of baling per hectare. The number of bales per hectare depends on the density and size of the bales. The size can be adjusted as desired, but the bale density is influenced by the material to be baled, its moisture content, and the characteristics of the baler. In the calculation, the density of the bale is predicted based on the moisture content by retrieving a density value from a table based on the moisture content of the material. The values in the table are estimated from two actual measurements taken during two different harvests in 2021, but the remaining values of the table are estimated based on literature sources (Murto 2020) and linear extrapolation. Therefore, the results of the bale volume calculation should be treated with caution. An attempt was made to verify the values in the table on the basis of the literature (e.g., Murto 2020), but there was a large variation in the results.

The calculator has a Density correction-cell, which allows the results of the table to be adjusted in order to match the tightness of the bales made by the baler used. The measured bale densities were weighed from bales made with the MCHaleFusion combi-baler, combined with moisture obtained from the feed analysis. The bale density calculator needs more research data about bale densities to be more accurate, but in this context, it should give accurate enough results even now.

### 4.4.6 Long-distance hauling

This tab is used to calculate the cost of long-distance transportation. The main variables used in the calculator are the net load of the truck used and the transport capacity. The net load is the carrying capacity of the vehicle in tons, and the transport capacity is the number of bales that can be carried in the load compartment. Based on the weight of the bales, the calculator calculates which factor is met first, i.e., which limits the load. Figure 11 shows the layout of the tabs' Input part The calculator takes into account, among other things, the variations due to the moisture content of the material being transported.

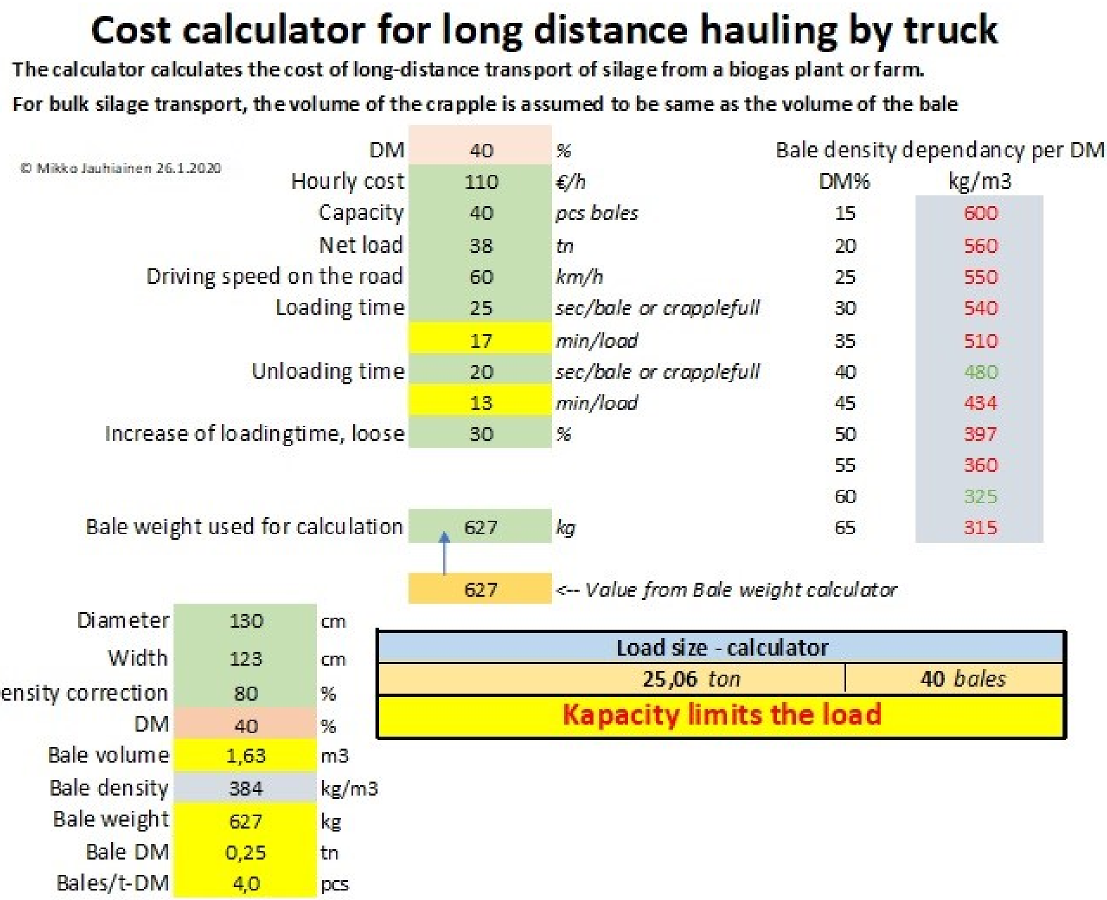


FIGURE 11. Cost calculator tab for long-distance transportation.

The weights of the bales used by the calculator are based on the same calculation method as in the Baler tab described above. The same uncertainties affecting the bale density are also present here, so the load sizes calculated by the calculator should be treated with caution until the calculation basis can be refined. However, the results obtained by the calculator seem to be in line with the load sizes observed in the real-life time studies, so in this context and with the normal moisture contents of the transported material (30-50% DM), the calculator can be expected to give sufficiently accurate results.

# 5 RESULTS

The Excel calculator was used not only to examine the costs of the two case studies, but also to carry out a general analysis to answer the main question of the study: "is grass feed economically feasible as a feedstock for a biogas plant?" Furthermore, the calculator was used for sensitivity analyses where graphs and tables could be compiled on the effect of the variable on the production cost by adjusting the target variable. The effect of yield and dry matter on the cost was of particular interest, along with the effect of field size on harvesting efficiency. The aim was also to find the maximum distance for which it is still possible to procure feedstock.

## 5.1 Results of the feasibility study

The initial aim of the calculator was to determine the price of the grass feed delivered to the plant in order to draw conclusions about the cost level in general, and whether there was any need to go into further detail at all. The solvency of the biogas plant was examined through the sales prices of their products. The absolute upper limit for the cost of the feedstock at the plant was defined as the retail price of the most valuable biogas sales product, which is compressed biomethane, minus the variable costs of its production and distribution. The price of processing, compressing, and distribution of biomethane production could not be determined based on the literature, but some estimates could be made.

The retail price of compressed biomethane used as a transport fuel (CBG) is around 2 €/kg, VAT included (Gasum 16.11.2022).

When 1 $Nm^3$ of methane weighs 0.72 kg, and the calorific value is ~ 35.8 $MJ/Nm^3$ (~10 $KWh/Nm^3$ $CH_4$) then 1 kg of methane equals to ~1,39 $Nm^3$ and thus, 1 $Nm^3$ costs about 1.44 € at the filling station. This equals to 144 € per MWh (1 $Nm^3$ ~ 10 kWh) (equation 4):

$$\frac{1[kg]}{0,72\,[\frac{kg}{Nm3}]} \approx 1,39\ [Nm3] \rightarrow \frac{2\ [€]}{1.39\ [Nm3]} \approx 1,44\ \left[\frac{€}{Nm3}\right] \rightarrow \frac{1,44\left[\frac{€}{Nm3}\right]}{10\left[\frac{kWh}{Nm3}\right]} = 0,144\frac{€}{kWh} \rightarrow 144\ €/MWh \quad (4)$$

According to Kaparaju, Rasi, and Rintala (2013, 175), the average cost for upgrading is about 0,25 €/$Nm^3$-$CH_4$, which equals to 25 €/MWh. The cost of compressing was estimated to be about 10 €/MWh, based on the electricity consumption from compressing and the price of the compressor (Metener 2022).

$$Retail\ price\ (144\ €/MWh) - VAT\ 24\%\ \ (28\ €) - upgrading\ cost\ (25\ €) - compressing\ cost\ (\ 10\ €) = 81\ €/MWh \quad (5)$$

Based on the calculation (5), it could be assumed that the upper limit for the production cost of the feedstock would have to be well below 80 €/MWh, to be even close to a feasible price. This calculation does not take the distribution costs and the fixed costs of the AD plant into account, nor the possible subsidies or other added values.

Based on the literature review, it was known that in previous studies (e.g. Sairanen 2018, 13-14), the production costs of grass forage from the farms surveyed could be considered favorable if the cost was below 10 cents/kg DM (100 €/t DM). On this basis, it could be calculated that with a methane production potential of 330 $m^3$ $CH_4$/t-DM regarding grass feedstock, the feedstock price would then be about 30 € per MWh of gas produced, which is significantly lower than the feasibility limit determined by the retail price and the cost of producing biomethane.

$$\frac{100\,[\frac{€}{tDM}]}{330\,[\frac{Nm3\ CH4}{tDM}]} \approx 0{,}303[\frac{€}{Nm3}]\,, \quad if\ \frac{10\ kWh}{Nm3} \rightarrow \approx 30\ €/MWh \qquad (6)$$

On this basis, it made sense to further investigate the production costs.

### 5.1.1 Yield and dry mater content

A calculator was used to study the impact of grass yield on production costs. Fallow fields and unfertilized water protection buffer zones, as well as small, awkwardly shaped fields, or fields with a poorer soil type and lower nutrient quality - which are not suitable for efficient crop production - are often suggested as sources of grass feedstock for biogas plants. The production of grass-based biogas feedstock is often thought to offer a solution for keeping such fields in arable conditions. Similarly, grass-feedstock production has been proposed as an alternative to the cultivation of so-called 'natural management' fields, where the aim is to keep agricultural land open with low-inputs and no intention of producing edible crops.

The subject was examined by a sensitivity analysis, in which the other variables were held constant, but the yield per hectare was varied every 500 kg/ha-DM between 2000 kg/ha-DM and 7500 kg/ha-DM. The fixed variables of the calculator were adjusted in this analysis to match the input values of the "Industrial- scale plant" case study. Production costs were determined and tabulated for all three harvest chains. The analysis was performed at two different dry matter contents (30% DM and 60% DM), corresponding to the normal upper and lower end of the variation range of pre-dried grass feed dry matter. The tabulated production costs were normalized by dividing them by the average cost of the table (115 €/t-DM) and multiplying the result by 100, giving an average cost the value of 100. The normalization was done to make it easier to see the relative effect of dry matter yield, and to avoid over-generalizing the actual figures given by the calculator in this particular case.

TABLE 8. Standardized production costs (in %) of grass silage feedstock relative to yield and dry matter content. Average value of the table (115 €/t-DM) gets the relative value of 100%.

| | 30% DM | | | 60 % DM | | |
|---|---|---|---|---|---|---|
| Yield | Combi baler | Tube wrapping | Harvester chain | Combi baler | Tube wrapping | Harvester chain |
| kg-DM / ha | | €/t of DM | | | €/t of DM | |
| 2000 | 249 | 231 | 220 | 219 | 208 | 207 |
| 2500 | 218 | 200 | 188 | 188 | 177 | 169 |
| 3000 | 197 | 179 | 166 | 167 | 156 | 146 |
| 3500 | 182 | 165 | 151 | 152 | 141 | 130 |
| 4000 | 171 | 154 | 139 | 141 | 130 | 118 |
| 4500 | 162 | 145 | 131 | 132 | 122 | 109 |
| 5000 | 155 | 138 | 124 | 125 | 115 | 102 |
| 5500 | 149 | 132 | 118 | 119 | 109 | 96 |
| 6000 | 145 | 128 | 113 | 114 | 104 | 91 |
| 6500 | 141 | 124 | 109 | 110 | 100 | 87 |
| 7000 | 137 | 120 | 106 | 107 | 97 | 84 |
| 7500 | 134 | 117 | 103 | 104 | 94 | 80 |

Table 8 shows that the yield has a significant impact on the production cost of grass feedstock. On average, the cost of production can be found to double when the yield level drops from a good yield level (6000 kg DM/ha) for efficiently-managed fertilized grassland to a level such as 2000 kg DM/ha, reflecting unfertilized fallows and buffer zones of the potential yield.

A source of error in this analysis is the fact that fertilization was standardized at all examined yield levels to a same level that would produce good yields, so as a 'per hectare' variable in this analysis, it introduces an error in the case of poor yields, as those yields would not require the same level of fertilization used in the calculation. The cost of annual fertilization at a yield level of 2500 kg DM/ha represents about 25% of the total cost of production; while the effect can be considered significant, it does not exclude the conclusion that the effect of yield level on production costs is very high, and that the production of grass at low yield levels may be unprofitable in relation to the biogas plant's ability to pay for it.

The automatic consideration of fertilization according to the yield level was not included in this calculator due to the need for expertise outside the study scope and the lack of resources. However, it is possible to include it in future versions of the calculator. At this stage, case-by-case considerations will have to be used, where the fertilization level is manually set to match the situation to be addressed. For the sake of interest, the calculator was also used to determine an example value for the corresponding unfertilized production in fallow at a yield level of 2500 kg-DM/ha, 50% dry matter, and 1.5 ha field size, but it is otherwise with the same variables as in the case presented in Table 8. The relative cost of the Combi-baling chain was 167 (1.67 times the average). The relative cost of the harvester chain rose to 370 (3.7 times the average cost), indicating that the chain is totally unsuitable for the conditions of small plot sizes and low yields.

If the same table is scaled up to match the analysis in the original feasibility study, where the production cost is changed to match the cost of potential methane production, the following table is obtained (Table 9). It further confirms the notion that high yields are a prerequisite for profitable herbage production. The same methane yield potential of 330 m3 $CH_4$/t-DM of grass feedstock was used here as earlier.

TABLE 9. Production costs of grass silage feedstock relative to yield and dry matter content. Presented as the cost per potential MWh produced. Potential $CH_4$ yield used in calculation =330 $m^3$/t-DM

| | 30% DM | | | 60 % DM | | |
|---|---|---|---|---|---|---|
| Yield | Combi baler | Tube wrapping | Harvester chain | Combi baler | Tube wrapping | Harvester chain |
| kgDM / ha | €/MWh | | | €/Mwh | | |
| 2000 | 87 | 81 | 77 | 76 | 73 | 72 |
| 2500 | 76 | 70 | 65 | 65 | 62 | 59 |
| 3000 | 69 | 63 | 58 | 58 | 54 | 51 |
| 3500 | 63 | 57 | 53 | 53 | 49 | 45 |
| 4000 | 60 | 54 | 49 | 49 | 45 | 41 |
| 4500 | 56 | 50 | 46 | 46 | 42 | 38 |
| 5000 | 54 | 48 | 43 | 44 | 40 | 36 |
| 5500 | 52 | 46 | 41 | 42 | 38 | 33 |
| 6000 | 50 | 44 | 39 | 40 | 36 | 32 |
| 6500 | 49 | 43 | 38 | 38 | 35 | 30 |
| 7000 | 48 | 42 | 37 | 37 | 34 | 29 |
| 7500 | 47 | 41 | 36 | 36 | 33 | 28 |

The diagram in Figure 12 shows that the production costs relative to the potential energy content approach the earlier defined absolute upper limit of 80 €/MWh when going towards the lower end of the crop yield. The increase in costs is the steepest below the 4000 kg DM/ha yield level, but the curve flattens towards higher yield levels. It is also worth noting the cost difference between harvesting methods (Combi-baler vs Harvester-chain), which appears to be in the order of 10 €/MWh for both the dry matter contents studied. For the sake of clarity, the tube wrapping method has been excluded from the diagram, as its costs fall somewhere between the two chains shown.

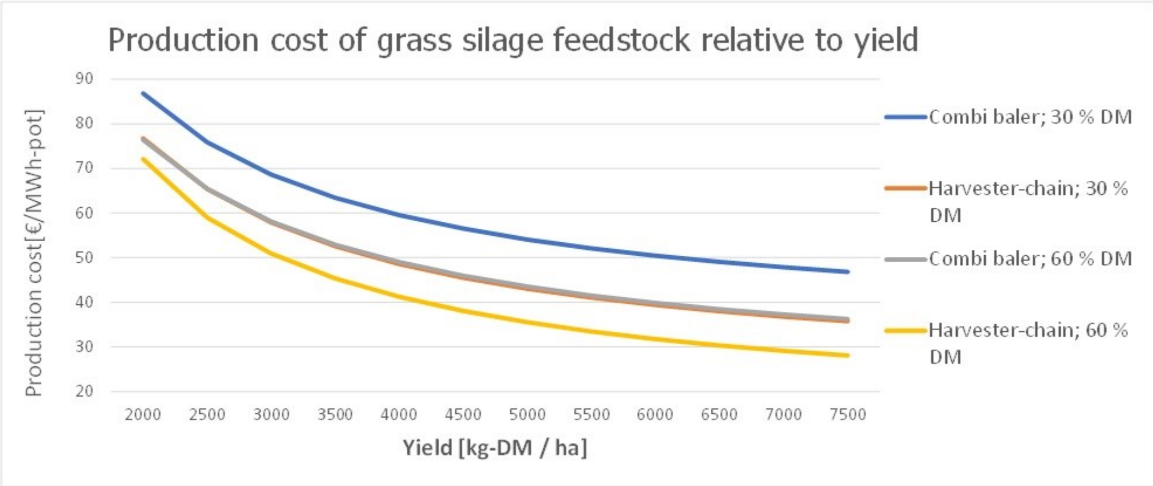


FIGURE 12. Diagram presenting the relation of production cost to the harvest yield.

The graph in Figure 12 shows that the dry matter content of the harvested material has a significant effect on the production cost. The effect of dry matter was further investigated by standardizing the other variables, and using the calculation base to perform a sensitivity analysis on the effect of dry matter content.

The starting setup for the analysis was defined to be the same "Industrial-scale plant" case study, with the same input data as in the previous yield-based analysis. Again, all three harvesting methods were compared. The production costs were calculated for them with the different dry matter contents of the crop at 5 percentage points between 20 and 65% DM. The analysis was carried out at two different yield levels between 3000 and 5000 kg DM/ha. The results were tabulated and calculated to reflect the cost of methane extraction potential at a potential yield of 330 m3 $CH_4$/t-DM. Again, the tube wrapping method was left out from the diagram to make it easier to read.

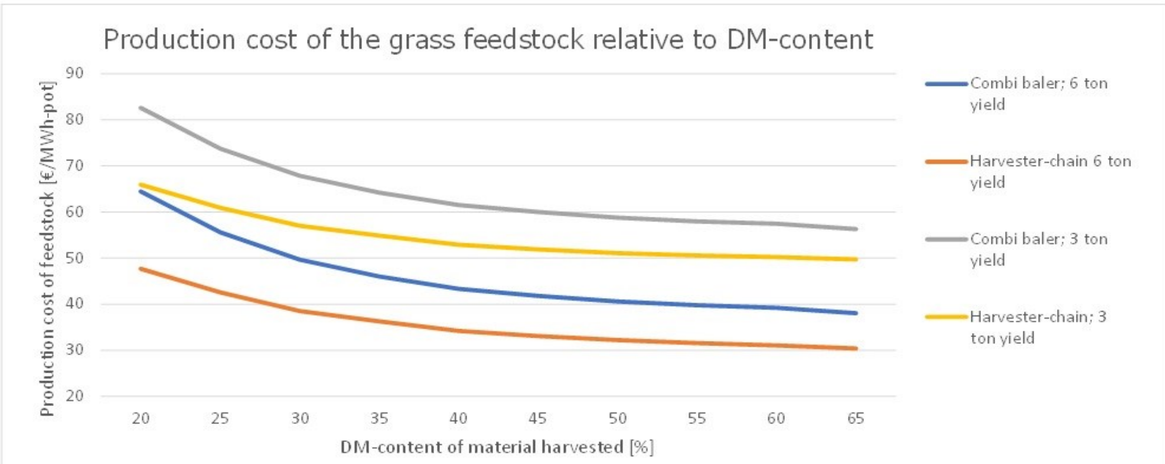


FIGURE 13. Diagram presenting the relation of production costs to the harvest DM content.

The graph in Figure 13 shows that the dry matter content of the crop also has a significant impact on the production cost of the feed. The effect of the reduction in dry matter was greater for the baling chain, as seen by the steeper increase in the graphs of the baling chains with lower dry matter contents. The harvester chain did not show the same sensitivity from the effect of harvest moisture. For the bale chain, this is influenced by the rapidly increasing number of bales, which increases the gain in baling working time by increasing the relative time taken to drop the bales, and by the increase in the cost of plastic. Another factor affecting the bale chain is the cost of long-distance transportation, where the net load capacity of the truck limits the load size at lower DM concentrations. For the harvester chain, the effect is not as big, as the relative work efficiency of the harvester is not as significantly affected by the DM content. On the other hand, a part of the difference may be due to the way the calculator calculates the transport capacity requirement based on the carrying capacity of the transfer wagons, which may lead to unrealistically large load sizes and underestimated transport costs at the highest DM contents. The effect of DM content decreases significantly above 45%.

### 5.1.2 Long-distance transport

The long-distance transportation cost of the silage varies linearly with the transport distance. Figure 14 shows the transportation cost (€/t-DM) for two different dry matter contents of the material to be transported (25%-DM and 45%-DM). The effect of the dry matter content on the transportation cost is significant. This is due to the fact that in the 25%-DM case, the load capacity of the vehicle limits the size of the load, whereas in the 45%-DM case, the volume of the load space becomes the limiting factor. On the other hand, in the case of a higher dry matter content (45%-DM), one load could accommodate 14.02 t of dry matter, whereas in the 25%-DM case, the load was only 9.5 t-DM.

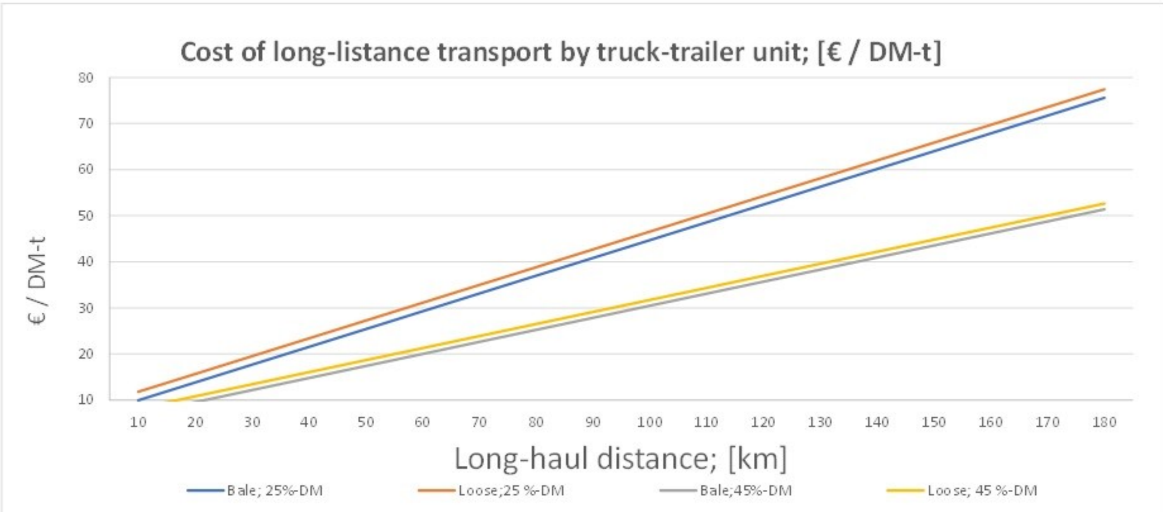


FIGURE 14. Cost of long distance transportation depending on the distance.

The long-haul modelling assumed a net load of 38 tons and a load capacity of 44 bales. The average speed of the truck on the road is 60 km/h and the hourly cost is 110 €/h. The calculator assumes that loading and unloading of loose material is 30% slower than loading and unloading of bales, but the vehicle load space and load capacity can be utilized in both methods at the same rate. Loading is assumed to take 25 sec/bale and unloading 20 sec/bale. Bale size is 130 cm diameter.

In the context of this study, it was not possible to measure the time consumption of loading the loose silage, but the assumptions chosen for the default values of the calculator are based on previous practical experience. The assumption is, based on experience, that the utilization rate of the load compartment's capacity is better when transporting bulk fodder than in the case of bales, which makes it easier to fit a so-called "full net-weight load" into the vehicle when transporting bulk fodder. On the other hand, the time taken to load bulk fodder depends on the type of crane grapple, and the moisture content and chaff length of the silage to be loaded, so the assumption of a 30% increase in the time consumption of loading may cause an error source in the calculation.

TABLE 10. Production costs of DM and potential MWh before long-distance transportation in the analysis. Long-distance transportation costs are added to these figures to get the total cost at the plant. The basis for the calculation is the same "50-km industrial" scenario from earlier.

| | BALE | | LOOSE |
|---|---|---|---|
| | Combi | Tube | Harvester |
| *DM-%* | *€/t-DM* | | |
| *45* | 79 | 65 | 49 |
| *25* | 120 | 97 | 75 |
| | *€/ MWh-pot* | | |
| *45* | 24 | 20 | 15 |
| *25* | 36 | 29 | 23 |

Table 10 shows the production costs of the feed before long-distance transport. By adding the cost of long-distance transport from the graph in Figure 14 to the production cost prior to the long-distance transport costs, the total cost and the economically longest possible long-distance transport distance can be estimated. If the limit of the total viable cost is set at 60 €/MWh-pot, which corresponds to a bulk price of about 200 €/DM-t, then for a 25% dry matter combi-bale chain, the limit of viability is about 55 km; for a tube-bale chain, about 110 km;and for a harvester chain, 160 km. For 45% dry matter, the distances rise to about 250 km for bale chains and 350 km for bulk feed.

These transport distances are significantly higher than, for example, the estimate presented by Räisänen et al. (2014, 3), according to which "silage harvesting is profitable at a distance of 25-50 km from the farm centre. Several factors influence the costs on a case-by-case basis." The loading and driving speeds assumed by the calculator are the values of the so-called ideal situation, where transportation is as efficient as possible, and the transport equipment is optimally dimensioned for the transporting of feed bales.  Thus, the distances presented here should be considered as the maximum economically feasible, and may  be considerably lower in reality depending on the conditions and the equipment. However, as a general observation, the transportation distance is not such a significant cost factor compared to the variables presented earlier (yield level, harvest moisture).

## 5.2 Case study in two different scenarios

The case study looked at two different types of cases, one of which was a generalization of a farm-scale plant using grass silage from the vicinity of the plant as a supplementary feed to the reactor. In this case, the grass was assumed to come from smaller fields (2 ha) than in the 50 km case (3.5 ha). The distance between fields was kept constant in both cases (1 km). The definition of field size is based on the idea that in a farm-scale facility, grass was assumed to be produced on fields less favorable to other production, whereas in an industrial facility, grass production is based more on contract farming on a larger scale.

The second case examined a fictional industrial-scale plant with a larger procurement area of about 50 km, for which the aim was to seek the maximum profitability of the procurement radius.

The hourly costs and capacities of the machine chains used for the calculation were kept the same in both cases. Similarly, the cultivation costs and ensiling variables were kept constant. The dry matter was the same in both cases (40% DM), but results were calculated for two different yields in both cases, (3000 kg DM/ha and 5500 kg DM/ha). The variables used in the case study are detailed in Appendix 2.

The differences between the cases consisted of transportation distances and field variables, and their impact on the mutual cost between harvesting chains.

Case 1: Small (farm) scale wet fermentation plant where silage is used as an additional feedstock for the mainly manure and slurry-based substrate. Grass silage is harvested from a maximum of 15 km radius from the plant, and a long-term storage of the feedstock material takes place at the immediate vicinity of the facility.

Case 2: Big (industrial) scale dry fermentation plant where grass silage is the main feedstock of the biogas plant. Silage procurement radius was assumed to be approximately a 50 km radius from the plant due to the estimated need for the industrial scale plant´s procurement area. Feedstock is transported to the plant at the pace of its consumption and only a small buffer stock can be stored on site. During the year, the feedstock material is temporarily stored near the fields where it was produced.

For the calculation of the production cost in both cases, the input data were chosen to reflect as closely as possible the situation described in the assignment. In the Harvester method, transportation was assumed to take place directly to a storage facility at the biogas plant, with an average transporting distance of 7 km in the first case, and 3 km to the intermediate storage area in the second case.  The long-distance transportation of the bale chains was done by a truck for an average distance of 7 km in the first case and 25 km in the second case. The distance of the field transportation was 1 km for the Combi method, and 2 km for the Tube method in both cases. The calculation did not examine in detail whether the long-distance transportation of bales by a tractor or lorry was more profitable.

TABLE 7. Production cost for grass silage feedstock in two case-scenarios calculated with two yields for three different supply chains.

| | *Case-small scale 15 km* | | | *Case- industrial scale 50 km* | | |
|---|---|---|---|---|---|---|
| Yield | **Combi baler** | **Tube wrapping** | **Harvester chain** | **Combi baler** | **Tube wrapping** | **Harvester chain** |
| *kgDM / ha* | | *€/t of DM* | | | *€/t of DM* | |
| 5500 | 149 | 137 | 116 | 149 | 138 | 119 |
| 3000 | 206 | 194 | 178 | 202 | 191 | 174 |
| | | *€/ m3 CH4 potential* | | | *€/ m3 CH4 potential* | |
| 5500 | 0,45 | 0,41 | 0,35 | 0,45 | 0,42 | 0,36 |
| 3000 | 0,62 | 0,59 | 0,54 | 0,61 | 0,58 | 0,53 |

The results for both cases are summarized in Table 7. The table shows that the harvesting cost of the “Harvester chain” is by far the cheapest in both cases. The cost of dry matter production is between 116 and 119 €/T-DM for a yield of 5500 kg DM/ha. This corresponds to a cost of about 35 cents per the potential $m^3$ of methane produced. It is noteworthy in the results that the harvesting cost does not increase much between cases, even though the average transport distance increases from 7 to 25 kilometers, and, for example, a long-distance transporting step is added to the "harvester chain." The phenomenon is explained by the effect of the size of the field, which was 2 ha in the former case and 3.5 ha in the latter. If the size of the field is held constant, the difference between the cases is, e.g., in the case of the "harvester chain," about 9 €/t of DM.

The importance of DM yield for production costs cannot be ignored here either. The increase in the total cost is in the range of 60-70% for all chains, and in both cases when the DM yield falls from a good level (5500 kg DM/ha) to a mediocre level (3000 kg DM/ha). Of course, in this study, the cost of cultivation and the fertilization cost was standardized at a level that allows for higher yields, but the result still shows that the best possible yield is a very important factor in determining the cost of production, and thus desirable in order to achieve profitability in production.

The production cost of feedstock relative to the potential methane yield is an interesting result. In both cases considered, the cost was in the range of 0.35 € / $m^3$-$CH_4$-pot at the lowest end.

If the feedstock production cost (35-60 €/MWh) is compared to price of woodchips (~30 €/MWh) or pellets (~60 €/MWh) for instance, it is found to be at the same level (Ruutana Heating Oy 2022). So, as a feedstock for biogas production for heat generation, grass silage can be unprofitable compared to alternatives.

It can be seen that the cost of producing the feedstock is, even in the cheapest case, around 25% (0,5 €/ kg-CH4) of the VAT-included sales price of the CBG fuel at the filling station.

# 6 FINDINGS AND CONCLUSIONS

Initially, it was assumed that the biogas plant does not own the fields and is not responsible for farming operations. Therefore, the unsubsidized production cost of feedstock used in this analysis was an appropriate measure to reflect the real situation of the biogas plant's feedstock supply chain, although it did not consider the investment cost of the field and ignored the effect of the agricultural subsidies. The study was not so much concerned with the plant's ability to pay for feedstock, but with the plant price at which the feedstock would be available for the biogas plant

The results showed that the dry matter production cost of grass feed is an important target for optimization, because if it is not successful, grass is not necessarily a profitable feed. It is also clear from the sensitivity analyses that the cost structure cannot withstand inefficiency, and production must be based on high yields per hectare and efficient harvesting methods. In addition to the calculator analysis, it is also known from the literature that there is potential for reducing production costs in grassland farming through efficiency improvements. In particular, the utilization rate of harvesting equipment has a significant impact on their hourly costs. This view is supported by the observation by Seppälä et al. (2014, 15) that if a harvesting chain suitably dimensioned for the harvesting volume is used exclusively for the biogas plant feed, harvesting could be scheduled to cover almost all days of the summer with good weather conditions, thus maximizing the equipment utilization. In an optimal situation, an efficient forage harvester chain could be used at its maximum capacity of utilization.

The biogas feedstock is unlikely to be profitably grown on small fields or ones with a low yield potential, so it is unlikely to offer a solution for profitable cultivation of those fields. Biogas plants should not base their feedstock supply on them. However, it can provide a cost-effective way to process crops from these areas in the following example: if subsidy policies require harvesting, or if there is a desire to keep the areas open for landscape management.

In contrast, the transportation distance is not a very critical factor for reasonable distances. Long-distance transportation by suitable trucks is relatively cheap and cost-efficient. However, it should be noted that the cheapest feed can be obtained if the feed is harvested within the vicinity of the plant (less than 5 km) by a forage chopper-chain and stored directly in the vicinity of the plant at a cost of about 100 €/t-DM, which is equivalent to about 30 €/MWh or 30 cents/Nm3-$CH_4$.

The effect of crop yield and field size is more significant. The harvesting efficiency is significantly reduced when the field size falls below 2-3 hectares. The economics of harvesting silage suffer most from small field sizes, and they are not at all suitable for fields that are scattered and far from the storage site.

The findings support the conclusions Mäenpää (2010, 48) made in his final thesis on the procurement of grass feed for a biogas plant, according to which "it may be difficult to communicate to farmers clearly enough how important the yield and quality of the grass feed produced is for the profitability of cultivation," and "for silage harvesting chains and contractors, the most challenging factor is the small size of the fields and the fact that they are spread over a large area. The condition and shape of the fields in the procurement area and the existing road network also affect the efficiency of the harvesting operation." Exactly the same conclusions can be drawn from this study.

The cost of plastic film is significant in the Combi-baling chain, where bales are wrapped individually. The cost of plastic for 4 layers of wrapping is equivalent to the cost of a long-distance transportation of about 10 km at the current price of plastic film. As a generalization, the Combi-chain is therefore a viable option for smaller and distant fields where the logistics of other chains are not well suited. Further away from the biogas plant, the tube-rolling method is the most suitable if there are no readily-made intermediate storage sites available for the harvester chain. The long-haul transport cost of bulk silage requires further investigation to determine the cost difference between the harvester chain and the tube-baler chain in a situation where intermediate storage is necessary.

It appears that the price of the product from the biogas plant alone would not make the production of grass silage economically very attractive to the farmer, assuming that the biogas plant's ability to pay for the feedstock does not improve from the level used in the calculations of this work. This leads to the dilemma of finding enough incentive for farmers to supply feedstock for the BG plant if the business is not actually able to provide sufficient economic profit for them. BG plant management must make such a strategic and operational decision that the feedstock source is secured and sound, as the biogas process can’t stand big variations in the infeed without being disturbed. There is also the potential for value-addition, e.g., through nutrient cycling and manure logistics, as well as through the so-called "distribution obligation" tag trade. However, this is inevitably not a sufficient incentive for the production of silage if the factory price, which is made up of the production costs of the feed, is already close to the upper limit of their ability to pay, which is determined by the price of the final product; the biogas plant cannot pay sufficient compensation for the silage produced, as it may often be the case on the basis of the calculations in this study. However, in some cases, e.g., for a part-time farmer, even a small amount of compensation may be a sufficient incentive to produce grass if it does not require investment and high labor input, and if the profitability or demand for alternative products is low. In this case, the functioning of the supply chain, the quality of the operation, and good communication between all the actors in the chain are crucial. Communicating and proving this value addition for suppliers is somewhat essential, but this value addition has to be recognized, measured and validated beforehand.

There are sometimes batches of grass fodder (usually round baled) on the market, whose sales price per bale is lower than the baling harvesting costs calculated in this study. Such batches are often small in quantity and of uncertain quality, or even spoiled. The biogas plant cannot base its feedstock supply on these batches, as those can be considered only as an additional source of feedstock material. Of course, a biogas plant can provide a good way of dealing with batches of feed that are partially spoiled or at risk of spoilage, e.g., due to breakage in the wrapping.

Tighter sustainability criteria must also be taken into account when designing the feedstock for a biogas plant. A broadly grass-based feedstock is problematic if it excludes the incentives offered by environmental policy.

In the initial thesis topic plan, the original target was set to be that: "…the thesis should willingly include a feasibility analysis of a real-life scenarios and a development of a calculation tools for future consulting work..." and "…results of the thesis should be practical and beneficial in a real life business environment." Those same goals were also acknowledged by the client at the beginning of the thesis work. In this respect, this work fully met the objectives that were initially set.

The calculator was used to examine the cost of grass production and the factors affecting it at the biogas plant level, and when planning harvest logistics guidelines. For example, the calculator makes it possible to exclude or include sourcing areas or supply chains when exploring the feedstock for a biogas plant in the pre-feasibility phase. For a more detailed calculation of production costs per farm, ready-made calculators are available that take a better account of farm-specific parameters and costs. These calculators should be used instead of the calculator produced in this study when considering the profitability of biogas feedstock production on a farm level. Good farm-specific calculators for grassland logistics and production costs have been published by LUKE and Atria, among others (Atria Oyj 2022).

## 6.1 Error sources

The output production cost data produced by the calculation sheet should be treated with caution. The calculator will not automatically produce correct results simply by entering calculation parameters in the appropriate places, but the use of the spreadsheet requires background information and critical analysis of the results obtained. Although the aim in making the calculator was to create a calculator that could be used even by a user without in-depth knowledge of its operation, at this stage of its development, it may not yet be so.

A rapidly changing environment, such as rising costs and policy decisions, may affect the cost of harvesting more quickly than the selling price of the biogas plant's end product, and thus the ability to pay for the feedstock. This was clearly evident during the writing of this work, during which the unit cost of contracting and feedstock costs increased markedly, driven by rising fuel prices and general inflation. It was necessary to make significant upward corrections to the assumptions in the initial calculator to reflect the existing costs at the completion of this work. When using the calculator, care must be taken to ensure that the calculation assumptions are up to date.

The models and assumptions used in the calculation tool are derived from practical observations and studies on the production costs of grass forage for *animal feed*. However, it is expected that as the grass harvested for biogas feed allows more flexibility, e.g. in terms of harvesting time, it will be possible to better adapt the utilization and/or sizing of the harvesting equipment and thus achieve significant cost savings. If the logistics chain for the biogas feedstock can fully exploit these possibilities, and the supply chain can be made to work efficiently, production is likely to be more cost-effective than the level suggested by the calculation tool and current research. Put simply, the results given by the calculator may be too pessimistic compared to reality.

Some of the source data used as a baseline for the calculation is not as accurate as it should be. For example, the bale density table is derived from the data that is not adequate and has to be studied more.

## 6.2 Further steps:

The usability of the calculator should be improved. The layout and clarity of the interface could be further improved, e.g., by adding explanatory comments and background information and by using the form features provided by Excel. There is existing research data available as a basis for calculating the costs of the harvest chains in the calculator, which could be used to further refine the spreadsheet.

While the calculator is currently mainly suitable for strategic planning and preliminary studies of plants, it could be further developed to be useful at a tactical or even operational level, e.g., as a tool for the person responsible for the supply of feedstock to a biogas plant to plan and manage the supply chain.

It would be possible to further improve the calculation of the efficiency of baling and shredding, which would allow for an even more accurate calculation of the supply chain costs. For example, the results of the "Predicting Field Efficiency of Round-Baling Operations in High-Yielding Biomass Crops" concept paper by Grisso, Cundi, and Webb (2020) could be directly applied to further develop this work. The calculator could also be developed in such a way that it can be used to calculate the contract price for a contractor who is responsible for harvesting the grass feedstock of a biogas plant.

The calculator is also suitable at least partly and with certain reservations, for determining the costs of harvesting straw or maize silage, but in this case, more research is needed, e.g., on the productivity of harvesting straw.

In the future, the calculator could be developed to calculate emissions and energy consumption in the supply chain according to the RED II specifications, thus serving as a tool when a biogas plant needs to present calculations for sustainability verification.

# REFERENCES


Al Seadi Teodorita, Rutz Dominik, Prassl Heinz, Köttner Michael, Finsterwalder Tobias, Volk Silke and Janssen Rainer. 2008. Biogas handbook. University of Southern Denmark Esbjerg https://energypedia.info/wiki/File:Biogas_Handbook.pdf. Cited 11.7.2020.

Arffman, Mika ja Taavitsainen, Toni. 2019. Maatilamittakaavan biokaasun tuotanto. Biokaasu 1/2019 [digilehti]. Saatavissa: https://biokierto.fi/wp-content/uploads/2019/11/Biokaasulehti-2019_light.pdf. Cited 28.7.2022.

Atria Oyj.2022. Nurmen tuotantokustannuslaskuri. www page. https://www.atriatuottajat.fi/tuotannonkehitys/nautasuomi/palvelut/sailorehulaskuri/. Cited 11.11.2022.

Busato Patrizia, Sopegno Alessandro, Pampuro Niccolò, Sartori Luigi, Berruto Remigio. 2019. Optimisation tool for logistics operations in silage production, Biosystems Engineering, Volume 180, Pages 146-160.

Christensen Morten L., Christensen Knud V., Sommer Sven G. 2013. Solid–Liquid Separation of Animal Slurry. *In publication: Animal Manure Recycling: Treatment and Management edited by Sven Gjedde Sommer, Morten L. Christensen, Thomas Schmidt, Lars Stoumann Jensen.*

Demeca Oy. 2022. www-page. https://demeca.fi/en/biogas/. Cited 15.11.2022.

Doranova Oy. 2022. www-page. https://www.doranova.fi/en/biogas-plants/. Cited 15.11.2022.

El Bassam, N. 2010. Handbook of bioenergy crops: A complete reference to species, development and applications. Earthscan. ISBN: 978-1-84407-854-7

Envitecpolis Oy. 2022. Web page. https://www.envitecpolis.fi/envitecpolis-in-english. Cited 3.11.2022.

European Commission 2019. Communication from the commission; The European Green Deal. Brussels, 11.12.2019 https://eur-lex.europa.eu/legal-content/EN-FI/TXT/?uri=CELEX:52019DC0640. Cited 28.7.2021.

European Commission 2021. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions; Press release. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541. Cited 28.7.2021.

Gaia Consulting Oy (2021) Lummaa Mirka, Simanainen Miikka, Vanhanen Juha, Ylimäki Laura, Saario Mari. Selvitys biokaasuhankkeiden rahoitusmahdollisuuksien parantamiseksi. Gaia consulting Oy. tem.fi/documents/1410877/2132212/Biokaasuhankkeiden+rahoitusmahdollisuudet+Loppuraportti+2021.06.14.pdf/d5298995-6fe5-36e2-c0a0-5a0ac69eafe2/Biokaasuhankkeiden+rahoitusmahdollisuudet+Loppuraportti+2021.06.14.pdf?t=1625137640755 *5a0ac69eafe2%2FBiokaasuhankkeiden%2Brahoitusmahdollisuudet%2BLoppuraportti%2B2021.06.14.pdf%3Ft%3D1625137640755&usg=AOvVaw2jRboRpd1-vJkXZ1MGGf6U.* Cited 28.10.2022.

Gasgrid 2022. www-page. https://gasgrid.fi/en/gas-network/gas-transmission-network/. Cited 15.11.2022.

Grisso, Robert "Bobby", Cundi, John S., Webb, Erin G. 2020. Predicting Field Effciency of Round-Baling Operations in High-Yielding Biomass Crops. Concept Paper 1. Biological Systems Engineering, Virginia Tech. https://www.mdpi.com/2624-7402/2/3/30?type=check_update&version=1. Cited 17.11.2022.

HE 48/2021. (2021) Hallituksen esitys eduskunnalle laiksi biopolttoaineiden käytön edistämisestä liikenteessä annetun lain muuttamisesta ja eräiksi muiksi laeiksi. https://valtioneuvosto.fi/paatokset/paatos?decisionId=0900908f8071a324. Cited 20.10.2022.

HE 70/2021 Hallituksen esitys eduskunnalle laiksi biopolttoaineista ja bionesteistä annetun lain muuttamisesta. https://finlex.fi/fi/esitykset/he/2020/20200070#idm45949344527120. Cited 20.10.2022.

Helenius Juha, Koppelmäki Kari and Virkkunen Elina (toim.) 2017. Agroekologinen symbioosi ravinne- ja energiaomavaraisessa ruoantuotannossa. Ympäristöministeriön raportteja 18/2017. http://urn.fi/URN:ISBN:978-952-11-4716-6. Cited 6.12.2022.

Hopkins, Alan 2000. Grass: its production and utilization. Blackwell Science. 3rd ed.

Huttunen, Suvi 2013. Sustainability and Meanings of Farm-Based Bioenergy Production in Rural Finland. Doctoral thesis. University of Jyväskylä. https://jyx.jyu.fi/handle/123456789/40848. Cited 5.11.2022.

Kajan, Tuomas and Pasanen, Mirva 2009, Säilörehun korjuustrategia, Opinnäytetyö; Savonia ammattikorkeakoulu. Luonnonvara-ala. https://urn.fi/URN:NBN:fi:amk-201001191375. Cited 6.12.2022.

Klemola, E., Karttunen, J., Kaila, E., Laaksonen, K., & Kirkkari, A-M. 2002. Lohkon koon ja muodon taloudelliset vaikutukset. Työtehoseuran julkaisuja 386. Cited 10.11.2022.

Korres, Nicholas E and Nizami Abdul Satar. 2013. Variation in anaerobic digestion. Chapter 12, 194-219. in publication*: Korres N., O´Kiely P., Benzie J., West J.: Bioenergy Production by Anaerobic Digestion Using agricultural biomass and organic wastes.*

Kymäläinen, Maritta; Pakarinen, Outi (2015). Biokaasuteknologia: Raaka-aineet, prosessointi ja lopputuotteiden hyödyntäminen. HAMKin e-julkaisuja 36/2015. https://www.theseus.fi/handle/10024/104180. Cited 15.11.2022.

Lehtomäki, Annimari 2006. Biogas production from energy crops and crop residues. Doctoral thesis. University of Jyväskylä. https://jyx.jyu.fi/handle/123456789/13152. Cited 1.11.2022.

Lehtomäki, Annimari, Paavola, Teija, Luostarinen Sari. & Rintala, Jukka. 2007. Biokaasusta energiaa maatalouteen, raaka-aineet, teknologiat ja lopputuotteet. Jyväskylän yliopiston bio- ja ympäristötieteiden laitoksen tiedonantoja 85.

Lianhua L., Changda C., and Yongming S. Anaerobic processes and biogas technology. *2017.* In publication: *Bioenergy. Volume 1: Principles and Technologies, edited by Zhenhong Yuan, and Longlong Ma, Walter de Gruyter GmbH, 2017.* https://ebookcentral-proquest-com.ezproxy.savonia.fi/lib/savoniafi/reader.action?docID=4911700&ppg=159. Cited 31.10.2022.

Luostarinen, S. Biokaasutuotannon raaka-aineet. 2015. In publication: *BIOKAASUTEKNOLOGIA. Raaka-aineet, prosessointi ja lopputuotteiden hyödyntäminen. 2015, 32-39. edited by: Kymäläinen, M. ja Pakarinen, O. Suomen Biokaasuyhdistys ry. Hämeenlinna:* Hämeen ammattikorkeakoulu. http://urn.fi/URN:ISBN:978-951-784-771-1, Cited 21.7.2020.

Lätti, Markku, Tuure, Veli-Matti, Eskelinen, Pasi, Räisänen, Janne. 2014. Säilörehunkorjuu laajentuvalla karjatilalla TTS:n tiedote, Maataloustyö ja tuottavuus; 4/2014. ISSN 1799-5485. https://www.tts.fi/uutishuone/tts_n_tutkimusjulkaisut/maatalouden_julkaisut/sa_ilo_rehunkorjuu_laajentuvalla_karjatilalla.2865.news. Cited 6.11.2022.

Marttinen, S., Luostarinen, S., Winquist, E., Timonen, K. 2015. Rural biogas: feasibility and role in Finnish energy system. BEST suitable Bioenergy Solutions for Tomorrow. Research Report no 1. http://bestfinalreport.fi/files/Rural%20biogas%20-

%20feasibility%20and%20role%20in%20the%20Finnish%20energy%20system.pdf. Cited 7.11.2022.

Mattila Tuomas J., Hagelberg Eija, Söderlund Sanna, Joona Juuso. 2022. How farmers approach soil carbon sequestration? Lessons learned from 105 carbon-farming plans. Soil and Tillage Research 215 105204, ISSN 0167-1987. https://doi.org/10.1016/j.still.2021.105204. Cited 15.11.2022

McEniry, Joseph, Korres, Nicholas E. and O´Kiely Padraig. Grass and grass silage. Agronomical characteristics and biogas production. Chapter 4, 49-56 in publication*: Korres N., O´Kiely P., Benzie J., West J.: Bioenergy Production by Anaerobic Digestion Using agricultural biomass and organic wastes.*

Melville Lynsey, Weger Andreas, Wiesgickl Sonja and Franke Matthias 2014. Anaerobic digestion. Pages 31-59 at the publication edited by: *Hornung, Andreas. Transformation of Biomass: Theory to Practice, John Wiley & Sons, Incorporated, 2014*.

Metener Oy 2022. Homepage, References. https://www.metener.fi/en/references/. Cited 31.10.2022.

MMM 2022. Biomassan kestävyyskriteerit. Maa- ja metsätalousministeriö. Internet- sivu. https://mmm.fi/metsat/puun-kaytto/biomassojen-kestavyys. Cited 15.11.2022.

Murto, Kalle. 2020. Pyöröpaalaimen kammiotyypin vaikutukset paalin tiheyteen ja polttoaineenkulutukseen esikuivatulla säilörehulla. Maisterintutkielma. Helsingin yliopisto. Maataloustieteiden laitos Agroteknologia 12.5.2020. http://urn.fi/URN:NBN:fi:hulib-202006052582. Cited 5.7.2022.

Mykkänen, Eeli. 2008. Biokaasun tuottaminen säilörehusta lehmänlantaa käsittelevällä biokaasulaitoksella. Jyväskylän yliopisto. Bio- ja ympäristötieteiden laitos. Ympäristötiede. Pro gradu -tutkielma. http://urn.fi/URN:NBN:fi:jyu-200806265558. Cited 1.11.2022.

Mäenpää, Mika 2010. Kasvimassojen tuottaminen biokaasulaitokselle. Opinnäytetyö, YAMK-tutkinto. Seinäjoen ammattikorkeakoulu. Maaseudun kehittämisen koulutusohjelma. https://urn.fi/URN:NBN:fi:amk-201005047678. Cited 1.11.2022.

NurmiArtturi-hanke 2014. ProAgria Etelä-Pohjanmaa ry ja Työtehoseura ry. https://www.proagria.fi/sites/default/files/attachment/nurmiartturi-lehti_pienempi_resoluutio_2.pdf Cited 10.11.2020.

Paavola, Teija. Kapuinen Petri 2015. Mädätysjäännöksen käsittely ja hyödyntäminen. Chapter 6. In publication: *Kymäläinen, Maritta; Pakarinen, Outi (2015). Biokaasuteknologia: Raaka-aineet, prosessointi ja lopputuotteiden hyödyntäminen. HAMKin e-julkaisuja 36/2015 https://www.theseus.fi/handle/10024/104180 Cited: 10.10.2022.*

Palva, Reetta 2017. Powerpoint esitys: Tiivistymisen onnistuminen NurmiArtturi tiloilla. Säilöntälaadun varmistaminen – korjuutekniikka ja säilöntä seminaarissa 27.1.2017 Seinäjoki Areena, Sarkamessut.

Programme of Prime Minister Sanna Marin’s Government 2019. Inclusive and competent Finland - a socially, economically and ecologically sustainable society. http://urn.fi/URN:ISBN:978-952-287-811-3. Cited 15.6.2021.

Pyykkönen, V., Seppänen, A.-M., Markkanen, J., Rasi, S., Luostarinen, S., Virkkunen, E. & Järvinen, M. 2021. Pohjois-Savon maakunnalliset erityispiirteet biokaasun tuotannossa ja ravinteiden kierrätyksessä: FarmGas-PS 1 -hankkeen loppuraportti. Luonnonvara- ja biotalouden tutkimus 45/2021. Luonnonvarakeskus. Helsinki. http://urn.fi/URN:ISBN:978-952-380-233-9

Rasi, Saija; Timonen, Karetta; Joensuu, Katri; Regina, Kristiina; Virkajärvi, Perttu; Pulkkinen, Hannele; Tampio, Elina; Pyykkönen, Ville; Luostarinen, Sari (2019). Nurmi biokaasun raaka-aineena: RED

II direktiivin mukainen kasvihuonekaasupäästöjen laskenta. Luonnonvara- ja biotalouden tutkimus 46/2019. Luonnonvarakeskus. Helsinki. 29 s. https://jukuri.luke.fi/handle/10024/544351. Cited 5.11.2022.

Riiko oy. 2022. www.page. https://konekorjaamoriikonen.fi/paallirakenteet/ Cited 16.11.2022.

Ruutana Heating Oy. 2022. Oral communication. Mikko Jauhiainen, wholesale price North Savo November 2022. Cited 15.11.2022.

Räisänen, Janne; Eskelinen Pasi; Mönkkönen Seppo; Partanen, Jarkko; Viitala, Hannu; Lätti, Markku; Tuure, Veli-Matti 2014. Rehulogistiikan kehittäminen karjatiloilla. REKKA – Rehulogistiikan kehittäminen karjatiloille hankeen loppuraportti. Savonia-ammattikorkeakoulun julkaisusarja E2/4/2014. https://urn.fi/URN:ISBN:978-952-203-190-7. Cited 3.11.2022.

Saarinen Elina. 2018. BioGTS:n jäljiltä jäi miljoonien eurojen korjaukset. Kiertotalouden erikoislehti Uusiouutiset.fi. https://www.uusiouutiset.fi/biogtsn-jaljilta-jai-miljoonien-eurojen-korjaukset/ cited 14.11.2022.

Sairanen, Auvo. 2018. Säilörehun tuotantokustannus kuriin. Artikkeli. Käytännön Maamies 5/2018. s. 12-16 EuroMaito-hankkeen julkaisu. https://euromaito.savonia.fi/julkaisut Cited 17.11.2022.

Scarlat, Nicolae; Dallemand Jean-Francois & Fahl Fernando 2018. Biogas: Developments and perspectives in Europe. *Renewable energy, 129*, 457-472. https://doi.org/10.1016/j.renene.2018.03.006. Cited 5.7.2022.

Seppälä, A., Kässi, P., Ervasti, S., Kuoppala, K. Sormunen-Cristian, R., Särkijärvi, S., Heikkilä, T., Luostarinen, S. and Rinne, M. 2013: Biochemical methane potential of timothy, tall fescue and red clover silages harvested at different stages of maturity. In: Helgadóttir, Á. and Hopkins, A. (Eds.) The Role of Grasslands in a Green Future, Threats and Perspective in Less Favoured Areas. Proceedings of the 17th Symposium of the European Grassland Federation, Akureyri, Iceland 23–26 June 2013. pp. 525–527

Seppälä, Arja; Kässi, Pellervo; Lehtonen, Heikki; Aro-Heinilä, Esa; Niemeläinen, Oiva; Lehtonen, Eeva; Höhn, Jukka; Salo, Tapio; Keskitalo, Marjo; Nysand, Matts; Winquist, Erika; Luostarinen, Sari; Paavola, Teija 2014. Nurmesta biokaasua liikennepolttoaineeksi. Bionurmi-hankkeen loppuraportti. MTT. http://www.mtt.fi/mttraportti/pdf/mttraportti151.pdf. Cited 1.11.2022

Smyth, B., Energy and agricultural policy in relation to biomethane, with particular reference to the transport sector. In publication*: Korres N., O´Kiely P., Benzie J., West J.: Bioenergy Production by Anaerobic Digestion Using agricultural biomass and organic wastes, 9-29.*

Suomen biokierto ja biokaasu Ry 2022 (a). Tiedote: Suomeen tarvitaan yli 100 uutta biokaasulaitostahttps://www.epressi.com/tiedotteet/ymparisto-ja-luonto/tiedote-suomeen-tarvitaan-yli-100-uutta-biokaasulaitosta.html. Cited 3.11.2022.

Suomen biokierto ja biokaasu Ry 2022 (b). Tiedote: Biometaanin ja biokaasun tuotanto kovassa kasvussa. https://biokierto.fi/tiedote-biometaanin-ja-biokaasun-tuotanto-kovassa-kasvussa/. Cited 1.11.2022.

Suomen Lantakaasu Oy. 2022. Biokaasulaitoksen ympäristövaikutusten arviointi. YVA-ohjelma. https://www.ymparisto.fi/download/Suomen_lantakaasu_Oy_YVA_ohjelmapdf/%7BC979DF0C-AA4E-4609-AB4B-0C6B813A9CB7%7D/177354. Cited 13.11.2022.

Taavitsainen, Toni 2020. Lopputyön aloitusalaverin muistio 8.10.2020.

Taavitsainen Toni. 2021. Toteutettavuusselvitykset, Kaasua liikkeelle hankeen loppuraportti; Kehitysyhtiö Savogrow Oy ja Envitecpolis Oy. https://savogrow.fi/wp-content/uploads/2021/09/2021-04-27-Loppuraportti-Toteutettavuusselvitykset-1.pdf. Cited 14.11.2022.

Tiainen, J., Hyvönen, T., Hagner, M., Huusela-Veistola, E., Louhi, P., Miettinen, A., Nieminen, T., Palojärvi, A., Seimola, T., Taimisto, P., & Virkajärvi, P. (2020). Biodiversity in intensive and extensive grasslands in Finland: the impacts of spatial and temporal changes of agricultural land use. Agricultural and Food Science, 29(2), 68–97. https://doi.org/10.23986/afsci.86811

Työ- ja elinkeinoministeriö 2020. Biokaasuohjelmaa valmistelevan työryhmän loppuraportti. Työ- ja elinkeinoministeriön julkaisuja 2020:3. http://urn.fi/URN:ISBN:978-952-327-482-2. Cited 6.11.2022

Työtehoseura 2022. TTS-kone konekustannuslaskuri ja urakoinnin hintatilasto. https://www.tts.fi/tutkimus_ja_kehitys/tutkimushankkeet/maatalous/tts-kone. Cited 10.11.2022.

Työtehoseura 2021. Konetyön kustannukset ja tilastolliset urakointihinnat. Toimittanut Reetta Palva. TTS:n julkaisuja 457. https://www.tts.fi/tutkimus_ja_kehitys/tutkimushankkeet/maatalous/koneurakointi/urakointihintakysely. Cited 6.11.2022.

Valtioneuvosto 2021. Fossiilittoman liikenteen tiekartta- Valtioneuvoston periaatepäätös kotimaan liikenteen kasvihuonekaasupäästöjen vähentämisestä. Liikenne- ja viestintäministeriö. https://valtioneuvosto.fi/hanke?tunnus=LVM050:00/2019 Cited 15.11.2022.

Valtioneuvoston asetus eräiden maa- ja puutarhataloudesta peräisin olevien päästöjen rajoittamisesta. 18.12.2014/1250. https://www.finlex.fi/fi/laki/ajantasa/2014/20141250 Cited 11.1.2022.

Vanhanen, Lasse 2009. Säilörehun korjuuajan ja lannoituksen vaikutus sadon laatuun ja määrään. Opinnäytetyö. Savonia-ammattikorkeakoulu. Luonnonvara-ala. https://urn.fi/URN:NBN:fi:amk-200905062472. Cited 6.11.2022.

Virolainen-Hynnä, Anna. 2020. Biokaasun tuotanto ja käyttö Suomessa 2030, Suomen biokaasu ja biokierto Ry:n julkaisuja (verkkojulkaisu). Suomen Biokierto ja Biokaasu ry. Helsinki. 2020. www.biokierto.fi. Cited 10.11.2022.

Williams L., Gallagher J., Bryant D., Rao S. 2017. Anaerobic Digestion and the Use of Pre-treatments on Lignocellulosic Feedstocks to Improve Biogas Production and Process Economics. 121-141. *In publication: Editors Singh l. and Chaudhary G. Advances in Biofeedstocks and Biofuels, Biofeedstocks and Their Processing : Biofeedstocks and Their Processing*

Ympäristökorvauksen sitoumusehdot 2022. Ruokavirasto. https://www.ruokavirasto.fi/viljelijat/oppaat/sitoumus-ja-sopimusehdot/ymparistokorvauksen-sitoumusehdot/ymparistokorvauksen-sitoumusehdot-2022/ Cited 11.11.2022.

604/2021. (2021) Laki biopolttoaineista, bionesteistä ja biomassapolttoaineista annetun lain muuttamisesta (Kestävyyslaki). https://finlex.fi/fi/laki/alkup/2021/20210604

# APPENDIX 1. VARIABLES AND CONSTANTS USED IN CASE- STUDY; 50 KM PLANT

## RESULTS PAGE: €/DM t

**50 km industrial scale**

*Cost calculation of the silage feedstock*

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| | | |
|---|---|---|
| Grass, vegtation esteblishment | 26 | €/t DM |
| Grass, annual fertilization and weed control | 28 | €/t DM |

| Harvesting cost based on chosen method | BALING | | LOOSE | | |
|---|---|---|---|---|---|
| | Combi baler | Tube wrapping | Harvester chain | Own values | |
| Mowing | 6,0 | 6,0 | 6,0 | N/A | |
| Windrowing | 3,8 | 3,8 | 2,9 | N/A | |
| Baling+neting+wrapping OR Harvester costs | 32,2 | 27,7 | 10,4 | N/A | |
| Ensiling costs | 15,0 | 15,0 | 15,0 | N/A | |
| Short distance hauling directly to plant or intermediate storage | 13,4 | 12,8 | 7,9 | N/A | |
| Compacting of the pile or silo | | | 0,5 | N/A | |
| Cost of plastic films | 10,9 | 4,4 | 0,9 | N/A | |
| Storage slab or silo | | | 6,4 | N/A | |
| Additional costs: (snow removal, pile weighting, etc) | 1,0 | 1,0 | 0,9 | | |
| Cost of harvesting and ensiling before long-distance transportation | 82,2 | 70,5 | 50,8 | 0,0 | |
| Long-distance transportation | 13,8 | 13,8 | 15,4 | N/A | |
| Cost of the feedstock, at the biogas plant | 149 | 138 | 119 | #ARVO! | €/t DM |
| | 14,9 | 13,8 | 11,9 | #ARVO! | cent/kg DM |
| Cost of the feedstock at the plant €/m3 CH4 potential | 0,45 | 0,42 | 0,36 | #ARVO! | €/m3 CH4-pot |

## INPUT DATA FOR THE CALCULATION

Input data fed by user

Values fetched from the sub-calculation tabs

Values fetched from the input data sheet

Calculated results, locked cells

1

**Grass silage yield data:**

| | | |
|---|---|---|
| DM % of the crop | 40 | |
| DM- yield of the crops | 5500 | |
| Yield fresh t/ha | 13,8 | |

**Field data:**

| | | |
|---|---|---|
| Average field size | 3,5 | ha |
| Distance between fields | 1 | km |

**Transport distances:**

*Close-haul distance*

| | | |
|---|---|---|
| bale , combi | 1 | km |
| bale, tube | 2 | km |
| harvester chain | 3 | km, max 35 km |

*Long-haul distance*

| | | |
|---|---|---|
| bale chains | 25 | km |
| harvester chain, | 25 | km, |
| expected CH4 yield | 330 | m3 CH4/tn ka |

**Cultivation data**

| | | | |
|---|---|---|---|
| Cultivation rotation | 4 | years | |
| Harvests | 1 | times per year | *<- not operational at the moment* |

**Ensiling films**

| | | |
|---|---|---|
| Prize of the wrapping film | 90 | €/roll |
| Amount of film layers | 4 | layers |

**Ensiling additive**

| | | |
|---|---|---|
| Amount used | 4 | liters/tn, fr |
| Price | 1,5 | €/l |

| | | |
|---|---|---|
| Hourly cost; tractor and mower (conditioner) | 200 | €/h |
| Mowing speed (avg) | 14 | km/h |
| Additional time per field | 4 | min |
| Mower, operating width | 10 | m |
| hourly cost; tractor and windrower | 110 | €/h |
| Windrowing speed (avg) | 12 | km/h |
| Windrowing width for harvester | 15 | m |
| Windrowing width for baler | 7 | m |
| Moving speed on the road (avg) | 40 | Km /h |
| Effective worktime ratio mowing % | 61 | % effective/waste |
| Effective worktime ratio windrowing, harvester % | 59 | % effective/waste |
| Effective worktime ratio, windrowing, baler % | 82 | % effective/waste |

### Eff. ratio calculator for mowing; square field

| | | |
|---|---|---|
| Driving speed when mowing | 14 | km/h |
| Driving speed at headland | 6 | km/h |
| Size of the field | 3,5 | ha |
| Width of the headland | 3 | times the working |
| Theoretical lenghth of the A-B line | 127 | meters |
| Working width | 10 | meters |
| Driving distance on headland per turn | 35 | m |
| Time spent on headland turn | 16 | sec |
| Time spent mowing | 25 | sec |
| Efficiency ratio; mowing/headland turning | 61 | % |

### Eff. ratio calculator for windrowing, HARVESTER; square field

| | | |
|---|---|---|
| Driving speed when windrowing | 12 | km/h |
| Driving speed at headland | 6 | km/h |
| Size of the field | 3,5 | ha |
| Width of the headland | 2 | times the working |
| Theoretical lenghth of the A-B line | 127 | meters |
| Working width | 15 | meters |
| Driving distance on headland per turn | 45 | m |
| Time spent on headland turn | 21 | sec |
| Time spent windrowing | 29 | sec |
| Efficiency ratio; windrowing/headland turning | 59 | % |

### Eff. ratio calculator for windrowing, BALER; square field

| | | |
|---|---|---|
| Driving speed when windrowing | 12 | km/h |
| Driving speed at headland | 6 | km/h |
| Size of the field | 7 | ha |
| Width of the headland | 3 | times the working |
| Theoretical lenghth of the A-B line | 223 | meters |
| Working width | 7 | meters |
| Driving distance on headland per turn | 24,5 | m |
| Time spent on headland turn | 11 | sec |
| Time spent windrowing | 52 | sec |
| Efficiency ratio; windrowing/headland turning | 82 | % |

## ANNUAL CULTIVATION COST FOR THE BIOGAS FEEDSTOCK GRASS

**50 km industrial scale**

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| | | |
|---|---|---|
| Yield, kg of DM | 5500 | kg DM |
| crop harvests | 1 | per year |
| year rotation | 4 | years |

| | | Establishment cost, first year | Annual cost, divided for rotation years | |
|---|---|---|---|---|
| **Entablishment costs per hectare:** | | € | € | basis for cost: |
| | Basic fertilization , establishment year | 90 | 22,5 | *solid fragment 30 tn /ha* |
| | Ploughing or other basic cultivation | 100 | 25 | |
| | Tillage, (soil preparation before sowing) | 45 | 11,25 | |
| | Sowing of grass seeds | 25 | 6,25 | *roller+pneumatic drill* |
| | Basic liming | 144 | 36 | *36 € /t; 4 t/ha* |
| | Grass seed cost | 108 | 27 | *27 kg; 4€/kg* |
| | Weed control, establishment year | 50 | 12,5 | *Ariane S* |
| | TOTAL | 472 | 140,5 | |
| **Annual costs** | | | | |
| Fertilization: | Manure/digestate | 0 | 0 | *30 m3, free of charge* |
| | spreading | 90 | 90 | *3 €/m3* |
| | Mineral fertilizer | 135 | 135 | *150 kg/ha; 0,9 €/kg* |
| | spreading | 17 | 17 | |
| Weed control if needed | Herbicide | | 0 | |
| | spreading | | 0 | |
| | TOTAL | | 152 | |
| Entablishmen costs and annual costs in TOTAL per a: | | | 292,5 | €/ha |
| | €/kg DM | | 0,053 | |
| | €/t DM | | 53 | |

## Cost calculation sheet for self propellent harveste

Project: **50 km industrial scale**

| | | |
|---|---|---|
| Hauling distance | 3 | km |
| DM content; harvest | 40 | DM % |
| Yield, DM | 5500 | kg DM |
| Field size | 3,5 | ha |
| Distance to move between fields | 1 | km |
| Yield, fresh | 13,8 | tn/ha |
| Hourly cost of SPH | 375 | €/h |
| Max capacity of SPH | 130 | t/h |
| SPH moving speed on the road (avg) | 40 | km/h |
| Additional time per field | 2 | min |
| Hourly cost of hauling unit | 95 | €/ha |
| Carrying capacity of the hauling unit | 20 | t |
| Driving speed on road | 25 | km/h |
| Unloading time | 4 | min |
| Amount of hauling units needed | 3 | units |
| Effective worktime ratio chopping % | 79 | % effective/waste |
| Cost of storage pad | 30 | €/m3 |
| Height of the storage pile | 2 | m |
| DM density of the pile | 259 | kg DM/m3 |
| Cover consumption | 16,08 | m2/ha harvested |
| Cost of silage film | 0,3 | €/m2 |
| Amount of siling additive used | 4 | l/t silage fresh |
| Price of ensiling additive | 1,5 | € |
| Compacting cost | 110 | €/h |

## Cost calculation sheet for COMBI-baler:

Project: **50 km industrial scale**

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| | | |
|---|---|---|
| DM content; harvest | 40 | % |
| Yield, DM | 5500 | t DM |
| Yield, fresh | 14 | tn/ha |
| Field size | 3,5 | ha |
| Distance between fields | 1 | km |
| Wraping film prize | 90 | €/roll |
| Amount of siling additive used | 4 | l/t silage fresh |
| Price of ensiling additive | 1,5 | € |
| Hourly cost; baling | 220 | €/h |
| Baling capacity; theoretical | 25 | tn fresh/h |
| Baling capacity; eff. % corrected | 22,7 | tn fresh/h |
| Baling capacity; moving and add time corr | 22,1 | tn fresh/h |
| Hourly cost; hauling | 75 | €/h |
| Hauling capacity, wot additional time | 23 | pcs /h |
| speed on road | 40 | Km/h |
| Additional time per field, baler | 2 | min |
| web/film cost; binding | 0,7 | €/bale |
| Effective worktime ratio baling % | 91 | % effective/waste |
| Wraping film consumption | 33 | bales / roll; layers given in first page |

**Baling variables**

| | | |
|---|---|---|
| Diameter | 130 | cm |
| Width | 123 | cm |
| Density correction | 80 | % |
| Bale volume | 1,63 | m3 |
| Bale density | 384 | kg/m3 |
| Bale weight | 627 | kg |
| Bale DM | 0,25 | tn |
| Bales/tn DM | 4,0 | pcs |
| Bales/ha | 22 | pcs |
| Time consumption h/ha | 0,71 | h |
| Bales/h | 31 | pcs |

**Hauling variables**

| | | |
|---|---|---|
| avg distance | 1000 | m |
| hauling speed | 17 | km/h |
| Load | 3 | pcs |
| loading | 10 | sec |
| unloading | 7 | sec |
| time/round | 7,91 | min |
| time/bale | 2,64 | min |
| total huling capacity | 22 | bales/h |
| | 1,0 | ha/h |

Bale density dependancy per DM

| DM% | kg/m3 | DM kg/m3 |
|---|---|---|
| 15 | 600 | 90 |
| 20 | 560 | 112 |
| 25 | 550 | 138 |
| 30 | 540 | 162 |
| 35 | 510 | 179 |