

Article

Considerations on Potentials, Greenhouse Gas, and Energy Performance of Biofuels Based on Forest Residues for Heavy-Duty Road Transport in Sweden

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Abstract: This case study investigates the potentials, greenhouse gas (GHG), and energy performance of forest residue biofuels produced by new and emerging production technologies, which are commercially implemented in Sweden for heavy transport. The biofuel options included are ethanol (ED 95), hydro-processed vegetable oil (HVO), and liquefied biogas (LBG) produced from logging residues in forestry and sawdust generated in sawmills. The calculated life cycle GHG emissions, based on the EU Renewable Energy Directive calculation methodology, for all three pathways are in the range of 6–11 g CO₂eq./MJ, corresponding to 88–94% GHG emission reductions as compared to fossil fuel. Critical parameters are the enzyme configuration for ethanol, hydrogen supply systems and bio-oil technology for HVO, and gasifier size for LBG. The energy input is ranging from 0.16 to 0.43 MJ/MJ biofuel and the total conversion efficiency from the feedstock to biofuel, including high-value by-products (excluding heat), varies between 61 and 65%. The study concludes that the domestic biofuel potential from estimated accessible logging residues and sawdust is equivalent to 50–100% of the current use of fossil diesel in heavy-duty road transport in Sweden, depending on the biofuel production technology selected and excluding energy by-products. Thus, an expansion of forest-based biofuels is a promising strategy to meet the ambitious climate goals in the transport sector in Sweden.

Keywords: logging residues; sawdust; ethanol; HVO; LBG; GHG emissions; energy efficiency; biofuel potential

1. Introduction

The global production and use of biofuels represent around 3% of the total fuel consumption in transportation today [1]. The dominant biofuels are ethanol, representing 65% in energy terms, followed by biodiesel (or FAME, fatty acid methyl esters) 29%, and HEFA (hydro processed esters and fatty acids)/HVO (hydro-processed vegetable oil) or renewable diesel (RD), representing 6% [2]. In comparison, the biofuel consumption in Sweden is around 21% today, where HVO is the dominant fuel representing ≈67% of total biofuel usage. Additional biofuels are FAME (19%), ethanol (6%), and biogas (7%). Although Sweden has already achieved the European Union (EU) target of using 10% biofuels in the transport sector, the major part, approximately 90%, of the biofuels or feedstocks used for production are imported from within the EU and the rest of the world [3]. Currently, there is a mix of feedstock, including agricultural crops and residues used for various types of biofuel production. However, there is growing policy support for increasing the share of non-crop feedstock in biofuel production to avoid a potential risk of land-use competition between food and biofuel production.

For example, the revised Renewable Energy Directive (RED2) within the EU, covering 2021–2030, determines that advanced biofuels (based on non-crop biomass) should amount to 3.5% by 2030. It is regulated that crop-based biofuels shall be limited to a maximum of 7% [4]. The forest industry in Europe has huge potential for biofuel production, and large-scale biofuel production would influence the economics of the forest sector [5,6]. Therefore, strong and clear policy decisions are needed for the implementation and allocation of forest residues for the use of heat, power, and biofuel production [7].

The global production of advanced biofuels is marginal today, representing less than 1% of the total biofuel production [1]. However, projects regarding advanced biofuel production are growing rapidly in many countries around the world, such as in the USA, Brazil, India, China, etc. In Sweden, there are several pilot and demonstration plants under planning, or construction, that are aiming toward forest-based by-products and residues as a potential feedstock for advanced biofuel production [8]. Sweden has a large forest resource, covering approximately 70% of the land area, and a sizable forest industry sector; thus, the potential of forest-based by-products and residues available for energy purposes, such as biofuels, is estimated to be significant [9].

The use of biofuels has been promoted by different policy incentives for a long time in Sweden, leading to the high share of biofuels in road transports [10]. The Swedish government has also recently introduced a new, additional incentive called greenhouse gas (GHG) reduction quota where the producers and distributors of transportation fuels are obliged to blend biofuels into fossil diesel and gasoline to reduce the GHG emissions from the transportation fuels. This instrument has a direct implication on the promotion especially of low-blend biofuels in diesel and gasoline. This incentive has resulted in a significant increase in the use of HVO as a drop-in fuel in diesel. One benefit with HVO is that there are practically no technical limitations in blending levels in diesel, since it can be used in conventional diesel engines and distributed by existing distribution systems for diesel [10]. This is one reason for the high share of HVO in the current Swedish biofuel mix and also why the majority of the ongoing lignocellulosic-based biofuel projects in Sweden are targeting HVO. A minor share of the HVO sold on the market is also used in pure form (HVO 100), as heavy-duty vehicle manufacturers have approved the use of pure blends. However, there is still a limitation of pure blend in light vehicles. The feedstocks used for making HVO used in the Swedish market in 2018 were palm fatty acid distillate (PFAD) (46%), slaughterhouse waste (37%), tall oil (10%), corn oil (4%), and palm oil (3%) [3]. Today, there is one commercial plant in Sweden that uses refined tall oil, a by-product from pulp production, for HVO production [11].

Sweden has a long tradition in the research and development of lignocellulosic ethanol production [12–15]. Today, there is one forest biomass-based commercial ethanol plant, Domsjö, that is operational in Sweden [16], but additional commercial projects are also being planned. The current use of ethanol as transportation fuel is divided between low-blend use in gasoline and high-blend use in both light-duty and heavy-duty vehicles. ED 95 (95% ethanol and 5% additives) is an ethanol-based fuel used in trucks and buses (with modified diesel engine) in Sweden.

Another type of biofuel under commercial development is liquefied biogas (LBG) for trucks [17]. Today, compressed biogas (CBG) is utilized as transportation fuel both in light-duty and heavy-duty vehicles. The biogas is mainly domestically produced from organic waste substrates, such as sewage sludge, organic municipal waste, liquid manure, and food industry waste. The increased interest in LBG is due to the possibility to use this as a high-blend fuel in dual-fuel diesel engines, and the energy density will be similar to diesel. Sweden has developed a demonstration plant called GoBiGas in Gothenburg for the thermochemical conversion of biomass to biomethane [17]. The plant has a production capacity of 20 MW of biomethane from woody biomass and has shown that the technology is mature and can be used for large-scale deployment. However, due to some financial issues, the plant is not currently operational, but it has been seen in the past that the technology is viable.

A current trend in Swedish road transports is an increased allocation of biofuels to the heavy-duty vehicle sector, since electrification has developed much faster in the light-duty vehicle sector [3]. Furthermore, the Swedish Parliament has decided, within the national climate law adopted in 2017,

that the GHG emissions from domestic road transport shall be reduced by 70% by 2030, compared with 2010 [18]. This implies that the need for high-blend biofuels will increase rapidly, and especially for heavy-duty vehicles and long-haul transport operations since the electrification is estimated to be more limited here within the coming decades. As a response to the anticipated increased market of long-haul road trucks fueled with high-blend biofuels, the Swedish truck manufacturer Volvo offers dual-fuel trucks fueled with LBG [19]. In addition, the Swedish truck manufacturer Scania offers ED95-fueled trucks [20]. Both these categories of trucks are based on diesel engines adapted for the new types of biofuels. Together with these new categories, traditional diesel trucks can use pure HVO or HVO100. To conclude, there are different options today, i.e., ethanol, HVO, and LBG, which can be based on forest-based residues for heavy-duty road vehicles [21].

The new and emerging biofuels also need to fulfill the sustainability criteria stated in the EU RED2, such as reducing the life cycle emissions of greenhouse gases (GHG) by at least 65%, compared with diesel and gasoline, regarding new production plants after 2020 [4]. There are some studies that evaluate the GHG performances of ethanol [22–24], HVO [25], and LBG [26] based on forestry residues. However, there is no study that together considers the feedstock potential and also analyzes the GHG and energy performance for the existing (ethanol) and emerging (HVO and LBG) technologies. There is still a need to integrate the existing literature on the mentioned biofuels in order to contribute knowledge and insights from systems perspectives. Therefore, the aim of this article is to study (i) the potential of forestry residues, i.e., logging residues (tops and branches) generated in final felling in conifer forests and sawdust generated as a by-product in sawmills; (ii) GHG performance; and (iii) energy performance for ethanol, HVO, and LBG production in Sweden. In order to meet the national targets of GHG emissions reduction, Sweden would eventually have to reduce dependence on imported feedstock and rely more on the domestic feedstock. Therefore, this study highlights the use of forestry residue-based biofuel in Sweden both from a potential as well as sustainability perspective. The early development of forest-based biofuels in Sweden will also lead to important experiences for other countries with similar conditions as Sweden, following a similar progress regarding lignocellulosic biofuels.

2. Methodology

This study focuses on forestry-based biofuels characterized by their ability to blend in conventional fuels or to be used as pure blends (with/without requirements in the modification of the engine). Three different pathways considered are ethanol production via fermentation, HVO production via fast pyrolysis and upgrading, and LBG production via gasification followed by liquefaction. The study uses a systems analysis approach to cover three different aspects: (i) biomass potential assessment based on analysis of data from previous published literature; (ii) GHG performance based on the life cycle calculation methodology specified in the EU RED2 [4]; and (iii) energy analysis including all the input of primary energy during well to tank (WTT) life cycle.

The scope includes the energy input and GHG emissions during all the operational activities but excludes all the infrastructure-related processes such as the construction of the plant, manufacturing of the equipment, vehicles, etc. GHG emissions include CO₂, CH₄, and N₂O that are categorized in the GWP and expressed in kg CO₂eq. and then adjusted to the functional unit as g CO₂eq./MJ biofuel.

The method to determine GHG emissions according to the EU sustainability criteria is based on the following procedure [4]:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \quad (1)$$

where E = total emissions from the use of the fuel; e_{ec} = emissions from the extraction or cultivation of raw materials; e_l = annualized emissions from carbon stock changes caused by land-use change; e_p = emissions from processing; e_{td} = emissions from transport and distribution; e_u = emissions from the fuel in use; e_{sca} = emission saving from soil carbon accumulation via improved agricultural

management; e_{ccs} = emission saving from carbon capture and geological storage; e_{ccr} = emission saving from carbon capture and replacement; and e_{ee} = emission saving from excess electricity from cogeneration.

In the case of residual feedstock, EU RED recommends some parameters such as e_l , e_{sca} , e_{ccs} , and e_{ccr} as irrelevant. Furthermore, the component e_{ee} is not applicable for the selected pathways since they all represent stand-alone technologies. Excess energy generated from by-products during processing is handled by energy allocation. Residual feedstocks do not lead to any land-use change and do not impact soil organic carbon. Emissions arising from the use of biofuels are also considered zero, as they are biogenic and therefore excluded in the calculations.

So, the final calculation of GHG emissions in this case study is based on the following formula:

$$E = e_{ec} + e_p + e_{td} \quad (2)$$

where e_{ec} includes emissions from the collection of feedstock from forest and sawmill, e_p includes emissions from the processing/conversion of feedstock to biofuel, and e_{td} includes emissions from the storage and transport of raw materials, an intermediate product, and a final product.

Furthermore, GHG emissions savings are calculated based on the following formula:

$$\text{GHG emissions savings (\%)} = (E_f - E_b) \times 100 / E_f \quad (3)$$

where E_f = total emissions for fossil fuels, and we use a default value of 94 g CO₂eq./MJ and E_b are the total emissions from the biofuel.

As described above, the energy analysis includes all the input of primary energy during well to tank life cycle of all three biofuels in their respective pathways. This also includes the energy used in the collection, transport, and pretreatment of feedstocks. Electricity use in all the base case scenarios is assumed to be supplied from Swedish mix. Pathways generating excess electricity, after meeting the plant's internal demand together with other by-products is treated using energy allocation, as in the case of ethanol. Excess steam generated, which cannot be used further in the process, is considered as heat loss as in the case of HVO.

2.1. Time Horizon

With the aim of reducing emissions in road transport by 70% up to 2030 as compared to 2010, alternative fuels in heavy transport have already gained considerable attention. Therefore, considering the current Swedish climate targets, the time frame chosen for this study is 2030. The technical systems in base case scenarios represent the best available technology (BAT) or new technologies that are now being commercially implemented in Sweden (or planned to be implemented). Depending on the fact that the situation is likely to change in the coming years, focusing the study toward 2030 would bring some uncertainties, especially with respect to development in emerging technologies. These uncertainties in this study are dealt in the sensitivity analysis.

2.2. Scope

Although developments in biofuel use in transport are global, while analyzing potentials, GHG emissions, and energy performance in this case study, the scope is limited to Sweden. When looking at the future development, a few processes align globally, i.e., the feedstock conversion technologies, whereas feedstock collection, transportation mode, distances, and carbon intensities of inputs such as electricity are dependent on the local conditions. Non-biogenic emissions from the collection, transportation, and processing activities are considered in this study. Since the CO₂ emissions from the combustion of biofuels are considered as zero when the fuel origin is biogenic, therefore, this study only includes well to tank GHG emissions and the energy performance of biofuels. It has also been assumed that forest residue today is a waste, and the removal of waste does not create any extra burden

on the cultivation practices; therefore, land use changes (LUC) are not included (in accordance with the RED2 calculation methodology) [4].

2.3. Average Production Values

LCA conducted in this paper uses an attributional, well to tank (WTT) approach and is primarily based on secondary data presented in the last five years of scientific literature regarding LCAs of forest biomass-based biofuels in Sweden. These data are compiled and adjusted, when needed, to make comparable calculations and to fulfill the specific requirements stated in the EU RED2 calculation methodology [4]. When scientific literature-based data are missing, complementary data are also compiled from gray literature. In this article, we have opted for the use of average values for calculating GHG emissions and energy performance.

GHG emissions and energy performance for the pathways considered in this study are calculated using a two-step process. In the first step, referenced input data are gathered, reviewed, and compiled into a spreadsheet. The data consist of information on the material and energy requirements at each step of the collection, transport, production, and distribution of biofuel. Secondly, the input data are adjusted and analyzed for the WTT GHG emissions and energy performance per MJ of biofuel, which is also considered as the functional unit for each biofuel pathway. While making calculations, feedback loops are also taken into account in pathways where the output energy from the process is also used within the pathway, such as in the case of electricity and steam used within the process to supply power, heat, and steam to the boilers.

2.4. Feedstocks Analyzed

The forest sector in Sweden is responsible not only for the supply of timber and pulpwood but also for the production of biomass for bioenergy. The most common by-products from the forestry and timber industry are logging residues and sawdust that in current status are considered as zero-burden feedstock according to RED2. Therefore, these two feedstocks are assumed to be potential source for lignocellulosic biofuel production. The chemical composition of both feedstocks is given in Table 1.

Table 1. Chemical composition of logging residue and sawdust [15].

	Logging Residues	Sawdust
DM content (wt % wet basis)	45	45
Glucan (wt % of DM)	38.5	42.8
Xylan	5.1	5.6
Galactan	1.4	1.5
Arabinan	1.8	0.9
Mannan	8	10.1
Lignin	34.1	34.3
Extractives	9.2	3.3
Ash	1.1	0.3
Acetate	0.8	1.2
LHV (MJ/kg DM)	18.45	18.38

Forest residues consist of the logging residues from the logging operations in final felling, i.e., tops and branches that are just left in the forest to decompose. Typically, the share of logging residues in the final felling of conifer stands represents about 20% of the amount of stem wood harvested [27].

Sawmills, together with pulp mills, are the major forest industry in Sweden, and sawmills produce sawn goods from the timber. The processing of timber into the lumen and sawn goods produces by-products such as sawdust, bark, and woodchips. A typical sawmill converts 47% of timber into lumber, while the remaining 53% is composed of the by-products, of which sawdust constitutes,

on average, 13%. In a typical large sawmill, with an annual capacity of 350,000 m³ sawn wood, approximately 36,000 tonne dry matter (DM) sawdust is produced, which is equivalent to 730 TJ [28,29].

3. Systems Description

The well to tank LCA of forestry-based biofuels from logging residues and sawdust is described in three unit processes: (i) feedstock collection and transportation; (ii) feedstock processing; and (iii) biofuel distribution. However, the results section together represents the transportation of feedstock and biofuel distribution activities. The system boundary for the mentioned pathways and their respective biofuel as output is given in Figure 1 and is described in detail in the following paragraphs. The details on the material and energy input of each pathway are given in Appendix A.

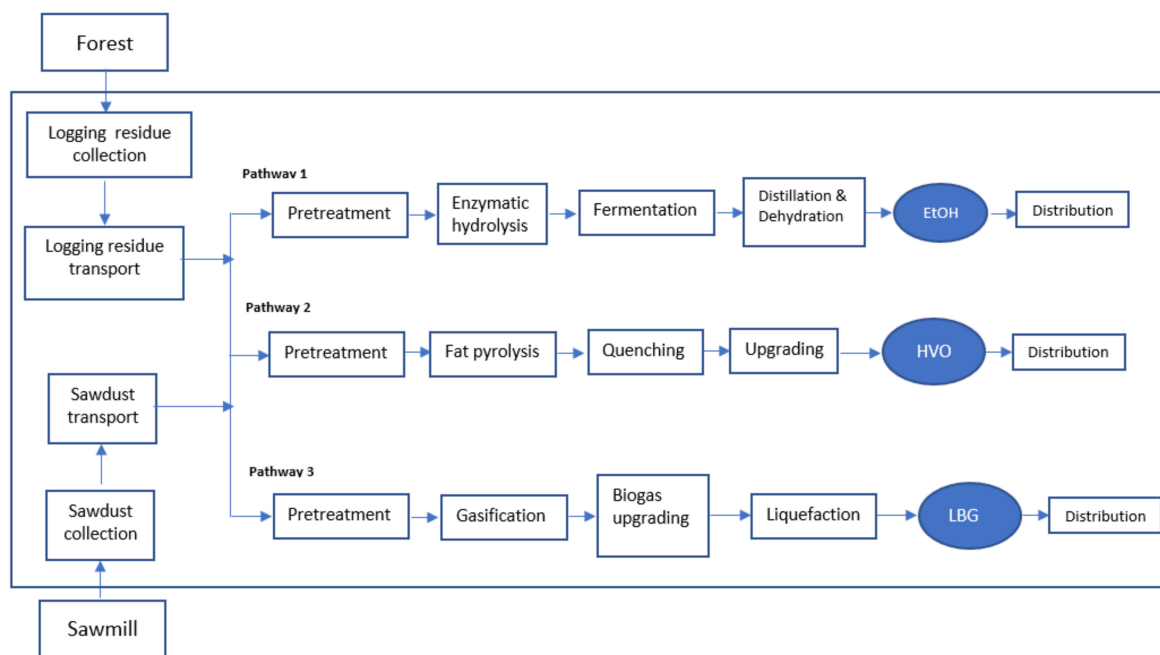


Figure 1. System boundary used in the case study.

3.1. Feedstock Collection

The collection and transportation of logging residues and sawdust is similar in all three pathways and can be described as follows.

3.1.1. Logging Residues

This includes the extraction, collection, forwarding, and chipping of tops and branches. Tops and branches are collected and stored at the forest site under paper for a period of eight months until their further processing. During storage, there is a substance loss of 1% dry weight per month. After storage, tops and branches are chipped at the forest site using a horizontal grinder. The chipped forest residues are loaded to dump trucks and then transported to the processing facility. The primary energy input requirement and the associated GHG emissions during the forest operations are adapted from [22,30].

3.1.2. Sawdust

Sawdust is collected from sawmills and then transported to the processing facility. The case study represents a typical forest-dominating area in Sweden with a high density of sawmills. It is assumed that two-thirds of the sawdust produced in the region will be available as feedstock for the biofuel production, whereas one-third is utilized for the production of pellets, etc. The primary energy input requirement and the associated GHG emissions during the sawdust collection are adapted from [24].

3.2. Feedstock Transport

The transportation of logging residues to the processing facility in all pathways is assumed to be 100 km via roadway. The transportation takes place by a 40 tonne (t) diesel-propelled truck with a carrying capacity of 8.4 t of wood chips per load, volume of 28 m³, and energy consumption of 0.67 MJ/tkm [22]. The transportation of sawdust to the production site in all pathways is assumed to be 70 km via roadway. The type of truck and its performance are similar as for the transport of logging residues. The emissions and energy use in this unit are represented together with the biofuel distribution phase.

3.3. Feedstock Processing to Biofuel

Three pathways analyzed for biomass conversion to biofuel are ethanol via fermentation, HVO via fast pyrolysis followed by upgrading, and LBG via gasification followed by liquefaction. The input of feedstock is considered the same in all three pathways, i.e., 1 t dry matter (DM) logging residue or sawdust, respectively, but the results are represented for 1 MJ liquid biofuel produced in all the pathways. The process parameters and technologies described in the following paragraphs represent the BAT and refer to the base case in this study.

3.3.1. Ethanol

The ethanol production process consists of five process steps: pretreatment, hydrolysis, fermentation, distillation, and dehydration. The process parameters for forest residues and sawdust are based on previous studies [22,24,31,32]. The process in general includes the following steps: first, the size of the biomass is reduced to approximately ≈50–80 mm using a shredder or a knife mill. After shredding, feedstock is soaked in 2% SO₂, and is steam pretreated for 1 h at 210 °C. During pretreatment, the rapid release of pressure opens up the feedstock structure and leads to the removal of hemicellulose. The pretreated slurry is used for the hydrolysis using cellulase enzymes, and enzyme dosage is dependent on the kind of biomass. In this study, the base case scenario represents on-site, low emission future European cellulase enzyme production from sugar beet molasses as a carbon source and biogas as the energy source for the production. During enzymatic hydrolysis, the complex sugars are broken into monomer glucose and xylose units, which are later converted to ethanol using a yeast called *S. cerevisiae* during the fermentation process. Ethanol produced after fermentation is distilled using multiple effect evaporators and dehydrated to anhydrous ethanol (pure ethanol). The solid residue left after the distillation can be used as a solid fuel, and the liquid fraction is digested anaerobically to produce biogas that can be used to produce steam and electricity.

3.3.2. HVO

The conversion pathway considered for HVO production in the base case is the fast pyrolysis of biomass followed by upgrading of bio-oil to diesel (referred to as HVO here) using renewable sources of hydrogen. The process parameters are based on [22,30]. The fast pyrolysis includes raw material pre-processing where the feedstock is dried from 55% moisture content to 8–10% and thereafter ground to a particle size < 5mm. Dried biomass facilitates the fast heat up in the pyrolysis process required for higher bio-oil yield, and a smaller size ensures the complete reaction of the particle in the short residence time in the reactor. Then, dried and ground biomass is rapidly heated to a temperature of 520 °C in a fluidized bed reactor under high atmospheric pressure and an oxygen-free environment using nitrogen. After the residence time of 1–2 s, there is a formation of pyrolysis vapors that are quickly condensed to about 35 °C for the formation of bio-oil product approximately (65–75%), by weight along with the char (16–23%), and non-condensable gases (10–12%). Bio-oil produced in the fast pyrolysis process is unstable, and in order to blend directly with conventional fossil fuel, it requires the hydrotreatment process with an input of hydrogen to upgrade it to a stable oil. The hydrogen use is considered to be renewable in origin produced via electrolysis using electricity produced by

wind turbines [33]. After upgrading, the bio-oil is distilled into the hydrocarbon fractions that boil in gasoline, diesel, and heavy products [30].

3.3.3. LBG

The conversion pathway from feedstock to LBG first includes conversion to biomethane using an indirect gasification unit of 520 GWh in the base case. The selection of gasifier is based upon the up-scale facility of the GoBiGas plant in Gothenburg, Sweden. The gasification of biomass generates gaseous products consisting of methane (CH₄), carbon dioxide (CO₂), carbon monoxide (CO), and hydrogen (H₂). Additionally, the gas is contaminated with various contaminants such as alkali, ammonia, dust, tar, and sulfur that must be removed prior to methanation. Raw biogas is upgraded using water scrubbing technology to remove sulfur and CO₂ followed by chemical scrubbing. The process parameters for biomethane production are based on [17,23,26]. The biomethane produced in gasifiers passes through various steps of gas cleaning and conditioning systems before the purified gas can pass through the methanation process, converting CO and H₂ to CH₄ and CO₂ [23]. Thereafter, biomethane is upgraded to liquefied form, where biomethane is chilled to −161 °C using a closed nitrogen reversed Brayton cycle method. The methane slip from the liquefaction process is assumed to be negligible. LBG produced is stored in a vacuum insulated vessel. Due to a lack of feedstock-specific data for the processing phase, it is assumed that the logging residue and sawdust uses a similar kind of input and gives a similar yield as the output.

3.4. Biofuel Distribution

Ethanol, HVO, and LBG are distributed from their production site to the fueling station via the road, and the distance is assumed to be 200 km. The carrying capacity of the truck for the distribution of ethanol and HVO is 24 t with an energy consumption of 0.59 MJ/tkm. In the case of LBG, the carrying capacity of the semi-trailer with a tank is 30 t or 40,000 Nm³ and the fuel consumption is 0.46 L/km.

3.5. Assessment of Feedstock Potential

Data regarding the feedstock potential in the form of logging residues for biofuel production are based on [9,21,34,35]. This assessment includes technical and environmental restrictions; thus, it represents the long-term sustainable harvest of logging residues after final felling in conifer stands. In addition, economic restrictions are partly included related to transportation distances and the productivity of forest sites. The assessment of the feedstock potential in the form of sawdust is based on data from Swedish Forest Industries [27] regarding the number and size of sawmills in Sweden and the generation of sawdust in sawmills from [28,29].

4. Results and Discussion

This section describes the results in three parts: (i) logging residue and sawdust potentials for biofuel production; (ii) GHG performance; and (iii) energy analysis of ethanol, HVO, and LBG pathways. The results of GHG emissions and energy analysis are represented for 1 MJ energy as the functional unit. Details of GHG emission and the primary energy factors of all the input materials are given in Appendix B.

4.1. Potential of Feedstocks

The assessment of the forest residue biomass potential in Sweden shows that the long-term sustainable potential of logging residues for energy purposes amounts to about 100 PJ per year. This potential includes restrictions regarding effects on biodiversity, forest soil acidification and nutrient balances, and soil carbon contents. Thus, in reality, only about 50% of the productive forest area in Sweden is available for logging residue recovery, also taking into account other critical sustainability parameters [34]. The use of logging residues for energy purposes in Sweden is currently

equivalent to about 35 PJ, mainly in district heating systems for heat or combined heat and power production. Thus, two-thirds of the potential is not utilized today and could theoretically be available for biofuel production, which is equivalent to about 65 PJ per year. This unused potential is mainly located in northern Sweden, having less densely populated regions, compared with central and southern Sweden. From this perspective, future large-scale biofuel plants may be suitable to locate in the northern part of Sweden close to available feedstock. However, the demand of, for example, district heat is estimated to be reduced in the future driven by energy efficiency improvements in the building stock, leading to an increase in the unused potential of logging residues also in the central and southern part of Sweden [9]. Therefore, feedstock in the form of logging residues for large-scale biofuel plants is also estimated to be available in more densely populated regions in Sweden.

The corresponding potential of sawdust is estimated to amount to about 35 PJ per year in Sweden, but this amount of energy is almost completely utilized today for energy purposes such as for the production of process heat in the forest industry, district heat, and pellets. A minor amount is utilized as feedstock for wood-based panels. Increased demand of sawdust as feedstock for biofuel production may lead to various dynamic effects, which is driven by increased prices. Today, the price of by-products such as sawdust and bark for district heating plants is around 15% lower than for wood chips from logging residues and around 40–45% lower than for refined by-products such as pellets [36]. Of the total yearly revenue for an average sawmill in Sweden, approximately 3% and 2% come from sawdust and bark, respectively [37,38]. Thus, when the sawdust is refined to pellets, the gross income for sawdust may increase equivalent to some 5% of the yearly total revenue for a sawmill. It is here estimated that the willingness to pay for sawdust as feedstock for biofuel production will correspond to a level that gives sawmills at least equivalent or somewhat higher net revenues for the sawdust compared to when it is utilized for pellet production. This is because sawdust is regarded as a promising feedstock for various biofuel production routes due to it being a homogeneous feedstock with few or no impurities [24]. In addition, large amounts of sawdust are used for heat generation today, although other low-cost wood fuels, such as bark, could be used instead. Bark is a less suitable feedstock for biofuel production, but it is appropriate for heat production, and the bark potential in Sweden, which exceeds the sawdust potential (equivalent to about 45 PJ per year including both sawmills and pulp mills), is not effectively utilized for energy purposes today. Furthermore, there are significant energy efficiency potentials within the forest industry leading to increased surpluses of both sawdust and bark [39,40]. Therefore, a rough estimation is that up to two-thirds of the total sawdust potential may be available as feedstock for biofuel production in the future, equivalent to about 25 PJ [24], due to the dynamic price effects and re-allocation of wood fuels discussed above. The remaining potential is estimated to be used mainly for continued pellet production.

To sum up, the total long-term sustainable potential of logging residues and sawdust in Sweden for energy purposes is estimated at approximately 100 PJ and 35 PJ per year, respectively, of which two-thirds of this total amount could be available as feedstock for biofuel production in the future. This amount, equivalent to 90 PJ (about 25 PJ from sawdust and 65 PJ from logging residues), could then generate between 30 and 60 PJ biofuel (excluding other co-products generated), depending on the system and biofuel. The potential production of ethanol, HVO, and LBG from 90 PJ lignocellulosic feedstock amounts to roughly 32, 35, and 59 PJ, respectively. For comparison, the current use of diesel in the Swedish transport sector amounts to approximately 130 PJ annually, of which about 60 PJ is used for heavy-duty road transport [41]. Thus, according to the estimated biofuel potentials presented above, between 50% and 100% of the current use of diesel in heavy-duty road transport in Sweden could theoretically be replaced by domestic forest residue-based biofuels in the future. The various amounts of liquid biofuels generated in the different production systems, for example, almost half the amount of ethanol compared with LBG, do not mean that the ethanol production systems are less suitable from a broad energy systems perspective. As can be seen in Table 2, the overall energy conversion efficiency, also including valuable by-products for other energy purposes, is almost similar (61–65%) for the various biofuel systems. Future production systems of forest-based biofuels are expected to be

mainly integrated into existing infrastructure in the form of forest industries, district heating plants, etc., due to economic reasons where the total energy conversion efficiency can be fully utilized.

Table 2. Brief overview of conversion technology, conversion efficiency (%) MJ LHV/MJ LHV, products and byproducts produced in different pathways.

Technology	Ethanol		HVO	LBG
	Fermentation		Fast Pyrolysis Followed by Upgrading	Gasification Followed by Liquefaction
	Logging residue	Sawdust	Logging Residue/Sawdust	Logging Residue/Sawdust
Biofuel (%)	33	37	39	65
By-products (%)				
Biogas	24	25	-	-
Electricity	5	2	-	-
Others ^a	-	-	22	-
Overall efficiency (%)	62	64	61	65

^a Other by-products in HVO production are gasoline and heavy hydrocarbons.

4.2. GHG Performance

GHG performance, categorized in the global warming potential (GWP) and expressed as g CO₂eq. per MJ biofuel, is summarized in Figure 2 for all three pathways. The results for the individual pathways are described in more detail below.

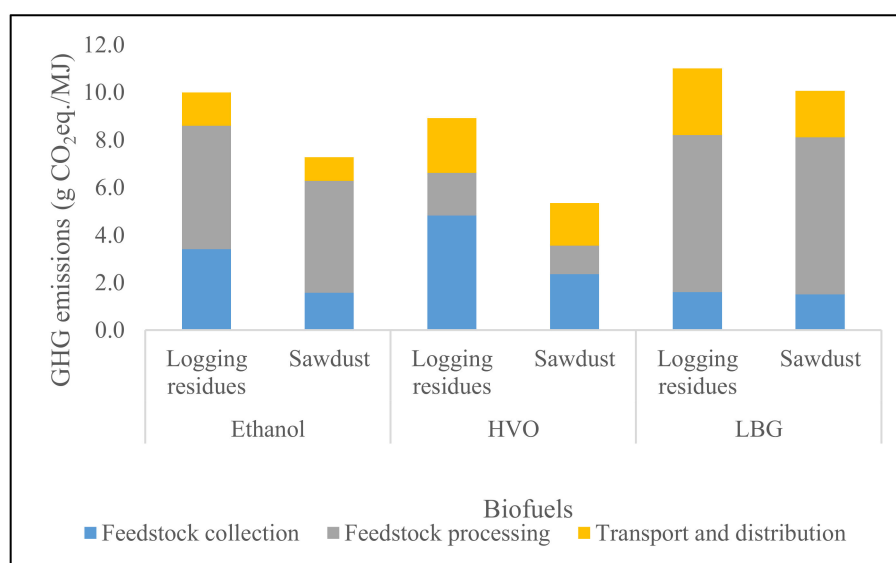


Figure 2. Well to tank greenhouse gas (GHG) performances of ethanol, hydro-processed vegetable oil (HVO) and liquefied biogas (LBG) from forestry residues and sawdust.

4.2.1. Ethanol

Ethanol production from logging residues and sawdust results in GHG emissions of 9 and 7 g CO₂eq./MJ, respectively (Figure 2), corresponding to GHG emission reductions of 91 and 92% respectively when compared to the fossil reference value of 94 g CO₂eq./MJ. Emissions from forest residue-based ethanol result in less than one-fourth of the default life cycle GHG emissions of 30 g CO₂eq./MJ from ethanol being currently used in Sweden produced from crops and cereal feedstock. This difference in emissions is explained by the variation in choice of feedstock, conversion technologies, and calculation methodologies. Cereal and food crops are burdened with a large amount of GHG emissions from the cultivation phase, whereas residues have zero burden from similar processes.

At the same time, comparing the results to [31], the authors studied the forest residue-based ethanol life cycle GHG emissions and reported them to be 14.9 g CO₂eq./MJ, which are higher than the current study. This is because of a change in enzyme configuration where the previous study uses the purchase of enzyme produced outside the ethanol plant, which is referred to as off-site enzyme production, whereas in the present study, we have assumed the on-site production of the enzyme using molasses residue from the sugar industry as a carbon source and internally generated biogenic electricity. The use of molasses in on-site production is associated with zero emissions, whereas the off-site enzymes using commercial cellulose also contributes toward GHG emissions.

From previous studies, it has been concluded that the major emission hotspots in the ethanol life cycle are enzyme and chemical use in the process [32,42]. The use of enzymes prepared off-site results in higher GHG emissions than the enzymes produced on-site [24,32,43]. One of the reasons for higher GHG emissions during off-site enzyme production and use is the excess energy use in stabilizing and drying of the enzyme.

4.2.2. HVO

HVO production from logging residues and sawdust results in GHG emissions of 8 and 5 g CO₂eq./MJ, respectively (Figure 2), corresponding to GHG emission reductions of 91 and 94% respectively when compared to the fossil diesel reference value of 94 g CO₂eq./MJ. Emissions from forest residue-based HVO results in more or less half of the default life cycle GHG emissions, i.e., 14 g CO₂eq./MJ from waste vegetable oil-based HVO being currently used in Sweden. Biomass conversion to HVO consists of three steps: pretreatment, fast pyrolysis, and upgrading, and it consumes heat, electricity, and hydrogen as the main input. Many authors have reported that the production and use of hydrogen during upgrading constitute the major emission hotspot in the life cycle [44–47]. In this case study, hydrogen use is considered to be renewable in origin produced via electrolysis and therefore results in lower emissions as compared to [30]. Life cycle GHG emissions are largely dependent on the source of hydrogen and switching from non-renewable to renewable sources significantly reduces GHG emissions. Furthermore, the oxygen content of bio-oil produced after pyrolysis determines the hydrogen demand to meet the standard oxygen level from the refinery and engine perspective [48]. The impact of emerging technologies that can result in lower oxygen content of bio-oil change, e.g., hydrothermal liquefaction (HTL) and change in hydrogen production systems, is further studied in the sensitivity analysis.

4.2.3. LBG

LBG production from logging residues and sawdust results in GHG emissions of 11 and 10 g CO₂eq./MJ, respectively (Figure 2), corresponding to GHG emission reductions of 88 and 89% respectively when compared to the fossil diesel reference value of 94 g CO₂eq./MJ. The liquefaction of 1 Nm³ of raw biomethane results in 21 MJ of LBG and is the only product generated from the processing [17]. The gasification and upgrading process is responsible for higher emissions as it includes various steps such as tar removal, sulfur removal, and CO₂ removal before methanation, and it consumes electricity. Due to the large amount of pressure used in the water-scrubbing technology, the consumption of electricity increases. Some authors have reported that plants using amine scrubbing technology for upgrading, instead of water scrubber as assumed here, have lower GHG emissions as it operates slightly above atmospheric pressure, which reduces the need for a compressor and can work by implementing the only blower, which reduces the electricity demand [17].

4.3. Energy Analysis

The results from the energy analysis for all three pathways are represented as MJ/MJ and are shown in Figure 3.

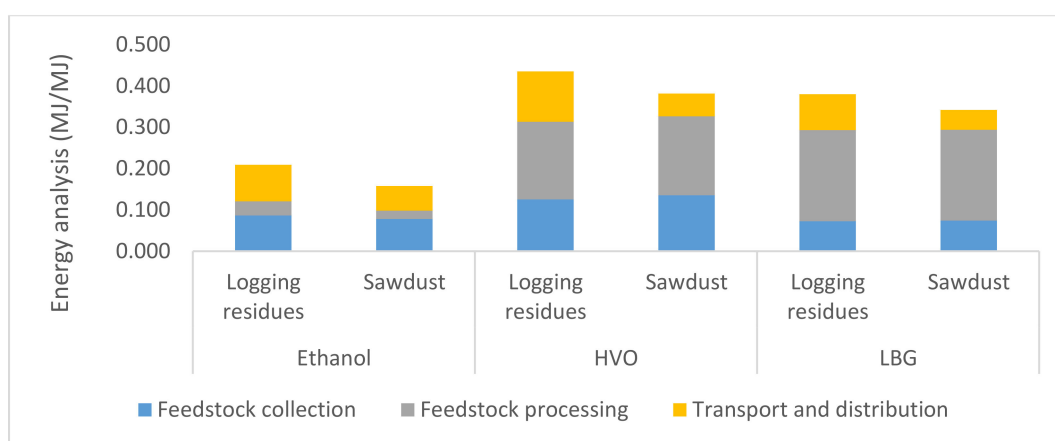


Figure 3. Energy analysis (MJ/MJ) for ethanol, HVO, and LBG from logging residues and sawdust.

For ethanol, the primary energy input for forest residue and sawdust is 0.20 and 0.16 MJ/MJ ethanol, respectively. The highest energy input is related to the chemical and enzyme use during biomass conversion to ethanol. The heating and electricity requirement in the plant is met internally from the co-products generated during the process.

For HVO, the primary energy input for forest residue and sawdust is between 0.43 and 0.38 MJ/MJ HVO, respectively. The highest energy input is related to the process of electricity consumption and energy use in hydrogen production. The heating requirements of the fast pyrolysis process are met by burning the biochar, and power requirements are met by the electricity from the grid.

For LBG production, the primary energy input varies between 0.38 and 0.34 MJ/MJ LBG. The highest energy input is related to the liquefaction process.

4.4. Sensitivity Analysis

The analysis of new technologies now being implemented is more complex than the already existing and commercial technologies, such as ethanol production from crops or biogas production from anaerobic digestion. Therefore, results drawn from the LCA studies include inherent uncertainties, which are addressed in this study by conducting extensive sensitivity analysis. By keeping the LCA methodology constant (RED 2) and changing the design of the production systems, the impact on GHG emissions and energy performance is evaluated. The details of each sensitive parameter analyzed for different pathways are given in Table 3.

Table 3. Sensitivity analysis parameters used in the study for various biofuels.

Biofuels	Parameters Changed
Ethanol	<ul style="list-style-type: none"> Changing off-site enzyme configuration to on-site
HVO	<ul style="list-style-type: none"> Changing H₂ supply system from renewables to fossil feedstock Using HTL as an emerging technology instead of fast pyrolysis for bio-oil production
LBG	<ul style="list-style-type: none"> Change in size of gasification plant from 520 to 1600 GWh methane per year

4.4.1. Ethanol

Changing Enzyme Configuration

As reported in the literature, one of the important GHG emission hotspots in the life cycle of ethanol is the enzyme dosage [22,31,32]. Emissions related to enzymes are mainly in the production phase with the contribution from the carbon source and energy use. In the base case, data are based on future European plants with an on-site enzyme production facility using molasses as feedstock and renewable electricity. In addition, enzyme dosages are on the lower side, i.e., 2.1 and 2.7 kg enzyme protein per ton of logging residues and sawdust, respectively, compared to commercially purchased 8.1 kg enzyme/ton logging residue [31] and 30 kg/t sawdust [32]. The difference in the amount of enzyme is due to the higher enzyme activity obtained on-site, which in turn reduces the enzyme dosage [24]. Table 4 compares the GHG emissions arising from BAT in the base case to the off-site enzyme technology reported in the previous literature. It is evident from Table 4 that the life cycle GHG emissions are reduced while integrating on-site production of enzymes together with ethanol facility. Apart from integration, the choice of carbon source, energy source, and enzyme dosage are also critical in determining GHG emissions.

Table 4. Impact of changing enzyme configuration on ethanol life cycle GHG emissions.

	On-Site		Off-Site	
	Logging Residue	Sawdust	Logging Residue	Sawdust
Enzyme used (kg/t)	2.1	2.7	8	30
GHG emissions (g CO ₂ eq./MJ)	9	7	14	30

4.4.2. HVO

Hydrogen Production System

As reported in several studies [44,45], the use of hydrogen for bio-oil upgrading could be the major emission hotspot in the life cycle of HVO depending on the source of hydrogen production. For fair understanding and realizing the importance of renewable sources for hydrogen production, sensitivity analysis is performed for evaluating the impact of different sources for hydrogen production on the overall life cycle GHG emissions of HVO. Based on the literature, different sources of hydrogen production such as electrolysis, biomass gasification, steam methane reforming, and coal gasification are studied here [49]. GHG emission factors for hydrogen production from various methods are given in Table 5 [50].

Table 5. Emission factor for hydrogen production from various sources [50,51].

Method	Feedstock	GHG Emission Factor (kg CO ₂ eq./kg H ₂)
Electrolysis (wind)	Wind turbine electricity	0.0325
Electrolysis (photovoltaic)	Solar electricity	0.37
Biomass gasification	Biomass	2.67
Steam methane reforming	Natural gas	11.95
Coal gasification	Coal	24.2

The impact of these sources on the overall life cycle GHG emissions is shown in Figure 4. It is evident from Figure 4 that fossil sources for H₂ production such as coal gasification and steam methane reforming (SMR) increase the emissions up to 80–90% compared with the current base case based on electrolysis via renewable sources. GHG emissions are lowest when the H₂ is produced from the electrolysis of wind and are highest when H₂ is produced from the gasification of coal. Thus, the source of hydrogen is a determining factor in the life cycle of GHG emissions, and only renewable H₂ has the potential to meet the GHG emission reductions target.

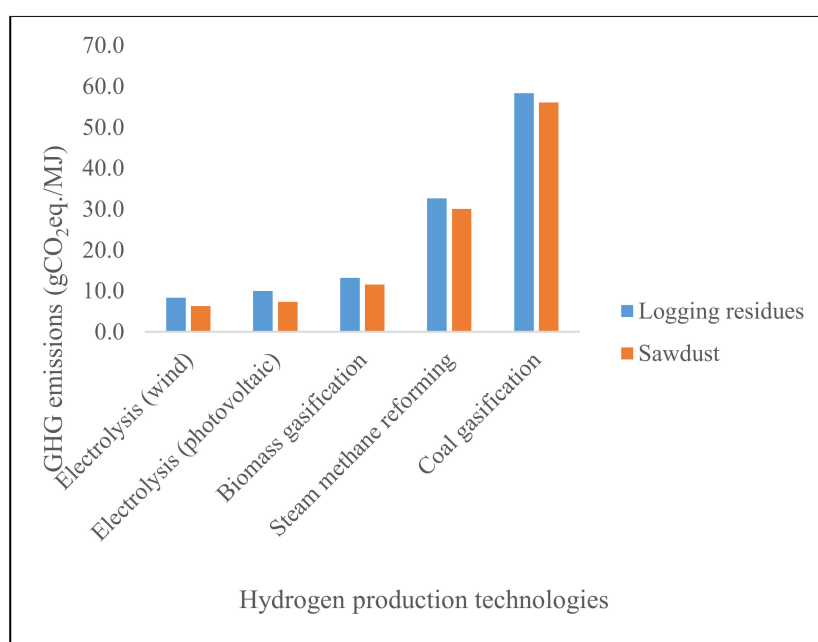


Figure 4. Change in HVO life cycle GHG emissions using renewable and non-renewable sources for hydrogen production.

Change in the Production Technology from Fast Pyrolysis to Hydrothermal Liquefaction (HTL)

HTL is an emerging technology to produce oil referred to as bio-crude or bio-oil, which is further upgraded to produce different fuels [48,52]. The major differences in the process as compared to fast pyrolysis are that during the pretreatment process in HTL, biomass is ground to fine particles without drying, and biomass is softened by direct injection of the hot water. The particle size in HTL does not require a reduction in size to a great extent, and slurry comprised of 8 wt % solids loading is feasible for the processing. The slurry is directed to the HTL reactor for further preheating and pressurization. The biomass slurry undergoes a conversion to the bio-crude along with various aqueous and gas phase products. The filtered solids consist of the unreacted biomass mainly in the form of char and unprecipitated minerals. The liquids produced from the liquefaction of the biomass are upgraded through a catalyzed reaction process, where the oxygenated product is treated with hydrogen under high pressure and temperature. The end result improves the overall quality of the finished product [30]. GHG emissions from the HTL of forest residues and sawdust results in GHG emissions of 3 and 2 g CO₂eq./MJ respectively (Figure 5).

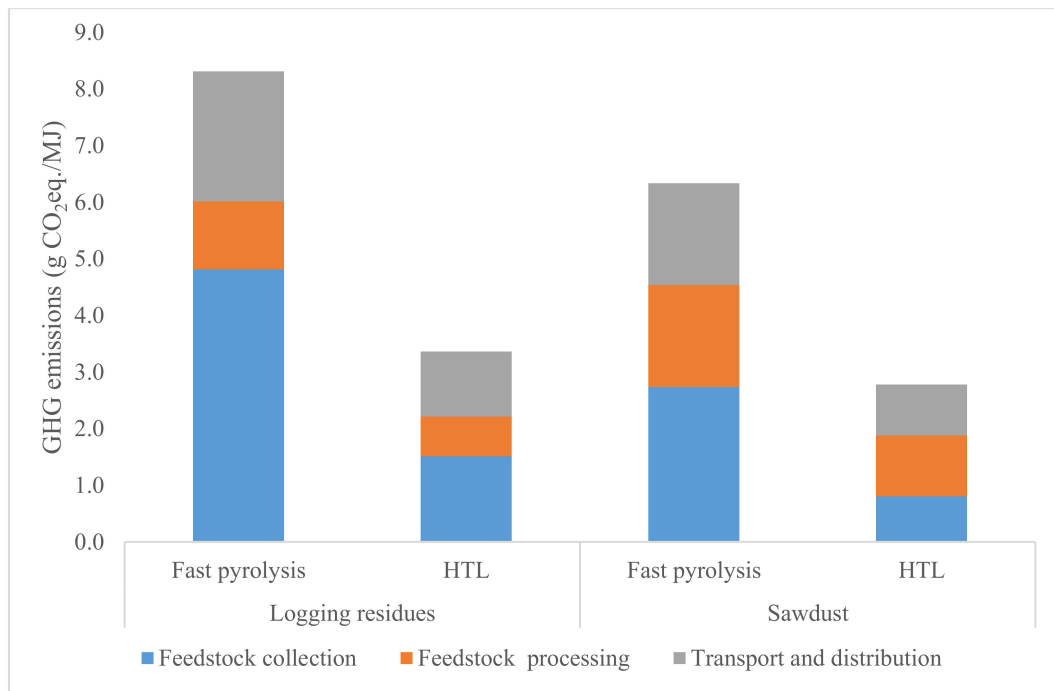


Figure 5. Impact on HVO life cycle GHG emissions by changing fast pyrolysis to hydrothermal liquefaction (HTL).

The emissions are lowered down to around 50% as compared to emissions using the fast pyrolysis pathway due to the lower consumption of electricity and hydrogen during the liquefaction and upgrading. As HTL oil is less oxygenated than pyrolysis oil, the requirement of hydrogen per unit of fuel decreases. The oxygen content of the produced oil is crucial in determining the hydrogen input to meet the required oxygen. Moreover, the yield of HVO also doubles in the case of HTL, and therefore, emissions per MJ are lowered from all the unit processes, as shown in Figure 4. The sensitivity analysis results show that HTL is a promising emerging technology for bio-oil production with a reduced need for H₂; thus, if only fossil H₂ is available, it will have much better GHG performance than pyrolysis.

4.4.3. Liquefied Biogas (LBG)

Changing the Size of the Gasifier Unit

The type of gasifier provides different gas qualities and compositions, and the choice of gasifier type also has a strong influence on the design of the subsequent gas cleaning and conditioning as well as on methane synthesis. In order to expand the production of LBG in the future, this is expressed as an emerging technology with a need for a larger gasifier unit. An oxygen blown and circulating fluidized bed gasifier (CFB) of 1600 GWh capacity per year has been analyzed and compared with the base case gasifier unit of 520 GWh. By increasing the size of the gasifier unit, there is a reduction of about 16% GHG emissions from the LBG production process using forest residue (Table 6).

This is because in a large capacity plant, the demand of electricity per functional unit is lower, and there is also an excess production of electricity from the system. The smaller size gasifier unit of 520 GWh with indirect gasification is only self-sufficient to meet its own energy demand.

Table 6. Impact of gasifier size on GHG emissions during feedstock processing [26].

Feedstock Processing Steps	GHG Emissions (g CO ₂ eq./MJ)	
	Gasifier (520 GWh)	Gasifier (1600 GWh)
Gasification ^a	4.6	4.2
Liquefaction	2.4	1.7
Total	7.0	5.9

^a Emissions from upgrading are included in this step.

5. Conclusions

The overall conclusion in this study is that forest residue-based liquid biofuels for heavy-duty vehicles have the potential to reduce the WTT GHG emissions by 88 to 94% compared to fossil diesel fuel. Ethanol, in the form of ED 95 (HVO) from pyrolysis oil and liquefied biogas (LBG) produced via thermal gasification will have WTT GHG emissions equivalent to 7–9, 5–8, and 10–11 g CO₂eq./MJ, respectively, according to the GHG calculation method defined in the EU RED. The lower emissions relate to sawdust as feedstock, whereas the higher emissions relate to logging residues from forestry. The energy input in the assessed production pathways varies between 0.20 and 0.43 MJ/MJ, whereas the total conversion efficiency from the biomass feedstock to the final biofuel, including by-products, varies between 61 and 65%. For example, critical parameters for the GHG performance are enzyme production systems for ethanol, hydrogen production systems for HVO, as well as bio-oil production systems (e.g., fast pyrolysis or hydrothermal liquefaction, HTL), and size and design of the thermal gasification unit for LBG.

The biomass feedstock potential for biofuel production in the form of sawdust from the Swedish forest industry sector and logging residues after final felling in conifer stands in Swedish forestry are estimated to be significant compared with the current use of fossil diesel fuel in road transport. The estimated biomass potential refers to a long-term sustainable utilization of the forest residue feedstock also including other critical sustainability criteria, such as preserving biodiversity, etc. The potential production of ED 95, HVO, and LBG from available sawdust and logging residues in a future growing biofuel market is here estimated to be equivalent to 50 to 100% of the current use of diesel in heavy-duty vehicles for road transport in Sweden. Thus, this significant production volume potential, in combination with the significant GHG savings of biofuels, makes a large-scale commercial expansion of forest-based biofuels a promising strategy for Sweden to reach the ambitious climate goals of reducing the GHG emissions in the road transport sector by 70% until 2030.

Author Contributions: S.S. collected the data, designed methodology and performed LCA and energy analysis for all three mentioned pathways. P.B. developed the framework of study, collected background data and assessed the feedstock potential. Both authors have an equal contribution in writing and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Life cycle inventory of ethanol production from 1000 kg feedstock [24,31,32].

	Logging Residues	Sawdust
INPUT		
<i>Feedstock collection</i>		
Diesel (MJ)	230	112
<i>Feedstock processing</i> ^a		
Feedstock (kg)	1000	1000
SO ₂ liquid (kg)	13	10
Ammonia 25% (kg)	8	0
NaOH (kg)	0	30
Enzyme (kg) ^b	2.1	2.8
Antifoam (kg)	16	16
Electricity (MJ) ^c	463	448
Steam (kg) ^d	180	179
<i>Transport and distribution</i>		
Diesel (MJ)	94	68
OUTPUT		
Ethanol (MJ)	5250	6250
Biogas (MJ)	3805	1575
Lignin Pellets (kg)	180	298

^a Feedstock processing includes pretreatment, hydrolysis, fermentation, distillation, and dehydration; ^b Enzyme here represents enzyme protein and not the enzyme formula; ^c Electricity is produced internally in the plant from leftover lignin after fermentation; ^d Steam requirements are met by the secondary steam produced while burning the lignin in plan.

Table A2. Life cycle inventory of HVO production from 1000 kg feedstock [22,30,53].

	Logging Residues	Sawdust
INPUT		
<i>Feedstock collection</i>		
Diesel (MJ)	230	112
<i>Feedstock processing</i> ^a		
Feedstock (kg)	1000	1000
Bio-oil ^b (kg)	659	747
Hydrogen (kg)	32	36
Electricity ^c (MJ)	884	1024
Heat (MJ) ^d	2337	2705
<i>Transport and distribution</i>		
Diesel (MJ)	110	85
OUTPUT		
Biochar ^e (MJ)	5888	4600
Gasoline (MJ)	9024	9844
Diesel (MJ)	3620	3949
Heavy hydrocarbon (MJ)	1933	2109

^a Processing includes pretreatment, fast pyrolysis, and upgrading; ^b Bio-oil is produced during the pyrolysis process and is an input for the upgrading process; ^c Also includes electricity used in hydrogen production; ^d Heating requirements are met by burning the biochar internally; ^e Biochar is an output of pyrolysis process but is used as an input to produce the heat.

Table A3. Life cycle inventory of LBG production from 1000 kg feedstock [17,23,26].

	Logging Residues	Sawdust
INPUT		
<i>Feedstock collection</i>		
Diesel (MJ)	230	112
<i>Feedstock processing</i>		
Feedstock (kg)	1000	1000
Electricity ^a (kWh)	0.63	0.63
<i>Transport and distribution</i>		
Diesel (MJ)	133	93
OUTPUT		
Biomethane (MJ)	12025	12025

^a Liquefaction consumes 0.63 kWh/Nm³ upgraded biogas.

Appendix B

Table A4. GHG emission and primary energy factor of various inputs used in three pathways.

Input	GHG Emission Factor		Primary Energy Factor		Reference
	Unit	Value	Unit	Value	
Sulfur	kgCO ₂ eq./kg	0.84	MJ/kg	7.8	[32]
Phosphorus	kgCO ₂ eq./kg	2.32	MJ/kg	5.52	[31]
Ammonia	kgCO ₂ eq./kg	3.23	MJ/kg	11.1	[31,32]
Sodium hydroxide	kgCO ₂ eq./kg	0.95	MJ/kg	16	[24,42]
Sulfuric acid	kgCO ₂ eq./kg	0.09	MJ/kg	3.6	[24,32]
Molasses	kgCO ₂ eq./kg	0.14	MJ/kg	0.57	[24]
Antifoam	kgCO ₂ eq./kg	1.33	MJ/kg	24.4	[32]
Enzyme	kgCO ₂ eq./kg	6.05	MJ/kg	NA ^a	[24]
Hydrogen	kgCO ₂ eq./kg	0.0325	MJ/kg	12.01	[33]
Diesel ^b	gCO ₂ eq./MJ	77	MJ/MJ	1.09	[24,26]
Swedish electricity mix	gCO ₂ eq./MJ	13.1	MJ/MJ	2.1	[24,26]

^a Data are unavailable on electricity use in on-site enzyme preparation. However, the calculations include the electricity use (internally produced electricity) of 0.59 kWh/L ethanol, and this also includes the enzyme preparation [42]. ^b Diesel is blend of 23% biodiesel and 77% fossil diesel.

Table A5. Lower Heating Value of the intermediate product, main product (biofuel), and by-products of three pathways.

Input	Unit	Value	Reference
Intermediate product			
Bio-oil	MJ/kg	17	[30]
Biochar	MJ/kg	26	[30]
Biofuels			
Ethanol	MJ/kg	27	[22]
HVO	MJ/kg	44	
Biomethane	MJ/Nm ³	35	[24]
By-product			
Dry lignin	MJ/kg	18	[42]
Gasoline	MJ/kg	43	[30]
Heavy hydrocarbon	MJ/kg	39	[30]

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