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- according to the EU renewable energy directive calculation methodology

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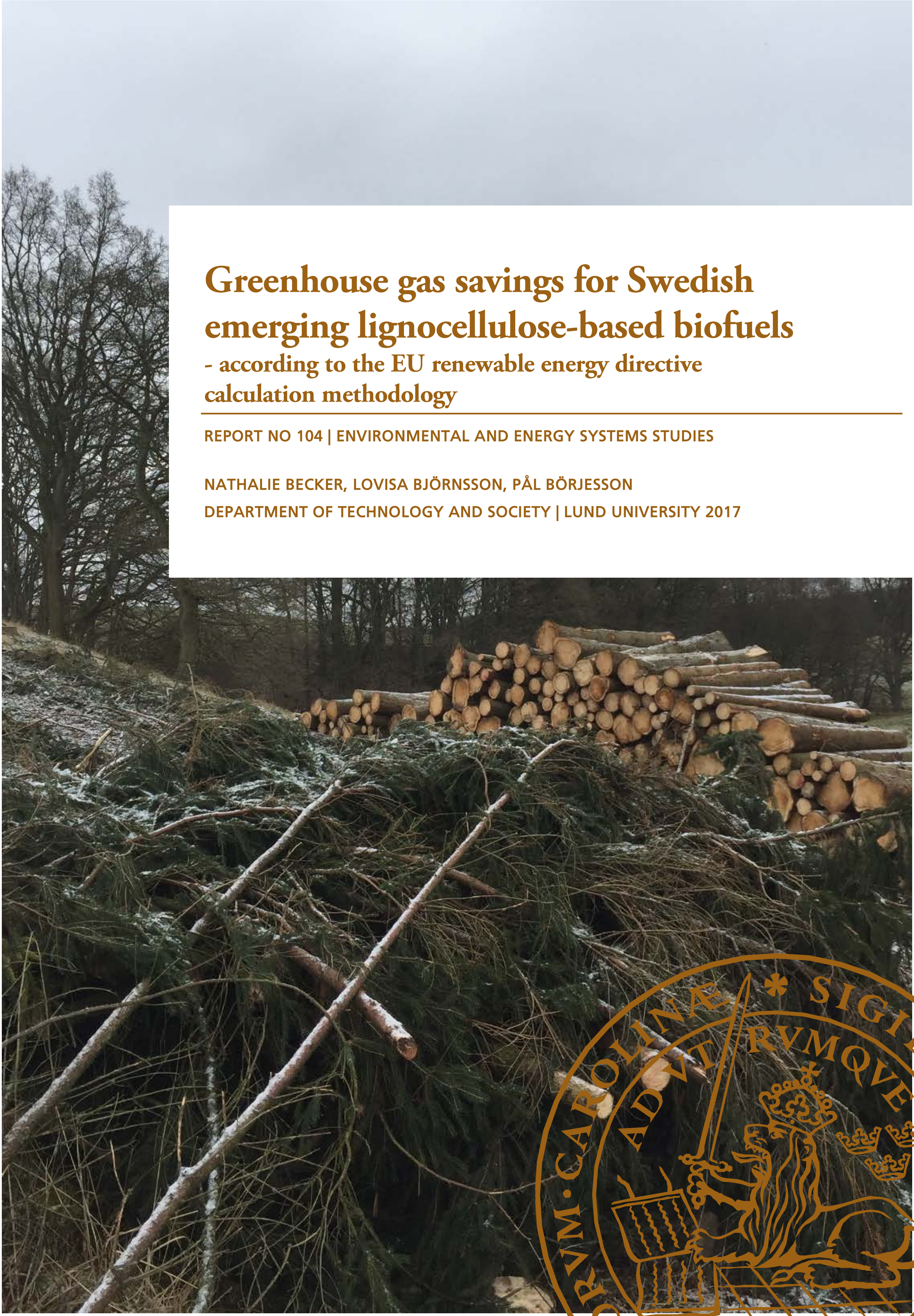
DEPARTMENT OF TECHNOLOGY AND SOCIETY | LUND UNIVERSITY 2017



Greenhouse gas savings for Swedish emerging lignocellulose-based biofuels

- using the EU renewable energy directive calculation methodology

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Cover photo: logging residues (branches and tops) left to dry in the cutting area before removal for energy purposes. Photo Lovisa Björnsson

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Foreword

This report is based on a study conducted within the research project “Improved sustainability performance in cellulose based ethanol production”, financed by the Swedish Energy Agency, who are gratefully acknowledged. Special thanks to Emmi Josza for valuable input to the study.

Lund, October 2017

The authors

Summary

According to amendments to the EU Renewable Energy Directive (EU RED) from 2009, biofuel production installations starting operation after October 2015 are required to present greenhouse gas (GHG) savings of at least 60% compared to the currently suggested fossil fuel reference of 83.8 g CO_2e MJ^{-1} fuel (Directive 2009/28/EC; EU 2015/1513). The objective of this study is to present updated calculations of the GHG savings for emerging lignocellulose-based biofuel production systems in the Swedish context. The considered biofuels are ethanol, methanol, hydrogenated vegetable oil (HVO) and methane based on feedstock from cultivated short-rotation coppice (willow), logging residues from forest operations, black liquor from pulp and paper industry and straw from cereal production. The GHG savings of the biofuel production pathways are evaluated using the method as suggested in the EU RED from 2009. Calculations include emissions from the extraction or cultivation as well as the collection of feedstock, emissions from processing and conversion as well as emissions from transport and distribution. The GHG emissions are expressed as carbon dioxide equivalents (CO_2e) per Mega Joule (MJ) of the biomass-based fuel, using the lover heating value (LHV). Technology-specific data from previous research and industry collaborations is applied. Since the calculation method in EU RED excludes emissions prior to the extraction of residual and waste biomass, the directive is explicitly favourable for biofuel production systems making use of logging residues, black liquor and straw. Thus, the residue based production pathways of methanol, methane, and ethanol showed lowest climate impact (<6 g CO_2e MJ^{-1}), followed by the production pathways of HVO from residue tall oil, lignin oil from black liquor, and pyrolysis oil from logging residues (<9 g CO_2e MJ^{-1}). The cultivation of willow feedstock accounts for a significant part (>10 g CO_2e MJ^{-1}) of the biofuels' total GHG emissions. However, it could be seen that GHG savings for all investigated feedstock and pathways are between 81 – 96%, implying that the emerging ligno-cellulose-based production pathways considered in this study could fulfill current GHG reduction criteria. Also, the more rigid sustainability criteria discussed in the ongoing revision of EU RED for the period after 2020, with a GHG savings demand of 70% could be fullfilled.

Abbreviations

CFB	Circulating Fluidised Bed process (type of gasification technology)
CNG	Compressed Natural Gas
CO_2e	CO_2 equivalents calculated using equivalency factors provided in the Renewable Energy Directive (2009)
CTO	Crude Tall Oil
DM	Dry Matter
DV	Default Value
el	electricity
EtOH	Ethanol
GHG	Green House Gas
GWP	Global Warming Potential
ha	hectare, 10 000 m^2
HHV	Higher Heating Value
HVO	Hydrogenated Vegetable Oil
LHV	Lower Heating Value
m3ub	square meter [wood] under bark
MeOH	Methanol
RED 2009	Renewable Energy Directive 2009
RTD	Raw Tall Diesel
wc	wood chips

Chemical formulas

CH_4	Methane
CO_2	Carbon dioxide
H_2	Hydrogen
H_2SO_4	Sulphuric acid
N_2O	Nitrous oxide
SO_2	Sulphur dioxide

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1. Introduction

According to the amendment to the European Renewable Energy Directive (hereinafter referred to as EU RED), biofuel production installations starting operation after October 2015 are required to fulfil a sustainability criteria requiring a greenhouse gase (GHG) saving of at least 60% (Directive 2009/28/EC; EU 2015/1513). As biofuels based residues and waste are ascribed zero emissions until the biomass's point of extraction according to the EU RED, biofuel production systems based on these resources, are promoted. A recent analysis of the biomass supply potential in Sweden shows a significant unexploited potential of lignocellulosic biomass, both forest-based biomass deriving from agricultural operations (Börjesson, 2016). Previous studies show that Swedish biofuel systems based on Swedish biomass account for a significant reduction of GHG compared to current liquid fossil fuels (Börjesson *et al.*, 2013). The GHG performance of biofuels varies greatly depending on the design, technology and location of the production systems studied, as well as the calculation method and data used. The aim of the report is thus to present updated calculations of the GHG performance of lignocellulose-based biofuel production systems in Sweden (according to the EU RED method), which are currently under development and not in all cases commercially available technologies. The biofuel production pathways considered include the conversion processes hydrogenation, gasification, pyrolysis and fermentation. The choice of currently available and potential biomass in Sweden is based on recent studies conducted by Börjesson (2016), who provides extensive data on the Swedish context covering the last decades. Table 1 illustrates the biomass to biofuel pathways included in this report.

Table 1. Production pathways considered in this report.

	HVO	Methanol	Methane	Ethanol
tall oil (from black liquor)	√			
pyrolysis oil from lignin (from black liquor)	√			
pyrolysis oil (from logging residues)	√			
wood chips (from logging residues)		√	√	√
wood chips (from short-rotation coppice willow)		√	√	√
Straw				√

The technology for biofuel conversion selected for this report features best-available technology guided by a report on biofuels in the Swedish context by Börjesson *et al.* (2013). Greenhouse gas emissions arising analogue to production pathways are calculated according to the EU RED methodology. Furthermore, results on GHG emissions of yet unestablished Swedish cellulosic-based biofuels are compared to default values presented in the EU RED, and on new calculcations made by the JRC (2017) regarding suggested revised default values in the ongoing revision of the EU RED (COM(2016)767 final2, february 2017). The assumptions made and method used is introduced and described in the subsequent chapter. For a schematic overview over the pathways included in the study, consult Figure 1.

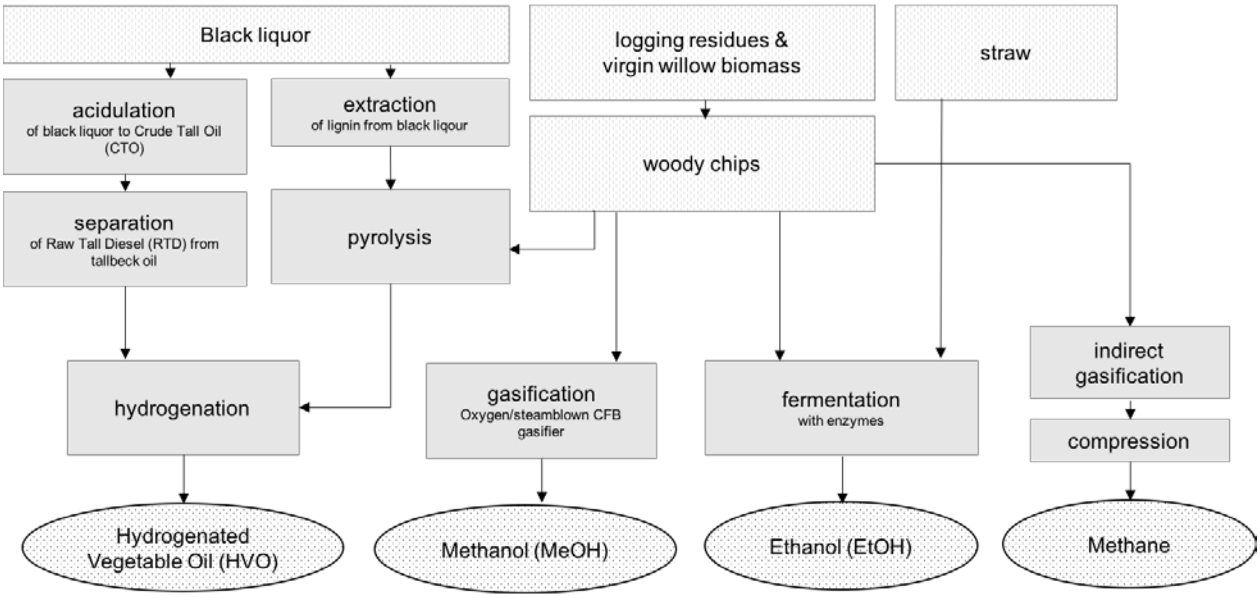

Figure 1. Schematic overview over biomass, pathways and biofuels considered in this report.

2. Assumptions and Method

2.1 Method

The greenhouse gas emission calculation method used in this study is described in the EU RED, and includes the greenhouse gas emissions caused by processes before conversion to biofuels, cultivation and/or extraction of raw material, intermediate processes and transport of intermediate products as well as distribution of final biofuel. The greenhouse gas emissions for fuel dispersion is not included in the calculations for this report.

2.1.1 EU RED method

The method to determine the GHG emissions of biofuels, to determine if they fulfill the GHG emission reduction according to the EU sustainability criteria, is outlined in Annex V, part C, §1 of the EU RED. The calculating procedure is as follows:

$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}$

where

E = total emissions from the use of the fuel;

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualised 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 products, the EU RED renders the parameters e_l, e_{sca}, e_{ccs} and e_{ccr} irrelevant. Also, the component e_{ee} is not applicable for the chosen technologies, that is stand-alone technologies. Excess energy from process is handled as described in the subsequent paragraph 'Allocation of emissions on by-products/intermediate products'. Land use change does not take place in case of the considered residual products, whereas the short rotation coppice willow is assumed to be cultivated on agricultural land, with no land use change taking place. The exhaustion emissions during use of biofuels are zero for biogenic CO_2 emissions (according to EU RED) and disregarded as well in the calculations. The EU RED methodology does not take into account soil organic carbon impacts possibly arising from the removal of residues like straw and logging residues.

Emissions eec, ep and etd

According to the EU RED methodology, e_{ec}, that is, emissions from the extraction or cultivation of raw materials, emissions from the extraction or cultivation process itself, from the collection of raw materials, from waste and leakages and from the production of chemicals or products used in extraction or cultivation are to be included. Emissions from processing, e_p, include emissions from the processing itself. Emissions from transport and distribution, e_{td}, include emissions from the transport and storage of raw and semi-finished materials and from the storage and distribution of finished materials (see EU RED, Appendix 5, C, §6/11/12). For calculations, e_p includes these emissions which arise during the final processing of the biofuel (for example gasification, hydrogenation, fermentation), whereas e_{ec} describes all these emissions that are precedent to the final processing (for example chipping, pyrolysis etc.)

Default Values

Results for GHG emissions calculated within this study for the specific choices of technology, biomass and transport distance are compared to default values for GHG emissions in the respective chapters. Default value signifies "a value derived from […] the application of pre-determined factors and that may, in circumstances specified in this Directive, be used in place of an actual value." (EU RED; article 2, n/o).

Greenhouse gas emission saving

The greenhouse gas emission saving is calculated based on following method[1] with an emission for fossil fuels of 83.8 g CO_2e/MJ[2].

$$\frac{(E\ F - E\ B)}{E\ F}$$

Where EB is the total emissions from the generation of the biofuel and EF is the emissions from combusting fossil fuel.

Global warming potential

CO_2	1
CH_4	23
N_2O	296

In order to calculate the GHG emissions, emissions of methane and nitrous oxide are recalculated to global warming potential and expressed as CO_2 equivalents (CO_2e), using the factors outlined to the right in accordance to the EU RED method[3], over a 100-year horizon. These factors deviate from the values outlined by the Intergovernmental Panel for Climate Change (IPPC) in their fourth and fifth assesment reports (IPCC, 2009; 2013), but for the sake of consistency of following the method outlined in the EU RED, the factors from the Directive are chosen.

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[1] EU RED: appendix V, part C, §4

[2] EU RED: appendix 5, part C, §19

[3] EU RED: appendix V, part C, §5

Documentation method

The report follows the data documentation recommendation, as outlined in the guidance on the use of the EU RED by the Swedish Energy Agency (2012), requiring:

- A description of production chain with the choice of system boundaries, including the quantification of energy flows;
- A description of the respective process steps, particularly for these calculations that require allocation of greenhouse gas emissions on tangible by-products (excluding electricity and heat);
- A description and reasoning of which data were used and which assumptions have been made as well as how missing data was handled; and
- Reporting which processes have been excluded from the calculations and why.

Functional unit

The global warming potential of the intermediate and final products is expressed in gram carbon dioxide equivalents (CO_2e) and relates to one Mega Joule (MJ) of the biomass based fuel. Also, the results of this report are based on the lower heating value (LHV) of fuels and dry mass (DM) of biomass..

Allocation of emissions on by-products/intermediate products

According to the EU RED method allocation of GHG emissions pertinent to the biofuel production process is carried out in proportion to the fuel's and the intermediate or by-product's energy content (determined by their lower heating values). In most cases, biomass fed into the conversion process is used to generate process heat and from process itself excess heat and electricity is generated. In case heat and electricity is fed back entirely to the process emissions deriving from the process were fully allocated to the final product. In these cases, where electricity beyond the process's needs is generated and leaves the process, emissions were allocated to this electricity, as to other by-products, according to their energy content. In Table 2, details on process's by-products and excess energy can be obtained.

2.1.2 Further clarifications

Data used for GHG calculations mostly is based on amount and type of energy used in the process (see tables in pathway descriptions and annex to replicate results). In cases where such values were not available, aggregated data, that is in this case GHG emission values for single process steps are used. However, in order to arrive at results of similar resolution, it was aimed for data of similar quality. More recent data was given preference over older data. For electricity utilization, the GHG emissions for a Nordic electricity mix of 34.9 g CO_2e/MJ electricity according to the calculations of Gode *et al.* (2011) is applied, as currently defined in the Swedish implementation guidelines for EU RED (Swedish Energy Agency, 2012). For diesel use in forestry operations and fossil fuel use in production processes the emission of 80.4 g CO_2e/MJ is used (Swedish Energy Agency, 2017), reflecting the emission for the 2016 average diesel blend in Sweden, with 21% biodiesel.

Transport

Data for energy demand for transport efforts is based on data from 2010 by ProBas[4] published within the academic publication on forestry and biofuels of Heinimann (2012) where the transport of fluids and final biofuels accounts

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[4] ProBas is the official database by the German Ministry for the Environment providing information on processes and their environmental impacts. The abbreviation denotes 'Prozessorientierte Basisdaten für Umweltmanagementsysteme' http://www.probas.umweltbundesamt.de/

for 0.59 MJ/tkm, referring to transport on road with a 40 ton truck, 24 ton load capacity, euro 5 standard (100% load, one way, no empty return included). Transport of woody biomass accounts for 0.67 MJ/tkm via road with a 40 ton truck with a volume capacity of 28 m^3 (one way, no empty return included) (ibid). For the transport of straw, GHG emissions from transportation derive directly from Karlsson *et al.* (2014) (one way, no empty return included) and are estimated to be transported the same distance as woody biomass (see chapters describing ethanol production). The distribution efforts for the transportation of methane are obtained from a study by Benjaminsson (2009) (see appendix logistics (SNG)).

Biofuel yield

The yields of biofuel (as described in Table 2) from biomass, including the yields in intermediate processes, provide information on the output of biofuel in relation to the biomass. The total conversion efficiency for the biomass resource will in some cases be higher, since some conversion pathways also include the production of other chemicals, fuels, heat and electricity.

The following Table 2 outlines the process parameters for the within the calculations chosen technology.

Table 2. Conversion technologies chosen in this report with brief descriptions on technology, conversion efficiency, capacity and by-products produced. Values as derived from references indicated.

	HVO		methanol	ethanol	ethanol	methane
	tall oil and logging residues*		logging residues and willow	straw	logging residues and willow	logging residues and willow
Technology	*hydrogenation*		*oxygen/steam-blown CFB gasifier*	*enzymatic hydrolysis and anaerobic digestion*	*enzymatic hydrolysis and anaerobic digestion*	*indirect gasification, oxygen blown CFB pressurised*
Reference	(Olofsgård & Englund, 2015)	(Huber & Corma, 2007)	(Börjesson et. al, 2013)	(Karlsson, Börjesson, Hansson, & Ahlgren, 2014)	(Olofsson et al., 2015)	(Heyne & Harvey, 2014)
capacity MW	1000	/	430	60	117 ***	90
feedstock to .. (MW)						
Biofuel	not available	/	219	30	38 **	63
Electricity	0	/	26 *****	3	1**	4
Heat	0	/	0	10	0	0
Others	****	/	0	2	30 **	0
yield % (MJ LHV / MJ LHV)						
feedstock to biofuel	87 (tall oil)	70 (pyrolysis oil)	51	49	33 **	65 ******
feedstock to biofuel and el	/	/	59	54	34 **	/
total conversion efficiency	not available		68	74	60 **	>90 ******
Details	By-product naphtha	/	/	By-product biogas	By-product pellets	/
choice of technology						
Details	established process, traditionally used for the hydrogenation of fossil fuel		established process, but case is based on theoretical calculations	purchased enzymes	on-site enzyme production on laboratory scale	established process

* for information about lignin oil from black liquor see section 3.2.3. ** values are calculated on the basis of case B described in the study by Olofsson *et al.*, (2015).

*** besides wood chips, molasses is included as raw material input. **** 27 kg naphtha/ton raw tall diesel (Olofsgård & Englund, 2015).

***** calculation assuming 0.6% of the biomass to be transformed into electricity according to Base case configuration with heat pump, condensing turbine with two steam levels by Holmgren *et al.* (2012).

****** based on the GobiGas project described in (Domínguez de María, 2016). For the description of the pathway, data from Heyne & Harvey (2014) were used.

3. Biofuel production pathways & emissions

In this chapter, results for chosen biofuel pathways are summarised. The subsequent chapters introduce the biofuel production pathways with a descriptive text on chosen technologies and process parameters applied. Tables furthermore outline data which served as base for calculations. These processes repeated in more than one biofuel production pathway are more thoroughly described in the appendix and only briefly introduced in the perspective pathways, in order to avoid redundant descriptions of process steps.

3.1 Summary of results

Investigations show that all production pathways considered in this report show good climate performance. This means that greenhouse gas savings vary between 81– 96% compared to the fossil fuel reference of 83.8 g CO_2e/MJ, and thus with good margin fulfill the sustainability criteria, requiring 60 % savings for installations starting operation after October 2015 (EU, 2015). A graphical overview on GHG emission savings and GHG emissions for the different parts of the production chains of the investigated lignocellulose-based biofuels is provided in Figure 2 and Figure 3. More details are given in the following chapters.

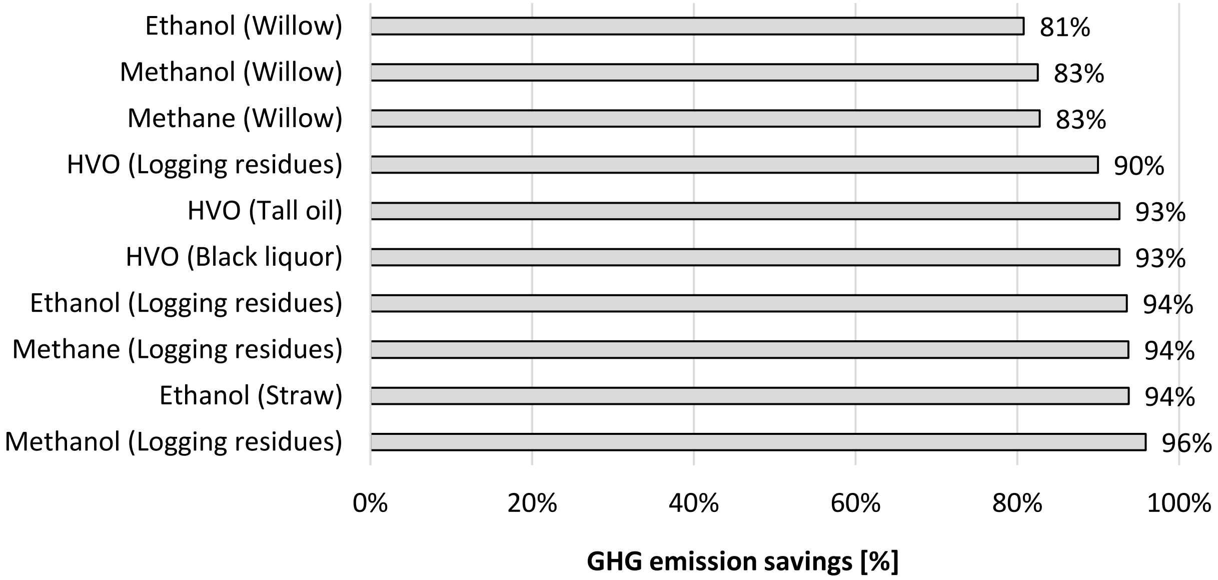
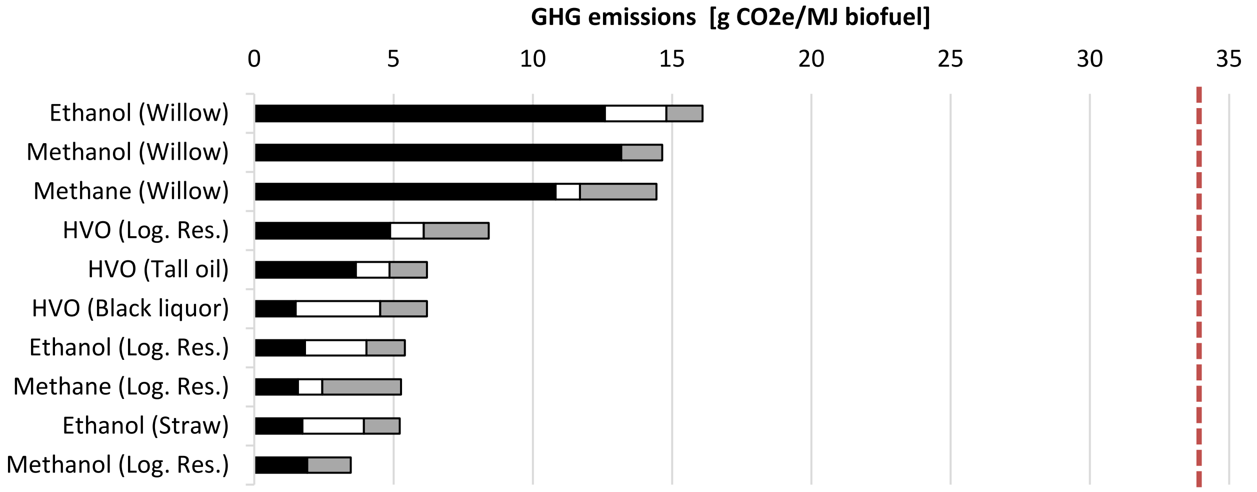


Figure 2. Aggregated results on GHG emission savings for the biomass-biofuels pathways investigated.



	Methanol (Log. Res.)	Ethanol (Straw)	Methane (Log. Res.)	Ethanol (Log. Res.)	HVO (Black liquor)	HVO (Tall oil)	HVO (Log. Res.)	Methane (Willow)	Methanol (Willow)	Ethanol (Willow)
■ e:ec	1.9	1.7	1.6	1.8	1.5	3.6	4.9	10.8	13.2	12.6
□ e:p	0.0	2.2	0.9	2.2	3.0	1.2	1.2	0.9	0.0	2.2
▨ e:td	1.6	1.3	2.8	1.4	1.7	1.3	2.3	2.8	1.5	1.3

Figure 3. GHG emissions of extraction and cultivation efforts (e:ec), production and conversion of feedstock (e:p) and transportation and distribution (e:td) according to the EU RED methodology for the biofuels methanol, methane, ethanol and HVO with different feedstock and conversion pathways. The dashed line indicates GHG emissions of 34 g CO_2e/MJ biofuel, corresponding to a 60% GHG emission saving compared to fossil fuel reference used in the EU RED.

3.1.1 Biofuel yield of production pathways

While the total conversion efficiency of the biomass is similar when by-products as solid fuels, chemicals, electricity and heat are included, the yield of biofuel (MJ per MJ biomass feedstock) differs (Figure 4[5]). Conversion to methane via thermal gasification gives the highest biofuel yields irresepctive of biomass.

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[5] The studied ethanol production pathway from straw includes both ethanol production from cellulose and microbial production of methane as a co-product. The given yield in Figure 4 includes also the methane.

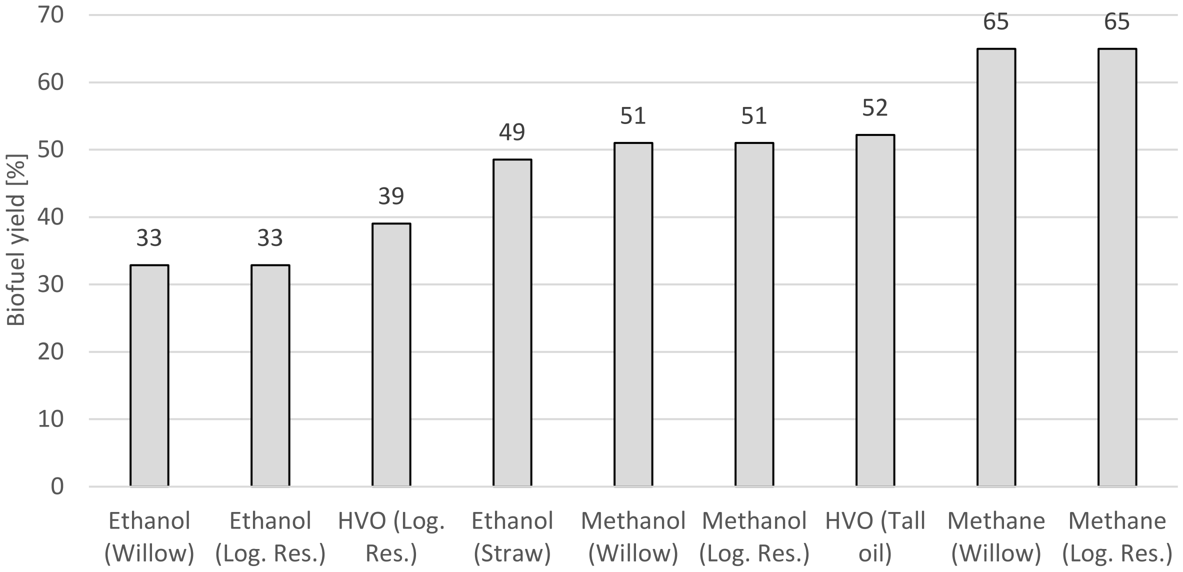

Figure 4. Biofuel yield (MJ biofuel per MJ biomass feedstock (LHV)).

3.1.2 Comparison of climate performance of residual biomass feedstock to cultivated feedstock

Calculations indicate that biofuels based on straw and logging residues present the lowest total greenhouse gas emissions (see Figure 3). Efforts for extraction and cultivation (e:ec) of cultivated feedstock such as willow are up to seven times higher compared to extraction efforts of residue feedstock, rendering these biofuels produced from residues more favorable with regards to their climate performance.

3.1.3 Comparison of calculated GHG emissions to EU RED default values

In Table 3, the values calculated within the study are presented besides the default values (DV) outlined in the EU RED. As there were no default values on methane available in the Directive, only the calculated values in this study are presented. In addition, new calculations made by the JRC (2017) regarding suggested revised default values in the ongoing revision of the renewable energy directive (EU, 2017) are included for comparison.

Hydrogenated Vegetable Oils (HVO)

For the cases of hydrogenating pyrolysis oil and tall oil, preparative steps have to be carried out before the actual hydrogenating takes place. Calculated process GHG emissions in the integrated refinery in Gothenborg (Preem) are small compared to stand alone values indicated in the EU RED and by JRC (2017) for this conversion process.

Methanol (MeOH)

Results for cultivation of wood for methanol production are significantly higher than presented in the EU RED but lower than in JRC (2017). This may arise due to differences in conversion technologies' efficiencies and/or cultivation system. Calculated transport emissions for all fuels are lower than presented in the EU RED and JRC (2017) since only production chains based on locally avaliable lignocellusic feedstock is included. For methanol based on residue feedstock, values are in the same order of magnitude compared with EU RED, but lower compared with JRC (2017).

Ethanol (EtOH)

Fermentation of woody biomass presents lower calculated values than presented in the EU RED and JRC (2017). The default values for straw fermentation obtained from the EU RED and JRC (2017) are also higher than the results in this report. The differences are both due to the lower emissions from regional biomass transport, and the lower process emissions. For ethanol from straw, the assumed co-production of methane, instead of as in JRC (2017) heat and electricity, is the main reason for the lower process emissions. For wood based ethanol production, the assumed in-house production of lignocellulosic enzym assumed in the present study has a large impact on the result.

Table 3. Overview of calculated GHG emissions compared to default values (DV) currently valid in EU RED (EU, 2009) and suggested post 2020 (JRC, 2017) for production pathways of different biofuels and biomass included in this report.

				EU, 2009 (JRC, 2017)			EU, 2009 (JRC, 2017)					EU, 2009 (JRC, 2017)				
	HVO (tall oil)	**HVO** (log. res)	**HVO** (black liq.)	***HVO*** *(waste veg. oil)*	**MeOH** (log. res.)	**MeOH** (willow)	***MeOH*** *(waste wood)*	***MeOH*** *(farmed wood)*	**EtOH** (straw)	**EtOH** (log. res.)	**EtOH** (willow)	***EtOH*** *(straw)*	***EtOH*** *(farmed wood)*	***EtOH*** *(waste wood)*	**Methane** (log.res.)	**Methane** (willow)
g CO_2e/ MJ biofuel				*DV*			*DV*	*DV*				*DV*	*DV*	*DV*		
e:ec	3.6	4.9	1.5	*0 (0)*	1.9	13.2	*1 (3.1)*	*5 (11.4)*	1.7	1.8	12.6	*3 (1.8)*	*6*	*1*	1.6	10.8
e:p	1.2	1.2	3.0	*13 (10.6)*	0.0	0.0	*0 (0)*	*0 (0)*	2.2	2.2	2.2	*7.0 (6.8)*	*17*	*17*	0.9	0.9
e:td	1.3	2.3	1.7	*1 (1.8)*	1.6	1.5	*4 (10.4)*	*2 (8.6)*	1.3	1.4	1.3	*2 (7.1)*	*2*	*4*	2.8	2.8
E	6.2	8.4	6.2	*14 (12.4)*	3.5	14.6	*5 (13.5)*	*7 (20)*	5.2	5.4	16.1	*13 (15.7)*	*25*	*22*	5.3	14.4
GHG saving	93%	90%	93%	*83% (85%)*	96%	83%	*94% (84%)*	*91% (76%)*	94%	94%	81%	*85% (81%)*	*70%*	*74%*	94%	83%

3.2 Hydrogenated vegetable oils

Below, the production pathway of hydrogenated vegetable oils (HVO) from the residues crude tall oil from pulp and paper industry, pyrolysis oil from logging residues and lignin from black liquor are presented. For this study, all feedstock is hydrogenated at the Preem refinery in Gothenburg. Herefore, process insights are based on the consultant report by Olofsgård & Englund (2015). In Table 4 results of the GHG emissions from the three feedstocks are summarised and compared to values outlined in the EU RED.

Table 4. Results of GHG emissions according to the EU RED methodology of HVO production from tall oil, logging residues and black liquor. For comparison the default value (DV) in g CO_2e/MJ biofuel values indicated for HVO in the EU RED for waste vegetable oil are given.

		Tall oil (from black liquor)	**Via pyrolysis oil** (from wood residues)	**Via lignin oil** (from black liquor)	*comparison EU RED for waste vegetable oil*
	description	**g CO_2e/ MJ HVO**	**g CO_2e/ MJ HVO**	**g CO_2e/ MJ HVO**	**DV**
e:ec	extraction or cultivation of raw materials	3.6	4.9	1.5	0
e:p	processing	1.2	1.2	3.0	13
e:td	transport and distribution	1.3	2.3	1.7	1
E[6]	total emissions from the use of the fuel	6.2	8.4	6.2	14
greenhouse gas savings		93%	90%	93%	83%

3.2.1 Tall oil from black liquor

For the case of tall oil, the preceding process of separation of crude tall oil from black liquor subsequent to hydrogenation is included in the calculations. This extraction effort has to be included due to the fact that this process step of separation not commonly takes place in a pulp and paper mill. Instead the black liquor is usually fed back to the pulp and paper process to generate process heat.

Extraction or cultivation of raw materials

Preparing process (black liquor): Separation of crude tall oil from black liquor at the pulp and paper mill through skimming and acidulation: 50 weight% of the black liquor is separated to crude tall oil (CTO) (Cashman *et al.*,

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[6] Mind that odd sums (not matching the sum of the rounded values indicated in the table) display the sum of values derived from actual calculations.

2016). In Europe, acidulation takes place at the respective pulp and paper mill, according to Cashman *et al.* (2016), and is hence assumed as the location for separation of CTO from black liquor. The yield efficiency is not included in the calculations but the impact of energy and resources used to arrive at crude tall oil.

Logistics (CTO): on average a transport of crude tall oil (CTO) of 200 km from pulp and paper mill to Piteå (*Sunpine* facility) via road is assumed. Data from Heinimann (2012) is used for transport related GHG emissions, which are in the same order of magnitude as these described by the Preem refinery specific consultancy report by Olofsgård & Englund (2015). See details for logistics in appendix under transport, logistics (CTO).

Processing

Intermediate process (CTO): at the *Sunpine* facility in Piteå, separation of raw tall diesel (RTD) from CTO is conducted. 60 weight% of the CTO separated is RTD and 40 weight% tall beck oil (Olofsgård, 2012). Allocation of emissions to tall beck oil is not conducted as tall beck oil is considered a residue product and not a by-product (Olofsgård, 2012).

Logistics (RTD): via boat, the raw tall diesel is being shipped to the refinery in Gothenburg. More details are indicated in Table 5 below.

Hydrogenation (RTD): Process steps[7] of the hydrogenation of tall oil (87% conversion efficiency) at Preem refinery in Gothenburg, include:

- generation of naphtha from crude fossil oil;
- catalytic reforming unit to convert the naphtha into hydrogen and hydrocarbon; and
- final step where crude fossil oil together with hydrogen and hydrocarbons is converted into ‘green diesel’ by a ‘green hydro treater’ unit.

Aggregated data for the greenhouse gas emissions are directly obtained from an unpublished report by Olofsgård & Englund (2015), which analysed the Preem process in detail, calculated greenhouse gas emissions according to the method described in the RED 2009 and allocated these according to the lower heating value (LHV) of the processed products. The analysis results in significantly lower (1.21 g CO_2e/MJ HVO) greenhouse gas emissions compared with other established processes such as the *NexBTL* process (by Neste Oil) where process emissions arise to up to 5.3 g CO_2e/MJ HVO (JRC, 2014). Older reports, employing the same method, suggest emissions around 5-6 g CO_2e/MJ HVO (Börjesson et al., 2013; Olofsgård, 2012). A by-product from the hydrogenation is naphtha, which, based on its LHV, accounts for 3% of the total sum produced products. The product HVO is thus allocated 97% of upstream emissions.

Transport & distribution

Logistics (HVO): Data for distribution is taken from Olofsgård & Englund (2015) and includes boat transport from Gothenburg to Piteå and lorry from Piteå to Kiruna. This transport structure (0.27 g CO_2e/MJ HVO) is a worst-case scenario but lies in the same order of magnitude as when the HVO would have been transported 200 km with a lorry (0.21 g CO_2e/MJ HVO) based on Heinimann (2012). A distance of 200 km is in line with the assumptions made by the well-to-wheel study by the Joint Research Centre of the European Commission (JRC, 2014). See details for logistics in Table 5.

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[7] According to Olofsgård & Englund (2015)

Input data and assumptions

Table 5. Input data and descriptions of the production pathway of hydrogenated oil based on tall oil.

tier	process	energy
Preparing process	Separation of crude tall oil (CTO) from black liquor	Acidulation (separation) of soap from black liquor (250 MJ steam/ton raw tall oil), adding sulphuric acid to convert soap into raw tall oil and warm storage (50-80°C) of raw tall oil (Cashman et al., 2016). Electricity for centrifugation, stirring and pumping is estimated to be around 50 MJ el/t raw tall oil. The GHG emissions for these processes is calculated to be 0.2 g CO_2e /MJ crude tall oil for a biomass based heat production and Nordic electricity mix. The greenhouse gases from sulphuric acid production (off-site) are calculated to be 0.47 g CO_2e /MJ crude tall oil. Warm storage of the product crude tall oil is calculated to be 0.32 g CO_2e /MJ CTO, based on biomass heat production and Nordic electricity mix.
Logistics (CTO)	Transport to distillation facility 200 km (Piteå)	200 km via road
Intermediate process	Distillation of CTO in raw tall diesel (RTD) and tall beck oil	0.05 MJ oil/MJ raw tall diesel and 0.08 MJ el/MJ raw tall diesel (Olofsgård, 2012).
Logistics (RTD)	Transport from Piteå to Gothenburg refinery via boat	Transported amount per boat load 27845 ton, 50% load capacity, using 155 t fossil bunker oil per trip, 2.2 kg CO_2e/kg bunker oil used, resulting in a GHG emission of 0.61 g CO_2e $_2$/MJ HVO (Olofsgård & Englund, 2015).
Conversion process	Hydrogenation with a conversion efficiency of 87%	1.21 g CO_2e /MJ HVO (Olofsgård & Englund, 2015) for hydrogenation process. Hydrogenated Oil as main product receives 97% of the upstream emissions and naphtha as by-product is allocated 3% of the emissions (based on energy content).
Logistics (HVO)	Distribution of HVO	Transport via lorry is assumed to be at 0.022 kg CO_2e $_2$/kg HVO, and transport via boat 0.012 kg CO_2e /kg HVO (Olofsgård & Englund, 2015). Emissions for storage are set at 0.010 g CO_2e/MJ HVO. The indicated aggregated emission data (0.27 g CO_2e/MJ HVO) by (Olofsgård & Englund, 2015) for this process step is used for the calculations in this report.

3.2.2 Pyrolysis oil from logging residues

Extraction or cultivation of raw materials

Forest operations: Extraction, collection, forwarding and chipping of wood residues as described in the appendix.

Logistics (wc): Wood chips (wc) transport via roadway 100 km to pyrolysis process. Parameters for logistics of wood chips is described under logistics (wc) in the appendix.

Processing

Intermediate process (pyrolysis): The moisture content for wood chips from tops and branches is assumed to be 50 weight % and a particle size of >5 mm, requiring both drying and grinding of the wood chips material before conducting pyrolysis (Onarheim *et al.*, 2015). During pyrolysis process, heat and char is generated, which is used to dry the feedstock. For grinding efforts, external electricity is required (see Table 6). The same accounts for process pumps, compressing efforts and a belt dryer. As mentioned by Börjesson *et al.* (2013), the subsequent hydrogenation requires feedstock with a lower oxygen content than achievable with the chosen fluidizing-bed fast pyrolysis. The technology in favour, that is Fluid Catalytic Cracking (FCB), would entail a catalytic process whose process parameters are not available as of today. For the sake of data quality, data for the established fluidizing-bed fast pyrolysis process by Onarheim *et al.* (2015) is chosen.

Logistics (po): Transport of pyrolysis oil 200 km to refinery in Gothenburg. Parameters for logistics of the pyrolysis oil is described under logistics (po) in the appendix.

Hydrogenation (po): For the unestablished process of hydrogenating pyrolysis oil, a conversion efficiency lower than the existing process based on tall oil was assumed (see preceding chapter 1.1). This due to the difference in lower heating values of the feedstock, compare pyro oil 17.5 MJ/kg (G. Benjaminsson, Benjaminsson, & Bengtsson, 2013) to tall oil with 36.9 MJ/kg (Ikonen, 2012). According to Huber & Corma (2007) the conversion efficiency for lignin to HVO is 70% and hence is used as a proxy for the conversion efficiency of pyrolysis oil. Process steps are assumed to follow these of hydrogenation of tall oil.

Transport & distribution

Logistics (HVO): see description of distribution in Table 5 above.

Input data and assumptions

Table 6. Input data and descriptions of the production pathway of hydrogenated oil based on pyrolysis oil derived from wood residues.

tier	**Process**	**energy**
Forest operations	See appendix	
Logistics (wc)	Transport to biofuel conversion facility	100 km
Intermediate process	Pre-treatment before pyrolysis (grinding and drying)	The grinding process to decrease particle size below 5 mm requires 71.2 kWh/t DM wood chips >5 mm (Onarheim et al., 2015).
	Conversion from chips from wood residues to pyrolysis oil	The described industrial fluidizing-bed fast pyrolysis of wood chips shows a conversion efficiency of 56% for forest residue feedstock in relation to pyrolysis oil (based on energy content LHV). Feedstock shows a moisture content of 8 weight % and particle size of the feedstock of 5 mm. Process capacity of pyrolysis plant is 49.8 MW (LHV). External electricity input of 3 % of feedstock (LHV) (Onarheim et al., 2015).
Logistics (po)	Transport to refinery	transport lorry over land 200 km
Conversion process (HVO)	Hydrogenation with a conversion efficiency of 70%	1.21 g CO_2e/MJ HVO (Olofsgård & Englund, 2015)
Logistics (HVO)	Distribution of HVO	See Table 5

3.2.3 Lignin oil from black liquor

Extraction or cultivation of raw materials

Preparing process (lignin): Lignin is a byproduct within black liquor deriving from the *kraft* process of wood pulping and is usually due to its heat value burned onsite to generate process heat (Bernier, Lavigne, & Robidoux, 2013). In order to make use of the lignin for other purposes such as feedstock for biofuel it has to be separated from the black liquor. One particular technology that is able to isolate the lignin from black liqour is the *LignoBoost* process[8]. Here, in a first step, lignin is precipitated with the help of carbon dioxide, whereby one ton black liquor precipitates to around 0.6 ton lignin (Backlund & Nordström, 2014; Bernier et al., 2013). The precipitated wet lignin needs to undergo dehydration, conducted for example via filtration requiring electrical energy.

Logistics (l): lignin (l) transport via roadway 200 km to further conversion to lignin oil. See logistics (l) in the appendix.

Intermediate process (lo): In a next step, the lignin is pyrolised in order to turn the lignin into lignin oil, which in the final step is hydrogenated to HVO. Due to the inherent structure of lignin the pyrolysis of lignin is said to

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[8] for more information on the Lignoboost process consult (Benali *et al.*, 2016)

differ from that of biomass and thus results in lower oil yields in comparison to pyrolised biomass (Trinh *et al.*, 2013). Therefore, the conversion efficiency only amounts to 33% (Obydenkova *et al.*, 2017) compared to 56% for residual wood to pyrolysis oil (Onarheim *et al.*, 2015). The process parameters used here derive from a process where lignin residue is a byproduct from ethanol production: Fast pyrolytic conversion of lignin at a temperature of 499 °C during 1 s with an energy consumption of 68 kWh/ton of lignin for exhaust gas compression (ibid). The lignin from ethanol production is however, compared to kraft lignin, sulfur free, which is not the case for the lignin from black liquor feedstock where lignin contains up to 2-3 w% sulfur (Obydenkova *et al.*, 2017)

Processing

Conversion process (lo): Hydrogenation of the lignin oil to HVO at a conversion efficiency of 42%, electricity consumption of 549.6 kWh/ton HVO and hydrogen consumption of 10'360.7 MJ/ton HVO (Obydenkova *et al.*, 2017). According to the well to wheel analysis by the European Joint Research Center, and applying the *NExBTL*[9] process, hydrogen production from natural gas is assumed to amount to greenhouse gas emissions of 6.24 g CO2e/MJ hydrogen (Edwards *et al.*, 2013).

Transport & distribution

Logistics (HVO): transported 200 km with a lorry 24 ton capacity and 0.59 MJ/tkm arising to 0.21 g CO_2e/MJ HVO based on (Heinimann, 2012). A distance of 200 km is in line with the assumptions made by the well-to-wheel study by the Joint Research Centre of the European Commission (JRC, 2014).

Table 7. Input data and descriptions of the production pathway of hydrogenated oil based on lignin derived from a pulp and paper mill.

Tier	**process**	**energy**
Preparing process	Separation of lignin from black liquor at the pulp and paper mill with 0.30 kg carbon dioxide per 1 kg dry lignin for precipitation and electricity use for filtration (Bernier et al., 2013)	0.010 kWh/kg dry lignin (Bernier et al., 2013), with a 60% conversion efficiency (Backlund & Nordström, 2014). Total emissions for lignin amounts to 0.57 CO_2e/kg lignin (Bernier et al., 2013)
Logistics (l)	Transport to biofuel conversion facility	200 km
Intermediate process (lo)	Pyrolysis of lignin to lignin oil with a 33% conversion efficiency (Obydenkova et al., 2017).	energy consumption of 68 kWh/ton of lignin for exhaust gas compression (Obydenkova et al., 2017).
Conversion process (HVO)	Hydrogenation with a conversion efficiency of 42% (Obydenkova et al., 2017).	549.6 kWh/t HVO and 10'360.7 MJ hydrogen/ton HVO (Obydenkova et al., 2017), with 6.24 g CO_2e/MJ hydrogen (Edwards et al., 2011).
Logistics (HVO)	Distribution of HVO	200 km

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[9] A process established by Neste Oil.

3.3 Methanol

The technology chosen for the evaluation of the gasification pathway is a stand-alone circulating fluidised bed (CFB) steam/oxygen-blown gasification (430 MW LHV biomass input at 50 weight % moisture), based on Börjesson (2013) and Holmgren *et al.* (2012). The conversion efficiency on LHV of raw material to biofuel is 51% (Holmgren *et al.*, 2012; Isaksson *et al.*, 2012; JRC, 2014). As Holmgren *et. al* (2012) exemplifies, this technology constitutes a contemporary technology relevant in the Swedish context. A heat pump, condensing turbine with two steam levels are employed (ibid). Two raw materials, wood chips from residue wood residues and wood chips from cultivated short-rotation coppice (willow) on agricultural land, are considered. Table 7 below provides an overview on the results obtained for the pathways included, in comparison to pathways described in the RED 2009. Details for production pathways are described in the following paragraphs and are complemented with data in the appendix.

Table 8. Results of GHG emissions according to the EU RED methodology of methanol (MeOH) production from logging residues and willow wood. For comparison the default value (DV) in g CO_2e/MJ biofuel indicated for methanol from farmed wood is given

		Wood residues	**Willow**	*comparison EU RED for farmed wood*
	description	**g CO_2e/ MJ MeOH**	**g CO_2e/ MJ MeOH**	**DV**
e:ec	extraction or cultivation of raw materials	1.9	13.2	5
e:p	processing	0.0	0.0	0
e:td	transport and distribution	1.6	1.5	2
E	total emissions from the use of the fuel	3.5	14.6	7
greenhouse gas savings		96%	83%	91%

3.3.1 Wood residues

Extraction or cultivation of raw material

Forest operations: Extraction, collection, forwarding and chipping of wood residues as described in the appendix.

Logistics (wc): wood chips (wc) transport via roadway 100 km to the gasification plant. Parameters for logistics of wood residues is described under logistics (wc) in the appendix. According to Holmgren *et al.* (2012) a distance of 100-150 km in the Swedish context is realistic.

Processing

Conversion process (MeOH): As outlined above, the technology chosen for the evaluation of the gasification pathway is a stand-alone circulating fluidised bed (CFB) steam/oxygen-blown gasification. A reduced feedstock moisture content of 15% is reached by on-site drying at the gasification plant with heat from production process (Holmgren et al., 2012) (initial moisture content of 40% of feedstock). Since heat derives from fuel production process drying wood chips is not assigned any greenhouse gas emissions (in line with the RED 2009 calculation method). No excess heat is produced. Electricity generation is carried out with a heat pump. Net electricity generation from process amounts to 0.6% of LHV biomass feedstock (Holmgren et al., 2012). As the electricity indirectly is generated from feedstock production process and not from a combined heat to power process, excess electricity is not granted emission reduction e_{ee}.

Transport & distribution

Logistics (MeOH): the distance for distribution of methanol is set at 200 km. For details see appendix logistics (MeOH).

Input data and assumptions

Table 9. Input data and descriptions of the production pathway of methanol based on wood residues feedstock.

tier	**process**	**energy**
Forest operations	Wood chips from tops and branches, see respective appendix, forest operations.	
Logistics (wc)	Transport to biofuel conversion facility	100 km
Conversion process (MeOH)	Direct gasification with a conversion efficiency of 51%	Stand-alone oxygen-blown pressurised Circulating Fluidized Bed (CFB) gasification at 25 bar and 850 °C with Air Separation Unit (ASU). Oxygen-blown Auto-Thermal Reformer (ATR) operating at 25 bar and 1000 °C. Liquid Phase Methanol Synthesis (LPMeOH). 90 bar 240 °C. No CO_2 removal. Back-pressure in steam cycle due to steam demand for background process. Electricity generation with heat pump and condensing turbine (two steam levels) data by Holmgren *et al.* (2012) based on Isaksson *et al.* (2012).
Logistics (MeOH)	Distribution of methanol	200 km

3.3.2 Willow

Extraction or cultivation of raw material

Willow cultivation: Cultivation of short-rotation coppice willow as described in the appendix willow cultivation.

Logistics (wc): wood chips of willow wood (wc) transport via roadway 100 km to the gasification plant.

Processing

Conversion process (MeOH): No difference in the conversion is made for willow wood and wood residues, meaning that the conversion process resembles the one chosen as described for wood residues in the preceding paragraph.

Transport & distribution

Logistics (MeOH): the distance for distribution of methanol is set at 200 km. For details see appendix logistics (MeOH).

Input data and assumptions

Table 10. Input data and descriptions of the production pathway of methanol based on willow wood.

Tier	**process**	**energy**
Willow cultivation	Willow cultivation according to appendix, willow cultivation.	
Logistics (wc)	Transport to biofuel conversion facility	100 km
Conversion process (MeOH)	Direct gasification with a conversion efficiency of 51%	Stand-alone oxygen-blown pressurised Circulating Fluidized Bed (CFB) gasification at 25 bar and 850 °C with Air Separation Unit (ASU). Oxygen-blown Auto-Thermal Reformer (ATR) operating at 25 bar and 1000 °C. Liquid Phase Methanol Synthesis (LPMeOH). 90 bar 240 °C. No CO_2 removal. Back-pressure in steam cycle due to steam demand for background process. Electricity generation with heat pump and condensing turbine (two steam levels) data by Holmgren *et al.* (2012) based on Isaksson *et al.* (2012).
Logistics (MeOH)	Distribution of methanol	200 km

3.4 Methane

For the calculations in this report a stand-alone indirect gasification oxygen-blown, pressurised, Circulating Fluidized Bed (CFB) system was chosen. Woody biomass is turned into raw syngas, comprising of hydrogen, CO, CO_2 and methane (Arvidsson, 2016). Data by GobiGas (based on Dominguez de Maria, 2016) suggest that the technology is high-yielding with a conversion efficiency of 65%, which can be found in a similar order of magnitude in studies by Arvidsson (2016) and Börjesson *et al.* (2013). Due to the lack of data on the process of GobiGas, data by Heyne & Harvey (2014) is used to describe a process which shows similar conversion parameters. The process generates electricity (see more in Table 2). GHG emissions are allocated according to their LHV (see more details below). In order to distribute the methane, a final compression step is conducted (see details in table below). The production of methane receives 94% of the upstream emissions (allocation according to LHV). Generated electricity is allocated 6% of the GHG emissions. The raw materials included are wood chips from wood residues and from short-rotation coppice willow. Table 10 summarises the results from the production pathway methane. Details for production pathways are described in the following paragraphs and are complemented with data in the appendix.

Table 11. Results of GHG emissions according to the EU RED methodology of methane production from logging residues and willow wood. Comparative default values are not given in EU RED.

	description	Logging residues g CO_2e/MJ methane	Willow g CO_2e/MJ methane
e:ec	extraction or cultivation of raw materials	1.6	10.8
e:p	Processing	0.9	0.9
e:td	transport and distribution	2.8	2.8
E	total emissions from the use of the fuel	5.3	14.4
greenhouse gas savings		94%	83%

3.4.1 Wood residues

Extraction or cultivation of raw material

Forest operations: Extraction, collection, forwarding and chipping of wood residues as described in the appendix.

Logistics (wc): see appendix.

Processing

Conversion (SNG): see description in the introduction of chapter 3.4 and in table below.

Transport & Distribution

Logistics (SNG): Compressed Natural Gas (CNG) tank transport with a capacity of 6000 m^3 (J. Benjaminsson & Nilsson, 2009). JRC (2014) assumes a distribution distance of 150 km, for the sake of consistency, a distance of 200 km is assumed. Data for cooling efforts have not been collected or quantified and are dismissed in the calculation.

Input data and assumptions

Table 12. Input data and descriptions of the production pathway of methane based on wood residues feedstock.

Tier	Process	energy
Forest operations	See appendix	
Logistics (wc)	Transport to gasification facility	100 km
Conversion process	Conversion with a conversion efficiency of 65%	65% conversion efficiency as in the GobiGas project based on (Domínguez de María, 2016); gasification facility capacity of 90 MW, SNG production of 63 MW and electricity generation of 4.3 MW (Heyne & Harvey, 2014).
	Compression	0,9 MJ el/m^3 methane gas (97% methane content) (Tufvesson *et al.*, 2013). According to data by the Joint Research Centre of the European Commission, compression is carried out with a 75% compression efficiency and 90% electric driver efficiency (JRC, 2014)
Logistics (SNG)	Distribution of methane	200 km

3.4.2 Willow

The production of methane to willow wood resembles the production pathway of wood residues to methane from the point of process where wood chips from willow wood are transported to the conversion facility.

Extraction or cultivation of raw material

Willow cultivation*:* Cultivation of short-rotation coppice willow and chipping on-site. See appendix, willow cultivation.

Logistics (wc): see appendix, logistics (wc).

Processing

Conversion (SNG): see description in the introduction of chapter 3 and in table below.

Transport & Distribution

Logistics (SNG): See description of distribution of SNG in the production pathway in the preceding chapter 3.1.

Input data and assumptions

Table 13. Input data and descriptions of the production pathway of methane based on wood residues feedstock.

tier	**process**	**energy**
Willow cultivation	See appendix, willow cultivation.	
Logistics (wc)	Transport to gasification facility	100 km
Conversion process	Conversion with a conversion efficiency of 65%	65% conversion efficiency as in the GobiGas project based on (Domínguez de María, 2016); gasification facility capacity of 90 MW, SNG production of 63 MW and electricity generation of 4.3 MW (Heyne & Harvey, 2014).
	Compression	0,9 MJ el/m^3 methane gas (97% methane content) (Tufvesson et al., 2013). According to data by the Joint Research Centre of the European Commission, compression is carried out with a 75% compression efficiency and 90% electric driver efficiency (JRC, 2014).
Logistics (SNG)	Distribution of methane	200 km

3.5 Ethanol

For the production of ethanol, three raw materials, that is residue straw, cultivated willow wood and logging residues, have been chosen for further investigation. The conversion technology and scale of fermentation is relevant for the Swedish context (see more in Table 2). For all feedstocks, the conversion process is carried out with enzymes prepared on-site, which is estimated to be the case in future commercial ethanol plants in Sweden. Purchased, off-site preparation of enzymes has been shown to have a large impact on the GHG balance of the production pathway of ethanol (Karlsson *et al.* 2014). Table 13 summarises the results from the production pathways of different feedstock materials to ethanol. Details for production pathways are described in the following paragraphs and are complemented with data in the appendix.

Table 14. Results of GHG emissions according to the EU RED methodology of ethanol based on the feedstock straw, willow wood and logging residues. For comparison the default value (DV) in g CO_2e/MJ biofuel values indicated for ethanol in the EU RED for comparable biomass types are given.

					comparison EU RED		
		Straw	**Willow**	**Logging residues**	**Straw**	**Farmed Wood**[10]	**Waste Wood**
	description	**g CO_2 e/ MJ EtOH**	**g CO_2 e/ MJ EtOH**	**g CO_2 e/ MJ EtOH**	**DV**	**DV**	**DV**
e:ec	extraction or cultivation of raw materials	1.7	12.6	1.8	3	6	1
e:p	processing	2.2	2.2	2.2	7	17	17
e:td	transport and distribution	1.3	1.3	1.4	2	2	4
E	total emissions from the use of the fuel	5.2	16.1	5.4	13	25	22
greenhouse gas savings		94%	81%	94%	85%	70%	74%

3.5.1 Straw

Extraction or cultivation of raw material

Agricultural operations: Collection of straw with diesel propelled agricultural machinery (Karlsson *et al.*, 2014).

Logistics (s): lorry transport of straw (s) over a distance of 100 km. The shorter biomass transport distances could be realistic as fermentation plants can be run on small scale, decentralised and close to the source of feedstock generation (Karlsson *et al.*, 2014).

Processing

Conversion process (EtOH): Enzymatic hydrolysis and anaerobic digestion (mesophilic with continuous stirred tank) of straw at a dry matter content of 82% (Karlsson et al., 2014). Parallel methane production, excess heat and electricity generation and application of purchased molasses. The original study by Karlsson et al. (2014) include also purchased enzymes, but this has been updated and changed in this analyses equivalent to on-site enzyme production, analogue to the wood-based ethanol cases, based on data from Olofsson *et al.* (2015). The total GHG contribution from the conversion process calculated by Karlsson *et al.* (2014) has then been reduced equivalent to 22% of the GHG emissons in the original study based on data from Olofsson *et al.* (2015), due to the replacement of purchased enzymes by on-site production. Based on data from Karlsson *et al.* (2014) a yield (biomass-to-fuel; LHV DM raw material to final product LHV) of 49% is calculated. This yield includes the production of both ethanol and methane, and total biofuels yields for the co-production of ethanol and methane from straw in the same range (54%) has been presented by e g Joelsson et al. (2016). Emissions are allocated according to the LHV of the final products from conversion process.

Transport & Distribution

Logistics (EtOH): distribution of ethanol 200km. For more details, see appendix logistics (EtOH).

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[10] As used in the EU RED, not further defined term.

Input data and assumptions

Table 15. Input data and assumptions of the production pathway straw to ethanol.

Tier	**process**	**energy**
Agricultural operations	Collection of straw	Collection, handling and unloading from storage of straw with diesel propelled (agricultural) machinery 0.27 MJ/kg DM straw; straw harvest 2 t/ha (Karlsson et al., 2014).
Logistics (s)	Transport to fermentation facility	100 km lorry transport with a loading capacity of 33 ton and a maximum load of 110 m^3 (175 kg/m^3) results in 0.066 MJ diesel/kg DM straw, including empty return (Karlsson et al., 2014); data is adapted to method of this report, without empty return by assuming an energy input of 75% for one way (without empty return).
Conversion process	Hydrolysis	The process employs enzymes (12.4 g/kg DM straw), molasses (31.5 g/kg DM straw), ammonia (2.3 g/kg DM straw), phosphorus (0.62 g/kg DM straw) and sulphur (0.08 g/kg DM straw). See emission factors in appendix. Allocation of inputs according to the final product ethanol and by-products (see next paragraph).
	Fermentation	Process parameters: conversion of feedstock to ethanol 0.13 kg DM straw/MJ ethanol (Karlsson et al., 2014) resulting in a 2.06 MJ straw LHV DM/MJ ethanol based on a LHV of straw of 15.8 MJ/kg DM (Börjesson, 2007). Allocation of GHG emissions to the output products according to the LHV (Karlsson et al., 2014).
Logistics (EtOH)	Distribution of ethanol	200 km

3.5.2 Logging residues

Extraction or cultivation of raw material

Forest operations: Extraction, collection, forwarding and chipping of logging residues as described in the appendix.

Logistics (wc): Wood chips transport via roadway 100 km to fermentation process. Parameters for logistics of tops and branches is described under logistics (wc) in the appendix.

Processing

Conversion (EtOH): Fermentation with on-site enzyme preparation, yeast cultivation with purchased molasses and chemicals supporting the process (see more details: case B in Olofsson *et al.* (2015)[11]). Based on this data, the

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[11] Case B was chosen as no external electricity import required and on-site enzyme preparation included.

conversion efficiency for the fermentation process of wood residues is 33% (biomass-to-fuel, based on a LHV of 15.8 MJ/kg DM for wood)[12]. Parallel biogas and solid fuel (pellets) production and generation of excess of electricity (ibid). Greenhouse gas emissions from the on-site production of enzymes and purchased molasses employed during the conversion process are included in the calculations and derive from aggregated data from Olofsson *et al.* (2015). Ethanol is allocated 55% of the GHG from fermentation process. For more details on the process see the extended report by Olofsson *et al.* (2015).

Transport & Distribution

Logistics (EtOH): distribution via road 200 km. For transport parameters see logistics (EtOH) in the appendix.

Input data and assumptions

Table 16. Input data and assumptions of the production pathway logging residues to ethanol.

tier	**process**	**energy**
Forest operations	See appendix	
Logistics (wc)	Transport to fermentation facility	100 km
Conversion process	Pre-treatment	2.6 g SO_2/kg DM wood chips (Olofsson *et al.*, 2015).
	Hydrolysis	The process employs enzymes and molasses for continuous cultivation of yeast. For more details see Olofsson *et al.* (2015).
	Fermentation with a conversion efficiency of 33%	Process parameters: conversion of 2.86 MJ wood chips DM/MJ ethanol (Olofsson *et al.*, 2015) with a LHV for spruce wood chips 15.4 MJ/kg DM (Börjesson, 2007). GHG emission calculations are based on aggregated data by Olofsson *et al.* (2015), where the molasses and chemicals amount to a value of 4 g CO_2e/MJ ethanol and are allocated to the output products electricity, ethanol and pellets according to the LHV as follows: 2% electricity excess, 43% pellets, and 55% ethanol.
Logistics (EtOH)	Distribution of ethanol	200 km

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[12] (Börjesson, 2007)

3.5.3 Willow

Extraction or cultivation of raw material

Willow cultivation: crop cultivation of willow see in appendix, willow cultivation.

Logistics (wc): wood chips transport via roadway 100 km to further conversion to ethanol. Parameters for logistics of tops and branches is described under logistics (wc) in the appendix.

Processing

Conversion (EtOH): Fermentation with on-site enzyme preparation, yeast cultivation with purchased molasses and chemicals supporting the process resembles case wood residues in chapter 4.2 wood residues. It was assumed that the fermentation system suggested by Olofsson *et al.* (2015) of spruce wood chips also is applicable for the fermentation of willow chips.

Transport & Distribution

Logistics (EtOH): it is assumed that the ethanol is distributed via road 200 km. For transport parameters see logistics (EtOH) in the appendix.

Input data and assumptions

Table 17. Input data and assumptions of the production pathway willow to ethanol.

tier	process	energy
Willow cultivation	See appendix, willow cultivation	
Logistics (wc)	Transport to fermentation facility	100 km
Conversion process	See chapter 3.5.2 wood residues	
Logistics (EtOH)	Distribution of ethanol	200 km

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Appendix

Lower Heating Values

Table 18. Lower Heating Values of resources used in this report. If not else indicated, values are on dry matter (DM) basis.

Resource	MJ/kg	MJ/L	reference
Raw materials			
Logging residues /Straw/Willow	15.8		(Börjesson, 2007)
Lignin	25.9		(Tomani, 2010)
Crude tall oil	36.9		(Ikonen, 2012)
Tallbeck oil	37.9		(Gode et al., 2011)
Molasses	13.6		(Olofsson et al., 2015)
Naphtha	43.4		(Olofsgård & Englund, 2015)
Intermediate products			
Pyrolysis oil	17.5		(G. Benjaminsson et al., 2013)
Lignin oil	29.7		(Trinh, Jensen, Kim, et al., 2013)
Raw Tall Diesel	37.0		(Olofsgård & Englund, 2015)
Biofuels			
Methane	53.7[13]	35.9 (MJ/m^3)	(f3, 2016; Landersjö, 2000)
Biomethanol	20.0	16.0	RED 2009
Bioethanol	27.0	21.0	RED 2009
HVO	44.0		(Olofsgård & Englund, 2015)

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[13] based on a density of methane of 0.668 kg/m^3

Forest operation

Extraction, collection, forwarding and chipping of tops and branches: Collection of tops and branches from spruce trees after logging. Storage of tops and branches outside at the forest site under paper for the period of 8 months until their further processing. Under the assumption of a substance loss of 1% loss of dry weight per month under these circumstances (Jirjis & Norden, 2005), the woody biomass undergoes a dry matter weight loss of 8% during storage. After storage, it is further assumed that the tops and branches are being chipped at the forest site. Chipping at the forest site is the dominant system in southern Sweden (Gode et al., 2011) and is assumed for this biofuel production chain.

Table 19. Data for the process of extracting, collecting, forwarding and chipping of logging residues.

tier	**process**	**energy**
Forest operations	Extraction, collection, forwarding and chipping of logging residues	Primary energy input for forwarding 4.1 kJ/MJ chips, load and unload 0.71 kJ/MJ chips, comminution 8.9 kJ/MJ chips. 1 MJ diesel relates to 1.16 MJ primary energy. Harvesting levels account for 506 GJ/ha (62 m^3 solid woody biomass). A value of 425 kg DM/m^3 solid wood is assumed (Lindholm, Berg, & Hansson, 2010). GHG emissions used for calculations in this report are obtained from Lindholm (2010) on an aggregated level, that is 0.35 g CO_2e/MJ wood chips. The equivalency factors are based on the GWP 100 method, assigning CH_4 a factor 25 and N_2O a factor 298. The values derived from this study, thus, are slightly higher than if calculated with the equivalency factors used for this report. Due to the high relevancy of the study, suitable for the Southern Swedish system, data is taken irrespectively.

Willow cultivation

Crop cultivation including fertilisation of the short rotation coppice willow. Assumption that no land use change takes place as willow is cultivated on agricultural land (no change in classification of land). Short-rotation coppice (willow), harvested every 3 years, over a total duration of, on average 22 years. Willow wood is extracted and chipped at the cultivation site preceding further processing. Emission data for the latter process is based on the ISO 14040 method and employs different GWP factors (see table below) but due to the lack of data, these values are being used as a proxy for greenhouse gas emissions related to extraction and chipping.

Table 20. Data for the process of willow cultivation.

tier	**process**	**energy**
Agricultural operations	Cultivation with fertilization	Biomass yield of 155 GJ/ha and year short-rotation coppice (willow), harvested every 3 years, over a total duration of, on average, 22 years. 0.41 g CO_2e/MJ willow wood chips for fossil fuels used in field, 5.9 g CO_2e/MJ willow wood chips for fertiliser production and biogenic emissions at field-site (Börjesson, 2006).
	Extraction of wood and chipping on-site	1.2 g CO_2e/MJ DM willow wood chips (calculation method ISO 14040 and GWP factors CH_4 21 and N_2O 320). Values derive from Börjesson (2006).

Logistics and distribution

Table 21. Data for transportation and distribution of raw materials, intermediate products and biofuels.

tier	process	energy
Logistics (wc)	Transport of logging residues chips and willow chips	logging residues/willow wood chips dry with a LHV of 15.8 MJ/kg DM (Börjesson, 2007) calculated to 6732 MJ/m^3 ub; 40 ton diesel propelled truck, transported amount 8.4 ton woodchips per load, volume 28 m^3, 0.67 MJ/tkm (Heinimann, 2012).
Logistics (p, l, po, CTO, HVO from lignin, MeOH, EtOH)	Transport / Distribution	transport lorry over land, 40 ton load, 24 ton capacity; 0.59 MJ/tkm (Heinimann, 2012). GHG emissions assuming the use of diesel with low blend biodiesel based on Swedish average diesel blend in 2016 (Swedish Energy Agency, 2017) 80.4 gCO_2e/MJ.
Logistics (SNG)	Distribution	Lorry transport over a distance of 200 km with a loading capacity of 6000 m^3 (4.2 ton) 0.0016 kWh diesel/m^3/km for a round trip with empty return (J. Benjaminsson & Nilsson, 2009). For calculations, it is assumed that merely 75% of the energy demand is applied when excluding empty return. This amounts to an energy demand in diesel fuel of 7.2 kWh/km.