Fields of Dreams: Scenarios to Produce Selected Biomass and Renewable Jet Fuels that Fulfill European Union Sustainability Criteria

Torry J van Slyke
Fields of Dreams: Scenarios to Produce Selected Biomass and Renewable Jet Fuels that Fulfill European Union Sustainability Criteria

Torry J van Slyke

Supervisor: Gunnar Larsson
Subject Reviewer: Anders Eriksson
Contents

Abstract ............................................................................................................................ iv
Summary ........................................................................................................................... v
List of Figures ................................................................................................................... vi
List of Tables .................................................................................................................... vi

1. Introduction ................................................................................................................ 1

2. Background ................................................................................................................ 3
   2.1. Aviation emissions, climate impact, and projected growth .............................. 3
   2.2. Industry pledges and government strategies to mitigate aviation emissions .......... 5
       2.2.1. Global targets and pillars of the aviation industry ...................................... 5
       2.2.2. Climate and energy targets of the European Union .................................. 6
       2.2.3. The European Union’s Renewable Energy Directive ................................. 7
   2.3. Current efforts to reduce climate impact of European aviation ....................... 8
       2.3.1. Engine efficiency and air traffic management improvements .................... 8
       2.3.2. Emissions cap-and-trade schemes .......................................................... 9
   2.4. Renewable jet fuels ............................................................................................ 10
       2.4.1. Hydroprocessed ester and fatty acid biojet fuel from Camelina sativa .......... 11
       2.4.2. Fischer-Tropsch biojet fuel from forestry residues .................................... 12
       2.4.3. Life cycle emissions and land use change ................................................ 14

3. Methods ...................................................................................................................... 18
   3.1. Scenario analysis scope and assumptions ......................................................... 18
       3.1.1. Data sources and calculation methods used ................................................. 18
       3.1.2. RJF conversion pathways and biomass feedstocks included ....................... 18
       3.1.3. Geographic and methodological scope ...................................................... 19
   3.2. Camelina renewable jet fuel scenario and input variables ................................. 19
       3.2.1. Crop classifications and lands selected .................................................... 19
       3.2.2. Camelina cultivation and HEFA conversion input variables ...................... 21
   3.3. Forestry residue renewable jet fuel scenarios and input variables ....................... 22
   3.4. European aviation input variables .................................................................... 23

4. Results ......................................................................................................................... 24
   4.1. Camelina biojet potential .................................................................................. 24
   4.2. Forestry residue biojet potential ...................................................................... 26

5. Discussion ................................................................................................................... 28
   5.1. RED-II compliance of scenario biofuels ............................................................ 28
       5.1.1. Camelina HRJ ......................................................................................... 28
       5.1.2. Forestry Residue FTJ ............................................................................. 29
   5.2. Comparisons to other biomass availability studies ............................................ 30
       5.2.1. Projecting RJF yields against competing biomass demand ....................... 30
       5.2.2. Future availability of forestry residues ...................................................... 30
Fields of Dreams: Scenarios to Produce Selected Biomass and Renewable Jet Fuels that Fulfill European Union Sustainability Criteria

TORRY VAN SLYKE

van Slyke, T., 2019: Fields of Dreams: Scenarios to Produce Selected Biomass and Renewable Jet Fuels that Fulfill European Union Sustainability Criteria. Master thesis in Sustainable Development at Uppsala University, 2019/12, 38 pp, 30 ECTS/hp

Abstract:

Aviation greenhouse gas (GHG) emissions have risen faster than any other transport sector to double between 1990 and 2005. Such emissions from aviation could increase another 700 percent globally, and at least 150 percent in the European Union (EU), by 2050 due to continuously increasing consumer demand. To reverse the trend of rising emissions writ large, the EU has set 2030 climate goals of reducing its GHG emissions by 40 percent (relative to 2005) and having 32 percent of gross final energy consumption from renewables. The EU’s recast Renewable Energy Directive (RED-II) calls for 14 percent of transport energy from renewables, gives multipliers to advanced biofuels, and restricts biomass that is from ecologically valuable lands or that causes land use change. Energy security and energy independence are also long-term EU goals. Many of these goals and targets have also been adopted by the European Free Trade Area (EFTA). Despite these efforts, options are limited to reduce aviation emissions compared to other transport sectors, leaving aviation biofuels, also known as renewable jet fuels (RJFs), as currently the only commercialized option. Against this backdrop, in this thesis scenario analyses were conducted to produce biomass from EU+EFTA lands, project RJF yields from this biomass, and estimate emissions savings of these RJFs compared to petroleum jet fuel. Particular effort was devoted to identifying biomass, biofuels, and EU+EFTA lands that comply with RED-II criteria. The two RJF pathways selected were hydroprocessed esters and fatty acid (HEFA) conversion of Camelina sativa vegetable oil and Fischer-Tropsch (FT) synthesis of forestry residue lignocellulosic biomass.

Over 117 million hectares in the EU+EFTA was identified as available for Camelina sativa cultivation, which could yield over 64 Mt of RJF each year, or 113 percent of the total jet fuel consumed in the EU+EFTA in 2017. Conversely, if 50 percent of the forestry residues generated as by-products from EU+EFTA roundwood harvesting operations in 2017 were extracted from harvest sites, 40 Mt of forestry residues would be available as biomass, which would yield almost 7.6 Mt of RJF annually (13% of 2017 jet fuel consumption). If all 144 million hectares of EU+EFTA forest lands deemed available for wood supply were logged, 1.772 Mt of forestry residues would be produced in total (at 50 percent extraction), which could result in almost 337 Mt of RJF, or 590% of the jet fuel consumed in the region in 2017. Hence, RJF can be feasibly produced from biomass from EU+EFTA lands, in amounts that meet or exceed the annual jet fuel consumption of the EU+EFTA, and in ways that meet or exceed RED-II sustainability criteria. However, the proportion of these RJFs yields to total annual EU+EFTA jet fuel consumption will decrease over time as the number of flights and their resulting emissions increase. The two RJFs also emit 67 percent and 91 percent fewer GHG emissions, respectively, than petroleum-based jet fuel, showing them to be important tools for the EU to meet its 2030 renewables and emissions reductions targets. Producing the biomass feedstocks and RJFs in these quantities will require the EU to make serious decisions on land use trade-offs, such as whether livestock production is more important than biofuel production.

Keywords: aviation biofuel, Camelina sativa, forestry residues, land use change, Renewable Energy Directive, sustainable development

Torry van Slyke, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden
Fields of Dreams: Scenarios to Produce Selected Biomass and Renewable Jet Fuels that Fulfill European Union Sustainability Criteria

Torry van Slyke

van Slyke, T., 2019: Fields of Dreams: Scenarios to Produce Selected Biomass and Renewable Jet Fuels that Fulfill European Union Sustainability Criteria. Master thesis in Sustainable Development at Uppsala University, 2019/12, 38 pp, 30 ECTS/hp

Summary:

Aviation greenhouse gas (GHG) emissions have risen faster than any other transport sector, doubling between 1990 and 2005, and could increase at least 150 percent further in the European Union (EU) by 2050 due to continuously increasing consumer demand. To reverse the trend of rising emissions from all sources, the EU has set 2030 climate goals of reducing its overall emissions by 40 percent (relative to 2005) and having 32 percent of energy consumption from renewable energy sources. The EU’s Renewable Energy Directive (RED-II) calls for 14 percent of transport energy from renewables but restricts the feedstock inputs (biomass) from natural or sensitive lands. Energy security and energy independence are also long-term goals of the EU. Options are limited to reduce aviation emissions compared to other transport sectors, leaving aviation biofuels, also known as renewable jet fuels (RJFs), as currently the only near-term option. In this thesis, scenario analyses were conducted to produce biomass from lands of EU and European Free Trade Association (EFTA) countries, project how much RJF is possible from these biomass feedstocks, and estimate emissions savings of these RJFs compared to petroleum jet fuel. Particular effort was devoted to identifying biomass and EU+EFTA lands that are not for human food crops. The two RJF pathways were selected: one uses *Camelina sativa* vegetable oil and the other uses the tree trimmings from logging operations (forestry residues).

Over 117 million hectares in the EU+EFTA was identified as available for *Camelina sativa* cultivation, a highly adaptable, fast-growing, and low-input oilseed plant native to Europe, which could result in over 64 million metric tonnes (megatonnes, or Mt) of RJF each year, or 113 percent of all the jet fuel consumed in the EU+EFTA in 2017. The second RJF used forestry residues: all the branches, tops, and trimmings generated as by-products from logging operations. If half of all available forestry residues were extracted for RJF, almost 40 Mt of biomass would be available each year from logging operations in the EU+EFTA, which could result in 7.6 Mt of RJF (or 13 percent of all jet fuel consumed in the region in 2017). Conversely, if all 144 million hectares of EU+EFTA available forest were logged and 50 percent of the residues were extracted, the over 1,700 Mt of forestry residues could result in almost 337 Mt of RJF, or almost 600% of 2017 jet fuel consumption in the region. Hence, RJF can be feasibly produced from biomass from EU+EFTA lands in amounts that meet the annual jet fuel consumption of EU+EFTA aviation and in ways that meet or exceed RED-II sustainability criteria. However, these percentages will decrease over time as the number of flights and the resulting emissions continue to grow. The two RJFs much lower emissions than petroleum-based jet fuel, showing them to be important tools for the EU to meet its 2030 renewables and emissions reductions targets. Producing biomass feedstocks and RJF in such quantities will require the EU to make serious decisions on land use trade-offs, such as whether livestock production is more important than biofuel production.

Keywords: aviation biofuel, *Camelina sativa*, forestry residues, land use change, Renewable Energy Directive, sustainable development

Torry van Slyke, Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden
List of Figures

Fig. 1. Fuel consumed and emissions produced from typical two-engine commercial jet aircraft during one-hour flight with 150 passengers ................................................................. 3
Fig. 2. Projected aviation emissions and mitigation effects of industry measures ........................................ 5
Fig. 3. Hydroprocessed ester and fatty acid biofuel conversion pathway .................................................... 11
Fig. 4. Fischer-Tropsch synthesis fuel conversion pathway ........................................................................ 13
Fig. 5. System boundaries for life cycle analysis of camelina-based biofuel .............................................. 15
Fig. 6. Carbon intensities of renewable jet fuels, grouped by feedstock and production pathway category .................................................................................................................. 16

List of Tables

Tab. 1. Average fuel burn and emissions for EU+EFTA commercial aircraft ................................................. 4
Tab. 2. Eurostat crop classifications used in camelina scenario analysis ..................................................... 21
Tab. 3. EU+EFTA commercial aviation variables used in scenario analysis ................................................. 23
Tab. 4. Camelina cultivation and HEFA biojet fuel production variables used in scenario analysis 24
Tab. 5. Annual camelina HRJ biofuel yields, passenger kilometers, and emissions under EU+EFTA agricultural land conversion scenarios ................................................................. 25
Tab. 6. Forestry residue extraction and FT biojet fuel production variables used in scenario analysis 26
Tab. 7. Forestry residue FTJ biofuel yields, passenger kilometers, and emissions under EU+EFTA annual roundwood harvest and total available area scenarios ........................................... 27

Reused figures and tables are included in accordance with the copyright policy of the cited source
1. Introduction

The contemporary, globalized world is built upon a well-connected network of people, materials, and services. But the ever-growing transport system behind this network presents a quandary: it consumed 28 percent of the world’s end-use energy in 2010, with 94 percent of this energy coming from fossil fuels. This dependence has caused transport carbon dioxide (CO₂) and greenhouse gas (GHG) emissions to increase at a faster rate than any other economic sector to reach 23 percent and 14 percent of the global total, respectively, in 2010. These shares have doubled since 1970 and are projected to double again by 2050 (IPCC 2014; Sims et al. 2014). Such findings have led climate experts to conclude that reducing transport emissions “will be a daunting task given the inevitable increases in demand and the slow turnover and sunk costs of stock (particularly aircraft, trains, and large ships) and infrastructure” (Sims et al. 2014, p. 605). Aviation stands as a particular challenge. Despite aviation GHG emissions currently accounting for a relatively small 2 percent share of the global total, they are increasing faster than all emissions from other transport sectors, doubling between 1990 and 2005 (Ibid.). As demand continues to grow worldwide, the number of flights is projected to at least double by 2040 and emissions from aviation could grow by as much as 700 percent by 2050 (European Commission 2016d; El Takriti et al. 2017).

Despite these challenges, optimism remains that reductions in transport GHG emissions could emerge from new technologies, more stringent policies, and behavior changes. The 2015 Paris Agreement represents one such sign of optimism, as world governments committed to rapid reductions in global emissions to limit the increase of the average global temperature to 2°C above pre-industrial levels, if not 1.5°C (European Commission 2016c). Research shows that, to stay below this 2°C threshold, 2050 global GHG emissions must be 40-70 percent of 2005 levels, and be zero or net-negative by the end of the century (IPCC 2014; de Jong 2018).

One party to the Paris Agreement is the European Union (EU). With over 500 million inhabitants in an area of almost 4.5 million square kilometers, the EU’s 28 Member States represent the largest single trade bloc and one of the three largest economies in the world—one built on the free movement of people, goods, and services (European Commission 2019a). To help meet the Paris Agreement targets, the EU has pledged to reduce its GHG emissions by at least 80 percent by 2050 compared to 1990 levels, including a 60 percent reduction in transport emissions (EASA et al. 2019). Increasing emissions from the petroleum-reliant transport sector, however, and particularly aviation (currently 3 percent of the EU total), may make it difficult for the EU to achieve these goals. In fact, EU aviation emissions could increase by 150 percent by 2050, relative to 2005 levels (de Jong 2018). Nonetheless, the EU and industry groups believe that aviation industry growth and emission reductions are not mutually exclusive; both can be achieved through a combination of technical advancements, efficiency improvements, and aviation biofuels.

As in other transport sectors, aviation fuels of non-petroleum origin have received much attention in recent years as researchers explore ways to power the increasing number of flights while reducing the climate impact. Such fuels are commonly known as aviation biofuels, sustainable aviation fuels, or (the main term used in this thesis) renewable jet fuels. Climate researchers have recognized a knowledge gap in feedstock and infrastructure requirements for large-scale deployment of low-carbon transport fuels (Sims et al. 2014; de Jong 2018). This gap can also be seen in EU policy documents and industry publications that tout renewable jet fuels as playing a central role in reducing aviation and transport GHG emissions (IRENA 2017; EASA et al. 2019; IATA 2019). These entities commit to fostering and deploying renewable jet fuels, yet their documents lack specifics about how and where to generate the biomass to produce these fuels and how producing these feedstocks would balance competing demands to grow food and protect ecosystems. Furthermore, many scientific studies have explored the emissions-savings potential and techno-economic feasibility of jet fuels made from renewable biomass, e.g., (Natelson et al. 2015; de Jong 2018; Li et al. 2018). While these aspects are important, relatively few projects have devoted significant attention to the supply potential of biomass for aviation biofuels from specific land areas within defined geographic and policy boundaries, such as the European Union and its Renewable Energy Directive.

Given these research needs, this thesis sought to research the following:
A. Explore the theoretical supply potentials of two types of biomass from EU+EFTA lands

B. Project renewable jet fuel yields from these biomass feedstocks using two biofuel conversion pathways

C. Estimate life cycle emissions savings of the resulting renewable jet fuels relative to petroleum jet fuel

The two fuels selected for analysis were, 1) hydroprocessed esters and fatty acid conversion of *Camelina sativa* vegetable oil, and 2) Fischer-Tropsch synthesis of forestry residue lignocellulosic biomass.
2. Background

The policy environment provides important context to understanding efforts to reduce the climate impact of aviation emissions. Government and industry alike are making pledges and setting targets for a more sustainable energy future and a climate that stays below the Paris Agreement threshold. This section presents efforts aimed at reducing aviation GHG emissions, showing that renewable biofuels may be the most promising and timely pathway to significantly reduce aviation’s climate impact. First, the emissions, climate impact, and projected growth of commercial aviation is presented, primarily focused in the EU+EFTA. Next, aviation industry initiatives and EU strategies to reduce aviation’s climate impact are discussed, including the EU’s Renewable Energy Directive and its provisions to encourage renewable transport fuels. Then efforts to reduce EU+EFTA aviation emissions are explored, especially system efficiency measures and emissions trading schemes. This section concludes by presenting renewable jet fuel, describing the two technologies and feedstocks selected for analysis in this thesis, and discussing the life cycle emissions and land use change aspects of such biofuels.

2.1. Aviation emissions, climate impact, and projected growth

Almost all modern commercial aircraft employ jet engines, which are turbine engines that achieve combustion through compressing air to very high pressures and temperatures and injecting fuel into the compressed air, which then auto-ignites. Jet fuel is essentially kerosene, a middle distillate of petroleum with properties similar to diesel fuel, with various additives to improve engine wear and performance in the extreme temperature and pressure demands of high-altitude flight (Bauen et al. 2009; de Jong 2018). Like with all combustion engines, using jet engines to move people and goods through the air comes at the cost of emitting polluting gasses and particulates. In 2016, aviation accounted for 3.6 percent of the EU’s total GHG emissions and 13.4 percent of its transport emissions, making aviation the second most important source of transport GHG emissions after road traffic (EASA et al. 2019). The main pollutants emitted by jet engines are carbon dioxide (CO₂), nitrogen oxides (NOₓ), Sulphur oxides (SOₓ), unburned hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) and soot. Figure 1 below shows the amounts of fuel consumed and pollutants emitted in a typical short-haul commercial flight.

![Image](image.png)

Fig. 1. Fuel consumed and emissions produced from typical two-engine commercial jet aircraft during one-hour flight with 150 passengers

Source: (EASA et al. 2019); reused in accordance with copyright policy
In a one-hour flight 2,700 kg of jet fuel are combusted and 8,500 kg of CO\textsubscript{2} are emitted, as Figure 1 indicates. This equates to 18 kg jet fuel burned and almost 57 kg pollutants emitted for each of the 150 passengers to travel through the air for one hour.

The EU has found that while improvements are occurring in aviation technology, air traffic management, and airport operations to reduce emissions, and through market-based measures to offset emissions, the combined effect has been outpaced by the increasing demand for air travel. This had led to an overall increase in emissions and environmental impact (EASA et al. 2019). In fact, Table 1 from the 2019 European Aviation Environmental Report shows how fuel consumption per-passenger and aviation emissions in the EU+EFTA have changed since 2005, and where they are projected to be by 2040.

**Tab. 1. Average fuel burn and emissions for EU+EFTA commercial aircraft**

<table>
<thead>
<tr>
<th>Units</th>
<th>2005</th>
<th>2014</th>
<th>2017</th>
<th>2040 Base forecast</th>
<th>% change since 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average fuel consumption of commercial flights</td>
<td>kg per passenger kilometre\textsuperscript{a}</td>
<td>0.0355</td>
<td>0.0294</td>
<td>0.0270</td>
<td>0.0210</td>
</tr>
<tr>
<td></td>
<td>litres per 100 passenger kilometres\textsuperscript{a}</td>
<td>4.4</td>
<td>3.7</td>
<td>3.4</td>
<td>2.6</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>million tonnes</td>
<td>141</td>
<td>148</td>
<td>163</td>
<td>198</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>thousand tonnes</td>
<td>669</td>
<td>749</td>
<td>839</td>
<td>972</td>
</tr>
<tr>
<td>HC</td>
<td>thousand tonnes</td>
<td>55</td>
<td>53</td>
<td>57</td>
<td>58</td>
</tr>
<tr>
<td>CO</td>
<td>thousand tonnes</td>
<td>110</td>
<td>102</td>
<td>108</td>
<td>99</td>
</tr>
<tr>
<td>volatile PM</td>
<td>thousand tonnes</td>
<td>126</td>
<td>123</td>
<td>136</td>
<td>157</td>
</tr>
<tr>
<td>non-volatile PM</td>
<td>thousand tonnes</td>
<td>76</td>
<td>55</td>
<td>53</td>
<td>71</td>
</tr>
</tbody>
</table>

1. Kilometres represent the actual flown distance between origin and destination

Source: (EASA et al. 2019); reused in accordance with copyright policy.

Average fuel consumption per passenger in the EU+EFTA has decreased since 2005 and is projected to continue decreasing, per Table 1, as are emissions of CO and non-volatile PM, largely due to cleaner-burning and more efficient engines. Other pollutants have increased, however, as the number of flights, aircraft size, and distance flown are increasing faster than efficiency gains. CO\textsubscript{2} and NO\textsubscript{x} show the largest increases, which could be 59 percent and 103 percent higher in 2040, respectively, than in 2005.

Most researchers conclude that aviation will continue to expand until mid-century, if not longer, as demand continues to grow. In 2017, the EU+EFTA saw 9.56 million commercial flights and this number is projected to increase by between 42 percent and 68 percent by 2040, possibly reaching 16.1 million flights (EASA et al. 2019). The region could see upwards of 25 million flights by 2050 (High Level Group on Aviation Research 2011). As more planes take to the sky to ferry more mass across greater distances, more pollutants will be emitted. Table 1 shows CO\textsubscript{2} and NO\textsubscript{x} increasing by around 60 percent and 100 percent, respectively, by 2040 from this increase in EU+EFTA flights. These trends reflect the projected stark rise in global aviation emissions, which are estimated to be 300-700 percent higher in 2050 than in 2005 (European Commission 2016d; Li et al. 2018). As these numbers indicate, policies and measures are likely needed to mitigate the increasing emissions from aviation.
2.2. Industry pledges and government strategies to mitigate aviation emissions

Industry and governments have committed to various goals, targets, strategies, and measures designed to spur innovation in aviation and mitigate the climate impacts of increasing aviation GHG emissions. The global strategies of the aviation industry are presented first. Following is a discussion of the broader climate and energy targets of the EU, and their Renewable Energy Directive.

2.2.1. Global targets and pillars of the aviation industry

Many within the airline industry recognize that climate change is a global challenge and are pursuing ways to mitigate the GHG emissions from air transport. Industry groups, aircraft manufacturers, and industry associations have voluntarily committed to the ambitious climate policy of the Air Transport Action Group (ATAG) and the International Air Transport Association (IATA), the two main aviation industry trade associations. The ATAG-IATA policy consists of “three targets and four pillars”, a set of technological and policy measures that they claim will significantly reduce aviation’s climate impact by mid-century and that many industry businesses and organizations have committed to (IATA 2019). The three targets, and the expected impacts of the four pillars, are displayed in Figure 2.

![Graph showing projected aviation emissions and mitigation effects of industry measures](https://example.com/graph.png)

**Fig. 2.** Projected aviation emissions and mitigation effects of industry measures

Source: (IRENA 2017); reused in accordance with copyright policy

The graph in Figure 2 shows the projected increase in global aviation CO₂ emissions. By improving aircraft fuel efficiency 1.5 percent per year and capping aviation emissions from 2020 for “carbon-neutral growth”, ATAG and IATA hope to see half of aviation’s 2005 emissions levels by 2050. The four pillars are the industry’s strategies to achieve the three targets, and are indicated by the green and blue areas under the projected emissions curve in Figure 2. These include improved aircraft technology and biofuels, more efficient air traffic and airport operations, improvements to air travel infrastructure...
(including air traffic management systems), and a global emissions trading scheme to offset any remaining emissions gap (IATA 2019).

As Figure 2 shows, the airline industry expects optimistic efficiency gains and emissions reductions through the pillars to meet their ambitious targets, especially given the high projected growth of flights and emissions. While IATA claims the industry is on track to meet the 1.5 percent efficiency improvement target, the other two will likely be harder to realize (de Jong 2018; IATA 2019). Emissions trading schemes are currently the main tools toward carbon-neutral growth and net emissions reductions, but as discussed further in this section, their results may prove elusive and disappointing. The industry assumes biofuels to yield the largest emissions saving, as the blue area in Figure 2 indicates. Often touting the climate benefits of biofuels, the industry states that sustainable aviation fuels can cut emissions by 80 percent (IATA 2019). However, as this thesis discusses in Section 2.4.3, GHG savings of aviation biofuels can vary widely and few can offer emissions savings that significant and at any sort of near-term, commercial scale. This target, along with the other two targets shown in Figure 2, constitute the aviation industry’s main approach to reducing its long-term climate impact.

### 2.2.2. Climate and energy targets of the European Union

Energy security, energy independence, and being “climate neutral” by 2050 are at the core of the EU’s long-term energy and climate strategy. These measures are also meant to meet the EU’s Paris Agreement commitments and ultimately achieve the EU’s goal of Clean Energy for All Europeans (European Commission 2017). Ultimately, with this bold climate policy, the EU hopes to achieve an 80 percent cut in GHG emissions by 2050 (from 1990 levels), including a 60 percent reduction in transport emissions (EASA et al. 2019). To achieve these long-term objectives, the EU has adopted increasingly stringent and legally binding interim climate and energy targets, with those for 2030 (and 2020) listed below (European Commission 2016a; b):

- at least a 40 percent reduction in total GHG emissions from 1990 levels (20 percent by 2020)
- at least 32 percent renewables in EU gross final energy consumption (20 percent by 2020)
- and at least 32.5 percent improvement in energy efficiency (20 percent by 2020)

Both the 2020 and 2030 climate and energy targets refer to total GHG emissions from all sources, not just transport. The EU plans to achieve these across-the-board targets through the combination of an EU-wide emissions trading system, national targets for each Member State in these three areas, and energy and climate plans from each Member State. The Renewable Energy Directive (RED) codifies the renewables target and is the principal EU legislation related to biofuels; it is examined in detail in the following subsection. Beyond the biofuel targets in RED, there is little in EU policy for actionable, binding measures directly related to reducing the climate impact of aviation.

In a 2011 white paper on transport, the European Commission states that low-carbon sustainable fuels will reach 40 percent of EU aviation fuel consumption by 2050, but offers scant specifics on how to such a goal will be realized (European Commission 2016b). Likewise, the EU’s long-term vision for aviation states there will be a 75 percent reduction in CO₂ emissions per passenger-kilometer and a 90 percent reduction in NOx emissions by 2050, although no details are presented on how the EU plans to achieve these reductions (High Level Group on Aviation Research 2011). The lack of clear policy guidance and initiative on reducing aviation emissions is perhaps best exemplified by the European Advanced Biofuels Flightpath. Launched in 2011 as a partnership between the European Commission and major European stakeholders, its main aim is to increase the supply and consumption of renewable jet fuel in the EU, with a goal of 2 million tonnes (megatonnes, or Mt) by 2020. This goal is far from being met, with only miniscule amounts of renewable jet fuel consumed at EU airports to-date (European Commission 2016f; de Jong 2018; EASA et al. 2019). The Flightpath target is currently being updated for 2030.
2.2.3. The European Union’s Renewable Energy Directive

The 2009 Renewable Energy Directive (RED) established the 2020 target of 20 percent of EU energy from renewables and a common framework to promote renewable energy among Member States. In updating its targets for 2030, the EU updated the RED to a higher renewables target and incorporate parameters such as land use change effects and new sustainability criteria for biomass feedstocks. Known as RED-II, this recast directive was enacted in 2018 and now mandates a target of at least 32 percent renewables in EU gross final energy consumption by 2030. The directive seeks to further decarbonize the EU’s transport and energy sectors, improve the emissions performance of renewable fuels, and decrease reliance on energy imports. While RED-II contains few provisions specific to aviation biofuels, it does present several sustainability criteria and GHG emission thresholds that bio-based fuels in general must fulfill in order to be counted towards any targets or sub-targets and to be eligible for EU government financial support. Member States are free to choose and enact their preferred methods to achieve the targets, and to set more stringent national targets and thresholds. Member States are also free to produce biofuels that do not meet these criteria, but such non-compliant fuels will not be counted toward the mandated targets. Below are the RED-II targets and criteria most relevant to transport biofuels, including aviation (Directive 2018/2001/EU; European Commission 2019c):

- The minimum share of renewables in the transport sector must be 14 percent by 2030
  - Advanced biofuels must contribute at least 0.2 percent in 2022, 1 percent in 2025, and 3.5 percent in 2030 and will be counted at 2 times their energy content toward the targets
    - “Advanced biofuels” are defined as those produced from certain biomass feedstocks, including algae, biomass wastes (e.g., municipal/industrial compost, animal manure, agricultural processing by-products), forestry and wood processing residues, and used cooking oils and animal fats
  - Aviation and shipping biofuels will be counted at 1.2 times their energy content

- Transport biofuels must have 60 percent lower GHG emissions than petroleum fuels, increasing to 65 percent savings after 2021

- Transport biofuels from food or feed crops can contribute no more than 1 percent above those fuels’ 2020 share of final energy consumption in a Member State’s road and rail transport sectors, with a maximum share of 7 percent

Note that no targets or limits apply specifically to aviation, only the energy multiplier. By allowing Member States to count aviation and shipping biofuels at 1.2 times their energy content toward Member States’ renewables targets, the EU hopes to encourage further production and consumption of biofuels in these sectors. Nonetheless, aviation biofuels will be counted toward the broader transport indicators and if they comply with the GHG emissions savings and feedstock sustainability provisions. In order to meet these transport biofuel targets and limits, RED-II contains GHG emissions (savings) values for biofuels of various biomass feedstocks, and provisions on how the life cycle emissions from biofuels should be calculated to determine their savings relative to fossil fuels.

In addition to these targets, RED-II contains provisions designed to discourage production and use of biomass from lands with high biodiversity, carbon stock, or undisturbed natural state—so-called land use change effects. As Section 2.4.3 discusses in detail, land use change arises when demand for biomass pushes agriculture onto land that was not previously used for agriculture, such as clearing forest for oil palm plantations or soybean cultivation. Research shows this can increase global carbon emissions and have significant negative ecological impact, and should therefore be avoided (Searle & Malins 2013; EASA et al. 2019). These provisions dovetail with RED-II’s minimum sub-targets and energy multiplier for advanced biofuel as the EU hopes to foster expansion of and transition toward such advanced biofuels in transport. The paraphrased RED-II provisions related to sustainable biomass sourcing for biofuels are as follows (Directive 2018/2001/EU):

- Fuels produced from feedstocks with a high risk of indirect land-use change will be limited to Member States’ 2019 consumption levels and must be phased down to 0 percent by 2030
• Agricultural biomass for biofuels must not originate from land that had high biodiversity or high carbon stock as of January 2008, including:
  o Primary forests with no visible indication of human activity or disturbance of ecological processes, continuously forested land, or forested areas with certain tree/canopy cover
  o Areas designated for protection of nature, species, or rare and endangered ecosystems
  o Grasslands, both natural (would remain grassland with no human intervention), and non-natural (not degraded, legally identified as biodiverse)
  o Wetlands or peatland
• Forestry biomass for biofuels must be from forest areas with monitoring, management, and enforcement systems in place to ensure harvesting:
  o Occurs legally on non-protected lands
  o Minimizes ecological impacts and allows forest regeneration
  o Maintains or improves long-term forest production capacity, carbon stocks, and sink levels

These criteria may appear restrictive. However, they do leave room for interpretation on aspects such as what constitutes a “high” level in terms of land use change risk or biodiversity, or what is sufficient to “minimize” ecological impacts of forest harvest. These aspects are explored further in Section 2.4 and the Discussion section. For the sake of this thesis, it was assumed and endeavored that all biomass analyzed in the scenarios and presented in the Results section complied with these RED-II criteria.

2.3. Current efforts to reduce climate impact of European aviation

Multiple approaches are being employed around the world to decrease aviation GHG emissions and mitigate their climate impact. Such methods attempt, both directly and indirectly, to achieve the ATAG-IATA targets and pillars and the EU’s climate and energy targets. Described here are the main efforts within this sphere that apply to EU+EFTA commercial aviation: technology and efficiency improvements, emissions trading, and, finally, biofuels.

2.3.1. Engine efficiency and air traffic management improvements

Since the Jet Age of the mid-twentieth century, jet engines have improved considerably in efficiency, cleanliness, and noise. The air traffic management system and airport operations has also evolved to accommodate the increasing numbers of aircraft (EASA et al. 2019). As the earlier Figure 2 highlights, the industry anticipates engine technology, system efficiency, and operations infrastructure to continue improving and reducing fuel consumption. System improvements consist of new communications, navigation, surveillance, and air traffic management systems that permit more efficient flight conditions in the form of more direct routings and optimum speeds and altitudes (El Takriti et al. 2017). However, research indicates that potential fuel and emissions reductions from advances in engine efficiency and air traffic management are limited since the modern aircraft may be at an efficiency plateau and the air traffic management system and most large airports operate at or near capacity (Li et al. 2018).

In the EU+EFTA, the Air Traffic Management Master Plan contains the ambition to reduce gate-to-gate flight time and CO₂ emissions by 3.2 percent and 2.3 percent, respectively, by 2035 due to improvements in these three areas (EASA et al. 2019). However, research in this area shows that year-on-year efficiency gains and operational improvements taken together in the EU+EFTA are estimated to be between 0.9 percent (least optimistic) and 1.8 percent (most optimistic) (de Jong 2018). Although
operational improvements and efficiency gains are projected to reduce GHG emissions, the continued sector growth leads to a gap between research-projected and industry-targeted GHG emissions from 2020 onwards. Within the EU+EFTA, this gap is 22 Mt of CO₂-equivalents in 2030 and 166 Mt by 2050, while globally this gap could reach 2,500 Mt of CO₂-equivalents by 2050 (Ibid.). (See Section 2.4.3 for a description of CO₂-equivalent emissions.) Thus, technological and operational improvements alone are not enough to meet the ATAG-IATA goal of carbon-neutral growth, showing that offsetting measures and low-carbon alternative fuels are needed for significant reductions in aviation emissions.

2.3.2. Emissions cap-and-trade schemes

Thirty-five percent of the world’s aviation emissions came from the EU in 2014 (Sims et al., 2014). One method to tackle this pollution is to price the carbon emissions of aviation fuel. Cap-and-trade systems, for example, set limits (caps) on the total amounts of pollutants that can be emitted and then divides pollution credits to industry polluters via allocation or a market (trade).

The EU’s Emissions Trading Scheme

Launched in 2005, the Emissions Trading System (ETS) is the EU’s primary tool to meet its GHG emissions reduction targets. Currently covering all EU+EFTA Member States except Switzerland, the ETS regulates about 45 percent of total EU GHG emissions (European Commission 2016e). In the ETS, the EU caps the overall emissions that can be emitted, and this is lowered each year in order reduce total emissions. Companies and installations covered by the ETS receive or purchase allowances to emit pollutants under the cap, and surrender allowances for every tonne of CO₂ emitted. If a company emits more than its allowances, it faces EU fines; if it emits less than its allowances, it can save them for the future or sell them to other companies. The ETS mainly focuses on CO₂ emissions from the power and heat sectors and heavy industry, with industrial nitrous oxide and perfluorocarbon emissions the only other pollutants included.

In 2012, CO₂ emissions from commercial aviation were included in the ETS with their own cap: for the period 2013-2020, aviation CO₂ emissions must be 5 percent below average annual emissions in the years 2004-2006 (European Commission 2016e). This effort represents the only binding policy in the world that attempts to mitigate aviation emissions (Sims et al. 2014). Originally intended to cover all flights to, from, and within the EU+EFTA (except Switzerland), the EU reduced the scope to include only flights within these 31 countries in order to support the efforts of the United Nations’ International Civil Aviation Organization (ICAO) to create a global, all-encompassing cap-and-trade system (see succeeding sub-section). However, the ETS may revert to its full scope by 2024 depending on the performance of the ICAO effort (European Commission 2016d).

The Carbon Offsetting and Reduction Scheme for International Aviation

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will attempt to reduce worldwide aviation CO₂ emissions through a cap-and-trade system similar to the ETS. Passed by the ICAO general assembly in 2016 and due to operate from 2021 to 2035, CORSIA seeks to cap global aviation emissions at 2020 levels and offset any emissions above that amount. So far 72 countries (including the 32 EU+EFTA Member States), currently representing almost 88 percent of international flights, have voluntarily agreed to participate. These countries will require their airline companies to purchase units in eligible emission-reduction projects in other sectors, such as renewable energy, to offset any aviation emissions above their 2020 caps (de Jong 2018; European Commission 2016d). Many details and mechanics of CORSIA are still being finalized (including whether intra-EU+EFTA aviation emissions can or should be included in both CORSIA and the ETS), but international airlines began monitoring and calculating their emissions in January 2019 (IATA 2019).
While any reduction in GHG emissions is laudable, cap-and-trade systems like CORSIA and ETS may not achieve their envisioned impact. First, they rely on an increasing price of carbon for their pollution credits to be viable investments. Second, they fail to address non-CO₂ aviation GHG emissions such as NOₓ and SOₓ, which can have a more potent climate impact and have increased at faster rates than CO₂ (EASA et al. 2019). Third, their intended reductions will not be enough to achieve the EU and IATA goals of aviation emission reductions, especially considering the forecasted doubling of global aviation by 2040. According to the EU, the ETS has reduced aviation CO₂ emissions by more than 17 Mt each year (European Commission 2016e). This amount represents not even 10 percent, however, of the total CO₂ emitted by EU+EFTA aviation in 2017 (EASA et al. 2019). IATA claims that CORSIA will offset 2.500 Mt of aviation CO₂ by 2035 (IATA 2019). On an annualized basis this roughly equals the total CO₂ emitted by all EU+EFTA commercial aircraft in 2017, which is about 20 percent of the global share in the same year (EASA et al. 2019). These numbers indicate that schemes to offset EU+EFTA and global aviation emissions depend on optimistic assumptions of many variables and will likely not allow future aviation growth to be carbon neutral. Therefore, alternative, renewable biofuels may be the technology with the most potential to mitigate aviation emissions.

2.4. Renewable jet fuels

Reducing emissions in the aviation sector has proven difficult compared to other transport sectors since technologies such as electric, hybrid, and hydrogen powertrains will likely not be commercially viable for aircraft until at least 2030 (EASA et al. 2019). Hence, as previously discussed, renewable jet fuels are promoted by the aviation industry and government as being a central component to achieve carbon-neutral aviation growth beyond 2020 and reduce global GHG emissions. Renewable jet fuels (RJF), also known as biojet fuels and aviation biofuels, are liquid hydrocarbon fuels produced from renewable biomass resources ranging from perennial grasses and sugarcane to waste oils and wood residues. RJF is considered the only viable, low-carbon, drop-in alternative to petroleum jet fuel currently available for turbine engines (de Jong 2018).

To ensure safety and performance of aircraft in the wide range of temperatures and pressures encountered in high-altitude flight, any fuels used in turbine aircraft engines must meet strict requirements on such parameters as volumetric energy density, thermal stability, freeze point, viscosity, and lubricity (Natelson et al. 2015; El Takriti et al. 2017; IRENA 2017; de Jong 2018). Due to these requirements and to lessen the significant costs and delays associated with changing aircraft design and fueling infrastructure, RJFs should be “drop in”: directly substitutable for, and have performance and characteristics comparable to, petroleum Jet A-1. The American Society of Testing and Materials (ASTM) provides the most common worldwide certification standards for petroleum jet fuel and is the main body certifying RJF for use in jet aircraft (Ibid.). While pure RJF can function as a 100 percent drop-in fuel, its lack of certain engine-protecting compounds normally found in petroleum fuel (e.g., for engine seals and lubrication) restricts its use for long-distance flights. This has led ASTM to certify RJF currently only as blends with petroleum jet fuel, ranging from 10 percent to 50 percent (Ibid.). As of 2018, ASTM had certified four main RJF conversion pathways:

- Hydroprocessed Esters and Fatty Acids (HEFA): Lipids, such as oils and fats, are converted into biodiesel using hydrogen, which can be further distilled into RJF; certified to 50 percent blend
- Fischer-Tropsch (FT) synthesis: Biomass is converted to synthetic gas (syngas) and then distilled into various fuels, including RJF; certified to 50 percent blend
- Direct Sugars to Hydrocarbons, or Synthesized Iso-Paraffins: Sugars or starches are converted to hydrocarbon fuels using modified yeasts; certified to 10 percent blend
- Alcohol-to-jet: Converts alcohols from sugars or starches, such as iso-butanol, into various hydrocarbon fuels; certified to 30 percent blend
These pathways can be divided into thermochemical and biochemical. Thermochemical pathways include the FT and HEFA processes, which use elevated temperatures and pressures to convert biomass to paraffinic and aromatic hydrocarbons. Biochemical pathways such as sugars-to-hydrocarbons and alcohol-to-jet employ bacteria or enzymes to convert biomass to certain molecules, such as ethanol or butanol, but often require additional processing to reach the final hydrocarbon product (Ibid.). Other RJF pathways exist, such as pyrolysis, hydrothermal liquefaction, and synthesis from CO₂, yet these are only in pilot stages and are not yet ASTM-certified (El Takriti et al. 2017; de Jong 2018). The following subsections discuss in further detail the two conversion pathways selected for analysis in this thesis: HEFA and FT. In addition to being the most established, common, and commercialized RJF production pathways, HEFA and FT are certified at the highest fuel blending limits (50 percent) and can accommodate a wide range of feedstock inputs.

2.4.1. Hydroprocessed ester and fatty acid biojet fuel from *Camelina sativa*

The HEFA conversion process is the most mature, established, and commercialized RJF pathway, and hence dominates current production. The jet fuels resulting from converting lipids via the HEFA pathway are commonly known as hydrotreated renewable jet (HRJ). To produce HRJ, the HEFA conversion first removes the oxygen from the plant oil or animal fat feedstock via decarboxylation and hydrodeoxygenation mechanisms, which require hydrogen. The resulting hydrocarbon fuel then requires selective cracking and isomerization to reduce the carbon number into the jet fuel range and achieve key jet fuel properties such as freeze and flash points. In addition to feedstock and hydrogen, the primary inputs into the HRJ production process are similar to a typical refining system: steam, natural gas, cooling water, and electricity. In addition to the biofuels, outputs include water (H₂O), CO, CO₂, and renewable co-products including naphtha, light fuel gas, and propane/butane (Shonnard et al. 2010; Li & Mupondwa 2014; Wang & Tao 2016; El Takriti et al. 2017). As discussed in more detail in the Results section, 80 percent is a typical HEFA conversion rate from unit of oil input to unit of HRJ output. Figure 3 provides a basic visual diagram of the HEFA process, with triglyceride shown as an input and biojet fuel (RJF) shown as an output.

![Fig. 3. Hydroprocessed ester and fatty acid biofuel conversion pathway](image)

Source: (Gutiérrez-Antonio et al. 2017). Reused with permission from Elsevier.

Despite the prevalence of the HEFA process, limited supply of sustainable oils and fats constrains the potential to expand HRJ production (de Jong 2018). Four principle lipid feedstocks exist for the HEFA pathway: oilseed crops, animal fats, certain algae, and waste materials including used cooking oils/fats and soap stocks (Moser 2010). Oilseeds likely show the most promise to sustainably expand HRJ supply, but using traditional, human-edible oilseed crops (e.g., rapeseed, soybean) as inputs is controversial and necessitates identifying inexpensive and sustainable alternative feedstocks. One oilseed crop, *Camelina*
*Camelina sativa,* has been proven to be a promising solution and continues to attract attention from governments, biofuel producers, and transport companies (Bauen *et al.* 2009; Iskandarov *et al.* 2014; El Takriti *et al.* 2017; IRENA 2017; EASA *et al.* 2019).

*Camelina sativa* (oil) as biomass

_Camelina sativa,* also known as camelina, false flax, or gold-of-pleasure (henceforth referred to as “camelina”), is a broadleaf oilseed flowering plant of the Brassicaceae family, along with Brussels sprouts, cauliflower, rapeseed, turnip, various mustards, etc. Native to Europe and Central Asia, it has been cultivated in Europe sporadically since the Bronze Age as a spring/summer annual crop or biennial winter crop and was widely grown in parts of Europe until the end of the nineteenth century (Moser 2010; Small 2013; Iskandarov *et al.* 2014; Natelson *et al.* 2015; Li *et al.* 2018). Camelina has several beneficial agronomic attributes, including: a short growing season from planting to harvest (60-100 days); tolerance of cold, drought, and semi-arid conditions; and an ability to grow on low-fertility or saline soils. It is compatible with existing farm practices and requires lower water, fertilizer, and pesticides than other oilseed crops like rapeseed. In fact, camelina often does not require pesticides or insecticides as its seeds are frost tolerant, germinate at low temperatures, and suppress many common weeds (Ibid.). And since camelina is well adapted to the temperate climate of central and northern Europe, it grows well in a rotational cycle with winter wheat to disrupt weed and pest cycles. Camelina also shows potential in rotation with barley, peas, lentils, and maize. Due these characteristics, camelina is well-suited for marginal lands and to control weeds and improve soil quality on fallow lands, which can reduce potential land use conflicts and impacts (Ibid). Given these factors, camelina is very promising as a sustainable biomass with relatively low carbon intensity or risk of land use change (see Section 2.4.3), thereby complying with RED-II sustainability criteria. Camelina also has the ability to contribute toward EU goals of energy security and independence (see Section 2.2). The Results section presents data on average camelina seed yields and oil content. Camelina oil is obtained by extracting and purifying the oil from the harvested seeds via mechanical and solvent-based means. While camelina oil is edible and nutritious for humans, most studies consider it to be a non-food crop since nowadays it is not widely cultivated for use as an edible oil, being displaced by similar oilseeds such as rape and sunflower (IRENA 2017; Li *et al.* 2018). By-products yielded from oil extraction can have various uses. The seed meal can be pressed into cakes for animal feed or heat/energy combustion and the straw can be used for its fiber, similar to flax (Small 2013).

### 2.4.2. Fischer-Tropsch biojet fuel from forestry residues

Another established and certified conversion pathway with many sustainable feedstock options is FT synthesis, also known as biomass-to-liquids. Considered one of the best methods to produce RJF, it was first used commercially in Germany in the 1930s to synthesize road fuels from coal. In its simplest form, the FT process gasifies carbon-rich feedstocks to produce a synthesis gas (syngas). The syngas then undergoes a series of catalytic conversions (the FT synthesis) to yield various chemicals and gases that are then hydrotreated to a bio-oil. Similar to HEFA, the resulting FT-produced hydrocarbon fuel is refined using selective cracking and isomerization to reduce the carbon number into the jet fuel range and achieve desired properties. System inputs are biomass, energy, and hydrogen. Outputs include biofuels, CO, CO₂, and significant amounts of steam (H₂O) which is used both to power the reaction and to generate electricity (Larson & Jin 1999; Wang & Tao 2016; El Takriti *et al.* 2017; Gutiérrez-Antonio *et al.* 2017).

The FT process is relatively efficient: one unit of energy input yields a unit of energy output of 45 percent, i.e., 1 MJ input $\rightarrow$ 0.45 MJ output (Bauen *et al.* 2009; Wang & Tao 2016; de Jong 2018). This is due to the feedstock itself supplying a large portion of the heat energy needed for the synthesis to occur, thereby requiring less external energy. However, most studies (including the ones cited) consider the energy output as the aggregate of the entire biofuel column, most of which will distill into biodiesel and other fuels. When considered as unit of RJF energy output per unit of feedstock input, the FT process...
Conversion efficiency is in the 13 percent to 25 percent range, as shown in the Results section. Fischer-Tropsch jet (FTJ) is a common term for the renewable jet fuels yielded from converting biomass via the FT pathway. A basic diagram of the FT process is in Figure 4, with biomass as an input and FTJ (termed biojet fuel) as an output.

![Fig. 4. Fischer-Tropsch synthesis fuel conversion pathway](source)

A wide range of biomass and fossil-based feedstocks (including coal and natural gas) can be synthesized to fuels in the FT process. However, the FT process is more efficient and has lower emissions when using biomass (Ibid.). Woody (lignocellulosic) biomass is considered an ideal feedstock given its energy density and conversion properties, and forestry residues are particularly well-suited for FTJ production as they are in relatively large, unused supply, have low economic value and life cycle emissions, and do not compete with food production (Moser 2010; de Jong 2018). The Results section presents the forestry residue-based FTJ life cycle emissions value used in this analysis and the emissions savings relative to fossil jet fuel.

**Forestry residue as biomass**

Forestry residues refer to the portions of trees that are removed from roundwood logs during harvesting operations. Also known as logging residues or primary forestry residues, they include treetops, branches, twigs, and leaves (collectively termed “slash”); they can also include stumps. Considered in the logging industry to have little commercial value, forestry residues are usually not collected but left on the forest floor. These primary forestry residues are distinct from the secondary residues, which are trimmings and sawdust that occur during industrial processing of harvested trees into wood products, and tertiary residues, which is post-consumer waste wood from items like furniture. The amount of primary forestry residues produced from logging can vary significantly, from 10 percent to 48 percent of the tree’s above-ground biomass depending on tree species, forest health, and logging practices (Searle & Malins 2013, 2016). While forestry residues currently have little commercial use in the EU+EFTA, interest in this biomass is growing from the heat, energy, and biofuel sectors, spurred by government initiatives toward renewable energy sources (Ibid.). Forestry residues is an example of an “advanced biofuel” feedstock that the EU hopes to expand via RED-II, meaning Member States can count transport biofuels produced from forestry residues at twice their energy content towards the 14 percent transport and 32 percent overall renewables targets (Directive 2018/2001/EU).

Much debate exists in the literature on the ecological impacts of removing forestry residues from forest sites. Extracting these trimmings from logged areas could hurt the health of the forest and reduce future tree growth, as slash and stumps provide both nutrients and biomass for wildlife, and nutrients, carbon, and erosion control for soil. There are benefits to removing at least some residues, however, such as exposing more undergrowth and the forest floor to sunlight, which can help plant growth and forest health. Many experts argue it impractical and irresponsible to extract all forestry residues, and advocate...
leaving sustainable amounts of stump and residue biomass in situ to ensure ecosystem health and function, with the exact proportions varying by site and depending on various factors of the local ecology, climate, and topography (Searle & Malins 2013, 2016; Verkerk et al. 2019).

Based on these characteristics, forest residues show excellent promise as a biofuel feedstock, with quite low carbon intensity and risk of land use change (see Section 2.4.3), therefore complying with the criteria for sustainable biomass and biofuels in RED-II and helping the EU move toward its goals of energy security and independence (see Section 2.2). The Results section provides the forest residue multiplier, residue extraction rate, wood density, and other related variables used in the analysis.

### 2.4.3. Life cycle emissions and land use change

Central to understanding the GHG emissions and climate impacts of RJF are life cycle analyses (LCAs). Such assessments show the overall environmental impact of a product, service, or process from “cradle-to-grave” by totaling the pollutants emitted or resources (e.g., water, energy) consumed at each stage of production or modification, from creation to final disposal. In the realm of aviation fuels, an LCA is usually “well-to-wake” (WtWa), encompassing all pollutants emitted from extraction of the petroleum or biomass input, through transport and processing, to combustion of the final jet fuel. These variables are summed into an aggregate value of its carbon intensity, usually presented as grams of carbon dioxide-equivalent per each megajoule of jet fuel energy (g CO₂-eq/MJ fuel). Carbon dioxide-equivalent expresses GHG pollutants in the equivalent amount of CO₂ that would have the same 100-year global warming potential. Emissions of carbon dioxide (CO₂) are multiplied by 1, methane (CH₄) by 25, and nitrous oxide (N₂O) by 298, in line with the United Nation’s Framework Convention on Climate Change (Shonnard et al. 2010; de Jong 2018).

The WtWa life cycle emissions of aviation (and all transport) biofuels comprises the well-to-tank portion (i.e., from extraction/cultivation up to the fuel tank) and the tank-to-wake portion (the combustion of the final jet fuel product), and that any emissions savings of RJF over petroleum jet fuel occur during the well-to-tank phase (Wang & Tao 2016). This is because the two fuels emit the same pollutants upon combustion (tank-to-wake), as RJF and Jet A-1 are practically identical in chemical composition and energy content due to the aforementioned drop-in criteria for RJF. However, many in the transport biofuel literature consider the combustion emissions of biofuels to be zero since renewable biomass inputs absorb the same amount of carbon that is released to the atmosphere upon biofuel combustion, within a closed cycle (Shonnard et al. 2010; de Jong 2018; EASA et al. 2019). This assumption is debated by scientists, due to possible GHG emissions consequences of harvesting and burning biomass rather than letting such biomass be naturally (and much more slowly) consumed by decomposers. However, both the ETS and RED-II consider all biofuel combustion emissions to be zero (Directive 2018/2001/EU; de Jong 2018).

Given this assumption, producing an RJF (its well-to-tank) must be less-carbon intensive than producing petroleum jet fuel for WtWa life cycle emissions savings to occur. Nevertheless, the WtWa life cycle value can vary considerably depending on methodological choices and assumptions made in the LCA. For example, the source and amount of the energy used in the extraction, processing, and transport of petroleum (for Jet A-1) can impact its life cycle emissions. Conversely, choice of feedstock, cultivation methods, and biofuel conversion processes, as well as land use effects, all contribute varying amounts to an RJF’s life cycle emissions. To visualize these various inputs, Figure 5 provides an LCA diagram for camelina-based RJF.
Many inputs, shown by the grey boxes on the left side of Figure 5, are required for the production stages (blue boxes in the center) to produce camelina-based RJF (“end use”) in this standard biofuel system. These include land and fertilizer, water and materials, and transport and energy. The carbon intensity of each input and production stage influences the final LCA value. This biofuel diagram also shows outputs on the right side, including seed cake and by-products that have uses beyond the final RJF product, but which the author had excluded from their LCA (hence the red boxes). One can also visualize a basic petroleum jet fuel LCA from this diagram, beginning at the oil extraction phase (which may include additional inputs) and omitting the “cake” by-product.

(In)direct land use change

The aviation industry touts the climate benefits of RJF, claiming emissions savings of 80 percent or higher (ATAG 2018; IATA 2019). In reality, the amount of emissions saved depends on the various aforementioned life cycle factors, mainly the emissions resulting from the cultivation and harvesting of the biomass feedstock. The concept of “land use change” is one important sustainability factor that can increase the life cycle emissions of biofuels. Direct land use change (LUC) occurs when biomass is cultivated from non-agricultural land that was converted to agriculture for the purpose of cultivating the biomass, such as clearing forest to grow oil palm. Indirect land use change (ILUC) can occur in two ways: agricultural land is converted from its original crop to a biomass crop, or the original crop is itself used as a biofuel feedstock. In either case, production of the original crop could expand to previously non-cropland areas to maintain supply for its original use (Bauen et al. 2009; EASA et al. 2019). For example, if more European rapeseed is diverted to RJF production, new land in Europe or abroad may be brought into rapeseed production to maintain rapeseed supply to the non-RJF demand sources.

Global emissions may increase from (in)direct land use change ((I)LUC) due to the energy, nutrients, and other inputs used for the new agricultural production (see the inputs to Farming in Figure 5). The carbon intensity of converting land to agriculture can be significant if the land had high carbon stocks in its soil and native vegetation, such as forest or peatland. However, negative LUC emissions are possible for feedstocks with low nutrient requirements that sequester more carbon than the original
vegetation (e.g., perennial grasses), especially on degraded or fallow land. Negative emissions can also occur with biomass that has significant energy or food/feed uses for their by-products (e.g., camelina), or from feedstocks that result from other processes and hence have no cultivation emissions (e.g., forestry residues). And while ILUC is difficult to directly measure or observe, its GHG emissions can be assessed through models (El Takriti et al. 2017; de Jong 2018). As an example, Figure 6 shows ranges of life cycle emissions for RFJs produced from various feedstocks and production pathways.

![Figure 6](image)

**Fig. 6.** Carbon intensities of renewable jet fuels, grouped by feedstock and production pathway category

Note: Unfilled dots include land use change emissions estimates. Highlighted green are the two fuels analyzed in this thesis. ATJ: alcohol to jet, DSHC: direct sugar to hydrocarbons, F-T: Fischer-Tropsch, HEFA: hydroprocessed esters and fatty acids, HTL: hydrothermal liquefaction, PtL: power-to-liquids.

Source: (El Takriti et al. 2017); reused in accordance with copyright policy

According to the LCAs referenced in Figure 6, most RJFs yield life cycle GHG emissions lower than petroleum jet fuel; some show near-zero or even negative overall emissions. Conversely, many food oil-based RJFs show very high emissions once (I)LUC effects are considered (cf. switchgrass and soybean), with palm oil-based RJF emitting up to 700 percent more GHGs than fossil jet fuel. Thus, industry claims that RJF emits 80 percent less GHGs is true only for select few conversion pathways and only under certain scenarios. Highlighted green in Figure 6 are the two fuels analyzed in this thesis, forestry residue-based FTJ and camelina-based HRJ, which show clear emissions savings relative to Jet A-1 and could well meet the industry claim and RED-II thresholds for GHG emissions savings.

Despite the promising RJF conversion technologies and their embrace by governments and industry, RJF’s ability to mitigate aviation emissions remains restricted by development and infrastructure costs and feedstock availability, mainly due to competing land uses for areas to cultivate biomass. While all feedstocks shown in Figure 6 are theoretically available for RJF production, in reality almost all are currently unavailable at quantities needed to produce significant quantities of RJF, due to various reasons of land and biomass supply, competing biomass demand, and possible ecological and climate impacts of large-scale biomass cultivation (El Takriti et al. 2017; de Jong 2018).

LUC is complex and nuanced, with varying effects on the life cycle carbon intensity of biomass and on the ultimate emission savings of biofuel relative to its petroleum counterpart. Nonetheless, the EU thought the risk and importance of (I)LUC high enough to incorporate RED-II provisions to mitigate its occurrence from EU bioenergy. Hence, for a transport biofuel (including RJF) to count toward the RED-II’s 14 percent transport and 32 percent overall renewables targets, and to qualify for EU financial support, its biomass must fulfill the criteria presented in Section 2.2.1, namely not be from food or feed crops, not have a risk of causing LUC, or not originate from lands with high biodiversity or carbon stock.
such as primary forests and wetlands. Therefore, as the following section presents, this thesis worked to identify land areas within the EU+EFTA suitable for biomass cultivation or extraction that meet these sustainability criteria. And once such biomass was secured, estimate potential RJF yields and GHG emissions savings.
3. Methods

This thesis investigated the potential of harvesting biomass in the EU+EFTA for two aviation biofuels and the ability of those biofuels to reduce the climate impact of EU+EFTA aviation. The principal analysis conducted to answer these questions was a series of scenarios to determine the theoretical feasibility of harvesting two types of biomass within the EU+EFTA, in accordance with RED-II criteria, and the amounts of HRJ and FTJ biofuel each scenario would yield. These fuel yields were then used to estimate the resulting passenger kilometers for EU+EFTA commercial aviation, their life cycle emissions savings relative to petroleum jet fuel, and the proportion of the EU+EFTA’s total annual jet fuel consumption that the biojet fuel yields would cover.

3.1. Scenario analysis scope and assumptions

The scenario analysis required a wide range and number of input variables for commercial aviation, agriculture, forestry, and biofuel production in order to conduct such a scenario analysis that answers the research questions.

3.1.1. Data sources and calculation methods used

An extensive amount of peer-reviewed literature, aviation and biofuel industry publications, and EU and international policy documents were thoroughly reviewed for data and information necessary for the analysis described in this section. Agriculture, forestry, and jet fuel use statistics for the EU+EFTA was extracted from databases of Eurostat (the European Statistical Office), a Directorate-General that aggregates statistics from Member States (including EFTA states and candidate countries), consolidates them within a harmonized methodology, and publishes these comparable statistics for open use (Eurostat). All data tabulation, comparison, calculation, and analysis conducted for thesis was performed using standard mathematical functions in Microsoft Excel 2016. The Excel functions used in the analysis are included in this section within square brackets [ ].

Significant variation was observed for many variables taken from the literature due to the age, purpose, geographic conditions, and assumptions of the studies reviewed. Hence, it was decided to use averages of these values for each variable. Averages were deemed to best capture and represent, in one value, the often-significant variations in agriculture and forest conditions and practices, biomass and biofuel yield potentials, and RJF life cycle emissions that exist across EU+EFTA Member States, and allow projection of the output results to the entire EU+EFTA study area.

3.1.2. RJF conversion pathways and biomass feedstocks included

The scenario analysis conducted in this thesis focused on two RJF conversion pathways, each utilizing one biomass feedstock: 1) hydroprocessed esters and fatty acids (HEFA) of Camelina sativa vegetable oil, and 2) Fischer-Tropsch (FT) synthesis of forestry residue lignocellulosic biomass. As discussed in sections 2.4.1 and 2.4.2, The HEFA and FT conversion pathways were chosen due to their relative technological maturity (and therefore potential to be in large-scale production in the near/medium term), high fuel blending limits (currently ASTM-certified up to 50 percent with petroleum jet fuel), and ability to produce RJF from a variety of feedstocks. Camelina was selected as the representative agriculture feedstock for the HEFA process as it a highly adaptable crop that is native to Europe, has relatively low carbon intensity, and which the literature considered to be a non-food oil crop. Similarly, forestry residues have a very low carbon intensity as they are a by-product of already occurring logging operations, currently have little commercial use, and their woody biomass is an ideal feedstock for the FT process. Both biomass feedstocks also have strong energy security and independence potential as they can be cultivated or extracted within the EU+EFTA region under current agricultural and forestry practices, which has the potential to further reduce life cycle RJF emissions.
3.1.3. Geographic and methodological scope

Unless otherwise specified, the analysis in this thesis included all 28 Member States of the European Union, as of May 2019, and the four Member States of the European Free Trade Association (EFTA). Like the EU-28, the EFTA states are parties to the Paris Agreement and have pledged similar emissions reductions and climate targets, both individually and in collaboration with the EU (EFTA 2015). Moreover, since the EFTA Member States are included within a common airspace with the EU and their aviation data and statistics are presented in the EU’s 2019 European Aviation Environmental Report, the scenario analyses likewise included agricultural and forest statistics for both the EU and the EFTA (EASA et al. 2019). (Note, however, that Liechtenstein is not included in the Report’s aviation data or Eurostat’s agriculture data.) The aviation, agriculture, and forestry statistics collected and analyzed were restricted to calendar year 2017, unless otherwise indicated.

Finally, the scenario analysis did not consider techno-economic aspects of biomass cultivation or biofuel production, such as the feasibility of cultivating or extracting biomass on all areas included or the economic costs of producing RJF using the selected feedstocks or conversion pathways. Instead, the scenario analysis investigated the theoretical yield potentials of camelina biomass and forestry residue biomass from EU+EFTA lands that attempt to fulfill RED-II land use criteria, the resulting amounts of HEFA and FT renewable jet fuels that could be produced from these biomass feedstocks, and the life cycle GHG emissions savings of these RJFs relative to petroleum jet fuel. It was also assumed that all biomass yielded in the scenario analyses would be used to produce RJF, thereby ignoring biomass demand from the energy, heating, or other transport sectors.

3.2. Camelina renewable jet fuel scenario and input variables

For the camelina-based HEFA biojet fuel, a land area scenario analysis was conducted to identify potential EU+EFTA agriculture lands that could be converted to camelina production and the amounts of camelina seed oil the converted lands would yield. The oil yields were then converted to RJF using conversion rates for the HEFA pathway.

3.2.1. Crop classifications and lands selected

The Eurostat Annual Crop Statistics database provided the land area and yield data associated with agricultural coverage and production in the EU+EFTA, which are national statistics that each Member State (except Liechtenstein) reports to Eurostat. In order to best comply with the aforementioned RED-II provisions that discourage biomass from food or feed crops, the 2019 edition of Eurostat’s Annual Crop Statistics Handbook was reviewed to identify such crop classifications for EU+EFTA lands.

Only five crop categories were found to exist that are not human food crops, described in the list below. However, one category (industrial crops not elsewhere classified (NEC)) may include stevia and sugarcane, crops that are processed to human food products, and another category (fallow land) may include lands that are within a rotation to produce crops for human food. For another category, wheat, camelina was assumed not to displace the wheat or spelt in the scenario analysis, but instead be cultivated as a rotation crop on those lands. Also note that two categories selected are feed crops for livestock (permanent grassland and plants harvested green). In total, eight crop categories were selected for camelina biomass cultivation and are presented in the following list, with descriptions paraphrased from the Handbook (Eurostat 2019a):

- **Permanent Grassland**: Land used for, normally, five or more consecutive years as pastures, meadows, or grazings; to grow, naturally or through cultivation, herbaceous fodder, forage, or energy purpose crops; also includes:
- Areas no longer used for production purposes but eligible for subsidies;
- Lands not in production for five years or more but maintained in “good agricultural and environmental conditions” (GAEC).

- **Wheat**: Includes cereal grains of common, durum, and einkorn wheat; and spelt; excludes plants harvested for fodder or energy purposes.

- **Plants Harvested Green**: All arable land crops that are harvested whole and intended mainly for animal feed, forage, or renewable energy production; namely cereals, grasses, leguminous or industrial crops, and other arable land crops harvested or used green.

- **Fallow Land**: All arable lands either included in the crop rotation system or maintained in GAEC, whether worked or not, but that is left to recover with no intention to produce a harvest for the duration of a crop year. Includes:
  - Bare land bearing no crops at all
  - Land with spontaneous natural growth, either used as feed or ploughed under
  - Land sown exclusively to produce green manure or green fallow.

- **Fibre Crops**: Plants harvested principally for their biomass fiber, including fiber flax, hemp, cotton, jute, abaca, kenaf, and sisal.

- **Tobacco**: Cultivated tobacco plants whose leaves are used to produce tobacco products.

- **Industrial Crops NEC**: Crops grown for industrial purposes and not elsewhere classified, includes fuller’s teasel, miscanthus for non-energy purposes, rolled lawn (sod), spurge, stevia, and sugar cane.

- **Energy Crops NEC**: Crops used exclusively for renewable energy production and not elsewhere classified, including miscanthus, reed canary grass, and other country-specific species; excludes short-rotation coppices.

It is important to note that due to nuances in how Member States and Eurostat categorize and report crop statistics, the classifications included in the analysis may, a) not be an exhaustive representation of all hectares currently dedicated to non-food crops in the EU+EFTA, and b) include some hectares that produce crops for human consumption.

The selected classifications were then filtered in Eurostat’s Annual Crop Statistics database (Crop Production in EU Standard Humidity) to show the number of hectares in the EU+EFTA where these crops were cultivated in 2017. To determine the total area under production for each selected crop category, the 2017 area values for all EU-28 and EFTA Member States were summed [\(=\text{SUM}(x, y\ldots)\)]. If a Member State showed a null value in a 2017 crop category but reported values in previous years, that Member State’s 2016 value was used in the 2017 summation. The total 2017 hectares for the eight crop categories are shown in Table 2.
Tab. 2. Eurostat crop classifications used in camelina scenario analysis

<table>
<thead>
<tr>
<th>Eurostat Crop Type</th>
<th>Total Hectares in EU+EFTA in 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Grassland</td>
<td>63,282,420</td>
</tr>
<tr>
<td>Wheat*</td>
<td>25,968,470</td>
</tr>
<tr>
<td>Plants Harvested Green</td>
<td>21,017,980</td>
</tr>
<tr>
<td>Fallow Land</td>
<td>6,358,460</td>
</tr>
<tr>
<td>Fibre Crops</td>
<td>481,760</td>
</tr>
<tr>
<td>Tobacco</td>
<td>80,390</td>
</tr>
<tr>
<td>Industrial Crops Not Elsewhere Classified (NEC)</td>
<td>56,890</td>
</tr>
<tr>
<td>Energy Crops NEC</td>
<td>44,960</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>117,291,330</strong></td>
</tr>
</tbody>
</table>

*Camelina to be cultivated as a rotation crop with wheat
Source: (Eurostat 2019c)

For reference, the over 117 million hectares presented in Table 2 represent almost 66 percent of the total 2017 Utilized Agricultural Area land in the EU+EFTA, a classification which includes all arable land, permanent grassland, and permanent crops (Eurostat 2019a). The combined hectares for the eight arable land crop types (i.e., all but permanent grassland) represents just over 51 percent of all arable land in the EU+EFTA in 2017, with the vast majority of that share taken by wheat and plants harvested green. The hectares contained in Table 2 represent diverse amounts and qualities of lands across the EU+EFTA. While certain plants like tobacco and fiber crops are mainly cultivated in Southern Europe, green crops and wheat are harvested in all EU+EFTA Member States except Malta, where no wheat is harvested.

3.2.2. Camelina cultivation and HEFA conversion input variables

Once the appropriate EU+EFTA agricultural lands were established, relevant literature was reviewed for input variables on camelina agricultural yields, seed oil content, RJF conversion rates, and life cycle biofuel emissions. As explained earlier, multiple values were encountered for all of these variables due to aim, method, scope, and other differences among the individual studies. Therefore, for each variable, the average was calculated \[=\text{AVERAGE}(x, y, \ldots)\] and used as the variable value in the scenario analysis. Table 4 (in Results section) provides these input variables.

The values for seed yield and oil content of camelina represent averages of over 30 variables each from camelina cultivation in Europe and North America, as identified through the literature review. For seed yield, the values ranged from 107 to 3,360 kg/ha, highlighting the large variation due to climate and growing conditions, seed cultivars, and agricultural practices. Oil content values showed a similarly wide variation, between 29.6 percent and 46.7 percent. The life cycle emissions values in the literature reviewed ranged from 3.06 to 47 gCO₂-eq/MJ fuel. This significant variance is due to differing assumptions regarding amounts of nutrients, water, and energy used in cultivation and processing; the origins of the hydrogen and energy used in the HEFA treatment process; and the ecological and agricultural quality of the lands where the camelina was grown. While changes to land use (i.e., from food crop or grassland to camelina) can contribute to life cycle GHG emissions, the sources reviewed (cited in Table 4) either do not mention or explicitly exclude potential (in)direct land use change emissions from their life cycle emissions numbers. Therefore, the averages used in the scenario analysis aim to capture the variation that could be experienced cultivating camelina in the diverse land areas represented in Table 2. Combining average camelina seed yield, oil content, and the HEFA process conversion rate \[=x \times y, \ldots\], the average amount of HRJ biofuel yielded per hectare of EU+EFTA agricultural land was determined. The results are presented in Table 4.
For each crop category in Table 2, the total hectares were multiplied by the average, per-hectare HRJ yield \[=\frac{(x\times y)}{1000000000}\] to determine the total amount of HRJ biofuel that could be produced if all hectares were converted to camelina production. (As the formula indicates, the result was divided by \(10^9\) to convert from kilograms to megatonnes.) These biojet yields were also calculated as proportions of the total amount of jet fuel consumed in the EU+EFTA in 2017 \[=\frac{(x\times y\ldots)}{y}\]. Using the input variables in Tables 3 and 4, simple mathematical functions were used \[\frac{(x\times y\ldots)}{y\ldots}\], \[\frac{(x\times y\ldots)}{y\ldots}\] for results that showed the commercial jet aviation passenger kilometers and life cycle CO\(_2\)-equivalent emissions produced by the HRJ biojet yielded in each crop category conversion scenario. These results are presented in Table 5.

### 3.3. Forestry residue renewable jet fuel scenarios and input variables

Two methods were used to calculate the forestry residue biomass potentially available in the EU+EFTA that fulfills RED-II provisions aimed at protecting forest areas with high biodiversity and carbon stock and limiting ecological impacts of logging and biomass extraction. One method was based on the annual amounts of roundwood harvested in Member States, with “roundwood” meaning not just logs from tree trunks but comprising “all quantities of wood removed from the forest and other wooded land, or other tree felling site during a defined period of time” (Eurostat 2018, p. 90). In this scenario, which estimates total forestry residues available per year, it was assumed that the roundwood was harvested legally, from non-protected forest lands with (relatively) low biodiversity and carbon stock value, and in compliance with applicable EU+EFTA logging regulations and the previously described RED-II sustainability provisions. Therefore, by extension, any forestry residues produced from roundwood harvest in the region also met these criteria.

The second method used the growing stocks of all forest areas available for wood supply in the EU+EFTA to estimate the complete (not annual) total of forestry residues that could be available for extraction. Eurostat’s defines “forests available for wood supply” as forested lands “where no legal, economic, or environmental restrictions” restrict the supply of wood available; “growing stock” refers to “the living tree component of the standing [aboveground forest] volume” (2009 p. 17). In this scenario, the forestry residues would be extracted within annual roundwood harvest or other thinning operations. Forest harvest cycles can vary considerably, and Section 5.1.2 discusses the results within the context of 20-year and 50-year cycles. Per these definitions, it was assumed that forestry residues yielded in this scenario would be extracted legally from non-protected lands with lower ecological value.

Input variables to the forestry residue scenario analysis included the volumes of roundwood harvested in EU+EFTA in 2017, and forest land areas and growing stocks available for harvest in the EU+EFTA in 2015 (the most recent year available). These values were extracted from three of Eurostat’s European Forest Accounts databases (Roundwood Removals by Type of Wood and Assortment, Volume of Timber, Area of Wooded Land) and all EU-28 and EFTA Member States’ values were summed \[=\text{SUM}(x, y\ldots)\]. Since the scenario analysis here was concerned only with forestry residues, multipliers were obtained via averaging \[=\text{AVERAGE}(x, y\ldots)\] those found in the reviewed literature to arrive at the average amounts of bark and above-ground tree residue biomass (tops, branches, and twigs) that are produced per volume of harvested roundwood. The residue multiplier used in this analysis was a somewhat conservative 24.3 percent in order to exclude the stump portion of the tree from the definition of forestry residue biomass as much as possible. This is because stump extraction can have significant ecological impacts and stumps are currently limited to less than 1 percent of extracted forest biomass within the EU+EFTA and (Searle & Malins 2013; Verkerk et al. 2019). It is also assumed that 50 percent of the produced forestry residues are extracted from the forest site; the remainder is left in situ for ecological purposes. This extraction rate is not an average, but a value chosen to represent a middle-ground estimate (based on the reviewed literature) since the amount of residue that should remain depends on several local ecosystem factors including tree species, climate, soil quality, ground slope, and forest management practices (Searle & Malins 2013).
Other important input variables were extracted from the reviewed literature and their averages were calculated \( \text{=} \text{AVERAGE}(x, y \ldots) \), including stemwood biomass density, FTJ biofuel conversion rates, and life cycle biofuel emissions. Multiple conversion rates for the FT synthesis process were found, and after extensive research it was determined that most values presented in the literature are for the overall conversion from feedstock input to the entire petroleum column output. However, multiple rates were identified for conversion to a final jet fuel product, and these variables were likewise averaged \( \text{=} \text{AVERAGE}(x, y \ldots) \) to achieve a single representative FT conversion rate. Finally, the various input variables in Tables 3 and 6 (Results section) were multiplied \( \text{=} (x*y \ldots) \), divided \( \text{=} (x/y \ldots) \), and subtracted \( \text{=} (x-y \ldots) \) as needed, as well as divided by \( 10^9 \) as needed \( \text{=} (x/1000000000) \) to get proper unit magnitude (e.g., from kilograms to megatonnes), to achieve the output results contained in Table 7.

3.4. European aviation input variables

In order to quantify the passenger aviation potential of the biojet fuels yielded in the scenario analyses, input variables were needed on EU+EFTA aviation. The EU’s 2019 European Aviation Environmental Report contained average jet passenger aircraft fuel consumption, total annual number of flights, and total annual number of passenger kilometers flown. Eurostat’s Energy Balances database (Supply, Transformation and Consumption of Oil and Petroleum Products) provided the total amount of jet fuel consumed in the EU+EFTA Member States per year \( \text{=} \text{SUM}(x, y \ldots) \), while RED-II provided the most current and highest number for the life cycle GHG emissions of petroleum jet fuel. These variables are displayed in Table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.56 x 10^6</td>
<td></td>
<td>Total number of flights (departures and arrivals) in EU+EFTA in 2017</td>
<td>(EASA et al. 2019)</td>
</tr>
<tr>
<td>8.9 x 10^6</td>
<td></td>
<td>Total number of passengers on EU+EFTA flights in 2017</td>
<td>Ibid.</td>
</tr>
<tr>
<td>1.643 x 10^{12}</td>
<td></td>
<td>Total passenger kilometers flown in EU+EFTA in 2017 (based on shortest great-circle distance)</td>
<td>Ibid.</td>
</tr>
<tr>
<td>37.04</td>
<td>person km / kg fuel</td>
<td>Average EU+EFTA commercial jet aircraft fuel efficiency in 2017</td>
<td>Ibid.</td>
</tr>
<tr>
<td>57.11</td>
<td>Mt</td>
<td>Total jet fuel consumed in EU+EFTA in 2017*</td>
<td>(Eurostat 2019e)</td>
</tr>
<tr>
<td>43.28</td>
<td>MJ/kg</td>
<td>Energy content of Jet A-1 fuel</td>
<td>(Gutiérrez-Antonio et al. 2017)</td>
</tr>
<tr>
<td>94</td>
<td>gCO_2-eq/MJ fuel</td>
<td>WtWa GHG emissions of fossil Jet A-1 fuel (WtWa)</td>
<td>(Directive 2018/2001/EU)</td>
</tr>
</tbody>
</table>

*No data reported for Switzerland

2017 saw over 9.5 million flights and over 1.6 trillion passenger kilometers in the EU+EFTA, as seen in Table 3. On average, EU+EFTA-registered commercial jet-powered aircraft moved 37 passengers a distance of one kilometer (or, conversely, one passenger a distance of 37 kilometers) on one kilogram of jet fuel. Over 57 Mt of jet fuel were consumed in the EU+EFTA in 2017, according to Eurostat data, and this figure is supported by a similar number in the EU’s 2019 European Aviation Environmental Report. Fossil-based Jet A-1 fuel emits 94 grams of CO_2-equivalent per megajoule of energy on a well-to-wake life cycle basis, according to the fossil fuel comparator in RED-II. As with the two biofuels, the literature showed that the life cycle emissions of jet fuel can vary depending on, for example, the method and energy used in the extraction and refining of the petroleum. The RED-II figure was chosen over the average of values found in the reviewed literature since this comparator is legally enshrined to serve as the EU baseline to calculate transport biofuel emissions savings.
4. Results

Using the input variables described in the Methods section, results were calculated to determine the potential amounts of camelina and forestry residue biomass, and the resulting RJFs, that could theoretically be produced annually in the EU+EFTA. This section presents the results of the scenario analyses, and the Discussion section contains further context and examination of these results.

4.1. Camelina biojet potential

Combining average camelina seed yield, oil content, and a HEFA process conversion rate of 80 percent, the average amount of HRJ biofuel yielded per hectare of EU+EFTA agricultural land was determined to be 548 kg/ha, as presented in Table 4.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,758</td>
<td>kg/ha</td>
<td>Average seed yield per hectare</td>
<td>(Iskandarov et al. 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Moser 2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Natelson et al. 2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Shonnard et al. 2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Small 2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Vollmann &amp; Eynck 2015)</td>
</tr>
<tr>
<td>39%</td>
<td></td>
<td>Average oil content of seed, by mass</td>
<td>(Iskandarov et al. 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Moser 2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Natelson et al. 2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Shonnard et al. 2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Small 2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Vollmann &amp; Eynck 2015)</td>
</tr>
<tr>
<td>686</td>
<td>kg/ha</td>
<td>Average oil yield per hectare</td>
<td>Author calculation</td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td>Average HEFA conversion rate, oil to HRJ biofuel</td>
<td>(de Jong 2018)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Li et al. 2018)</td>
</tr>
<tr>
<td>548</td>
<td>kg/ha</td>
<td>Average camelina HRJ yield per hectare</td>
<td>Author calculation</td>
</tr>
<tr>
<td>44</td>
<td>MJ/kg</td>
<td>Energy content of HRJ biofuel</td>
<td>(de Jong, 2018)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Directive 2018/2001/EU)</td>
</tr>
<tr>
<td>31.40</td>
<td>gCO2-ep/MJ fuel</td>
<td>Average WtWa GHG emissions of camelina HRJ biofuel (1,381.67 g/kg)</td>
<td>(de Jong 2018)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(EASA et al. 2019)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Li &amp; Mupondwa 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Shonnard et al. 2010)</td>
</tr>
</tbody>
</table>

Camelina was found to yield, on average, 1,758 kilograms of seed per hectare of land, and have an average oil content of 39 percent (by mass), giving an average camelina oil yield of 686 kilograms per hectare. Using a HEFA conversion rate of 80 percent, the key variable was determined: on average, EU+EFTA agricultural lands can expect to yield 548 kilograms of HRJ fuel per hectare of camelina land. Additionally, camelina-based HRJ was found to emit an average of 31.4 grams of CO₂-equivalent per megajoule of fuel (1,381.67 grams per kilogram) on a well-to-wake life cycle emissions basis. Using these HRJ yield and life cycle emissions variables, the results were calculated for each of the eight crop categories and are displayed in Table 5.
Tab. 5. Annual camelina HRJ biofuel yields, passenger kilometers, and emissions under EU+EFTA agricultural land conversion scenarios

<table>
<thead>
<tr>
<th>Crop Category</th>
<th>Total Hectares in 2017 (thousands)</th>
<th>HRJ Yield from Total Hectares (Mt)</th>
<th>HRJ Yield as Proportion of 2017 EU+EFTA Total Jet Fuel Consumption</th>
<th>Passenger Kilometers from HRJ Yield (billions)</th>
<th>Emissions Reduction of Passenger Kilometers on HRJ vs Jet A-1 (ktonCO₂ eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Grassland</td>
<td>63,282</td>
<td>34.71</td>
<td>61%</td>
<td>1,285</td>
<td>-93,254</td>
</tr>
<tr>
<td>Wheat</td>
<td>26,122</td>
<td>14.33</td>
<td>25%</td>
<td>530</td>
<td>-38,494</td>
</tr>
<tr>
<td>Plants Harvested Green</td>
<td>21,017</td>
<td>11.53</td>
<td>20%</td>
<td>427</td>
<td>-30,972</td>
</tr>
<tr>
<td>Fallow Land</td>
<td>6,358</td>
<td>3.49</td>
<td>6%</td>
<td>129</td>
<td>-9,370</td>
</tr>
<tr>
<td>Fibre Crops</td>
<td>481</td>
<td>0.26</td>
<td>0.46%</td>
<td>9.79</td>
<td>-710</td>
</tr>
<tr>
<td>Tobacco</td>
<td>80</td>
<td>0.04</td>
<td>0.08%</td>
<td>1.63</td>
<td>-118</td>
</tr>
<tr>
<td>Industrial Crops NEC</td>
<td>57</td>
<td>0.03</td>
<td>0.05%</td>
<td>1.16</td>
<td>-84</td>
</tr>
<tr>
<td>Energy Crops NEC</td>
<td>45</td>
<td>0.02</td>
<td>0.04%</td>
<td>0.91</td>
<td>-66</td>
</tr>
<tr>
<td>Totals</td>
<td>117,445</td>
<td>64.42</td>
<td>113%</td>
<td>2,386</td>
<td>67%</td>
</tr>
</tbody>
</table>

For the camelina HRJ fuel, EU+EFTA Member States could collectively produce 113 percent of the total jet fuel consumed in 2017 if they converted (or supplemented, in the case of wheat) all 117.4 million hectares of the selected agricultural lands. This would result in almost 2.39 trillion passenger kilometers, or 2,680 kilometers for each of the 890 million passengers in 2017. Table 5 displays these results. Notice that for each scenario, the emissions generated are 66 percent lower than the equivalent fossil jet fuel emissions.
4.2. Forestry residue biojet potential

Based on the calculations described in the Methods section, the resulting input variables, listed in Table 6, were used in the forestry residue RJF yield scenario analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>487,118,380</td>
<td>m3</td>
<td>Total underbark roundwood removals in 2017</td>
<td>Eurostat 2019d</td>
</tr>
<tr>
<td>143,982,200</td>
<td>ha</td>
<td>Total forest area available for wood supply*</td>
<td>Eurostat, 2019b</td>
</tr>
<tr>
<td>24,609,413,000</td>
<td>m3</td>
<td>Total growing stock in forest area available for wood supply*</td>
<td>Eurostat 2019f</td>
</tr>
<tr>
<td>1.136</td>
<td></td>
<td>Average ratio of overbark to underbark roundwood</td>
<td>Searle &amp; Malins 2013, 2016, UNECE 2010</td>
</tr>
<tr>
<td>0.32</td>
<td></td>
<td>Proportion of above-ground tree biomass (overbark roundwood) that are forestry residues</td>
<td>Searle &amp; Malins 2013, 2016, UNECE 2010</td>
</tr>
<tr>
<td>450</td>
<td>kg/m³</td>
<td>Density of oven-dry forestry residue biomass (stemwood)</td>
<td>Nabuurs et al. 2017, UNECE 2010, Verkerk et al. 2019</td>
</tr>
<tr>
<td>249.01</td>
<td>Mt</td>
<td>Total overbark roundwood removals in 2017</td>
<td>Author calculation</td>
</tr>
<tr>
<td>24.61</td>
<td>t/ha</td>
<td>Average yield of oven-dry residue biomass per hectare of forest area available for wood supply</td>
<td>Author calculation</td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td>Proportion of available forestry residues extracted from forest area</td>
<td>Searle &amp; Malins 2013, 2016</td>
</tr>
<tr>
<td>8.05</td>
<td>gCO₂eq/MJ fuel</td>
<td>Average WtWa GHG emissions of forestry residue FTJ biofuel (325.38 g/kg)</td>
<td>Bauen et al. 2009, de Jong 2018, ESA et al. 2019, Wang &amp; Tao 2016</td>
</tr>
</tbody>
</table>

*Data is for 2015

Over 487 million m³ of underbark roundwood was extracted from EU+EFTA forests in 2017, and over 24 billion m³ of woody biomass was theoretically available for wood supply on almost 144 million hectares, as highlighted in Table 6. The FT process was found to have an average conversion rate of 19 percent, based on unit mass FTJ biofuel output per unit mass biomass input. This value is an average of several experimental and production-level conversion rates presented in the literature. Forestry residue FTJ biofuel emits an average of 8.05 grams of CO₂-equivalent per megajoule of fuel, on a well-to-wake life cycle emissions basis. Similar to camelina, these values differ based on literature assumptions regarding the renewability of the residue feedstocks and the energy used to extract, transport, dry, and process the forestry residues, and the energy used in the gasification and FT synthesis of the biomass.

These variables were combined (per the calculations described in the Methods section) to determine how much FTJ could theoretically be yielded in the EU+EFTA based on forestry residue biomass from those Member States. Table 7 provides the results for this FTJ biojet scenario analysis.
Converting 50 percent of the residues produced from the 249 Mt of the roundwood harvested in the EU+EFTA in 2017 would cover almost 13 percent of those Member States’ combined 2017 jet fuel demand (7.57 Mt). This would result in 280 billion passenger kilometers per year, or 315 air kilometers for each of the 890 million passengers that flew in 2017. Conversely, if it were technically and ecologically feasible to extract 50 percent of the forestry residues from all 144 million hectares of EU+EFTA forest land available for harvest (second row of Table 7), 590 percent of the region’s 2017 jet fuel demand would be met, resulting in 14,010 kilometers per 2017 passenger (or 12.47 trillion total passenger kilometers). Note, however, that in this second scenario the results are NOT annual figures, but instead total numbers, which would be divided annually based on logging cycles (See Section 5.1.2 for more information). The FTJ biofuel produced in both scenarios would emit 91 percent less GHG emissions than petroleum jet fuel.

**Tab. 7. Forestry residue FTJ biofuel yields, passenger kilometers, and emissions under EU+EFTA annual roundwood harvest and total available area scenarios**

<table>
<thead>
<tr>
<th></th>
<th>Total Forest Area Available for Wood Supply (ha)</th>
<th>Total Roundwood Overbark Harvested in 2017 (Mt)</th>
<th>Forestry residues Available at 50% Extraction (Mt)</th>
<th>FTJ Yield from Forestry residues Available (Mt)</th>
<th>FTJ Yield as Proportion of 2017 EU+EFTA Jet Fuel Consumption (billions)</th>
<th>Passenger Kilometers from FTJ Yield (billions)</th>
<th>Emissions Reduction of Passenger Kilometers on HRJ vs Jet A-1 (ktonCO₂eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Roundwood Harvested</td>
<td>1.44 x 10⁶</td>
<td>249</td>
<td>40</td>
<td>7.57</td>
<td>13%</td>
<td>280</td>
<td>-28,115 (91%)</td>
</tr>
<tr>
<td>Total Forest Available for Wood Supply</td>
<td>1.44 x 10⁶</td>
<td>1.772</td>
<td>336.66</td>
<td>590%</td>
<td>12.469</td>
<td></td>
<td>-1,250,354 (91%)</td>
</tr>
</tbody>
</table>
5. Discussion

Results from the scenario analyses, presented in tables 5 and 7, show that based on the methods used, HRJ from camelina and FTJ from forestry residues can theoretically be produced within the EU+EFTA in quantities that meet or exceed 2017 jet fuel demand in the region, and reduce GHG emissions relative to petroleum-based jet fuel by over 65 percent. This section contextualizes these results, exploring the practical ability to produce these RJFs and debating whether the EU’s sustainability goals, may be difficult to achieve within the context of aviation. Given these challenges, renewable biofuels may be the most promising and timely pathway to significantly reduce aviation’s climate impact.

5.1. RED-II compliance of scenario biofuels

This section explores how the renewable jet fuels yielded in the HRJ and FTJ scenarios comply with the RED-II biofuel and biomass sustainability provisions outlined in Section 2.2.3.

5.1.1. Camelina HRJ

Based on the scenario analysis explained in the Methods and Results sections, the camelina HRJ as presented in Table 5 complies with RED-II criteria and is therefore countable towards the renewables targets. Specifically, the camelina HRJ exceeds the current 60 percent and future (from 2021) 65 percent GHG savings thresholds. In addition, the HRJ biomass was shown to be cultivated from current agricultural land not dedicated to human food crops and that was unlikely to have high biodiversity or high carbon stock. But such conclusions are based on three important caveats. First is that the EU considers camelina a non-food crop. Currently, RED-II provisions classify oil crops in general as food and feed crops (Directive 2018/2001/EU). As discussed in Section 2.4.1, even though camelina seed oil is edible, many in the literature consider it non-edible given its lack of contemporary cultivation or human consumption. Moreover, while camelina-based RJF would not be considered an “advanced biofuel” under RED-II since its biomass is not waste or residue, it has very low LUC risk. This is because camelina is currently not cultivated in any significant quantities in the EU+EFTA, so any oil used for HRJ would not be diverted from food or feed sources. Therefore, if camelina oil is considered a non-food feedstock, its biofuel derivatives are not subject to any RED-II caps and will count at 1.2 times their energy content toward the EU’s 14 percent transport and 32 percent overall renewables targets.

Second is that the assumption with wheat holds true, namely that camelina is cultivated on wheat lands as a rotation crop and thereby does not displace wheat, or any other such rotation crop. Referring to Section 2.4.1, since camelina has high adaptability, a short growing period, and needs relatively few inputs, it can work well cultivated in rotation with certain crops, especially wheat. Assuming that all 26.1 million hectares of wheat (see Table 5) would yield an annual camelina crop is quite optimistic and not highly likely, especially if farmers use a multi-year rotation/rest cycle, e.g., that discussed by Shonnard et al. (2010). But if, for example, one-third of the identified wheat hectares produced an annual camelina rotation crop, one could consider the other two-thirds of the land area (about 17.2 million hectares) to represent hypothetical hectares of other suitable EU+EFTA crop lands (e.g., barley, peas, lentils, and maize) where camelina could be harvested annually in rotation. While only a rough guide, this approximation indicates camelina’s potential as a rotation crop.

Third, and perhaps most contentious, is regarding the permanent grassland and plants harvested green crop categories. Growing camelina on these lands could risk ILUC effects as the displaced feed crops may be cultivated elsewhere, potentially on new agricultural lands. Regardless, the camelina biomass feedstock cultivated from these lands, and the more than 46 Mt of HRJ yielded from them, should be RED-II-compliant. In the case of permanent grassland, it is dubious to consider all 62.3 million hectares—classified by Eurostat as agricultural pastures, meadows, grazings, or fields for livestock fodder—as being what the RED-II intended as “natural”, “undisturbed” or “biodiverse” grassland (Directive 2018/2001/EU; Eurostat 2019a). Even more questionable is for the EU to restrict any biomass
cultivation on the 84.3 million hectares that these two categories comprise—almost half of the entire utilized agricultural area in the EU+EFTA—when most of this land’s current use is presumably to raise animals for human consumption (i.e., meat and animal products). In other words, converting these hectares to camelina (or another biomass crop) represents a trade-off of what the EU deems more important: feed for domesticated animals or biofuels for reduced emissions and energy independence.

Hence, if the EU were to consider a narrow interpretation of the “food and feed crops” definition, this would likely prohibit any oilseed crops, including camelina, from complying with RED-II sustainability criteria. In this situation, it is difficult to see how the EU could meet its 2030 emissions reductions targets, as they would have effectively banned significant sources of established, emissions-saving, non-food biofuel feedstock that can be sustainably cultivated on EU+EFTA lands.

5.1.2. Forestry Residue FTJ

The FTJ from forestry residues, as produced via the scenario analysis outlined in the Methods and Results sections and presented in Table 7, represents an ideal RED-II transport biofuel. As discussed in Section 2.4.2, since this biomass is a by-product of forest logging operations there is essentially zero risk of (I)LUC with this RJF. And as only 50 percent of the total available residues would be extracted in these scenarios, the risk of ecological impact to forest sites is likely to be relatively low. Moreover, this forestry residue biomass comes from EU+EFTA Member States; it is therefore safe to assume that harvests occur legally on non-protected forest areas that are sustainably managed for long-term biodiversity and forest health.

RED-II criteria of being both an advanced biofuel and an aviation biofuel not from food or feed crops are also fulfilled with this FTJ biofuel. Consequently, the FTJ yields presented in Table 7 would be counted at 2 times their energy content toward the RED-II’s 14 percent transport renewables target and advanced biofuel sub-targets. Furthermore, this RJF could receive an additional multiplier of 1.2 times its energy content for being an aviation biofuel, but the RED-II language is unclear if this double counting is permissible. In addition, these FTJ fuels easily meet the 60 percent and (from 2021) 65 percent GHG emissions savings criteria. Finally, since the feedstock is not a food or feed crop, the FTJ biofuel is not subject to any RED-II caps.

In the first scenario, based on annual roundwood already harvested in the EU+EFTA, the RJF yielded only represents 13 percent of all jet fuel consumed in the region in 2017. This shows that present FTJ conversion technologies produce relatively low yields of RJF from woody biomass feedstocks compared to, for example, the camelina HRJ yields in Table 5. However, the FTJ emits much lower GHGs over its life cycle than crop-based biofuels like camelina, due to its very non-carbon intensive feedstock. FTJ also has the aforementioned added benefit of being considered an “advanced biofuel” under RED-II and is thereby subject to multipliers toward its renewables targets.

In the second scenario, based on total forest available for wood supply, the figures require further context. This scenario is highly hypothetical and unlikely for practicality and sustainability reasons and is largely provided to spur further discussion and research. The 144 million hectares of forest area represent a significant amount of land: about 73 percent of all forest and other wooded lands in the EU+EFTA and almost 31 percent of the total EU+EFTA land area (Eurostat 2019b). Logging operations would need occur on all of these 144 million hectares in order to produce forestry residues as by-products. This would yield very high amounts of roundwood for commercial and industrial purposes, perhaps as much as 24.6 billion m³, which is more than 50 times the amount harvested in 2017 (see Table 6). Furthermore, the 336.66 Mt of FTJ produced in this scenario is a total and not an annual figure. Applying a rather optimistic forest harvest cycle of 20 years would mean this total yield would equate to 16.83 Mt of FTJ per year, or 29.5 percent of the 2017 jet fuel demand (Brown et al. 2014). For comparison, this is roughly equivalent to the annual HRJ yielded from the combined hectares of six of the eight crop categories in Table 5 (all except permanent grassland and plants harvested green). Harvesting those 144 million hectares over a 50-year cycle (corresponding to the 50-fold increase in roundwood yield between the two scenarios) would, naturally, produce FTJ yields roughly equivalent
to the FTJ yield in the annual roundwood harvest scenario. So while 336.66 Mt of total potential FTJ is impressive, once understood from an annual perspective this yield becomes quite modest.

5.2. Comparisons to other biomass availability studies

Many of the studies reviewed for this thesis focus on global estimates of future land cultivation and biomass extraction. They also tend to present results in terms of aggregate energy content of all biomass sources (i.e., combined lower heating value) or of the final RJF product, and do not disaggregate the biomass into its various types (e.g., oil crops, grasses, residues) or in terms of mass or volume, e.g., (Bauen et al. 2009; Verkerk et al. 2019). Direct comparison to these studies may not be fruitful, therefore, since the results presented from the scenario analysis conducted here are restricted to specific lands and types of biomass within the EU+EFTA. However, some studies were found that provide interesting comparison to the biomass and RJF yields results, and all indicate that further sustainable biomass cultivation and RJF production in the EU+EFTA region is necessary and possible.

5.2.1. Projecting RJF yields against competing biomass demand

With its long-term goals of carbon neutrality, energy security, and energy independence, the EU will require significant quantities of biomass for heat, electricity, and transport (El Takriti et al. 2017). These sectors will require increasing amounts of biomass to meet growing industry and citizen demands for energy. In his doctoral dissertation on RJFs, Sierk de Jong determined that policy measures, development of technology, price of petroleum jet fuel, and supply and demand of biomass all affect RJF availability within the region. Based on models using various parameters within these variables, de Jong found that the EU could produce 3.8-6.1 Mt of RJF per year by 2030, which would cover only 6-9 percent of total annual jet fuel consumption at EU airports based on projected increases in sector grown and fuel demand (2018). This RJF would offset 53-84 percent of the projected growth in EU aviation emissions by 2030. While this RJF yield is initially produced via HEFA conversion of oils and fats, de Jong’s model showed movement toward FT and other advanced (but, as of yet, not commercialized) conversion pathways of waste, residue, and woody biomass over the course of the decade. The model also showed this RJF supply would be achieved through a large biomass diversion effect from other bioenergy demand sources and an induced market incentive to expand RJF use due to the RED-II targets, caps, and multipliers for aviation and advanced biofuels (Ibid.).

The annual RJF yield range that de Jong projects for the EU roughly corresponds to RJF yields from this thesis. At the minimum, the combined 3.85 Mt of HRJ yielded annually from the five smallest crop categories in the camelina HEFA scenario conducted here (see Table 6) is almost equivalent to de Jong’s minimum value, while the 7.57 Mt of FTJ projected in the annual roundwood harvest scenario (see Table 7) is slightly higher than de Jong’s maximum. However, de Jong’s analysis can provide important techno-economic context to RJF yields and consumption that go beyond the scope of the scenario analyses conducted in this thesis. Namely, it demonstrates that despite any possible biomass or RJF yielded in such scenarios, most of any biomass produced in the EU region is likely to go to other biofuel or bioenergy uses due to those sectors’ strong demand and infrastructures being more established than the RJF industry (Ibid.). In addition, the lack of aviation targets or minimums in RED-II could result in biomass resources being pulled toward sectors subject to such provisions, such as power generation and road transport.

5.2.2. Future availability of forestry residues

While no studies were found on future projections of camelina biomass or HRJ for the EU+EFTA study area, some research exists on the amounts of current and future forestry (residue) biomass that is available within the EU and Europe more broadly. Their findings correlate well with the results of the FTJ scenario analysis, indicating that utilizing forestry biomass within the EU+EFTA for RJF
production is promising. In their white paper on plant residue and waste availability in the EU, the International Council on Clean Transport (ICCT) finds that 40 Mt of forestry residues can be sustainably harvested each year in the EU-28, and they project this annual yield to remain roughly the same to 2030 (Searle & Malins 2013). Note that this number is the same as the annual forestry residues yielded in the annual roundwood harvest scenario in Table 7. In contrast, other studies have estimated lower annual amounts of forestry residue biomass available in the EU-28 for uses such as RJF: Bauen et al. projects 7.2 Mt, while Searle and Malins project 9.23 Mt (2015; 2016). These lower annual figures are due, in part, to different input variable values and assumptions than those used in this scenario analysis (see Table 4). More importantly, however, is that the 7.2 Mt and 9.23 Mt figures represent annual forestry residues available in the EU-28 once demand is accounted for residue biomass from other bioenergy sources. This highlights that overall biomass availability for RJF production in the EU+EFTA is likely to be constrained in practice.

5.2.3. Reclaiming abandoned lands for biomass cultivation

Researchers have also discussed the possibility of cultivating biomass on abandoned lands: areas formerly used for agriculture yet now unused for economic, geographic, or ecological reasons. For example, Nabuurs and co-authors estimate that 15 million hectares of farmland in the EU-28 will be abandoned by 2030 (2017). As with most abandoned land, they surmise that such areas are likely not suitable for agriculture (hence their abandonment), but they could represent good areas for forestry biomass using fast-growing tree species (e.g., short-rotation coppice). While not forestry residues as defined in this thesis, the up to 60 million m³ of annual woody biomass that Nabuurs et al. estimates from these abandoned lands could yield around 0.93 Mt of FTJ each year using the scenario input variables in Table 6. This is a small FTJ yield, however, representing less than 12 percent of the annual FTJ yielded in the annual roundwood harvest scenario of this thesis. Therefore, replanting such areas as forest may have valuable land regeneration, biodiversity, and carbon sequestration effects, although their value is relatively limited for producing FTJ biomass. Conversely, if half of the 15 million abandoned hectares were able to be converted to camelina production, up to 4.1 Mt of HRJ could be produced, which is more than the fallow land scenario (see Table 5) and about 7 percent of the jet fuel consumed in the EU+EFTA in 2017. Hence, mobilizing abandoned lands in the EU+EFTA region could result in minor increases in biomass for RJF, but this could be one small step toward the emissions reduction goals of European aviation.

5.3. EU policy implications of scenario analysis results

Can the EU+EFTA region produce enough aviation biofuels to fuel aviation and reduce emissions? Results produced in this thesis indicate that the answer is yes, in theory, yet only with significant mobilization in the coming decades via the conversion of agricultural lands to biomass cultivation and extraction of forestry residues from forested areas. The answer is not a simple one, however, and the Intergovernmental Panel on Climate Change may summarize the dilemma best: “Many areas of climate policy-making involve value judgements and ethical considerations. Climate policy intersects with other societal goals creating the possibility of co-benefits or adverse side effects. These intersections, if well-managed, can strengthen the basis for undertaking climate action” (IPCC 2014 p. 5).

As indicated previously in Section 5.1.1, obtaining a reliable and sustainable supply of RJF that helps achieve energy security and independence is a trade-off: either cultivate crops for human food or animal feed (in the camelina scenario) or use at least some of these lands to cultivate biomass; either leave forest biomass in situ or extract at least a portion for bioenergy use (in the forestry residue scenario). An additional and perhaps more difficult trade-off is where the EU+EFTA should best use their renewable, but finite, supplies of biomass. The EU seems to understand this predicament, at least partly, through their setting of 2020 and 2030 EU-wide climate targets and their promotion of bioenergy through legislation like RED-II (see Section 2.2). However, those same emissions reduction targets and legal provisions also indicate that the EU may not fully understand or take seriously the trade-offs that
biomass extraction and biofuel production represent. There is only so much land available in the EU+EFTA region; how do citizens, landowners, and policy makers want to use it? Reducing emissions and climate change is good. Protecting biodiversity is good. Protecting lands with high carbon stock is good. Achieving energy security and independence is good. These goals, while noble, may in reality be mutually exclusive, as the RJF scenario analyses here have indicated. It is one thing to publish policy documents or pass legislation designed to encourage increased biomass production and biofuel consumption; it is quite another to actually make the hard choices of where and how such biomass and biofuels will be produced, and what will have to be displaced in the process.

A pivotal year for EU bioenergy could be 2019, as a new European Parliament will be elected and a new European Commission appointed. The potential change in leadership and political priorities could result in fresh outlooks and initiatives toward RJF and biofuels writ large, with the possibility of new measures and incentives to encourage biomass cultivation and extraction and RJF production. One pathway is through the EU’s Common Agricultural Policy (CAP), which is currently being negotiated for the post-2020 timeframe. One of the CAP’s nine objectives is “climate change action”, and its provisions contain explicit pushes toward the bio-economy in order to reduce the EU’s GHG emissions (European Commission 2019b). Hence the CAP recast presents a perfect opportunity for the EU to take action, to mobilize and expand its biomass and biofuel resources for high-value, high-emissions saving measures like production and consumption of RJF.

5.3.1. Food vs fuel debate and further emission reductions of RJF

The camelina scenarios are those with the most explicit trade-offs between food/feed production and biomass production, as this oil crop requires agricultural cultivation (unlike the forestry residues). However, of the 178.7 million hectares of utilized agricultural area in the EU+EFTA in 2017, the analysis conducted for this thesis identified only 664,000 that are not cultivated as food or feed crops (or are not fallow), which represents only 0.37 percent of the total area (Eurostat 2019c). As shown in Table 5, these 664,000 hectares from the four non-food/feed crop categories would only yield enough HRJ to cover a tiny 0.36 percent of the region’s 2017 jet fuel demand. These lands likely represent the lowest risk of (ILUC as they would not displace any food or feed crops. However, while not food or feed, the original crops do of course have economic value (e.g., tobacco) so ILUC displacement effects are still possible. Given this complexity, other options are clearly needed. If the EU is serious about reducing global GHG emissions, expanding aviation/transport biofuel use, and getting closer to energy security and independence, it must convert at least some land currently devoted to food or feed crops to camelina or other biomass cultivation in order to produce biofuels.

Furthermore, two crop categories represent a significant amount of land (a combined 84.3 million hectares) that is devoted to feeding animals for human consumption: permanent grassland and plants harvested green (see Table 2). These hectares could produce enough HRJ to cover almost 81 percent of the EU+EFTA’s 2017 jet fuel demand, which is well beyond the currently certified 50 percent blend limit. In addition to the HRJ emission reductions, the reduced livestock raising and meat consumption would do even more to reduce GHG emissions in the EU+EFTA. According to the United Nation’s Food and Agricultural Organization, Western European livestock production (for meat and animal products) produces about 600 Mt of CO₂-equivalent emissions annually, with about 45 percent of these emissions coming from the production, processing, and transport of feed (Gerber 2013). Converting just one-third of the permanent grassland and plants harvested green hectares to camelina production would yield enough HRJ to meet 27 percent of EU+EFTA 2017 jet fuel demand and reduce aviation emissions by 41.4 Mt each year (see Table 5). Such a conversion to camelina or another biomass crop could avoid up to 200 Mt of additional GHG emissions annually due to the reduced livestock production—a significant further contribution toward EU+EFTA emission reduction goals.
5.3.2. Demand reduction measures are likely needed to reduce aviation emissions

As discussed in the Background section, substantial aviation growth is projected in for the EU+EFTA region, with up to 25 million flights by 2050 (High Level Group on Aviation Research 2011). As a result, the EU may ultimately need to explore means to reduce the number of flights, as emissions reduction and offsetting measures (see Figure 2) will not be enough to counteract the projected 150 percent increase in the region’s aviation emissions by 2050 (de Jong 2018). While the RJF yielded in the two scenario analyses presented in this thesis can theoretically meet or exceed the total jet fuel demanded in 2017, full mobilization of these land areas to biomass cultivation and extraction is not likely in practice due to competing uses of agriculture and forest lands, relatively immature mobilization of RJF and related biomass infrastructure, and increasingly competing demands for biomass from other bioenergy sectors. When the projected growth in EU+EFTA aviation is paired with the practical, sustainability, and trade-off considerations of large-scale production and extraction of biomass in the region, the outlook is lowered on the ability of this EU+EFTA-produced RJF to significantly reduce aviation emissions and allow the EU to meet its broader emissions reductions and renewables targets. Hence, if EU+EFTA Member States are serious about reducing aviation emissions, they will need to employ additional measures to decrease aviation demand and capture the environmental impacts of aviation emissions. Per-passenger ticket fees and taxes on petroleum-based aviation fuels may represent the most immediate and direct options, when paired with expanded RJF supply and consumption, to monetize the climate impacts of aviation and direct the costs to those responsible for demanding and supplying the expanding service of commercial aviation: airline passengers and airline companies.
6. Conclusion

Of the 469 million hectares that make up the EU+EFTA land area, about 43 percent is currently cropland or grassland, 38 percent is covered by wooded areas, and 4 percent is artificial human-built areas (Eurostat 2017, 2019b). Most EU+EFTA lands are therefore already being used for some agricultural, economic, or ecological purpose, so expanding biomass cultivation or extraction for biofuels will require converting some of these lands from their current uses. Hence, this thesis sought to identify land areas for this conversion that fulfill the EU’s renewable energy sustainability criteria, and then estimate the agricultural and forest biomass those converted lands could yield for RJF.

Against the backdrop of rising global GHG emissions (especially from transport and aviation sources); international pledges to keep global warming below 2°C; aviation industry commitments to carbon-neutral growth; and ambitious EU goals to reduce its emissions, meet renewable energy targets, and achieve energy security and independence; this thesis recognized the need for solutions to reduce aviation emissions through aviation biofuels. The biofuel research literature has largely focused on techno-economic aspects of RJF production and paid less attention to identifying areas where biomass could be cultivated or extracted. As a result, the three research aims of this thesis were to:

D. Explore the theoretical supply potentials of two types of biomass from EU+EFTA lands

E. Project RJF yields from these biomass feedstocks using two biofuel conversion pathways

F. Estimate life cycle emissions savings of the resulting RJF relative to petroleum jet fuel

The scenario analyses conducted here showed that Camelina sativa oil and forestry residue woody biomass can be feasibly and sustainably supplied from EU+EFTA lands. The HRJ and FTJ biofuel amounts projected from these respective biomass supply potentials could meet or exceed the annual jet fuel consumption of the EU+EFTA as of 2017. Both the HRJ and FTJ fuels resulting from the scenario analyses complied with RED-II criteria: they exceed 65% emission savings relative to petroleum jet fuel; they can be cultivated and extracted sustainably from lands without high biodiversity or carbon stock; they are not from traditional food or feed crops; and they have very low risk of (I)LUC emissions. However, important caveats to the results are that such RJF yields would only occur in the EU+EFTA through a combination of, a) significant numbers of hectares currently devoted to livestock grazing and feed crops being converted to camelina, and camelina being cultivated in rotation on many of the hectares currently planted with wheat or other similar crop(s); and b) forestry residues being extracted from large areas of forest lands considered available for roundwood harvesting. Moreover, in practice, many competing and growing demands will be placed on biomass resources from heat, energy, and transport sectors in the EU+EFTA in the region-wide push for emission reductions. Combined with the substantial projected growth in aviation and its emissions, biomass and RJF produced in the EU+EFTA will likely not be enough to result in meaningful reductions in aviation emissions in practice. As a result, measures to monetize aviation’s environmental impacts and reduce aviation demand will likely be needed in tandem with an expanded mobilization of RJF resources.

Both RJF fuels analyzed and discussed in this thesis will be important tools for the EU to meet its 2030 targets of 14 percent renewables in transport and 32 percent renewables in all energy consumption. However, the EU will have to make serious decisions on trade-offs regarding land use, namely where such agricultural biomass should be cultivated and such forestry biomass should be extracted; and bioenergy uses, namely which sectors and industries should make use of highly demanded biomass resources. As governments, industries, and citizens desire to move more toward a low-carbon, bio-based economy, ever-increasing wants and needs will be placed on the renewable, yet finite, annual supplies of biomass resources. Collective and prudent action is needed from policy makers, biomass suppliers, bioenergy firms, and the voting public to decide whether aviation biofuels will remain fields of dreams or help build pathways toward a sustainable future.
7. Acknowledgements

I sincerely thank the faculty, staff, and researchers at the Department of Energy and Technology of the Swedish University of Agricultural Sciences for their assistance, input, and welcoming accommodation throughout my thesis project. I especially thank my supervisor, Gunnar Larsson, and subject reviewer, Anders Eriksson, both professors at this department, for graciously lending their time, expertise, and guidance. I also thank my colleague Lucia Korbelyiova for her insightful and valuable opposition.

My most heartfelt gratitude, appreciation, and love go to my parents, Kelly A. van Slyke and Jeannie M. van Slyke, for their lifelong love, support, and encouragement.

*verba ita sunt intelligenda ut res magis valeat quam pereat*
8. References


