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HVO PRODUCED FROM SWEDISH RAW MATERIALS

CURRENT AND FUTURE POTENTIALS

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PREFACE

This report covers a part of a project carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 46980-1, *Sustainable HVO production potential and environmental impact*. The project is financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

The Swedish Energy Agency is a government agency subordinate to the Ministry of Infrastructure. The Swedish Energy Agency is leading the energy transition into a modern and sustainable, fossil free welfare society and supports research on renewable energy sources, the energy system, and future transportation fuels production and use.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels. The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. Chalmers Industriteknik functions as the host of the f3 organization (see https://f3centre.se/en/about-f3/).

The project group consisted of research groups from the Swedish University of Agricultural Sciences and IVL Swedish Environmental Research Institute. A reference group with representatives from the Swedish and international HVO markets have also participated in the project.

This report presents the results from the first part of the project *Sustainable HVO production potential and environmental impact*, where the potential of domestic feedstock for HVO production in Sweden was assessed.

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EXECUTIVE SUMMARY

The demand for hydrotreated vegetable oil (HVO) has increased in recent years and it is now the dominant liquid biofuel on the Swedish market. However, only 5% of the 14 TWh HVO sold in Sweden in 2018 was produced from domestic raw material.

The project *Sustainable HVO production potential and environmental impact* addresses the possibilities to increase the use of domestic raw materials for HVO production in Sweden. This report presents the first part of the project, where the current (year 2020) and future (year 2050) potential supply of domestic feedstock for HVO production in Sweden was assessed. The assessment included raw materials already used today, such as tall oil (a residue from the pulp and paper industry) and used cooking oil, as well as raw materials and technologies with future potential (such as microbial oils or microalgae). The focus was on the Swedish potential to supply renewable oils and fats that can be produced under Nordic conditions. The theoretical, ecological, and technical potential of all raw materials identified was estimated, based on data from the literature or estimates from relevant actors. The economic potential was also assessed for some of the raw materials.

The results indicated that lignocellulosic materials such as forest residues have high future potential for HVO production (economic potential of 7.07 TWh per year in total by 2050). However, lignocellulosic materials require processing into oils and the option considered in this report (oleaginous yeast) is currently not an established technology, which means that further assessments of its technical and economic potential are needed.

The results also showed that the domestic supply of waste and residual oils, such as used cooking oil from households and restaurants, slaughterhouse waste fats *etc*., have relatively low potential (technical potential of 0.13 TWh per year by 2020, and 0.54 TWh per year by 2050).

Increasing the output of oilseed crops by growing rapeseed on fallow land or the low-input crop camelina (*Camelina sativa*) on marginal land or as a cover crop was also considered. Using marginal land and growing camelina as cover crop were found to have relatively low potential (technical potential of 0.37 TWh per year (by year 2020) and 0.40 TWh per year (by year 2050), respectively), while the future potential for growing rapeseed on fallow land was higher (technical potential of 0.94 TWh per year by 2020, and 2.70 TWh per year by 2050).

Oilseed crops, grown as cover crops or on marginal land, are interesting despite their relatively low potential, since they are exempted from the cap on food and feed crops in the EU Renewable Energy Directive. Therefore, demand for these might increase in the future.

Based on the results of this study and on potential relevance to the Swedish and Nordic HVO industry, two different feedstock alternatives will be investigated during the next stage of this project. These investigations will include environmental life cycle assessment and techno-economic assessment.

SAMMANFATTNING

De senaste åren har efterfrågan på hydrerad vegetabilisk olja (HVO) ökat och är nu det dominerande biodrivmedlet på den svenska marknaden. Trots detta var endast 5 procent av de 14 TWh HVO som såldes på den svenska marknaden 2018 producerad av inhemska råvaror.

Den här studien ingår i ett större projekt, som undersöker möjligheterna att öka användningen av inhemsk råvara för HVO-produktion i Sverige. Syftet med den här studien var att undersöka den potentiella tillgången på inhemsk råvara för HVO-produktion, idag (år 2020) och i framtiden (år 2050). Potentialbedömningen inkluderade råvaror som redan används idag, som tallolja och använd matolja, liksom råvaror med potential att användas i framtiden, som oljor framställda med hjälp av jästsvampar och alger. Studien fokuserade på råvarupotentialen i Sverige, och inkluderade därmed endast de råvaror som kan produceras under nordiska förhållanden. För alla identifierade råvaror bedömdes den teoretiska, ekologiska och tekniska potentialen baserat på data från publicerad litteratur eller uppskattningar från relevanta aktörer. Den ekonomiska potentialen bedömdes också för de råvaror där det var möjligt.

Resultaten indikerar att råmaterial baserade på lignocellulosa, som skogsrester (grenar, toppar och stubbar), har en hög framtida potential som råvara för HVO-produktion (ekonomisk potential år 2050: 7,07 TWh per år (år 2050)). Lignocellulosa måste dock omvandlas till olja för att kunna användas i HVO-produktion, och det alternativ som studerades i denna studie (oljejäst) är ännu inte en etablerad teknik. Därmed behövs ytterligare forskning för att kunna fastställa den tekniska och ekonomiska potentialen för dessa råvaror. Den inhemska tillgången på använd matolja från hushåll och restauranger och fett från slakteriavfall bedömdes ha en relativt liten potential (teknisk potential; 0,13 TWh per år (år 2020) respektive 0,53 TWh per år (år 2050)).

Möjligheten att öka produktionen av oljegrödor genom att antingen odla raps på mark som för närvarande är i träda, eller att odla oljedådra (lat. *Camelina sativa*) på marginalmarker eller som mellangröda inkluderades också i studien. Oljedådra som mellangröda och på marginalmarker hade båda relativt låg potential (teknisk potential: 0.37 TWh (år 2020) respektive 0,40 TWh per år (år 2050)), medan potentialen för att odla raps på mark som nu är i träda var högre (teknisk potential: 2,96 TWh per år (år 2050)).

Trots den relativt låga potentialen är odling av oljeväxter som mellangrödor och på marginalmarker intressanta då de är livsmedelsgrödor som kan undantas från begränsningen om användningen av livsmedelsgrödor för biobränsleproduktion i EU:s förnybartdirektiv. Därmed kan efterfrågan på dessa grödor komma att öka i framtiden.

Denna rapport redovisar en del av ett längre projekt som fortsättningsvis kommer att fokusera på två potentiella råvaror. Baserat på resultaten i denna rapport och relevansen för den nordiska HVO-industrin kommer två råvaror att väljas ut för att sedan analyseras med hjälp av livscykelanalys och teknoekonomisk analys.

CONTENTS

1 INTRODUCTION

The demand for hydrotreated vegetable oil (HVO) has increased in recent years and it is now the dominant biofuel on the Swedish market used in the transport sector (Swedish Energy Agency, 2019). HVO has a chemical composition similar to diesel and can therefore be used as a drop-in blend or up to 100% pure fuel without engine adaptations. In comparison to other renewable fuels such as rapeseed methyl-ester (RME), HVO is a stable fuel that can be stored for a longer period (Hartikka et al., 2013).

HVO offers a great potential to contribute to a renewable transport system with significant reductions of greenhouse gas (GHG) emissions. This potential, however, depends to a great extent on the type and origin of the raw material that the fuel is produced from. HVO is produced from a variety of raw materials, including palm fatty acid distillate (PFAD), slaughterhouse waste, tall oil, technical corn oil, palm oil and rapeseed oil (Swedish Energy Agency, 2019). Many of these raw materials are residual products, which means that their supply is limited or constrained.

In addition to that, almost 96% of the raw material used for HVO production in Sweden is imported (Swedish Energy Agency, 2019). In 2018, the raw materials used for producing the 14 TWh of HVO sold on the Swedish market originated from many different countries, with Indonesia being the largest supplier (34%), followed by Malaysia (11%), Germany (9%) and USA (7%). In the same year, only 5% of the raw materials used were of Swedish origin, with tall oil, a residue from the pulp and paper industry, being the dominant source. The current potential for HVO from Swedish tall oil has, however, already been reached (Peck et al., 2016).

Apart from availability, the adoption of certain feedstock for HVO production may also be influenced by regulatory requirements and compliance to national and international frameworks. One such framework is the updated Renewable Energy Directive (RED II) (European Parliament, 2018). RED II includes sustainability and GHG emissions savings criteria for biofuels, bioliquids and biomass fuels[1]. Biofuels, bioliquids and biomass fuels need to fulfil these sustainability criteria to be considered to contribute to the national and EU targets for renewable energy specified in the directive, and to be eligible for financial support. Specifically, for the transport sector outlined in Article 25 (1): “each Member State shall set an obligation on fuel suppliers to ensure that the share of renewable energy within the final consumption of energy in the transport sector is at least 14 % by 2030 (minimum share)”.

Based on the above, a need to increase understanding on the supply potential of domestic raw materials for HVO production is identified (focusing on raw materials that contribute to the national and international targets) along with the need for alternative raw materials that increase opportunities for a domestic, continuous, and sustainable HVO supply.

The work presented in this report deals mainly with the first part, investigating the potential supply of domestic raw materials for production of HVO. The assessment covered raw materials already used today (year 2020), such as tall oil and used cooking oil, as well as raw materials and

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[1] Biomass fuels refer to gaseous and solid fuels produced from biomass; biofuels refer to liquid fuel for transport produced from biomass; bioliquids refer to liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass

technologies that could be used in the future (year 2050). The focus was on using renewable oil and fats in existing plants in Sweden for production of HVO.

2 AIM OF THE STUDY

The aim of the present study was to identify and assess the potential of different domestic raw materials for HVO production in Sweden, expressed as TWh of HVO per year. The focus was on the Swedish supply potential of renewable raw materials that can be produced under Nordic conditions, *i.e.* raw materials grown or harvested on agricultural or forest land in Sweden, or raw materials in the form of co-products, residues or wastes from Swedish industries or households. Imported feedstock were not included. The theoretical, ecological, and technical potentials were estimated for all raw materials identified, while the economic potential was assessed when possible. The potentials were assessed for a short-term perspective (year 2020) and a long-term perspective (year 2050).

Relevant restrictions and classification of the different raw materials according to the updated Renewable Energy Directive (REDII) were considered and presented in a qualitative manner as it is expected to influence the level of utilization of different feedstocks.

Based on the outcome of this assessment, two identified raw materials will be selected and studied in the next step of this project, where life cycle assessment and techno-economic assessment will be performed.

3 METHOD

A literature review was performed to identify relevant raw materials and conversion pathways for HVO production and to collect background data for assessing the supply potential for each raw material. The study includes raw materials currently used for HVO production and raw materials that could potentially be used in the future as shown in Figure 1.

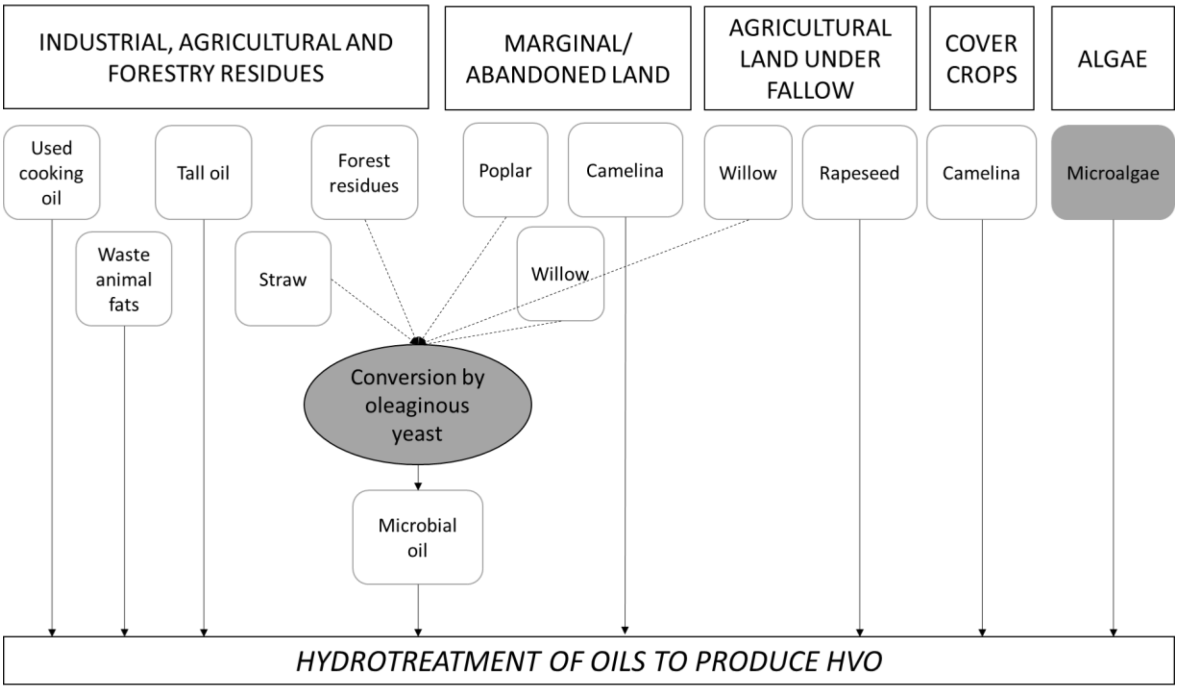

Figure 1. Illustration of the raw materials assessed in this study. Grey boxes indicate that the technology is currently not available but is expected to be in 2050.

The supply potential for each raw material was estimated following the framework of Egnell & Börjesson (2012) (see section 3.1). An additional aspect considered when the different raw materials were evaluated, was their classification and associated utilization restrictions as defined in the updated Renewable Energy Directive (RED II) (see section 3.2).

3.1 ASSESSMENT OF RAW MATERIAL SUPPLY POTENTIAL

The supply potential of a specific raw material varies depending on restrictions or limitations that can be applied to it. The highest form of potential is the theoretical potential which is commonly described as the theoretical availability when no restrictions are applied (Egnell & Börjesson, 2012; BEE, 2011).

The theoretical potential is based on existing available biomass resource, *e.g.* extraction of forest residues, or estimates from available land, *e.g.* crops grown on agricultural land currently unused. The theoretical potential has in turn limitations that can be divided in different categories:

- *Social;* could be due to public opinions on for example energy forest grown on agricultural land that alters the landscape view.

- *Environmental*; could be due to increased pressure on forest or agricultural land that affects future productivity negatively or increases environmental burdens.
- *Technical* limitations due to available technology, which can result in restrictions due to high costs and low profitability.
- *Economic;* raw material prices and production costs are limiting factors highly interlinked with technical developments.
- *Market-associated;* the market also considers policies, prices and subsidies for alternative energy carriers possibly affecting investments within the bioenergy sector.

The market potential is also referred to as the implementation potential, since it describes the 'actual potential' by considering all other limitations to the theoretically available potential (Egnell & Börjesson, 2012; BEE, 2011).

The assessment performed in this work was based on the framework presented in Egnell & Börjesson (2012) (Figure 2), which considers theoretical, social, ecological, technical, economic and market potentials. However, since the background data were collected from several sources, the definition of different types of potential may have varied slightly from those in the original data sources. The focus in this work was on the theoretical, ecological, and technical potentials, while the economic potential was assessed when data was available, and the market and social restrictions excluded.

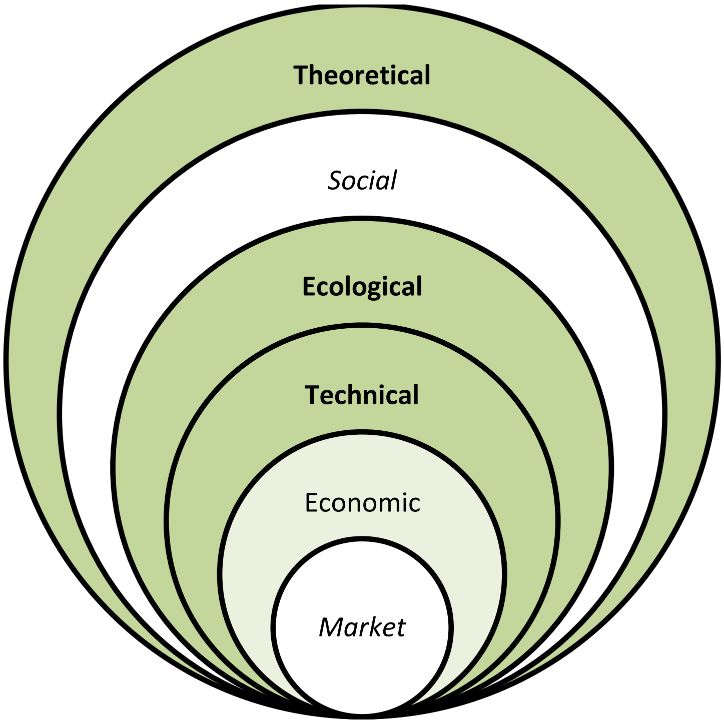

Figure 2. Potential assessment framework applied which considers different restrictions based on Egnell & Börjesson (2012). Potentials marked with green background (theoretical, ecological, technical) where included for all raw materials studied. The economic potential light green background) was included when possible, while social and market potentials (white background) were excluded.

The biomass supply potential can also be assessed based on different time perspectives, and in this work a short-term perspective (defined as year 2020) and a long-term perspective (defined as year 2050) were applied.

Data for the necessary calculations (such as feedstock availability, current and future capacity, yields or conversion efficiencies) was collected from previous studies. When no data for a specific raw material was found in literature, the potential was calculated based on personal communication with relevant actors from the fuel production sector and Swedish authorities. For all calculations, it was assumed that 0.97 MJ HVO can be produced from 1 MJ of fats (Edwards *et al*., 2014).

3.2 CLASSIFICATION AND THRESHOLS BASED ON THE RENEWABLE ENERGY DIRECTIVE (RED II)

Based on RED II (European Parliament, 2018), biofuels can be classified and defined in different ways which also influence the level of adoption of a certain fuel.

Two major categories can be identified; first-generation or advanced biofuels, based on the type of feedstock used for their production. First generation biofuels are produced from crops that could otherwise be used for food or feed. Advanced biofuels refer to biofuel produced from certain feedstock such as algae, biowaste, biomass fraction of wastes and residues from forestry and forest-based industries etc (detailed list available in Part A of Annex IX of the directive).

When demonstrating compliance for minimum share of renewable energy in the transport sector, RED II sets different threshold values when the use of biofuels is considered especially for first-generation biofuels. Production of biofuels and bioliquids from food and feed crops for example should be less than 7% of all energy used in road and rail transport (European Parliament, 2018). This does not apply to the so-called “Low indirect land-use change-risk biofuels and bioliquids”. In addition, RED II states: “*For the purposes of demonstrating compliance with the minimum shares referred to in Article 25(1): (a) the share of biofuels and biogas for transport produced from the feedstock listed in Annex IX may be considered to be twice its energy content*”. Annex IX contains two parts; Part A, which is a list of feedstocks for the production of biofuels which can be double-counted without limitation, and Part B, which is a list of feedstocks for the production of biofuels which also can be double-counted, but their contribution towards the target is limited to 1.7%. More information can be found in the respective document for RED II (European Parliament, 2018).

4 RAW MATERIALS FOR HVO PRODUCTION

This chapter presents background information on the different raw materials for HVO production. For every alternative raw material, a short definition and description is provided, together with information on its current use for HVO production in Sweden. Assumptions made while assessing the different forms of potential for each specific raw material are fully described. Moreover, every raw material is classified according to the updated EU Renewable Energy Directive (RED II) (European Parliament, 2018) and a short comment on their respective threshold value is included.

The numerical results on the estimated potentials for all raw materials are presented in the next chapter.

4.1 USED COOKING OIL (UCO)

Used cooking oil (UCO) mainly consists of vegetable oil that restaurants, food industry and households have used for frying or deep-frying. Discarded UCO can create major problems in pipe systems and wastewater treatment plants which is one of the reasons for collecting it (Swedish Waste Management and Recycling Association, 2015). The collected UCO can be used as a raw material for biofuels or other products. In 2018, around 40 GWh of UCO in the form of fat from grease traps and from restaurants were used for biofuel production (Marianne Pettersson, personal communication, 18 September 2019).

The reported share of vegetable and animal waste oils used as raw materials for HVO production has decreased substantially since 2017 (Swedish Energy Agency, 2019). This is most likely because producers have started to classify UCO as slaughterhouse waste, instead of vegetable and animal waste (Marianne Pettersson, personal communication, 20 September 2019).

A large part of the collected UCO is currently used for purposes other than biofuel production. Some companies use UCO collected mainly from restaurants and other sources in the food industry for producing soap, stearin, special fats for chemical use and detergents (Swedish Waste Management and Recycling Association, 2015). However, the Swedish Waste Management and Recycling Association does not collect statistics on the actual end-uses of UCO (Jenny Westin, personal communication, 10 September 2019).

4.1.1 Classification according to RED II

Biofuels from UCO are double-counted towards the overall target for transport biofuels in RED II (Article 25(1), Annex IX part B (a); European Parliament, 2018). However, while the contribution from UCO and that from waste animal fats are double-counted, the permitted contribution towards the minimum share of renewable energy in the transport sector is limited to 1.7% in total (for the raw materials listed in Annex IX Part B) as defined in Article 27 (b) of the directive.

4.1.2 Assessment of potential

In Sweden, collection of UCO is decentralised and carried out in different ways in different municipalities (Greenea, 2016). The theoretical and technical potential of UCO from the household and professional sector (restaurants *etc*.) has been estimated for all European countries for the present day and for 2030 (ibid). In our analysis, the values for 2030 were used to estimate the potential for 2050, based on population forecasts (Statistics Sweden, 2019a). Due to lack of data, the assessment of theoretical and technical potential includes all available UCO, i.e. we do not account for the use of UCO for purposes other than biofuel production. The ecological potential was assumed to be the same as the theoretical potential since there are no environmental constraints regarding collecting this type of waste.

4.2 WASTE ANIMAL FATS

Waste animal fats include waste fat from slaughterhouses and other waste oils of animal origin. Waste from slaughterhouses comprised 37% of the reported feedstock for HVO consumed in Sweden in 2018 (Swedish Energy Agency, 2019). In the statistics produced by the Swedish Energy Agency, animal fats are divided into “Animal fat category 1 and 2” and “Animal fat other”. Of these two categories, only 0.01% originated from Sweden in 2019, but the majority came from other EU and non-EU countries. For example, Germany delivered large quantities of “Animal fat other” to the Swedish biofuel market (around 22% of the total) (Marianne Pettersson, personal communication, 18 September 2019).

4.2.1 Classification according to RED II

Animal fats (categories 1 and 2 in accordance with Regulation (EC) No. 1069/2009 of the European Parliament and the Council) are classified as a feedstock that is available in limited amounts, and their energy content counts twice towards the minimum share of renewable energy in the transport sector (Article 25(1) in RED II (European Parliament, 2018)), according to Annex IX part B (b) (European Parliament, 2018). However, while the contribution from waste animal fats is double-counted, the permitted contribution towards the target is limited to 1.7% in total (for the raw materials listed in Annex IX Part B).

4.2.2 Assessment of potential

The use of animal fats is projected to undergo a moderate increase in the future, due to the limited availability and due to the cap for the use of them in RED II (European Parliament 2018).

The amount of residual animal fat generated in a region depends on meat production in the region and on the type of meat and meat products consumed (*e.g.* whether consumers prefer fat-free meat cuts or cuts with more fat, or whether or not animal fats are used for cooking). In this study, beef was assumed to generate 6% fat (of slaughter weight), pork 13% (Rundgren, 2016) and chicken 10% (Sari *et al*., 2016).

In Sweden, meat production and consumption have decreased slightly in recent years (Swedish Board of Agriculture & Statistics Sweden, 2019). Projections 2018 on European meat production up to 2030 indicate that production of pork and beef will fall by 2% and 6%, respectively. However, chicken production is expected to increase by 9% (European Commission, 2018). No similar projections for Swedish production could be found, so the projected change in Swedish production was assumed to be the same as the projected change in European production. The percentage change from 2018 to 2030 was extrapolated to 2050, assuming that the same trend as for 2018-2030 will continue.

Since almost all slaughter of farm animals is carried out in slaughterhouses, it was assumed that the theoretical value is equal to the technical potential. Ecological constraints were not considered relevant since animal fat is a waste product and there are no additional environmental consequences from collecting the waste. There are availability limitations, however, since other sectors (such as the food industry) also use animal fat.

4.3 TALL OIL

Tall oil is a by-product from the pulp and paper industry that can be further refined and used for HVO production. In 2018, around 10% of the raw materials used for HVO production in Sweden consisted of crude tall oil (Swedish Energy Agency 2019), of which 46% (0.7 TWh) originated from Sweden (Marianne Pettersson, personal communication, 19 September 2019).

4.3.1 Classification according to RED II

Tall oil pitch is listed in Annex IX (Part A (h)) in RED II as a feedstock for advanced biofuels and its energy content counts twice towards the minimum renewable energy share target (Article 25(1) in RED II (European Parliament, 2018)).

4.3.2 Assessment of potential

The total annual production of crude tall oil in Swedish pulp mills is around 266 000 tons (in 2015), according to calculations by Staffas *et al*. (2015). Based on yearly production of crude tall oil and a conversion factor of 0.66 from crude tall oil to biodiesel (Helena Sjögren, personal communication 14 January 2020), it was calculated that approximately 40% of the crude tall oil generated in Sweden was used for biodiesel in 2018.

Tall oil is also used for other purposes. Personal communications with several pulp mills in Sweden revealed that some of the tall oil produced is refined to tall oil pitch, which is then used as internal energy for the pulp process. Other uses of tall oil include soap production and direct combustion in district heating plants. Based on the above, it was assumed that the economic potential of HVO produced from tall oil was limited to 40% of the total crude tall oil produced.

Hänninen *et al.* (2014) assessed the outlook for the European forestry industry based on their own estimations and other studies. For the pulp and paper industry specifically, they projected a 28% decrease in European pulp production by 2030. However, others have projected an increase in production (*e.g.* Buongiorno *et al.*, 2012). As Hänninen *et al.* (2014) point out, there has been limited research on the impacts of a possible decline in pulp production on the bioenergy supply. While there is a need for research to confirm current projections, actors in the industry should prepare for a possible decrease in European pulp production (ibid). Swedish Forest Industries predict that by 2045, the production of crude tall oil in Sweden could be 4 TWh (Helena Sjögren, personal communication, 14 January 2020).

Based on these conflicting future scenarios, we estimated tall oil availability according to the Swedish Forest Industries prognosis and a future decline in line with the scenario in Hänninen *et al.* (2014), *i.e.* a 28% decline in pulp production in Sweden by 2050. We also assumed that the percentage distribution between the internal use at the pulp plant and the refining to biodiesel would remain the same. The distribution between internal use within the pulp and paper mills and export of crude tall oil could change in the future, but this was not addressed in the present study.

4.4 CROPS GROWN ON FALLOW LAND

The so-called first-generation biofuels are generally produced from feedstock that can also be used as food and feed (IEA, 2008). In RED II, they are defined as "Fuels produced from food and feed crops" (European Parliament, 2018). In 2018, around 3% of HVO used in Sweden was produced from palm oil and less than 1% was produced from rapeseed oil (Swedish Energy Agency, 2019).

4.4.1 Classification according to RED II

Towards the RED II targets, first-generation biofuels may only account for up to 7% of the energy used in road and rail transport (European Parliament, 2018). With total energy use in the Swedish transport sector of around 95 TWh, this corresponds to about 6.7 TWh. The possibility to increase the use of HVO from first-generation crops in Sweden thus depends on the total share of biofuels produced from first-generation crops.

4.4.2 Assessment of potential

In assessing the potential of first-generation biofuels, we focused on use of Swedish agricultural land that is currently not used for food or feed production, defined here as land reported as fallow land. The total area of fallow land reported in 2018, around 160 000 hectares (Swedish Board of Agriculture, 2018a), was used as reference to represent the current potential. The amount of fallow land in 2019 was significantly lower, most likely due to the dry summer in 2018 (farmers tended to report fallow land as non-fallow land after the drought in 2018) (Swedish Board of Agriculture, 2019a).

Fallow land can provide ecological and agroecological benefits, which includes growing crops with benefits for the cropping system, such as deep-rooted crops loosening the soil, nitrogen-fixing crops, or crops with benefits for biodiversity, *e.g.*, benefiting pollinators. However, the extent to which fallow land is used for these purposes is not known. Therefore, in assessing ecological potential, as a rough estimate we assumed that 50% of the fallow land available could be used for growing first-generation crops, such as winter rapeseed, for HVO production. It was assumed that rapeseed can be grown on fallow land in the same areas where it is currently grown, i.e., throughout southern and central Sweden (the northern regions Nedre Norrland and Övre Norrland were excluded).

The remaining fallow land area was multiplied by 80% of the standard rapeseed yield (normskördar; Statistics Sweden, 2019b) for each production area to account for the estimated lower productivity of fallow land (as done by Börjesson, 2016). For each production area it was assumed that winter rapeseed and spring rapeseed was grown to the same rate as 2018. Winter rapeseed is more common in the south and spring rapeseed is grown to a larger extent further north. Rapeseed normally needs to be included in a crop rotation where it occurs only once every 5-6 years. Using this land for production would also mean fallow land being integrated with other agricultural land. For each production area, rapeseed cultivation does not exceed 10% of the total arable land. Therefore, there could be room for more rapeseed in several crop rotations.

Land use change by 2050 in Sweden is difficult to estimate. It has been suggested that by 2050, up to 910 000 hectares will be either fallow land used for energy, or for growing crops for industrial applications, which corresponds to roughly one third of the current total used and unused agricultural land (Swedish Board of Agriculture, 2018a; 2012). This is not a prognosis, but a scenario (ibid). Because of the uncertainty, the figure was lowered by 50% in the present analysis. When estimating the ecological potential, it was again assumed (as above) that 50% of this land could be used for first-generation crops, in this case rapeseed. The distribution of rapeseed production throughout Sweden was assumed to be the same as it is today, and yield was estimated as described above.

For comparison, the potential for short-rotation coppice willow cultivation (*Salix* spp., fast-growing energy forestry) was also estimated. When assessing the ecological potential, it was assumed that 50% of fallow land could be used for energy cropping. It was assumed that willow can be grown throughout southern and central Sweden (the northern regions Nedre Norrland and Övre Norrland were excluded). Calculation of potential production of lipids from willow using oleaginous yeast is explained in section 4.6.

4.5 CROPS GROWN ON MARGINAL (ABANDONED) OR DEGRADED LANDS

Marginal (abandoned) or degraded land can sometimes be used to grow energy and oilseed crops. Marginal land can be defined as land that is no longer used or is used with very low intensity. This could be due to low agricultural productivity or to low economic potential (World Resources Institute, 2019), meaning that it may be possible to increase production on some of this land. According to RED II, Annex X (C. (point 9), severely degraded land is “land that for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded” (European Parliament, 2018).

To our knowledge, oilseed crops grown on marginal and degraded land are currently not used for HVO production in Sweden. In this study, three different crops were considered possible to grow on marginal land: willow, poplar (*Populus* spp.) and *Camelina sativa* (*oljedådra* in Swedish, hereafter referred to as camelina). The two first crops are lignocellulosic (woody) perennial crops, while camelina is an annual crop.

4.5.1 Classification according to RED II

Article 25 in RED II sets a cap on production of biofuels and bioliquids from food and feed crops (7% of all energy used in road and rail transport) (European Parliament, 2018). However, the so-called “Low indirect land-use change-risk biofuels, bioliquids and biomass fuels” are exempted from the 7% limit on use of biofuels from food and feed crops (ibid).

Abandoned or degraded land can be used for production of “Low indirect land-use change-risk biofuels” if all criteria in Article 4 in Regulation 2019/807 are met, including the so-called “Additional measures” in Article 5 in RED II. At present, the new updated regulations in RED II have not yet been implemented in Swedish law.

4.5.2 Assessment of potential

There have been a few assessments on the amount of marginal land in Sweden, but it is uncertain how much of this land could sustain productive crop growth. One study concluded that around half a million hectares of land (not including fallow land), were not categorised as arable land at that time, but could potentially be used as such (Johnsson, 2008). Half a million hectares represent roughly 20% of the total of around 2.6 million hectares of arable land in Sweden (Swedish Board of Agriculture, 2019a). However, much of this land consists of small and remote fields that are currently not economically feasible to cultivate.

To determine the amount of marginal land in Sweden for the purposes of the present analysis, data from Olsson and Börjesson (2016) were used. They estimated that there are around 88 000 hectares of abandoned agricultural land in Sweden, not including fallow land. We assumed this figure considers ecological constraints, since the study by Olofsson and Börjesson (2016) focused on marginal land considered available for bioenergy production. It did not include *e.g.* abandoned land, which was considered to have potentially higher ecological values.

4.6 CONVERSION OF LIGNOCELLULOSIC MATERIALS INTO MICROBIAL OILS

Microbial oils are lipids produced by using microbes that digest sugars from a variety of biomass. This can involve *e.g.* conversion of lignocellulose materials to lipids using oleaginous yeast (Sitepu *et al.*, 2014). Microbial oils from the oleaginous yeast can then be used for HVO production (Nogué *et al.*, 2018). To our knowledge, microbial oils are currently not used for HVO production.

4.6.1 Classification according to RED II

How a fuel is classified under RED II depends on the feedstock. Annex IX (Part A) in RED II lists several feedstocks suitable for production of microbial oils that can be used for advanced biofuels for which the energy content counts twice towards the minimum share of renewable energy in the transport sector (Article 25(1), European Parliament, 2018). Examples of suitable feedstocks are straw, crude glycerine (i) and possibly also feedstocks in the categories “Other non-food cellulosic materials” (p) and “Other lignocellulosic materials” (q).

4.6.2 Assessment of potential

The potential for production of lipids from lignocellulosic biomass using oleaginous yeast was estimated from different raw materials; willow from fallow land, poplar and willow from marginal lands, straw, forest residues (tops, branches and stumps) (see the previous sections 4.4 and 4.5). The potential feedstock supply for straw and forest residues was based on Börjesson (2016). We assumed that all these lignocellulosic materials were available for HVO production, although, in reality, they can be used for a variety of energy-related and non-energy related applications.

Conversion to lipids using oleaginous yeast was estimated based on sugar yield after pre-treatment by steam explosion and then enzymatic hydrolysis of the hexose and pentose sugars in straw (Linde *et al.*, 2008), forest residues (Biswas *et al.*, 2015), willow (Amarasekara, 2013, sugar recovery rate for willow as assumed to be the same as for forest residues) and poplar (assumed to be the same as for willow, due to lack of information). Information on lipid yields from hexose and pentose sugars was taken from Karlsson *et al.* (2016). Lipid production from lignocellulosic materials such as straw, crude glycerol, corn stover, rice straw and birch has been tested successfully at laboratory scale (Passoth & Sandgren, 2019; Passoth, 2017). To our knowledge, lipid production from forest residues and willow biomass has not yet been tested. At present, there is no large-scale production of oleaginous yeast using lignocellulosic biomass, although parts of the process required already exist at large scale, such as the steam explosion pre-treatment step. For this reason, only the future potential was assessed for this technology. Further, the technical and economic potential could not be assessed, due to uncertainties regarding production.

Apart from lipids, considerable amounts of yeast biomass are produced in the conversion process. This biomass can be either anaerobically digested to biogas (Karlsson *et al.*, 2016) or potentially used for other purposes, such as fish feed. If the yeast biomass is anaerobically digested, the energy yield from the process, using straw as raw material, has been estimated to be 4 MJ lipids per kg straw and 3 MJ biogas per kg straw (Karlsson *et al.*, 2017). This corresponds to around 76 kg lipids (or around 1100 kWh) and 830 kWh biogas per ton of straw dry matter.

4.7 COVER CROPS

Cover crops are crops grown after the main crop, and therefore they do not compete directly with food or feed production. However, this is context dependent. In many regions of the world, double- or even multi-cropping for food and feed production is possible. In Sweden, however, multi-cropping is generally not practised.

A suitable cover crop could be the fast-growing oilseed crop camelina, which has historically been an important food crop in northern Europe (University of Minnesota Extension, 2019; Zubr, 1997). Cultivation of camelina has gained some attention due to the fact that it has relatively low requirements for agricultural inputs such as fertilisers. That can enable cultivation on marginal land (Bansal & Durrett, 2016). However, it is also considered an interesting crop for double-cropping or relay cropping in cold climates (Berti *et al.*, 2017; Gesch & Archer, 2013). Relay cropping means that the main crop is planted in the growing cover crop and the cover crop can therefore be harvested later than if double-cropping is applied.

To our knowledge, cover crops are not used for HVO production in Sweden today. Camelina is only grown on a very small scale in Sweden for production of vegetable oil sold on a niche market for human consumption (see e.g. Camelina of Sweden, etc.[2]).

4.7.1 Classification according to RED II

Under RED II, cover crops are not considered as main crops and therefore do not lead to additional demand for land (European Parliament, 2018). According to the current interpretation of RED II by the Swedish Energy Agency, these crops are exempted from the cap on biofuels from food and feed crops, provided that they do not create extra demand for land, *i.e.* do not decrease yield of the main crop, for example (Emma Kjille, personal communication, 13 January 2020). Cover crops are

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[2] https://www.camelinaofsweden.se/

defined in RED II as “Non-food cellulosic material” (Article 2 (42)). These types of crop biomass are categorised as “Other non-food cellulosic material”; under Annex IX, Part A.

4.7.2 Assessment of potential

In assessing potential, it was assumed that camelina could be grown in two types of systems:

1. After early harvest in June, *e.g.* after harvesting new potatoes. It was assumed that spring camelina could be planted after harvesting the potatoes and would be able to mature fully during the same summer. New potatoes occupied 20% of the total area of arable land used for potatoes in Sweden in 2018, which was in turn 20% of available arable land, or around 3,000 hectares (Swedish Board of Agriculture, 2018c). These figures were used in the present study.

2. With a spring-sown crop, as a cover crop or intermediate crop. It was assumed that winter camelina could be grown in the crop rotation, most likely by relay cropping where the spring-sown cereal is planted in the growing winter camelina crop. The camelina would then mature and be harvested in June, while the main crop would continue to grow and be harvested as usual in late summer.

Based on experiences from growing winter camelina in cold climates with a relatively short growing season in Minnesota, USA, field peas (*Pisum sativum*), faba beans (*Phaseolus vulgaris*) and maize (*Zea mays*) were selected as likely candidate crops to be grown together with winter camelina in central and southern Sweden (*i.e.* excluding Övre and Nedre Norrland). This selection was based on reports that dry edible beans and sweetcorn can be grown together with camelina in Minnesota (Gesch, 2014; Gesch & Archer, 2013). This was quite a cautious selection, since these are crops that require relatively small areas for cultivation and that camelina might be possible to grow together with other crops, but it was made due to lack of data on cultivation under Swedish conditions. Furthermore, camelina is a brassica crop, like rapeseed, which is often grown in many areas of Sweden (especially in the south). Rapeseed is only grown every 5-6 years in crop rotations, to prevent the spread of various brassica-related diseases (Swedish Board of Agriculture, 2018b), and it is possible that this restriction would also be necessary for camelina. However, new technologies for pest control could make more land available for cultivating camelina as cover crop in the future.

In the assessment of ecological potential, an area proportional to the share of arable land given over to rotations involving rapeseed (assuming that rapeseed is grown every 6 years) was removed from the area available for cultivating crops suitable for HVO production. Data on the area used for the different crops (mentioned above) and total area of arable land in Sweden were taken from national statistics for 2019 (Swedish Board of Agriculture, 2019a). Based on field trial results reported by Berti *et al.* (2015) and Gesch (2014), the camelina yield was assumed to be 1,560 kg per hectare and the oil content was assumed to be 40%.

4.8 MICROALGAE

Microalgae that accumulate lipids have long been considered an interesting option for biofuel and especially biodiesel production (FAO, 2010). Previous studies have primarily focused on fatty acid methyl ester (FAME) production from algae oils (Parsons *et al.*, 2017; Gnansounou & Raman, 2016). Microalgae are currently not used for large-scale HVO production in Sweden.

4.8.1 Classification according to RED II

Algae cultivated on land, in ponds or photobioreactors, are listed in Appendix IX (Part A (a)) in RED II (European Parliament, 2018) and therefore their contribution towards the target may be considered to be twice their energy content.

4.8.2 Assessment of potential

Data on the estimated potential of microalgae were taken from a study by Börjesson (2016) which assumed that algae could be grown by the pulp and paper industries using excess heat from the process, or by sewage treatment plants using available resources. However, the estimated values in that study are based on large uncertainties and only the technical potential is described (Börjesson, 2016).

5 RESULTS

The results of the assessment of different raw materials for potential production of HVO are presented in Table 1 (in TWh HVO per year). Waste and residue oils, such as used cooking oil from households and restaurants, were assessed as having relatively low potential if only sourced in Sweden. Waste animal fats were estimated to have higher potential, but the availability for HVO production is uncertain, as it depends on how much of the total share is used for other purposes, such as food production.

For tall oil, the production increases projected by the industry meant that it had rather high potential for HVO production compared with the other waste and residue raw materials assessed. The information received from the pulp and paper industries indicated that much of the tall oil generated today is used as internal energy in the pulp and paper plants. Production of HVO from tall oil could therefore be higher if pulp and paper industries used other energy sources for their processes.

Cultivating more rapeseed on current fallow land presents an opportunity to increase production of oils from Swedish agriculture and, compared with waste and residue oils, the potential was estimated to be rather high. However, under RED II this raw material is categorised as a food and feed crop, which limits the potential for use in HVO production.

The use of marginal land and cover crops was found to yield a relatively low potential supply. However, these raw materials are excepted from the RED II cap on food and feed crops and might be interesting in that perspective. Further, use of an oilseed crop such as camelina as a cover crop provides an interesting opportunity to increase the overall productivity of Swedish agriculture. However, the estimate of available marginal land and arable land suitable for growing camelina as a cover crop is uncertain.

The use of lignocellulosic materials, such as straw and forest residues, was clearly associated with high potential. However, using oleaginous yeast is not an established technology and further assessments are needed to determine its technical and economic potential (the economic potential value in Table 1 only represents the economic potential for biomass supply).

The purpose of the study was to assess the potential of different raw materials available in Sweden, today (2020) and in the future (2050). We have chosen to only present the potentials separately for each raw material (Table 1) instead of summing them up to a total potential for several reasons. Firstly, none of the potentials were possible to assess for all raw materials due to a lack of data. Secondly, all the raw materials cannot be produced at the same time since some of them compete for the same land (Figure 1). In those cases, it does not necessarily mean that the raw material with the highest potential on that type of land is the best option, as other aspects than the potential amount of HVO may be important. Some of those aspects will be assessed further in the techno-economic assessment and life cycle assessment that will be carried out during the continuation of this project. Lastly, the assessments of different potentials for different raw materials were made in different ways using different assumptions, resulting in numbers with different levels of uncertainty. The numbers in Table 1 should therefore be interpreted alongside the descriptions of how each of them was generated (Chapter 4).

Table 1. Estimates of potential supply for all selected raw materials and technologies, expressed in TWh HVO per year. OY= biochemical conversion using oleaginous yeast. For comparison, approximately 14 TWh of HVO were sold in Sweden during 2018 (Swedish Energy Agency, 2019).

	Theoretical potential		**Ecological potential**		**Technical potential**		**Economic potential**		**Comments**
Year	2020	2050	2020	2050	2020	2050	2020	2050	
Used cooking oil (UCO) total	0.18	0.21	0.18	0.21	0.13	0.17			Demand from other sectors was not taken into account. Theoretical and ecological potential were assumed to be the same, as collection of used cooking oil was assumed to have no ecological consequences. Potential for 2050 was calculated based on expected population growth.
Used cooking oil from households	*0.04*	*0.05*	*0.04*	*0.05*	*0.02*	*0.02*			
Used cooking oil from professional kitchens	*0.14*	*0.16*	*0.14*	*0.16*	*0.11*	*0.15*			
Waste animal fats	0.54	0.56	0.54	0.56	0.54	0.56			
Tall oil	1.85	1.33-2.64	1.85	1.33-2.64	1.85	1.33-2.64	0.70	0.51-1.02	The estimated tall oil potential was based on the outlook for European pulp production and the Swedish forestry industry´s projection. The economic potential is based on the assumption that approximately 40% of the crude tall oil is available for HVO production.
Crops grown on fallow land									
Oilseed crop (rapeseed)	1.88	5.39	0.94	2.70	0.94	2.70			For ecological potential, it was assumed that 50% of fallow land could be used for rapeseed or willow production.
Willow OY		4.40		2.20					For ecological potential, it was assumed that 50% of fallow land could be used for rapeseed or willow production.
Crops grown on marginal land									
Oilseed crop (*Camelina sativa*)			0.37	0.37	0.37	0.37	0.24	0.24	For ecological potential, fields smaller than 1 ha were removed.
Willow OY				0.46				0.30	Future economic potential only considers economic aspects of biomass availability.
Poplar OY				0.62				0.41	Future economic potential only considers economic aspects of biomass availability.
Cover crops									
Oilseed crop (*Camelina sativa*)	0.59	0.59	0.40	0.40	0.40	0.40			Future potential assumed to be the same as current potential, due to large uncertainties related to future use of agricultural land.
Lignocellulosic residues from agriculture and forestry									Potential availability of raw biomass from Börjesson (2016). Future economic potential only considers economic aspects of biomass availability.
Straw OY		4.87		2.34				0.70	
Tops and branches OY		15.97		12.21				5.68	
Stumps OY		11.98		7.05				1.39	
Microalgae						0.43			Based on Börjesson (2016).

6 CONCLUSIONS AND FUTURE WORK

This study assessed the potential supply of domestic feedstock for HVO production, with the future aim of increasing the share in the Swedish HVO consumption mix. The assessment covered materials already used today, such as tall oil and used cooking oil, and raw materials and technologies that could be used in the future (2050). The analysis provided information on the theoretical, ecological, and technical potential for all raw materials identified.

Lignocellulosic materials (straw and forest residues) were assessed as having the highest potential for HVO production, and thus increasing the share of domestic raw materials in the HVO supply mix. However, one of the options studied, use of oleaginous yeast, is not an established technology and further assessments are needed on its technical and economic potential. Waste and residue oils of domestic origin, such as used cooking oil from households and restaurants, were assessed as having relatively low potential. Use of marginal land and cover crops were also assessed as having relatively low potential. However, these raw materials are currently exempted from the cap on food and feed crops in the EU Renewable Energy Directive, and therefore interest might increase in the future.

To obtain a more comprehensive picture of the potential of the selected feedstocks, during the next stage of the project the present analysis will be complemented with investigations on their environmental and economic performance. Based on the outcome of this work and on their relevance for the Swedish and Nordic HVO industry, two feedstock alternatives will be selected for further investigation. Investigations will include systematic environmental and techno-economic life cycle assessments.

REFERENCES

Amarasekara, A.S. (2013). Handbook of cellulosic ethanol: John Wiley & Sons.

Bansal, S. & Durrett, T.P. (2016). Camelina sativa: an ideal platform for the metabolic engineering and field production of industrial lipids. Biochimie, 120, pp. 9-16.

BEE (2011). Biomass Energy Europe, Project No. 213417. Final Report to the European Commission Directorate General for Research and Innovation.

Berti, M., Gesch, R., Johnson, B., Ji, Y., Seames, W. & Aponte, A. (2015). Double-and relay-cropping of energy crops in the northern Great Plains, USA. Industrial crops and products, 75, pp. 26-34.

Berti, M., Johnson, B., Ripplinger, D., Gesch, R. & Aponte, A. (2017). Environmental impact assessment of double-and relay-cropping with winter camelina in the northern Great Plains, USA. Agricultural systems, 156, pp. 1-12.

Biswas, R., Teller, P.J. & Ahring, B.K. (2015). Pretreatment of forest residues of Douglas fir by wet explosion for enhanced enzymatic saccharification. Bioresource Technology, 192, pp. 46-53.

Buongiorno, J., Zhu, S., Raunikar, R. & Prestemon, J.P. (2012). Outlook to 2060 for world forests and forest industries: a technical document supporting the Forest Service 2010 RPA assessment. Gen. Tech. Rep. SRS-151. Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station. 119 p., 151, pp. 1-119.

Börjesson, P. (2016). Potential för ökad tillförsel och avsättning av inhemsk biomassa i en växande svensk bioekonomi: Lund University. Department of Technology and Society. Environmental and Energy Systems Studies.

Edwards, R., Hass, H., Larivé, J.-F., Lonza, L., Maas, H. & Rickeard, D. (2014). WELL-TO-WHEELS Report Version 4. a JEC WELL-TO-WHEELS ANALYSIS. Institute for Energy and Transport, Joint Research Centre, Luxembourg: Publications Office of the European Union, 2014.

Egnell, G. & Börjesson, P. (2012). Theoretical versus market available supply of biomass for energy from long-rotation forestry and agriculture–Swedish experiences. International Energy Agency. Bioenergy: Task 43: 2012:02.

Elbersen, B., Staritsky, I., Hengeveld, G., Schelhaas, M., Naeff, H. & Böttcher, H. (2012). Atlas of EU biomass potentials: spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources: Alterra/IIASA.

European Commission (2018). EU agricultural outlook for markets and income 2018-2030.

European Parliament (2009). Directive (EU) 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/ECOJL 140/16).

European Parliament (2018). Directive (EU) 2018/2001 of the European Parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) L 328/82).

Gesch, R. & Archer, D. (2013). Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. Industrial Crops and Products, 44, pp. 718-725.

Gesch, R.W. (2014). Influence of genotype and sowing date on camelina growth and yield in the north central US. Industrial crops and products, 54, pp. 209-215.

Gnansounou, E. & Raman, J.K. (2016). Life cycle assessment of algae biodiesel and its co-products. Applied Energy, 161, pp. 300-308.

Grahn, M. & Hansson, J. (2015). Prospects for domestic biofuels for transport in Sweden 2030 based on current production and future plans. Wiley Interdisciplinary Reviews: Energy and Environment, 4(3), pp. 290-306.

Greenea (2016). Analysis of the current development of household UCO collection systems in the EU. European Waste-to-Advanced Biofuels Association.

Hammar, T., Ericsson, N., Sundberg, C. & Hansson, P.-A. (2014). Climate Impact of Willow Grown for Bioenergy in Sweden. BioEnergy Research, 7(4), pp. 1529-1540.

Hartikka, T., Kiiski, U., Kuronen, M. & Mikkonen, S. (2013). Diesel Fuel Oxidation Stability: A Comparative Study, SAE Technical Paper 2013-01-2678

Hänninen, R., Hetemäki, L., Hurmekoski, E., Mutanen, A., Näyhä, A., Forsström, J., Viitanen, J. & Koljonen, T. (2014). European forest industry and forest bioenergy outlook up to 2050: A synthesis. Cleen Oy, Helsinki, Finland.

i Nogué, V.S., Black, B.A., Kruger, J.S., Singer, C.A., Ramirez, K.J., Reed, M.L., Cleveland, N.S., Singer, E.R., Yi, X. & Yeap, R.Y. (2018). Integrated diesel production from lignocellulosic sugars via oleaginous yeast. Green chemistry, 20(18), pp. 4349-4365.

IEA (2008). From 1st- to 2nd generation biofuel technologies An overview of current industry and RD&D activities.

Johnsson, B. (2008). Kartläggning av mark som har tagits ur produktion. Jordbruksverket Rapport 2008:7.

Karlsson, H., Ahlgren, S., Sandgren, M., Passoth, V., Wallberg, O. & Hansson, P.-A. (2016). A systems analysis of biodiesel production from wheat straw using oleaginous yeast: process design, mass and energy balances. Biotechnology for biofuels, 9(1), p. 229.

Karlsson, H., Ahlgren, S., Sandgren, M., Passoth, V., Wallberg, O. & Hansson, P.-A. (2017). Greenhouse gas performance of biodiesel production from straw: Soil carbon changes and time-dependent climate impact. Biotechnology for Biofuels 10(217).

Linde, M., Jakobsson, E.-L., Galbe, M. & Zacchi, G. (2008). Steam pretreatment of dilute H_2SO_4-impregnated wheat straw and SSF with low yeast and enzyme loadings for bioethanol production. Biomass and Bioenergy, 32(4), pp. 326-332.

Olofsson, J. & Börjesson, P. (2016). Nedlagd åkermark för biomassaproduktion–kartläggning och potentialuppskattning. Report No. 2016: 01.

Parsons, S., Chuck, C. & McManus, M. (2017). Microbial lipids: Progress in life cycle assessment (LCA) and future outlook of heterotrophic algae and yeast-derived oils. Journal of Cleaner Production 172.

Passoth, V. (2017). Lipids of yeasts and filamentous fungi and their importance for biotechnology. In: Biotechnology of yeasts and filamentous fungi Springer, pp. 149-204.

Passoth, V. & Sandgren, M. (2019). Biofuel production from straw hydrolysates: current achievements and perspectives. Applied Microbiology and Biotechnology, pp. 1-12.

Pecchia, P., Russo, R., Brambilla, I., Reggiani, R. & Mapelli, S. (2014). Biochemical Seed Traits of Camelina sativa – An Emerging Oilseed Crop for Biofuel: Environmental and Genetic Influences. Journal of Crop Improvement, 28(4), pp. 465-483.

Peck, P., Grönkvist, S., Hansson, J., Lönnqvist, T. & Voytenko, Y. (2016). Systemic Constraints and Drivers for Production of Forest-Derived Transport Biofuels in Sweden—Part A: Report. Göteborg, Sweden: f3-The Swedish Knowledge Centre for Renewable Transportation Fuels.

Prade, T., Björnsson, L., Lantz, M. & Ahlgren, S. (2017). Can domestic production of iLUC-free feedstock from arable land supply Sweden's future demand for biofuels? Journal of Land Use Science, 12(6), pp. 407-441.

Rundgren, G. (2016). Vilket matfett ska man välja? Är palmolja alltid dåligt? Report, Matlust.

Sari, O.F., Ozdemir, S. & Celebi, A. Utilization and management of poultry slaughterhouse wastes with new methods. In: Proceedings of Eurasia 2016 Waste Management Symposium.

Sitepu, I.R., Garay, L.A., Sestric, R., Levin, D., Block, D.E., German, J.B. & Boundy-Mills, K.L. (2014). Oleaginous yeasts for biodiesel: Current and future trends in biology and production. Biotechnology Advances, 32(7), pp. 1336-1360.

Staffas, L., Hansen, K., Sidvall, A. & Munthe, J. (2015). Råvaruströmmar från skogen-tillgång och samband. IVL rapport C, 116.

Statistics Sweden (2019a) Befolkningsprognos för Sverige. Statistics Sweden. [accessed: 20191101].

Statistics Sweden (2019b). Normskördar för skördeområden, län och riket 2019 [Standard yields of cereals in 2019]. Report JO 15 SM 1901. Stockholm: Statistics Sweden.

Swedish Board of Agriculture (2012). Ett klimatvänligt jordbruk 2050: Report 2012:34. Jordbruksverket.

Swedish Board of Agriculture (2018a). Jordbruksmarkens användning 2018. JO 10 SM 1802. Jordbruksverket.

Swedish Board of Agriculture (2018c). Skörd av potatis: Jordbruksverket.

Swedish Board of Agriculture (2019a). Jordbruksmarkens användning 2019: Jordbruksverket

Swedish Board of Agriculture (2019b) Raps och rybs i växtföljden. Jordbruksverket. [accessed: 20191101].

Swedish Board of Agriculture & Statistics Sweden (2019). Jordbruksstatistisk sammanställning 2019: Jordbruksverket och SCB.

Swedish Energy Agency (2019). Drivmedel 2018 Redovisning av rapporterade uppgifter enligt drivmedelslagen hållbarhetslagen och reduktionsplikten. ER 2019:14.

Swedish Waste Management and Recycling Association (2015). Källsortering och behandling av matolja. Goda exempel från kommuner och bostadsbolag. Avfall Sverige, Rapport 2015:07

University of Minnesota (2019). Extension Winter camelina as a cover crop [accessed: 20190925].

World Resources Institute (2019) What is degraded land? [accessed: 20190901].

Zubr, J. (1997). Oil-seed crop: Camelina sativa. Industrial Crops and Products, 6(2), pp. 113-119.

PERSONAL COMMUNICATION

Emma Kjille, Swedish Energy Agency, 13th January 2020

Marianne Pettersson. Swedish Energy Agency, personal communication 18-20th September 2019.

Sjögren, Helena. Swedish Forest Industries, personal communication 14th January 2020.

Jenny Westin, Swedish Waste Management and Recycling Association, 10th September 2019.

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