ABSTRACT: The increasing demand for sustainable fuels lead to the research of alternative technologies, such as biogas production from lignocellulosic materials. These materials are the most common in earth and are mainly located in forests or marginal lands. However, operational problems have been emerging to exploit them in a cost and environmental efficient way. Difficult terrain topography, bad access infrastructures and poor soil conditions require a different approach. Efforts are being made to develop smaller, lighter and maneuverable machines which are able to perform harvesting operations autonomously.

This master thesis analyzes a marginal grass supply chain in Denmark using alternative harvesting equipment: an automated robot (GrassBot) versus a conventional tractor. Besides, major grass materials accepted by biogas plants are accounted: chopped and baled grass and compared regarding economical, energetic and environmental performances.

To do that, a model called Iris is developed and integrated with a process resource model (DRIFT) previously developed in Aarhus University. This way, production costs, energy use, greenhouse gases emissions for harvesting/collection, storage and transport to a biorefinery are accessed. The data is then gathered using a Life Cycle Analysis perspective and the results evaluated. The Iris model also allows the variation of the input parameters such as equipment or fieldwork conditions. This enables to see how the system is affected and therefore find the best compromise for the scenario considered.

KEYWORDS: Agricultural machines; Environmental Impact; Energy Use; Grass Supply Chain; Marginal Lands, Life Cycle Analysis.

1 INTRODUCTION

1.1 Motivation

Biomass fuels already play an important role in several European countries (nearly 20% in Sweden and Finland). But sustainable resources are needed in larger scales particularly in the transport sector. This sector accounts for approximately 30% of the total energy consumption, of which, 98% are dependent on fossil fuel and better living conditions in new EU countries led to higher demands (Sambra et al., 2008). The increasing demand for biomass fuels, has led to a significant need for corn and other feedstock commodities (sugarcane or corn for fuel production). If this tendency continues to rise, large quantities of these crops must be harvested every year and the area required for year around supply will not be sustainable. Thus, it is vital to find and explore alternative resources for biomass fuel production (Sharma et al., 2013). Agriculture was responsible for up to 15.5% of total GHG emissions in 2004 (Caffrey and Veal, 2013). By implement biomass fuels such as biogas the GHG emissions from transport and energy could be reduced (Jungbluth et al., 2008). Concerning the current EU polices, biofuels must reduce CO₂ emissions by at least 35% compared to petroleum, which means a limit of 53 kg CO₂ GJ⁻¹. However, emission requirements will be tightened in 2017, this percentage will be increased to 50%, which is translated to a maximum of 42 kg CO₂ GJ⁻¹, (Helgadottir et al., 2013).

Recent investigation have been made in order to quantify the potential cost of biomass on marginal grasslands. Exploring different supply chains would lead to an improve of the competitiveness of marginal grasslands comparing with annual crops due to higher yields (Schweier and Becker, 2013). However, to our knowledge, there are not studies that address altogether operational, economic, energetic and environmental analysis of marginal grass supply chains.

It is expected that cellulosic biofuels reduce GHG emissions compared to the use of fossil fuels (Demirbas, 2008). Denmark is one of the leading countries on using renewable energies and has been making a big effort is being made in the research field to accomplish a neutral carbon impact in 2050. In the past, marginal lands were used by farms to feed their animals, but the paradigm has now changed. Today, there is the opportunity to explore these fields for energy purposes. Animals are now fed inside the farms and there are lands with high phreatic level, bad access and difficult terrain morphology which are not appropriate for agriculture. This gives grasses and other plants the opportunity to grow, accumulate organic matter and attract animals, creating problems related to phreatic water contamination. In this sense, measures should be to taken to decrease nitrate and phosphate pollution (Peeters, 2009). By harvesting these lands nitrogen is removed, which reduces the leaching. Mowing also prevents scrublands to appear. Therefore visual impact is reduced since some vegetation can grow up to several meters (Mortensen, 2014).
Conventional tractors show several difficulties during marginal lands harvesting. Terrain quality and environmental considerations require equipment with special characteristics. Furthermore, technological advances combined with a higher demand for cost efficiency and environmental friendly equipment require new managerial approaches, including enhanced automation (Sørensen and Bochtis, 2010). Efforts are being made to develop smaller, lighter and maneuverable machines. In short, there is a greater need for technologies that, are able to maximize operational efficiency in a way that optimizes the use of scarce resources and minimizes the environmental impact (Sørensen and Nielsen, 2005).

Supply chain design plays a vital role in the operational, economic and energetic viability of the biomass conversion process (Sambra et al., 2008). Therefore it is imperative that the whole process machines interactions are studied and weakness eliminated.

1.2 Objectives

This dissertation aims to study the performance of an automated machine called GrassBot, which was developed at the Danish Biomass Research Centre at Foulum. This technology will be compared with a conventional tractor taking into account a variety of specific field conditions and operations in Denmark. This way, the main objective is to show which machine is most suitable in a grass supply chain – automated or conventional.

Another goal is to analyze a grass supply chain from harvesting to the biorefinery gate, considering three biomass materials: unchopped, chopped and bales. Each material is compared regarding costs, energy use and GHG emissions.

To fulfill these goals, a model was created regarding field and transport operations. Operational, economic and environmental performance indicators for each biomass material are calculated and compared.

Finally, it is intended to provide insights about the sustainability of the grass supply chain.

2 THEORETICAL BACKGROUND

2.1 Biomass on marginal lands

Marginal grasslands are abundant in Denmark and almost in any region of the world, because they do not require special care. There are several types of grasslands, which can be rich or poor in species, dominated by grasses, legumes or a mixture.

These low value lands are characterized by having little potential for profit due to diverse factors such as poor soil, difficult topography or bad access. The amount of inputs per ha (i.e. fertilizers, herbicides, irrigation, etc.) induce big differences on the field material output such as the yield or material quality. Low production fields only produce 2-3 tdm ha⁻¹, although a higher production of 10-12 tdm ha⁻¹ can be obtained by using fertilizers and other inputs (Peeters, 2009). Also when fields are located in protected landscape, the average yield is 4 tdm ha⁻¹ (Peeters, 2009), since no inputs can be applied.

2.2 Supply chain stages

A successful biomass supply chain must deliver materials on time, prevent excessive degradation and finally process the raw material in a way that optimizes the energy conversion process. A biomass supply chain is divided into:

- Harvesting and collection
- Transportation
- Local Storage Center (LSC)
- Biomass densification
- Biomass conversion (Biorefinery)

2.3 Biomass energy conversion

Grasses have a high protein yield and material shape flexibility, but because of their high MC, vapors released during combustion could easily develop corrosion in the biorefinery equipment. Therefore biogas is actually the most suitable technology process for grasses.

Regarding biogas technology, a second generation of biofuels is being developed. The first generation offered some CO₂ benefits and improved independence from fossil fuels. However, first generation of biofuels is appointed as the main responsible for the food stock rising prices (Naik et al., 2010). This way, second generation addresses this problem since biofuels source are lignocellulosic materials or plants.

Grass can be converted into methane by mixing it with slurry or as pure substrate. In this work only grass performance is studied apart from the slurry and other substances that can be added. The specific methane production of grass silage is 70-100 m³ CH₄ t⁻¹ with a DM content of 30-35%. Although chopping material can be fed directly into the biogas digester, unchopped and bales must be grinded previously due to their big particles size. Therefore, a processing unit called tub-grinder in which a hammer mill applies cutting and impact movements cuts the particles in line with the dimensions required for the biogas process. The machine operation costs are 4 € ton⁻¹; the energy required is 193.98 MJ tdm⁻¹ and the associated emissions are 14.83 kg CO₂ tdm⁻¹ (Morey et al., 2009).

To produce energy from harvested material, we need to know how many MJ and CO₂ are produced regarding 1 ton of grass. The main biogas components present in biogas made by anaerobic digestion are methane (65%) and carbon dioxide (35%), but only methane has calorific value. Thus 1Nm³ of methane has 9.67 kWh, and considering biogas composition the energy content is around 6 kWh. Knowing that 95 Nm³ of biogas can be obtained with 1 ton of grass (SGC, 2012), we found that the energetic value of 1 ton of grass is 2257 MJ. Moreover, the combustion emissions in Danish plants were estimated to be 0.0836 of kg CO₂ emitted per MJ of biogas (Nielsen and Plejdrup, 2014). Chopped material and bales have around 13 GJ ton⁻¹ of specific energy density whereas the preprocessed material such as biogas has 50,1GJ ton⁻¹ (SGC, 2012).
2.4 Recent approaches and models

The sustainability of biomass energy must be accounted using performance parameters such as fuel consumption and GHG emissions (Sokhansanj et al., 2006), besides economic benefits (Sambra, 2008). A framework of specific task models was developed by (Sørensen and Nielsen, 2005). This tool is called DRIFT and it, estimates the required machine input for each field operation. Parameters like the harvesting and transportation time, were obtained for a given field type, harvested area and equipment.

Nowadays, consumers and industry are becoming more aware of the environmental impacts related to equipment manufacturing, use and end of life. Due to the increase of fuel costs and competition, there is a need to find more efficient systems regarding not only the cost but also the environmental impact.

To analyze and evaluate the environmental impact of biomass supply chain and compare with other alternatives, a Life Cycle Analysis (LCA) approach was used. LCA has been standardized through the ISO 14040 series which define it as the “compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system through its entire life cycle.” According to Figure 1, this evaluation can be divided into four steps (Rafaschieri et al., 1999).

3 MATERIAL AND METHODS

3.1 Gathering data

Meetings were conducted with Professors, PhD students and staff from the Navitas and Aarhus Research Center for Agriculture and valuable information was obtained. The equipment and operations used were specifically designed for meadow grass involving general accepted procedures and combining data from expert advice to create reasonable and realistic scenarios found in Denmark. The standards EP496.3 2006 and D497.5 2006 from the American Society of Agricultural and Biological Engineers (ASABE/ASAE) were used to calculate the usual costs found on the agriculture fleet machines. Using this information and DRIFT, a model that gathers cost, energetic and environmental impacts was developed and its operation is explained in chapters, 3.3.2 and 3.3.3.

![Figure 2 Methodology diagram](image23.png)

Figure 2 Methodology diagram

3.2 Description of the Handling System

The GrassBot is designed to operate with the minimum human intervention but in an efficient and safe way. From the performance point of view, a conventional tractor weighting 2 tons has an output power of around 30kW, the present GrassBot model offers 74 kW with the same weight. A comparison between these two machines is presented in Table 1. Since the fields are not cultivated for several years and are very uneven it is assumed a speed of 6 km h⁻¹ for the majority of the field operations. Besides, according to the Danish law autonomous robots must be always monitored by an operator, each operator can be in charge up to 5 robots.

<table>
<thead>
<tr>
<th>Table 1 GrassBot and John Deere 6630</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Units</strong></td>
</tr>
<tr>
<td>Power to take off PTO (kW)</td>
</tr>
<tr>
<td>Field speed (km h⁻¹)</td>
</tr>
<tr>
<td>Fuel consumption (L h⁻¹)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>Selling price (€)</td>
</tr>
<tr>
<td>Tyres/Belt cost (€ ha⁻¹)</td>
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</tbody>
</table>

The purposed biomass supply considers three types of products, unchopped, chopped and baled that can be processed using a tractor or GrassBot. In total, there are six supply chain options and each one is divided in three stages.

![Table](image1.png)

In LCA analysis all product stages are examined, the extraction of natural resources, materials production, manufacturing, distribution, use and finally disposal. With this approach new opportunities are created, by developing "greener processes" that could lead to an overall cost reduction through a better use of energy, equipment and resources.

There have been more and more publications that have used the LCA framework for agricultural practices (Caffrey and Veal, 2013). Products like oil crops (Mattsson et al., 2000), wheat, apples and biofuels (Jungbluth et al., 2008) have been analyzed through this method. Using a LCA it is then possible to:

- Cover all the product life cycle, considering the phases required from the raw material to the final product deliver;
- With this evaluation a wide range of impacts are accounted;
- Standardization.

![Diagram](image4.png)

Figure 1 LCA methodology
In first stage, biomass is harvested and collected using a mower, tedder and a rake which are common for all final materials. In the second phase, the biomass is transported by tractor to the LSC and stored. At least, on third stage these materials are sent by truck to the biogas plant where are processed.

Materials should meet a specified quality to be accepted in the biorefinery. This quality depends on factors such as % Dry Matter (DM) and particle size. Chopped materials meet these requirements, however, unchopped and baled grass need to be chopped first. This process is done at the biogas plant using a grinding machine to obtain the same material quality as the chopped. However, this additional operation adds an extra cost of 7.6 € tdm⁻¹ (Huisman et al., 1997).

3.3 Model Description

Two process based models are developed, the DRIFT (process requirements) and the Iris (process resources). A global view of the inputs and outputs shared by the two models is presented in Figure 3. Typically agricultural machine systems are evaluated based on two criteria: the volume of material per unit of time (i.e. field capacity) and the cost per unit of volume processed (i.e. machine rate) - Cheng, 2009.

Field capacity is described as the amount of area covered per unit of time (ha h⁻¹). It is found multiplying the equipment field speed (s) by the implement working width (m) and the equipment field efficiency, u.

\[ FC = \frac{s \times w}{10} \times u \]  

(1)

By using DRIFT model, the required FC for each step is calculated and used as an input in the Iris model. Which process this data and calculate the resources required for each specific task such as machines operating hours, material capacity, fuel used, indirect energy, taking into account the defined equipment and field factors.

The resources obtained are then multiplied by factors regarding the field, equipment and price and final specific metrics are assessed.

Besides since projects evaluations are giving more and more importance to the long term costs, it is important use a life cycle cost (LCC) approach and also to complement these results a life cycle environmental analysis. Therefore a life cycle analysis (LCA) approach was integrated in Iris, to quantify the processes impacts over their full life cycle.

### 3.3.1 Resources Assessments

The time for each process is dependent of each process block such as baling capacity, chopping or transport on road. Each material chain use different machines and processes, therefore in order to find the total supply chain time all the blocks must be added.

\[ \text{Total SC time} = \sum \text{Required time for each block} \]  

(2)

\[ \text{Harvested Material} = \text{Yield} \times \text{Total Area} \times \text{Dry Matter \%} \times \text{Number of Fields} \]  

(3)

Besides it is an aim to account specific metrics regarding to volume of material processed and time, the total harvested material is given in a yearly basis by the equation (3) and the time required by the equation (4).

DRIFT calculates the field capacity for one field at a time, since contractors harvest several fields per year it is important to develop a method that allows several fields to be accounted. Therefore, the mean of the studied fields was assumed.

\[ \text{Total specific time} = \frac{\text{Total time} \times \text{Total Harvested Material}}{\text{Harvested Material}} \]  

(4)

The direct energy inputs from fieldwork operations are fuel consumption which are defined based on the engine load and type of fuel used. Diesel is used and the engine load is determined by dividing the minimum power required by the implement by the maximum power of the tractor (5). After, this factor is accounted in (6) to get the estimated consumption. These formulas were developed and used by the Agricultural Engineering Department of FRC.

\[ x = \frac{\text{mPR}}{\text{Pm}} \]  

(5)

\[ l = \frac{x \times \text{Pm} \times f_e}{1000 \times d} \]  

(6)

### Table 2 Fuel resources variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Term</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption</td>
<td>l</td>
<td>1 h⁻¹</td>
</tr>
<tr>
<td>Engine load</td>
<td>x</td>
<td>%</td>
</tr>
<tr>
<td>Maximum power of the tractor</td>
<td>Pm</td>
<td>kW</td>
</tr>
<tr>
<td>Fuel efficiency</td>
<td>fe</td>
<td>g kWh⁻¹</td>
</tr>
<tr>
<td>Fuel density</td>
<td>d</td>
<td>Kg l⁻¹</td>
</tr>
<tr>
<td>Minimum power required</td>
<td>mPR</td>
<td>kW</td>
</tr>
</tbody>
</table>

### 3.3.2 Cost Assessment

After calculating the process requirements, each resource is multiplied by the cost factor. These expenses are due to the ownership and operation of the equipment during its operating life.
and the formulas used can be found in ASABE Standards. Machines, maintenance and repair, labor, tyres, fuel, storage and lubricants are accounted as variable costs and machines ownership, which includes equipment depreciation.

Therefore the average annual ownership costs $C_0$ (% of purchase price) is based in three factors, depreciation, interest rate $i$ and TITH that accounts the percent of purchase price required for taxes, insurance and housing.

$$C_0 = 100\left[\frac{1 - RV}{EL} + \frac{1 + RV}{2}i + TITH\right] \quad (7)$$

Resell value (RV) refers to the machine’s value at the time considered and is calculated by (8). Is dependent on operating years ($n$) and working hours, expressed as a percentage of the purchased price. $C_1$, $C_2$, $C_3$ are coefficients which vary according to equipment type. EL is the estimated economic life of the equipment, this value is obtained from ASABE, (2009).

Maintenance and repair (RM) costs $C_{rm}$ are calculated as a percentage of the purchase machine price and are defined by equation (9), these are included in variable costs and vary according to equipment category and specific fieldwork time. RM factors are coefficients for each machine type.

$$C_{rm} = (RMF_1)\left[\frac{h}{1000}\right]^{(RMF_2)} \quad (9)$$

The parameter $n$ and $h$ is the machinery age in years and the average annual use, hours respectively.

Besides RM operations, also fuel costs $C_{FL}$ are considered. They are calculated using the time required $WT$, the average equipment fuel consumption per hour $Q_{avg}$ and fuel price $FP$.

$$C_{FL} = Q_{avg} \times FP \times WT \quad (10)$$

### 3.3.3 Energetic and Environmental Assessment

The energy used and emissions during the manufacturing, operating and disposal operations of the machines are accounted in gate to gate basis-Figure 4. It was accounted the:

- Manufacturing
- Biomass growth
- Fieldwork
- Energy conversion
- Recycling and disposal

The grass supply chain studied differs from agricultural supply chains since, fields and meadows are located in sensible areas. Thus certain operations that would compromise the ecosystem sustainability are not allowed by government policies. Fertilizers or other substances that would improve soil yield are forbidden.

The system net energy balance is calculated by subtracting the energy produced by the processed material and the total energy used.

$$\text{Net Energy} = \text{Biomass Energy Output} - \text{Fossil Energy Input} \quad (11)$$

To address each process in a fair manner, it is important to find the amount of agricultural machinery used for a specific operation. Therefore a use factor (UF) was used based on equipment economic life (EC), yearly operational time (OP) and machine life time ($LT_{rm}$).

$$UF = EL \times \frac{OP}{NU \times LT_{rm}} \quad (13)$$

This factor is then multiplied by several parameters such as energy and emissions. The total indirect energy (EI) allocated to a specific machine, or implement is therefore based on energy coefficients (EC), equipment weight (W) and the UF calculated by equation (13). To find the manufacturing emissions regarding the equipment manufacturing, EI is multiplied by the respective emissions factors (EF). The Danish electricity emission factor was assumed (EFE). Fieldwork emissions are mainly caused by fuel combustion. These are found multiplying emissions from fuel combustion (EFF) by the fuel required ($L$), as equation (15) describes.

$$EI = EC \times W \times UF \quad (14)$$

$$FE = L \times EFF \quad (15)$$

![Figure 4 Agricultural energy and emissions supply](image)

Waste due to maintenance, repair and the disposal of the equipment in the end of its lifetime are included in the last block.

It was assumed that the waste percentage is the same as the repair factors mentioned. Regarding to the disposal operations path, the following assumptions were made:
During the disposal and disassembly phase, electricity and emissions must be considered. Nemecek et al., (2007) estimated that the energy required to dismantle agricultural machinery (ERD) is 0.5 MJ per kg machinery, this energy also accounts the transport to the facility.

Costs, energy requirements and finally the GHG emissions are calculated using the operational data at an annual basis. The energy require for the equipment dismantle and disposal is estimated by equation (16). To calculate resultant emissions the electricity emission factor was considered since the majority of paths are dependent on it.

\[
DE = UF \times NU \times Weight \times ERD \times (1 + RF)
\]  

(16)

4 RESULTS AND DISCUSSION

The present chapter deals with the results for the six considered scenarios. Supply chain operational conditions, costs, energy requirements and finally the GHG emissions are calculated using the operational data at an annual basis. At least, two sensitivity analyses are performed the regarding major parameters, are and number of GrassBots.

4.1 Operational and Economic Performance

Total cost for all supply chains analyzed are given in Figure 5. Bales are the cheapest option, and from harvest perspective, it is observed that the automated process is more expensive than the regular option.

![Supply chain costs](image)

Figure 5 Supply chain costs

The higher production cost of chopped and unchopped materials is due to the bigger number of machines required. In order to have optimal efficiency during harvesting, the chopper needs a continuous storage flow and therefore several wagons are needed. Saying that, the number of machines responsible for chopped material transportation is high, which increases ownership costs and fuel expenses because more trips are necessary.

Transport cost to LSC is analogous in both technologies, however is more expensive for all automated process. The biggest difference was 6% for unchopped. The higher operational time required for automated process is the responsible for increasing machines maintenance and repairs costs.

![Uncropped and chopped](image)

1. proposal and disassembly

![Material](image)

During the disposal and disassembly phase, electricity and emissions must be considered. Nemecek et al., (2007) estimated that the energy required to dismantle agricultural machinery (ERD) is 0.5 MJ per kg machinery, this energy also accounts the transport to the facility.

Costs, energy requirements and finally the GHG emissions are calculated using the operational data at an annual basis. The energy require for the equipment dismantle and disposal is estimated by equation (16). To calculate resultant emissions the electricity emission factor was considered since the majority of paths are dependent on it.

\[
DE = UF \times NU \times Weight \times ERD \times (1 + RF)
\]  

(16)

Regarding unchopped materials, a description of the assessed parameters is done. The same approach was also used for the other materials. Automated process has lower operating costs than regular as Table 4 shows. This table also shows the difference in percentage between the two values.

| Stg 1 | Total Harvesting+Loading Cost | €/tdm | 45.14 | 28.25 | 60% |
| Stg 1: Total Time | hr/tdm | 1.75 | 1.37 | 28% |
| Stg 2: Total Transport Cost | €/tdm | 19.95 | 18.83 | 6% |
| Stg 2: Total Time | hr/tdm | 0.57 | 0.51 | 11% |
| Stg 3: Total Truck Transport+Grinding Cost | €/tdm | 14.71 | 14.71 | 0% |
| Truck Cost Rate | €/tdm km | 1.12 | 1.12 | 0% |
| Stg 3: Total Time | hr/tdm | 0.17 | 0.17 | 0% |
| Storage Costs | € year/tdm | 33.90 | 33.90 | 0% |
| Total Ownership Costs | € year/tdm | 42.09 | 70.75 | -41% |
| Tractor's Ownership Costs | € year/tdm | 20.44 | 40.82 | -50% |
| Robot and Implements Costs | € year/tdm | 21.64 | 29.92 | -28% |
| Total cost | €/tdm | 155.80 | 166.43 | -6% |
| Total time | hr/tdm | 2.31 | 1.88 | 23% |

4.1.1 Sensitivity Analysis

Area:
From a contractor perspective, the scale of the business is very important. If the production capacity is higher, fixed costs per unit are reduced which are translated in bigger operational margins. The best process is dependent on several parameters, being the total harvest area one of the most important to take
into consideration. In Figure 6, the total production cost regarding the field area for all the supply chains is calculated.

Figure 6 Detailed view total supply chain cost regarding area

According to Henrik Mortensen from F.R.C. an average contractor harvest per year around 1000 ha. This is translated in 10,000 ha in a 10 year timespan (project duration assumed). For the present case study, there were assumed 320 ha year\(^{-1}\) for the automated SC, due to the marginal land limited working conditions, such as the operating speed and field areas. In Figure 6, it can be noticed that costs in bale technology follow a decreasing exponential function, whereas in other chains this behavior is not seen. Above 32 ha, costs began to rise for unchopped and chopped technologies.

In a normal product manufacturing life, fixed costs decrease according to the production volume. However, variable costs are usually constant for each unit or hour and they can be reduced by economies of scale regarding for example raw materials. The explanation for this behavior is given by two factors. Equipment repair and maintenance (R&M) are assumed to be variable costs, thus these expenses are dependent on the fieldwork time. They increase exponentially with the fieldwork time. Therefore, despite of ownership costs decrease with the fieldwork area, R&M costs increasing ratio is higher and so, the production costs rise. Moreover, was also observed that field capacity also varies according to the field size, being constant from 24 ha. This influences variable and fixed costs, since less time is required to harvest a field which mean less resources used.

**Number of GrassBots**

In countries where labor costs are high, the number of workers should be optimized. Autonomous robots assess this concern. However, Danish policies demand that an operator must be presented to monitor the robot activity (up to 5 robots can be monitored by one operator). Therefore, it is important to analyze and compare operational and fixed costs using more than one self-propelled machine. A simulation was performed applying the more affordable SC material (i.e. baled). Figure 7, presents the results regarding the harvest and collect stage.

Changing the number of self-propelled machines, also change the number of implements required. Having more units available, the field capacity is higher. This means more biomass harvested and collected for the same area. On the other hand, operating costs are expected to rise.

Figure 7 show the costs given in € tdm\(^{-1}\) ratio and regards to the sum of ownership and variable expenses up to 5 GrassBot operating at the same time.

As expected, costs rise with the number of self-propelled machines i.e. tractors or GrassBot. The tractor growing rate is higher than in the automated process, which means that for 2 or more GrassBots, specific costs decrease. Also, it is seen that in the most extreme scenario (5 self-propellers), savings can go up to 54.7 € tdm\(^{-1}\).

**4.2 Energetic and Environmental Performance**

In order to have a clear picture of which are the most sustainable supply chains, a life cycle analysis approach was used regarding energy consumption and GHG emissions. To accomplish that, a comparison between all processes was made.

Figure 8 Supply chain energy

First, energy cycle is accounted in Figure 8. System inputs and outputs for each stage and technology are gathered and results are expressed in MJ tdm\(^{-1}\). As a convention, the energy that is used has a negative signal and the one that is converted in useful energy has a positive signal. The net value is the difference between the energy generated by a ton of grass processed in a biogas plant and the amount of energy required to process it.
Chopping technology consume less energy. Thus it has the highest net energy output, 1547 and 1606 MJ tdm⁻¹, for automated and regular technology respectively. Chopped and unchopped materials have similar results. In the worst scenario, it was calculated that the energy output from grasses is 200% higher than the energy required to process the biomass.

Regarding grass carbon uptake, a life cycle analysis of emissions was conducted. From biomass growing, operations, use phase (biogas combustion) results are given in Figure 9.

During plants growth the CO₂ present in air is stored in the plants through photosynthesis. This carbon uptake contributed to a large negative emission in the supply chain analyzed.

During harvesting and loading, both process have similar GHG emissions. Transportation GHG emissions were dependent on the biomass density and collection process. They were higher for the automated processes, because the operational time was higher. Tractor transport represent between 5 to 17 %of the net GHG.

For truck transport it is seen that emissions only depend on the material density. For the unchopped material which has the highest emission, truck transport was found to be responsible for 15% of GHG releases. Automated and regular processes have similar CO₂ emissions for each biomass material. The major difference is seen for chopped material regarding transport and (un)load operations. Due to this chopping has the highest net GHG emissions.

Regarding sustainability criteria for renewable biofuels, Figure 10 shows the goals for emission reduction set by the EU. From the results, bales and chop grass are suitable to meet these requirements to produce energy.

5 CONCLUSIONS

As a consequence of growing demand on alternative fossil fuels and the increasingly exigent energy policies, a big effort is being made to find sustainable energy sources. Biomass energy has the potential to become one of the most important. Nowadays several materials are available to produce biogas energy, and due to technological improvements marginal grasses now can be also converted into biogas. A variety of process can be used to perform harvesting and transport operations, but this work assesses the three most common setups for: unchopped, chopped and baled materials. Besides it is also an objective to compare an alternative harvesting machine: an automated robot (GrassBot) vs. a conventional tractor.

This way, a model called Iris was developed to estimate supply chain costs, energy and GHG emissions in a Life Cycle Analysis perspective. This model enabled to perform sensitivity analysis and provided insights about major cost drivers by changing input parameters such as field, cost and equipment characteristics.

Results showed that production costs can be reduced using autonomous robots in marginal lands. Comparing with the regular process, ownership costs where lower but operating expenses were higher. Total costs of unchopped and chopped biomass are similar and baling is the least expensive process to produce biogas from marginal grasslands. It was also found that using more than one GrassBot specific operating costs can be reduced.

Harvesting grasslands is a challenge due to the low field production and difficult access. The main factors that allowed these alternative machines to be competitive against tractors were the increasing of time for harvesting and the limited fieldwork speed imposed by the terrain.

Regarding all supply chains, storage costs can be reduced if unsheltered infrastructures are used. Specific transport energy and GHG emissions are higher when less dense materials are transported. Therefore, it is important to take advantage of the limit weight capacity of the truck to insure the lowest transport cost and environmental impact. Density can be increased by using square bales, however attention must taken to the fact that the baling equipment required is more expensive.
Comparing to other biomass supply chain studies such as switchgrass or miscanthus, grass processing from marginal lands turns to be a more expensive solution, due to the limited operating conditions.

As for energy consumption, equipment manufacturing, maintenance and repair, fieldwork and disposal steps were accounted. For all steps considered, fieldwork turned out to be the most demanded step. The majority of energy used regards to fuel consumption during harvesting operations. In this way, there is space for improvements to save fuel. Lighter and more efficient machines should be used and at the same time keeping the flexibility of bigger ones regarding the working width.

With respect to net energy consumption, chopped and baled materials have similar results. Therefore, transport distances and the efficiency of grinding machines must be carefully evaluated because they can easily influence the system performance. Regarding GHG emissions baling is the most viable option. The figures obtained were compared with other major alternative sources and both current and future policies regarding sustainable energy. According to the results, biogas from marginal grass is an environmental sustainable option to decrease the dependency on fossil fuel energy.

6 REFERENCES


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