

MSc Thesis

Greenhouse gas performance of renewable jet fuel: a comparison of conversion pathways.

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Abstract

The aviation industry has embraced the production and use of renewable jet fuel (RJF) to bring down greenhouse gas (GHG) emissions associated with the aviation industry. Currently, four types of RJF are certified to be blended with conventional jet fuel for the use in aircrafts. These are: HEFA RJF from vegetable oils and used cooking oil, FT RJF from lignocellulosic biomass, DSHC RJF from sugars and ATJ RJF from butanol. Other conversion pathways are still in an experimental phase. These are HTL- and Pyrolysis- RJF from forest residue. Promising GHG performances are reported for all pathways, but a coherent comparison cannot be made.

Several challenges emerge regarding the comparison of GHG performance of RJF pathways. Globally accepted harmonized methods to assess biofuel GHG performance in a coherent way do not exist as different regional and national regulation standards such as the Renewable Energy Directive (RED) in the EU and the Renewable Fuel Standard (RFS) in the US impose different methods. The main difference between the methods imposed by the regulation standards is the treatment of co-products when processes have multiple outputs.

The aim of this study was to make a coherent comparison of GHG performance of RJF conversion pathways, different combinations of feedstock and conversion processes are assessed, including different co-product treatment methods and coherent data assumptions.

Results of the assessment showed that GHG performance of RJF conversion pathways depends on applied co-product methods, feedstocks, conversion pathways and hydrogen inputs. Depending on the co-product treatment method, the highest GHG performance was found for FT pathways, of which FT from forest residue has the highest performance with GHG emissions lower than 5 g CO₂ /MJ RJF. The conversion pathways with the lowest GHG performance are found to be DSHC from sugarcane and ATJ from corn with GHG emissions larger than 50 g CO₂ / MJ RJF depending on the combination of feedstocks and conversion processes. GHG performances of HEFA pathways differ between -39 - 54 g CO₂ /MJ RJF, for ATJ pathways from sugar beet or sugar cane between 29 - 38 g CO₂ /MJ RJF ,for HTL pathways between 17 – 21 g CO₂ /MJ RJF and for Pyrolysis 23 – 63 g CO₂ /MJ RJF.

The results of this study show that a clear ranking of conversion pathways can only be made for pathways that are based on coherent data inputs and the same co-product treatment method.

Research partners

RENJET

This research is embedded in the EIT Climate-KIC project “Bio Jet Fuel Supply Chain Development and Flight Operations (RENJET)”. It aims to lay the basis for a self-sustaining network of regional bio jet fuel supply chains based on sustainable (European) feedstock sources, to account for 20% of bio jet fuel demand in the European Union in 2025. Project partners of RENJET are, amongst others: Utrecht University, Imperial College London, KLM, Schiphol, and SkyNRG. This three-year project is co-funded by Climate-KIC. Website: <http://www.climate-kic.org/case-studies/renjetrenewable-jet-fuel-supply-chain-and-flight-operations/>.

Master program Energy Science

The two-year research master Energy Science (120 ECTS) is organized by the department of Innovation, Environmental and Energy Sciences, Copernicus Institute of Sustainable Development, Utrecht University. The program provides a detailed insight on how energy systems work, and how they can be analyzed and modelled. Moreover, the program gives a detailed insight in energy technologies.

Annotation Sustainable Entrepreneurship & Innovation

The annotation Sustainable Entrepreneurship & Innovation is a university wide master track that is complementary to the master program Energy Science. This study qualifies for the annotation because 1) renewable jet fuel addresses new combination of processes, 2) at this moment it is not yet commercially applied on a large scale, 3) data is collected of lifecycle GHG savings of renewable jet fuel 4) the research component is larger than 15 ECTS

Climate-KIC master label

Climate-KIC is a knowledge and innovation community (KIC) founded by the European Institute of Innovation and Technology (EIT) that focuses on climate entrepreneurship. This research qualifies for the master label because it fits in the Climate-KIC target of making transitions and GHG mitigation happen. Making a comparison of GHG performance between jet fuel pathways aids in the transition towards renewable jet fuel.

Argonne National Laboratory – Energy System Division

Argonne is a multidisciplinary science and engineering research center where researchers work alongside experts from industry, academia and other government laboratories to address vital US challenges in clean energy, environment, technology and national security. This research is carried out in cooperation with the Energy Systems division, which is also responsible for the development of the GREET model.

European Commission – Joint Research Center– Institute for Energy and Transport

The Joint Research Center is a research center that provides EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle. The mission of the JRC Institute for Energy and Transport (JRC-IET) is to provide support to European Union policies and technology innovation to ensure sustainable, safe, secure and efficient energy production, distribution and use and to foster sustainable and efficient transport in Europe.

Acronyms

ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
ATJ	Alcohol to Jet
CaCO ₃	Calcium carbonate
CGF	Corn Gluten Feed
CGM	Corn Gluten Meal
CH ₄	Methane
CO ₂	Carbon dioxide
DGS	Distillers Grain Solubles
DOT	United States Department of Transportation
DSHC	Direct Sugar to Hydro Carbons
EC	European Commission
EPA	United States Environmental Protection Agency
FAA	Federal Aviation Administration
FT	Fischer-Tropsch
g	Gram
GHG	Greenhouse Gas
GREET .net	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation.net Model
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	Hydrothermal Liquefaction
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
JRC	European Commission Joint Research Center
K ₂ O	Potassium oxide
kg	Kilo gram
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LUC	Land Use Change
MJ	Mega joule
N ₂ O	Nitrous Oxide
P ₂ O ₅	Phosphorus pentoxide
RED	Renewable Energy Directive
RJF	Renewable Jet Fuel
IATA	International Air Transport Association
SMR	Steam methane reforming
TTW	Tank-to-Wake
WTP	Well-to-pump
WTPr	Well-to-product
WTW	Well-to-wheel
WTWa	Well-to-wake

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Greenhouse gas performance of renewable jet fuel: a comparison of conversion pathways.

1 Introduction

The aviation industry is currently responsible for 2% of global greenhouse gas (GHG) emissions, (ATAG, 2013; Blakey et al., 2011; Hamelinck et al., 2013). Air traffic is suggested, by major actors in the aviation industry, to grow 4 - 5% annually in the forthcoming years (Airbus, 2015; ATAG, 2013; Boeing, 2015; IATA, 2015a). Moreover, ICAO (2009) forecasts that CO₂ emissions caused by aviation can grow 3 - 10% annually compared to 2006 and research of Kousoulidou & Lonza, (2016) reports annual emission growth rates for Europe of 3%, 1% and 4% for a central, pessimistic and optimistic scenario. The industry is aware of aviation's environmental impact and in 2008 the aviation collectively agreed on a set of sector-specific climate change targets (IATA, 2015b).

Increasing annual anthropogenic GHG emissions are one of the main causes of global warming (Chum et al., 2011). This has driven the International Air Transport Association (IATA) to reduce and manage GHG emissions and other environmental impacts associated with the aviation industry. In order to reduce the environmental impacts of GHG emissions IATA has set out three goals: (1) improving fuel efficiency with 1,5% annually, (2) capping net emissions through carbon neutral growth from 2020, (3) reduce net GHG emissions by 50% in 2050, compared to 2005 (IATA, 2015a).

Several different strategies are developed by the industry to meet their emission reduction goals. These strategies include improvements in technology, operations and infrastructure, and deploying market-based measures (IATA, 2015a). Experts have identified that the gains in efficiency from technological advances and operational optimization will not offset the emissions generated by the expected growth rates, which results in a so-called 'mitigation gap' (ICAO, 2009). Therefore, other strategies are required in order to close the mitigation gap between air transport emissions growth (after incorporating efficiency improvements) and IATA's goal of a 50% reduction in net CO₂ emissions by 2050 (Elgowainy et al., 2012; ICAO, 2010).

The use of biofuels in aviation has the potential to save up to 80% GHG emissions compared to conventional fuel (Eurocontrol, EEA, & EASA, 2016). The potential large GHG emission savings are an important reason for the aviation industry to identify the use of biofuels in aviation as crucial for the industry's emission reduction strategy (EC, 2013; IATA, 2015; ICAO, 2014).

1.1 Renewable Jet Fuel

The aviation industry emphasizes the use of biofuels in aviation as key strategy to reduce GHG emissions and closing the mitigation cap. The industry's interest is mainly directed towards the development and use of drop-in Renewable Jet Fuels (RJF) (Hileman et al., 2009; ICAO, 2010). The term RJF is increasingly used for a series of biofuels, that are derived from renewable biomass sources and meet the specifications of petroleum jet fuel and results in the same overall performance (Blakey et al., 2010; Cherubini et al., 2009). The term 'drop-in fuel' means that a fuel can be 'dropped-in' existing fuel systems

and infrastructure and is compatible with current aircraft and engine technology (Carter et al., 2011; Gegg et al., 2014). The use of drop-in RJF is attractive for the aviation industry as it can continue to operate existing engines and aircrafts but use low carbon fuels (Kousoulidou & Lonza, 2016). The reduction of GHG emissions by the use of drop-in RJF is mainly the result of the uptake of CO₂ from the atmosphere during the cultivation of biomass, which eventually results in lower environmental impacts compared to conventional jet fuel (Krammer, Dray, & Köhler, 2013). Several conversion pathways for RJF from different feedstocks exist or are being developed.

A 'conversion pathway' describes a technology and feedstock combination (de Jong et al., 2015). Currently, four types of conversion pathways have been certified by the American Society for Testing and Materials (ASTM) to be blended with conventional jet fuels as drop-in fuels to power aircraft engines (ASTM, 2016). The certified fuels that are included in the alternative fuel standard of ASTM are the hydroprocessed esters and fatty acids (HEFA) fuels from vegetable oils and animal fats, Fischer-Tropsch (FT) fuels from biomass, Direct Sugar to Hydrocarbon (DSHC) fuels from sugar and Alcohol-to-Jet (ATJ) from butanol (ASTM, 2016). Several more conversion pathways for RJF exist. However, most routes have not yet achieved an industrial commercial status and they still require pilot/demo activities (Chiaramonti et al., 2014).

1.2 Problem definition

The potential environmental benefits of replacing conventional petroleum fuels with biofuels is the main driving force for promoting the production and use of biofuels in the transport sector in the EU and in the US developing its energy security and employment in rural areas (Cherubini et al., 2009). Reducing environmental impacts and achieve petroleum savings by using RJF in the aviation sector requires methods and tools to help quantify and compare the environmental impacts of different conversion pathways (Plevin et al., 2014).

Environmental impacts include climate change, stratospheric ozone depletion, tropospheric ozone creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use and noise (Chum et al., 2011; Rebitzer et al., 2004). Life Cycle Assessment (LCA) has become a widely accepted methodology by industry, academics and institutions for assessing environmental impacts of biofuel production systems (Baitz et al., 2013). LCA assesses environmental impacts by identifying emissions, energy use, consumption of material use and other environmental exchanges along all stages of a production process, from the extraction of raw materials through the materials' processing, manufacturing, distribution, use and disposal or recycling (ISO, 2006a, 2006b).

A number of studies have used the LCA methodology to calculate the GHG performance of biofuel conversion pathways in the road sector (i.e. Hoefnagels & Smeets, 2010; Kaltschmitt et al., 1997; Kendall & Yuan, 2013; Larson, 2006; Nanaki & Koroneos, 2012; Wang et al., 2011). One of the most important

studies in the EU is the Well-to Wheel study of the JRC, EUCAR and CONCAWE (JEC) (Edwards et al., 2014).

In recent years, more studies are conducted on the GHG performance of RJF pathways (i.e. Agusdinata et al., 2011; Bailis & Baka, 2010; Carter et al., 2011; Cox et al., 2014; Elgowainy et al., 2012; Shonnard et al., 2010; Staples et al., 2014). RJF LCA studies are primarily focused on the GHG performance of certified pathways as GHG savings requirements are imposed by regulatory schemes and market-based measures. Other studies focus on techno-economic aspects of RJF pathways (de Jong et al., 2015; Klein-Marcuschamer et al., 2013). Coherent comparisons on GHG performance of RJF pathways, as is performed by the JEC consortium for road fuels, are still scarce and the results between the studies are not directly comparable (Cox et al., 2014; Elgowainy et al., 2012; Stratton et al., 2010).

The difficulties in comparing GHG performance of conversion pathways are often the results of a number of existing problems and problematic decisions in the LCA framework (Reap et al., 2008). Cherubini et al. (2009) identified several methodological concerns in bioenergy LCA. These concerns include; the consideration of land use change (LUC) in bioenergy systems, which can have influence on the GHG balance; the effects on the GHG balance of crop residue removal; the comparison of the bioenergy system with the fossil reference system; the use of the functional unit; and the wide range of results in terms of energy balances and GHG emissions. Key factors in the determination of the GHG balances are found to be fertilizer induced N₂O emissions, co-product treatment methods, system boundaries and the use of fossil process fuels (Cherubini et al., 2009; Chum et al., 2011). The great variability and uncertainty caused by these concerns and different choices in relation to key factors, leads to inconclusive results for the GHG performance of biofuel conversion pathways (Kendall & Yuan, 2013).

GHG performance is one of the key indicators of sustainability performance and therefore implemented in regulations. For regulation purposes, existing standards (BSI, 2011; ISO, 2006a, 2006b, 2013) and regulation schemes instruct to calculate GHG emissions according to standardized methodological approaches for regulation (Alberici et al., 2014). The assumptions and standard methods, however, differ between regulatory schemes. Two of the most important regulatory schemes for the use of alternative transport fuels are the Renewable Energy Directive (RED) in the EU (EC, 2009) and the Renewable Fuel Standard (RFS) in the US (EPA, 2010). Between these regulatory schemes significant differences exist in the imposed sustainability criteria, but also in required co-product treatment methods for assessing lifecycle GHG emissions, which are not comparable with each other (Alberici et al., 2014). This results in different studies and reports that report diverging estimates of lifecycle GHG emissions and therefore large ranges for biofuel conversion pathways are found, which results in different rankings of RJF conversion pathways (Chum et al., 2011). Moreover, given the global character of the aviation industry, the differences in results impose obstacles for deploying global market-based measure as conversion pathways can only be assessed and compared based on equal methodological choices and input assumptions.

1.3 Research Aim

The lack of LCA studies assessing and comparing GHG performance of RJF pathways according to harmonized methods and assumptions indicates the need for a consistent and harmonized approach. RJF conversion pathways have to be assessed following different methods in order to assess the impact of choices and assumptions for calculating GHG performance and to compare GHG performance in different regulatory contexts. To this end, this research aims to make a consistent comparison of the GHG performance of RJF conversion based on a coherent assessment, including different conversion pathways and co-product treatment methods.

This research therefore aids in developing a widely accepted harmonized approach for assessing GHG performance of RJF pathways, which is of special interest in aviation given the current problems with comparing RJF fuel pathways, but also for reporting, monitoring and verification of GHG emissions in the context of globally deployed market-based measures. (IATA, 2015b; ICAO, 2014).

The general aim of this research is to assess and compare GHG performance of RJF conversion pathways and therefore the mitigation potential of using RJF in air transport. The general research question that is to be answered in this research is:

What is the GHG performance of renewable jet fuel conversion pathways?

In order to make a coherent comparison between RJF pathways, this research follows a stepped approach and objectives for answering the research question are defined below:

1. Make a selection of state-of-the-art RJF pathways to be assessed and compared.
2. Assess the life-cycle GHG performance of the selected RJF pathways following different methodological approaches.
3. Compare the GHG performance of RJF pathways.
4. Analyze the influence of different methodological approaches on GHG performance.

1.4 Research Scope

Various RJF pathways are considered in this research. The pathways in this research's scope produce drop-in RJF that has similar characteristics to conventional jet fuel. Six conversion processes are included:

- Hydro-processed Esters and Fatty Acids (HEFA)
- Fischer-Tropsch (FT)
- Direct Sugar to Hydrocarbons (DSHC)
- Alcohol-to-Jet (ATJ)

- Hydrothermal Liquefaction (HTL)
- Pyrolysis.

Almost all technologies are ASTM certified or under review for being ASTM certified (ASTM, 2016; de Jong et al., 2015). Most feedstocks in the research scope are in line with the aviation industry's commitment to use non-food feedstocks for RJF production only (IATA, 2015b). The ATJ pathways from sugar beet ethanol and sugarcane ethanol are included in the scope because of these feedstocks large market share in present biofuel production.

This research analyzes GHG emissions associated with the selected RJF conversion pathways. The boundaries of this research include feedstock production, pre-conversion, transport and main conversion. LUC effects and other environmental impacts are not included in this research's boundaries due to their complexity and location specific assumptions.

1.5 Outline

In the theory section, the different conversion pathways, the general LCA methodology and the regulatory context of the RED and RFS are described. In the methodology, the procedural overview, methodological choices and data inputs are explained. The results of this research and the sensitivity analysis are given in the results section. Finally, the applicability, limitations and quality of this research are discussed and conclusions are drawn.

2 Theory

In this section, the standard specifications of RJF and the selected RJF conversion pathways are discussed in more detail. Furthermore, the general LCA methodology and the regulatory context of biofuel use in transportation are described.

2.1 Standard specification of renewable jet fuel

Standard specifications for Renewable Jet Fuels are defined by the ASTM in the “standard specification for aviation turbine fuel containing synthesized hydrocarbons” (ASTM, 2016). The requirements and specifications are defined in terms of required performance properties (W. C. Wang & Tao, 2016). The requirements for Jet fuels are (1) acceptable minimum energy density by mass, (2) maximum allowable freeze point temperature, (3) maximum allowable deposits in standard heating tests, (4) maximum allowable viscosity, (5) maximum allowable sulfur and aromatics content, (6) maximum allowable amount of wear in standardized test, (8) minimum aromatics content, (9) minimum fuel electrical conductivity, and (10) minimum allowable flash point (U.S. Department of Defense, 2011). RJF from FT, HEFA, ATJ and DSHC processes are already certified by the ASTM to be blended to a certain amount with conventional jet fuel for use in commercial aircrafts (ASTM, 2016).

2.2 Renewable Jet Fuel pathways

Figure 1 shows the conversion pathways and feedstocks included within the scope of this research. The RJF pathways are discussed in more detail in sections 2.2.1 to 2.2.6.

2.2.1 Hydro-processed Esters and Fatty Acids

Hydro-processed Esters and Fatty Acids (HEFA) RJF is produced by hydro-processing vegetable oils, waste streams from food industry or by-products of vegetable oil refining (Hamelinck et al., 2013). Fats and oils are relatively easy to convert to drop-in RJF, because of their low oxygen contents and a H:C ratio that is closer to a Jet fuel than other feedstocks such as (poly)saccharides or lignin's (Karatzos et al., 2014).

The vegetable oil is extracted from oil crops, algae or microbial oil (Elgowainy et al., 2012). The cultivation and oil extraction phase for oil crops have similar characteristics, but material and energy inputs are different for each feedstock (Chiaramonti et al., 2014). In the hydrotreating process, the oxygen in the feedstock is removed and possible double bonds are saturated by a hydro-deoxygenation process (Pearlson, 2011). The deoxygenized hydrocarbon product is then catalytically cracked to the desired chain lengths (Pearlson, 2011). The RJF produced is known as HEFA Synthetic Paraffinic Kerosene

(HEFA-SPK) and is already ASTM approved for commercial use in a 50% blend (ASTM, 2016). Feedstocks for this process that are taken into the scope of this research are vegetable oils from jatropha and camelina and collected used cooking oil (UCO).

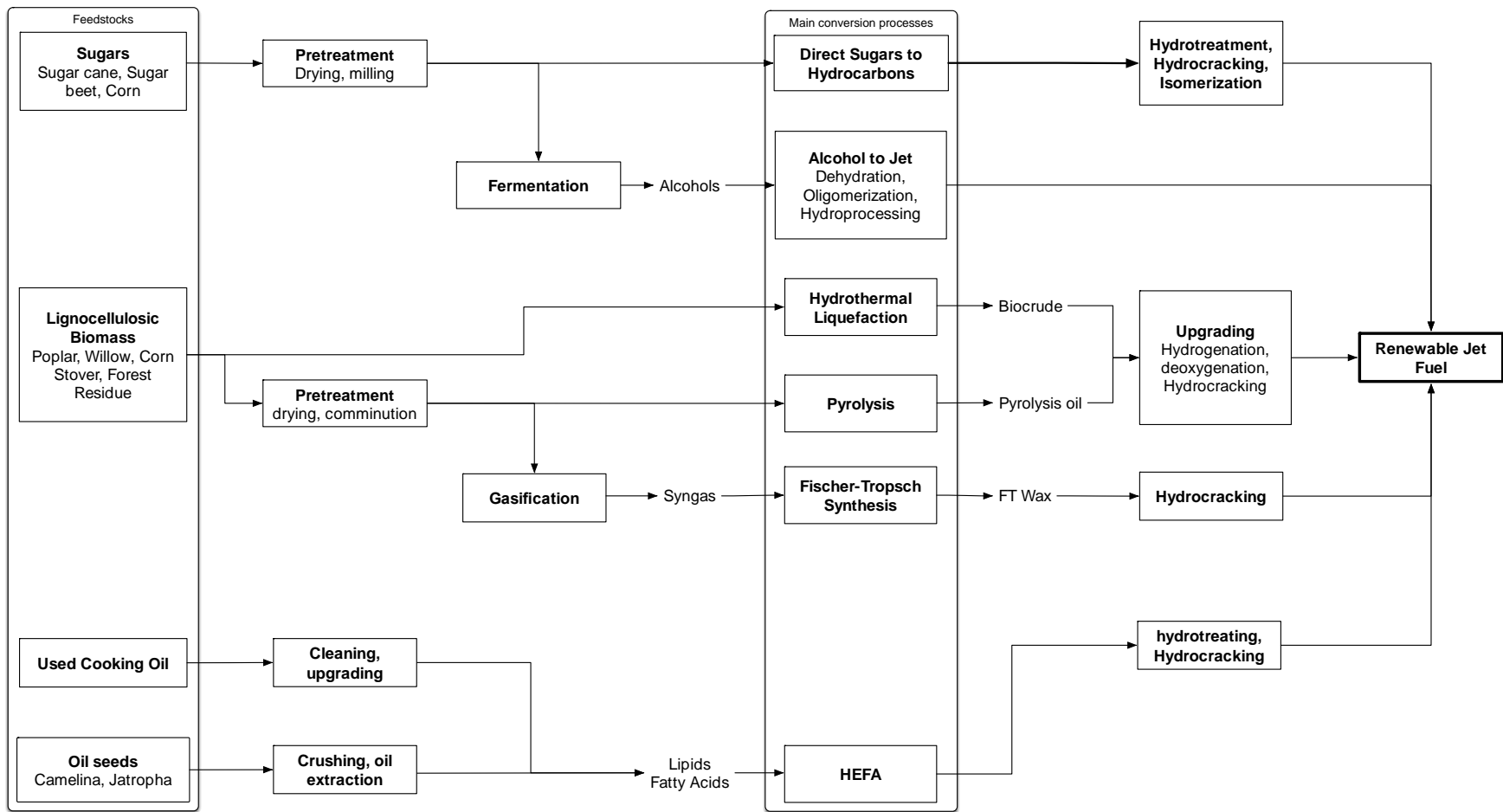


FIGURE 1 RENEWABLE JET FUEL PATHWAYS IN THE SCOPE OF THIS RESEARCH (ELABORATED FROM CHIARAMONTI ET AL., 2014; COX ET AL., 2014; TEWS ET AL., 2014; WANG & TAO, 2016).

¹Lignocellulosic biomass can also be converted to sugars by depolymerization and hydrolysis, but this is not included in this research.

2.2.2 Fischer – Tropsch

The Fischer-Tropsch (FT) to RJF pathway can have any carbon-rich material as a feedstock and converts it into a syngas by means of gasification (Elgowainy et al., 2012; Stratton et al., 2010). In the gasification process, carbon-rich material reacts with air or steam under extreme pressure and temperature. The syngas is then further processed through the FT synthesis process at controlled pressure and temperature into FT wax (Hamelinck et al., 2013). Unconverted syngas is used for further synthesis or electricity generation and other co-products are used to produce hydrogen internally (Stratton et al., 2010). The FT wax is then processed in a cracking process to get a range of end products. The jet fuel produced is known as Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK). This pathway is approved by the ASTM for commercial use in 50% blend with conventional kerosene (ASTM, 2016). Feedstocks considered as input for this pathway in this research are: poplar, willow, corn stover and forest residue biomass.

2.2.3 Alcohol-to-Jet

The main input of the Alcohol-to Jet (ATJ) pathway is ethanol produced from sugar crops. The ATJ process converts ethanol or other alcohols such as butanol to RJF (Karatzos et al., 2014). In the ATJ process, water in the alcohol is removed during a dehydration process (Karatzos et al., 2014). Thereafter the molecules are joined together into an oligomer in an oligomerization process. The hydrocarbons of different chain lengths are then separated in a distillation process and double bonds are removed by hydrogenation. ATJ fuel from butanol is certified by the ASTM (ASTM, 2016). The production of alcohol is an important step in the conversion pathway of ATJ RJF (Seber et al., 2014). Alcohols are obtained through different fermentation processes of sugars. These sugars are cultivated in sugar crops. In this research the three most important sugar feedstocks for ethanol are considered: sugarcane (Brazil), sugar beet (Europe) and corn (USA).

2.2.4 Direct Sugar to Hydrocarbons

In the Direct Sugar to Hydrocarbon (DSHC) process sugars are fermented to hydrocarbons which are then catalytically upgraded to jet fuel (Klein-Marcuschamer et al., 2013; Wang & Tao, 2016). In the fermentation process yeast is fed sugars and produces straight hydrocarbons (Wang & Tao, 2016). Several processes are being developed (Wang & Tao, 2016), but this research includes the certified process based on the Amyris process, which produces farnesene (ASTM, 2016). This research included sugarcane as feedstock for the DSHC process based on research from Cox et al., (2014).

2.2.5 Pyrolysis

Lignocellulosic biomass is dried and ground to fine particles in a feedstock pre-treatment process (Tews et al., 2014). The ground particles are rapidly heated to extreme temperatures ($\pm 500^{\circ}\text{C}$) (Wright et al., 2010). The resulting pyrolysis vapors and char exits the reactor (Tews et al., 2014). The char is combusted in a char boiler which heats the process. The pyrolysis vapors are quickly condensed and bio-oil is quenched and upgraded by hydroprocessing to RJF and other hydrocarbons. The non-condensable gases from the pyrolysis process can be used as fuel in the hydrogen reformer to produce hydrogen. In this research forest residue is considered as feedstock for pyrolysis RJF.

2.2.6 Hydrothermal Liquefaction

Where most conversion technologies need low levels of moisture in biomass, Hydrothermal Liquefaction (HTL) is a technology that can liquefy biomass with any level of moisture content (Akhtar & Amin, 2011). This makes the HTL technology especially interesting for the production of biofuel from algae (Fortier, Roberts, Stagg-Williams, & Sturm, 2014). Algae are however not yet ready to be used as feedstock for biomass on a commercial scale.

One of the main purposes of HTL is to decrease oxygen contents of biomass. In wood for example, oxygen represents 40-50% of the biomass (Akhtar & Amin, 2011). First, direct injection of hot water produces a slurry of solids and water (Tews et al., 2014). The biomass slurry undergoes a conversion reaction to biocrude under the influence of heat ($250 - 550^{\circ}\text{C}$) and pressure (5 - 25 MPA) in the HTL reactor (Akhtar & Amin, 2011). The biocrude is reacted with hydrogen gas and a catalyst until oxygen contents are low and hydrocarbon oil can be boiled into different fractions. The HTL RJF is currently not certified by ASTM. In this research forest residue is considered as main input for the process.

2.3 Life Cycle Assessment

LCA is a four-step framework that is used to quantify environmental impact of emissions of substances in the natural environment, energy and material consumption, and other environmental exchanges during the lifetime of a product (Rebitzer et al., 2004). According to ISO standard 14040:2006 (ISO, 2006a) the four main phases of LCA include: goal and scope definition, inventory analysis, impact assessment and interpretation. The steps of LCA are outlined in Figure 2. The interpretation of the results occurs at every stage of an LCA (Rebitzer et al., 2004). Examples of direct applications for LCA results are product development and improvement, strategic planning and public policy making. Below, the four principles are discussed in more detail.

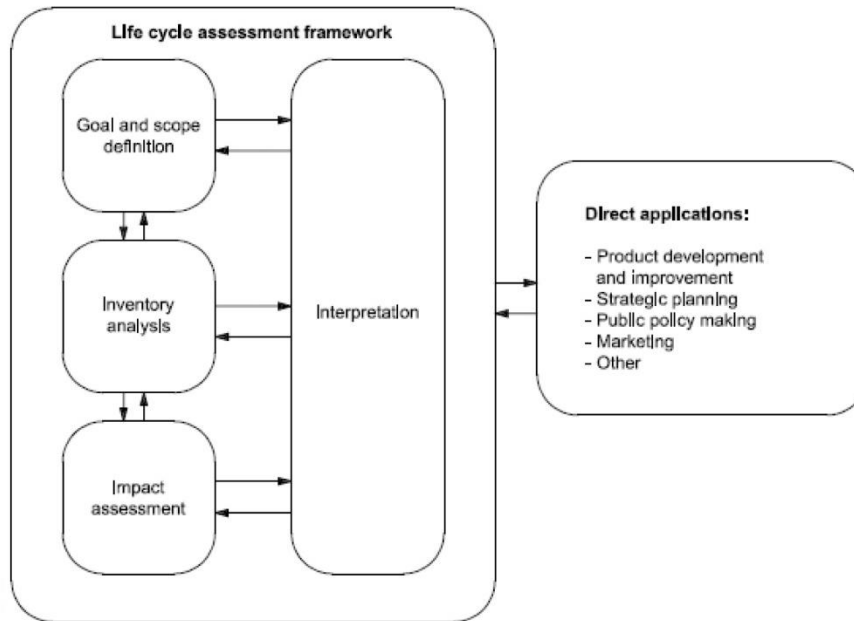


FIGURE 2 LCA FRAMEWORK ACCORDING (ISO, 2006A)

Goal and scope definition provides a description of the production system, the functional unit, the boundaries, the allocation methods and impact categories (ISO, 2006a).

Many production processes have more than one output product. The question that arises is how exchanges (e.g. GHG emissions) are distributed among the output products (Rebitzer et al., 2004). This question is still the origin of the controversial issue of co-product treating methods (Cherubini et al., 2009). Several types of allocation methods exist: allocation with respect to mass, the energy content or the economic value of the output products (Wang et al., 2011). Allocation can be avoided by expanding the boundaries of the assessed system. The latter is also known as the “displacement method” (or the “system boundary expansion method”, “or the substitution method”). The different methods pose different advantages and disadvantages, which are given in Table 1. It depends on the type of output products and purpose of the research which method is deemed most suitable. Energy and mass allocation are most suitable for either consumer fuel or consumer products. These methods, however become problematic when output products have different uses (e.g. ethanol and animal feed) or when co-products do not have mass or energy content,.

Table 1 Advantages and Disadvantages of co-product treatment methods. Adopted from: (Wang et al., 2011)

Co-product treatment method	Advantages	Disadvantages
Mass allocation	<ul style="list-style-type: none"> • Can be used for LCAs of consumer products (e.g., a ton of steel for use). • Physical relations bring less uncertainty. 	<ul style="list-style-type: none"> • Becomes problematic when products have a distinctly different use. • e.g. Electricity co-product does not have any mass. • Does not reflect the true use of individual products nor the energy use and emissions of producing individual products.
Energy allocation	<ul style="list-style-type: none"> • Can be used for LCAs of products that are used for their energy content purposes. • Physical relations bring less uncertainty. 	<ul style="list-style-type: none"> • Becomes problematic when products have a distinctly different use. • e.g. animal feed co-products have energy content in nutritional context. • Does not reflect the true use of individual products nor the energy use and emissions of producing individual products.
Economic allocation	<ul style="list-style-type: none"> • Normalizes all products to a common basis (their economic value) regardless of their use. 	<ul style="list-style-type: none"> • This method can be subject to great fluctuation of product prices.
Displacement	<ul style="list-style-type: none"> • Represents actual effects of generating multiple products in a process. 	<ul style="list-style-type: none"> • Implementation process of method poses some major challenges, such as conducting LCAs for displaced products. • Displacement effect could be circular. (e.g. soy meal from biodiesel plant could displace soy meal from regular soybean facility.) • Method generates distorted results when non-fuel products are a large share of the total output.

Two different general approaches towards LCA methodology exist: Attributional LCA and Consequential LCA (Wang et al., 2011). In an attributional LCA approach, individual processes of a fuel cycle are

identified and the environmental exchanges are allocated among different products. This methodology is used in most biofuel LCAs (Edwards et al., 2014; Michael Wang et al., 2011). The consequential approach takes into account the effects of processes that are directly involved in the generation of a given product, and all indirect effects, such as the effects of introducing the product in the marketplace.

Life cycle inventory analysis (ISO, 2006a) defines all exchanges with the environment by or attributable to all steps in a product's life cycle. These are likely to occur: at multiple sites and regions of the world; as different fractions of the total emissions at a specific site; at different times in the life cycle and over different time periods (Rebitzer et al., 2004).

Life cycle impact assessment (ISO, 2006a) converts inventory data into environmental impact estimates. It provides indicators and the basis for analyzing the potential contributions to a number of potential environmental impacts such as climate change, toxicological stress, noise, and land use (Rebitzer et al., 2004).

2.4 Regulatory context of biofuel policies

Methodological choices for LCA are often made in the context of standardized (regulated) approaches. A number of standardized approaches exist (RFS, RED, ISO/TS 14067:2013, PAS 2050). The most important regulatory sustainability standards for the production and use of biofuels are the Renewable Energy Directive (RED) (EC, 2009) in the EU and the Renewable Fuel Standard (RFS) (EPA, 2010) in the US (Alberici et al., 2014; IATA, 2014).

The goal of the RED is to ensure a 10% use of renewable energy in transport by 2020 across the EU (EC, 2009). While the goal of the RFS is to encourage the blending of renewable fuels into the nation's motor vehicle supply (EPA, 2007). Both sustainability standards impose mandatory requirements for biofuel sustainability in order to reach their main goals and have therefore implied minimum GHG saving targets for biofuels and requirements related to restrictions on land conversion (Alberici et al., 2014; EC, 2009; EPA, 2007). A comparison of the requirement in the RED and RFS related to GHG emissions are outlined in Table 2.

GHG saving thresholds

Biofuel in general has to comply with GHG saving thresholds imposed by the regulation standards. Under the RED, the GHG emission thresholds apply for all types of biofuels. In the RFS, different saving thresholds are developed for different categories of biofuels. The categories are: cellulosic biofuel, advanced biofuel, biomass-based diesel and renewable fuel (EPA, 2010). "Renewable fuel" is defined in the RFS as fuel produced from renewable biomass and that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel. "Advanced biofuel" is a renewable fuel other than ethanol derived from corn starch and for which emissions are at least 50% less than the fossil fuel it displaces.

“Cellulosic biofuel” is renewable fuel derived from any cellulose, hemicellulose, or lignin each of which must originate from renewable biomass. The fuel must also achieve 60% GHG emission reduction compared to the fossil fuel comparator. The “cellulosic biofuel” also qualifies for both “advanced biofuel” and “renewable biofuel”. “Biomass-based diesel” includes biodiesel and non-ester renewable diesel (including cellulosic diesel) made from renewable biomass, and lifecycle GHG emission reductions have to be at least 50% compared to the fossil fuel it displaces. Also, fuels that are co-processed with fossil feedstocks do not qualify for this category. The definition of renewable biomass under the RFS exclude biomass removed from federal lands and crops from forested lands as biofuel feedstocks (Bracmort, 2015) Under the RFS, the following biomass types qualify as renewable biomass (Schnepf & Yacobucci, 2013):

- crop residues such as corn stover;
- forest material including eligible forest thinning’s and solid residue remaining from forest product production;
- secondary annual crops planted on existing cropland, such as winter cover crops;
- separated food and yard waste, including used cooking oil.
- short rotation crops that are not removed from federal lands or forested land.

The RED and RFS are focused on biofuel consumption in the road sector, however, the use of RJF in aviation can count towards the respective targets under both standards (Alberici et al., 2014). However, to be counted under RED this requires implementation at the member-state level, which so far only has been done by the Netherlands (Alberici et al., 2014). Furthermore, RJF conversion pathways can apply for biotickets under RED and for Renewable Identification Numbers (RINS) under RFS. (Hamelinck, Cuijpers, Spoettle, & Bos, 2012; IATA, 2015b).The GHG calculation methods in the standards share a common basis of LCA analysis, but difference exists in the treatment of co-products. The differences can cause varying calculated savings under different standards (Alberici et al., 2014). Furthermore, the difference in results is also problematic for the deployment of GMBM. ICAO is committed to develop GMBM as the impact of RJF conversion pathways goes beyond the regional and national levels (ICAO, 2014). Currently, calculation methods for GMBM are still uncertain due to the lack of harmonization between important regulation schemes as the RED and RFS (Alberici et al., 2014).

GHG performance of pathways that have to comply with the RFS is not calculated on actual values as the Environmental Protection Agency (EPA) determines GHG emissions for fuel pathways through a formal review process (Alberici et al., 2014). GHG savings can be calculated using actual values under RED or by using default values, which are available for both standards. Significant difference between the default data of the standards exists due to the different calculation methods. Fossil fuel comparators are included in the standards for diesel and gasoline road fuels. The comparators in the RFS are, however around 10% higher than in the RED. A fossil fuel comparator for conventional jet fuel is not yet included.

Land use change

Land Use Change (LUC) is a fundamental issue in biomass sustainability and is recognized by both LUC and RFS. LUC has effect on ecosystem services, carbon balances and food chains (Fritsche et al., 2010). Land use for bioenergy production can cause direct LUC (DLUC) and indirect LUC (ILUC) effects. “DLUC” is the conversion of land, which was not used for crop production before, into land for biofuel feedstock production (Delzeit et al., 2011). “ILUC is a market effect that emerges when biofuel feedstocks are increasingly planted on areas used for agricultural products. Decreasing availability of land for food production causes a decrease in supply of food on the world market and therefore increasing prices. The higher prices create an incentive to convert unused land to areas for food production (Delzeit et al., 2011). Simply said, the DLUC, caused by increasing demand for biofuel production, can cause ILUC effects due to cross-price effects and increased demand for unused land areas. DLUC effects can be calculated relatively simple from a comparison of carbon balances of previous land use with those after the land has been used to produce biomass crops (Fritsche et al., 2010). ILUC effects can only be estimated by modelling displacement of previous land use with economic models, and the displaced production and its DLUC effects with biophysical models (Fritsche et al., 2010). The calculations are therefore more complicated and results entail high uncertainty.

LUC effects are approached differently in the two standards (European Commission, 2009; United States Environmental Protection Agency, 2007). The RFS takes into account an overall estimate of domestic and international LUC emissions. Moreover, the RFS considered the effects of ILUC in their definition of renewable biomass (Bracmort, 2015). The RED currently requires participants to only take into account any actual direct land use change emissions associated with the specific fuel pathway (Alberici et al., 2014). To the end of reducing the risk of ILUC effects , the RED has set rules and actions such as a limitation of the share of biofuels from crops grown on agricultural land to be counted towards the energy targets to 7%; and an indicative 0.5% target for advanced biofuels (European Commission, 2012).

Treatment of co-products

One of the most important differences exists on the topic of dealing with co-products along the fuel pathways. RED allocates emissions to co-products on an energy basis, while the RFS uses the displacement method. A detailed description of both methods can be found in section 3.1.3.

Grandfathering

Another important difference is on the subject of ‘grandfathering’. The term grandfather relates to when an old rule continues to apply for existing situations while new rules will apply only to future cases (Alberici et al., 2014). Under the RFS2 the exemption made for grandfathered facilities does not expire. This applies to renewable fuel facilities constructed before 19 December 2006, ethanol facilities that

commenced construction after 19 December 2007 but before 31 December 2009 and fired with natural gas or biomass. These cases are exempt for the 20% lifecycle GHG reduction.

The RED contains temporary grandfathering provisions. An expired provision did enable installations in operation on or before 23 January 2008 to be exempt from the 35% GHG savings requirement until 1 April 2013. Similarly, the 60% target applicable from 2018 does not apply to installations producing biofuel before January 2017.

Table 2 Requirements and methodological choices for calculating GHG savings under RED and RFS (Alberici et al., 2014)

	RED	RFS
GHG savings threshold (compared to fossil fuel baseline)	35% for all biofuels, moving to 50% from 1 Jan 2017 for existing installations and 60% from 1 Jan 2018 for installations producing after 1 Jan 2017	Cellulosic biofuel: 60% Advanced biofuel: 50% Biomass based diesel: 50% Renewable fuel: 20%
Fossil fuel baseline	Petrol: 83.8 gCO ₂ e/MJ Diesel: 83.8 gCO ₂ e/MJ (Referenced to 2008)	Petrol: 92.8 gCO ₂ e/MJ Diesel: 91.9 gCO ₂ e/MJ (Referenced to 2005)
System boundary	Extraction and cultivation of raw materials Land use change Processing Transport and distribution Saving from soil carbon accumulation Saving from carbon capture and storage Saving from carbon capture and replacement	Net Domestic Agriculture (w/o land use change) Net International Agriculture (w/o land use change) Domestic Land Use Change International Land Use Change Fuel Production Fuel and Feedstock Transport
GHGs included	carbon dioxide (CO ₂) methane (CH ₄) nitrous oxide (N ₂ O)	carbon dioxide (CO ₂) methane (CH ₄) nitrous oxide (N ₂ O)
Treatment of co-products	Allocation by energy content	System expansion (displacement)

3 Methodology

In the first part of this section, the general procedural overview of this research is discussed. Methodological considerations concerning GHG emissions, co-product strategy, analysis procedure, and functional unit are explained. Also, the research scope and goal is defined. In the second part, the input data and the assumptions made for every individual pathway are described.

3.1 Procedural overview

3.1.1 Goal

The goal of this research is to investigate GHG performance of various RJF pathways compared to conventional jet fuel GHG performance. To do so, the GHG performance is assessed with different calculation methodologies in order to compare results and to review the compliance with RED and RFS regulations. LCA is a broader methodology that can be used to account for all environmental exchanges of an industrial process, which requires wide datasets and complex, less transparent calculations, which make results less comparable (Edwards et al., 2014). The term 'LCA' can therefore be misleading and does not represent the calculations carried out in this research. A widely used and understood term for LCA carried out for biofuels that only includes GHG emissions in stages in limited boundaries is well-to-wheels (WTW) assessment for road transport and well-to-wake (WTWa) assessment for aviation (Edwards et al., 2014; Elgowainy et al., 2012).

3.1.2 Boundaries

Stages that are commonly included in a WTWa assessment are recovery and transportation of the feedstock from the well, field or mine to the production facility, processing the feedstocks to fuels, transportation and distribution of the fuel to the aircraft and eventually the combustion of the fuel in the aircraft (Edwards et al., 2014; Elgowainy et al., 2012; Stratton et al., 2010).

This study only focusses on the GHG emissions during the feedstock processing, transport to production facilities and the conversion to RJF, thus only the stages that constitute the well-to-product (WTP_r) stage are included. This cannot be confused with the well-to-pump stage which includes the distribution and storage to the airplane's tank as well. The distribution and storage processes are not included as these stages are very location specific and therefore do not increase generalizability of the results of this research.

The total well-to-wake (WTW) assessment includes the WTP_r stage, the distribution and storage of the fuel and the jet fuel combustion also known as the tank-to-wake (TTW) stage. This is shown in Figure 3.

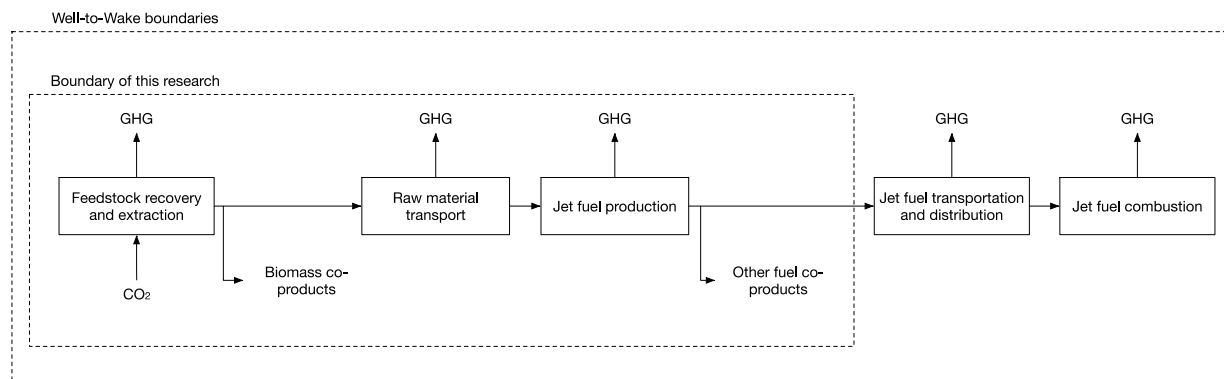


FIGURE 3 STEPS CONSIDERED IN THE BOUNDARIES OF A WTTA ASSESSMENT AND IN THE BOUNDARIES OF THIS RESEARCH.

This research does not cover GHG emissions associated with the initial creation of infrastructure such as extraction equipment, transportation vehicles, farming machinery and processing facilities. The impact of such emissions is usually relatively small and the fuel production is the major contributor to the final emissions (Stratton et al., 2010). LUC is not included due to its location specific assumptions and the lack of appropriate calculation methods and tool

Fossil feedstock such as coal and crude oil are created from geologically sequestered carbon sources, and the carbon is released as CO₂ in the atmosphere when fuels are combusted (Stratton et al., 2010). Biomass feedstocks absorb CO₂ from the atmosphere when they grow and the CO₂ emitted during fuel combustion is equal to that absorbed during biomass cultivation. Therefore, CO₂ emissions that come from the original biomass feedstocks are off-set by GHG emissions absorbed in the cultivation phase.

3.1.3 Co-product usage and allocation methodologies

Fuel production often results in the creation of co-products besides the primary fuel production. The embodied value of these co-products can be quantified based on physical metrics, or their ability to displace some other products elsewhere in the greater marketplace (Stratton et al., 2010). Four methods exist to assign life cycle GHG emissions between the main fuel product and any created co-products: Mass allocation, energy allocation, market-value allocation and displacement (or substitution, or system expansion).

Existing standards such as ISO 14044:2006 (ISO, 2006b) and regulations (RED, RFS) guide in which co-product treatment method is appropriate or needs to be used for pathways in order to comply with regulations. Advantages and disadvantages of each method are given in Table 1. The ISO 14044:2006 standard requires that allocation should be avoided by dividing a process into sub-processes when possible or expanding the product system to include additional function of co-products and taking into account displaced emissions (ISO, 2006b). When allocation cannot be avoided, inputs and outputs

should be partitioned between different products on a physical basis or on economic value if physical relations cannot be established or not deemed appropriate.

Where calculations under the RED are required to apply GHG emission allocation based on the energy content, the RFS requires the use of the displacement method. In this research, pathways are assessed including both co-product treatment methods. This way a comparison can be made under both regulatory schemes. The energy allocation approach distributes the lifecycle GHG emissions along output products, based on their energy content (Stratton et al., 2010). The displacement method assumes that the production of co-products displaces the production of substitute products. It tends to represent actual effects of generating multiple products from a pathway (Wang et al., 2011). As a result, emission credits for the displaced product are applied to the primary product. It is important to identify a suitable and realistic product to displace, to calculate the lifecycle emissions of the displaced product and to determine the displacement ratio (Huo et al., 2008). The appropriate allocation of land use change further complicates this method.

In literature, the problems with displacement are widely covered. Problems mainly emerge when non-fuel products constitute a large share of the total output of a process. In this case, the displacement method returns distorted GHG emission results (Wang et al., 2011). In general if the yield of fuel products in a process is lower than non-fuel product yields, the fuel products should be considered a co-product and displacement methodology is not appropriate (Wang et al., 2011). In this research displacement methodology is assumed not appropriate when fuel product yields are lower than 40%. This limit value is the result of a discussion with experts from ANL. In the case that fuel yields are low, hybrid allocation approaches including multiple allocation methods are suggested (Huo et al., 2008). In this research non-fuel products such as meal from oil extraction will be allocated based on economic value, when appropriate, while fuel products will be allocated based on energy value. The reason for this is that energy contents of non-fuel products such as meal and sugar beet slops are mainly reported in a nutritional context as they are often used as animal feed. The energy values in a combustion context are not widely available. It is believed that nutritional energy values do not represent the same as combustion based values (Stratton et al., 2010; Wang et al., 2011).

Product yields

The energy and economic values of the resources are provided in Appendix A. The fuel yields, to determine whether displacement is appropriate or not, are outlined in Table 3.

Table 3 Yields rations per process

Process and sub-process	Output products	Unit	Amount	Yield %	Fuel/non-fuel
HEFA process	Propane	MJ	0.10	8%	Fuel
	Naphtha	MJ	0.14	11%	Fuel
	Jet	MJ	1.00	81%	Fuel
Oil extraction jatropa	Electricity	MJ	5.72	25%	Fuel
	Jatropa oil	MJ	16.87	75%	Fuel
Oil extraction camelina	Camelina oil	g	26.88	36%	Fuel
	Camelina meal	g	47.79	64%	Non-fuel
FT process	Electricity	MJ	0.12	11%	Fuel
	Jet	MJ	1.00	89%	Fuel
DSHC	Electricity	MJ	0.02	1%	Fuel
	Diesel	MJ	0.15	9%	Fuel
	Naphtha	MJ	0.54	32%	Fuel
	Jet	MJ	1.00	58%	Fuel
ATJ process	Diesel	MJ	0.12	9%	Fuel
	Naphtha	MJ	0.21	16%	Fuel
	Jet	MJ	1.00	75%	Fuel
Sugar beet sugar extraction	Sugar beet pulp	g	28.00	43%	Non-fuel
	Ethanol	g	37.10	57%	Fuel
Corn dry mill ethanol production w/o corn oil extraction	DGS	g	31.74	46%	Non-fuel
	Ethanol	g	37.10	54%	Fuel
Corn dry mill ethanol production w/ corn oil extraction	DGS	g	31.74	45%	Non-fuel
	Corn oil	g	1.06	2%	Non-fuel
	Ethanol	g	37.10	53%	Fuel
Corn wet mill ethanol production	CGM	g	6.87	9%	Non-fuel
	CGF	g	29.74	38%	Non-fuel
	Corn oil	g	5.52	7%	Non-fuel
	Ethanol	g	37.10	47%	Fuel
HTL	Gasoline	MJ	0.59	24%	Fuel
	Diesel	MJ	0.30	12%	Fuel
	Heavy oil	MJ	0.60	24%	Fuel
	Jet	MJ	1.00	40%	Fuel
Pyrolysis	Gasoline	MJ	0.59	23%	Fuel
	Diesel	MJ	0.30	12%	Fuel
	Heavy oil	MJ	0.60	23%	Fuel
	Electricity	MJ	0.09	3%	Fuel
	Jet	MJ	1.00	39%	Fuel

Table 3 outlines the yield ratios of processes in RJF conversion pathways. It is shown that the majority of the pathway have RJF yields of >40%. Problems with displacement methodology emerge when non-fuel products have larger yields than fuel products. It is shown that this is the case with camelina oil extraction, where camelina oil yields are <40%. The camelina oil extraction process is therefore also calculated economic value allocation.

Displacement assumptions

In Table 4 the assumptions that have necessarily been made for the displacement method are given. For the purpose of showing the effect of the displacement method on HEFA (camelina) WTP_r results, the pathway is included in the displacement scenario analysis. The displacement ratios for animal feed are based on the protein contents.

Table 4 Displacement assumptions for co-products

Co product	Camelina meal	Jatropha husks, shells and meal	Sugar beet pulp	DGS	CGM	CGF	Corn oil	Electricity	Diesel	Naphtha	Propane	Gasoline	Heavy oil
Use	Animal feed	Burned for electricity	Animal feed	Animal feed	Animal feed	Animal Feed	Vegetable oil	Exported to net	Fuel	Chemical	Fuel	Fuel	Fuel
Displaced products	Soybean meal	Electricity	Soybean meal	Corn, Soybean meal, Urea	Corn, Urea	Corn, Urea	Soy oil	Electricity	Conv. Diesel	Naphtha for chemical industry	LPG	Conv. Gasoline	Marine fuel
Displacement ratio	75%	100%	16%	78%,31%, 2%	153%,2%	100%, 2%	100%	100%	100%	100%	100%	100%	100%
Protein content co-product	36%		0.079%	31%	67%	22%							
Protein content displaced product	52%		52%	9.4%, 52%	9.4%								
Source	(Cherian, 2012; Feedipedia, 2015c; Shonnard et al., 2010)	(Stratton et al., 2010)	(Edwards et al., 2014; Feedipedia, 2015c; Kelly, 1983)	(Arora, et al., 2008; Feedipedia, 2015c, 2016)	(Feedipedia, 2015b, 2016)	(Feedipedia, 2015a, 2016)	(Arora et al., 2008)	(Xie et al., 2011)	(Stratton et al., 2011)	(Pearlson, 2011; Xie et al., 2011)	(Shonnard et al., 2010)	(Pearlson, 2011)	(American Bureau of Shipping, 1984)

3.1.4 Analysis Procedure and data inputs

The analyses of WTPr GHG emissions for RJF pathways are carried out based on data inputs from public available literature and are given in Table 5. Furthermore, the data assumptions for fertilizer, transport and the fossil reference are discussed.

Table 5 Sources for data inputs and assumptions used in this research

Feedstocks production assumptions (energy use, fertilizer input and emissions)	Source	Technologies (energy use, material inputs and emissions)	Source
Poplar, Willow, Forest residue, corn stover	GREET.net	FT	GREET.net
UCO	Seber et al., 2014	HEFA	GREET.net
Jatropha, camelina	GREET.net	HEFA	GREET.net
Sugar cane	GREET.net	DSHC	Cox et al., 2014; Klein-Marcuschamer et al., 2013
Sugarcane	GREET.net	ATJ	Greet1_2015 excel
Sugar beet	JRC, EUCAR, CONCAWE, 2014	ATJ	Greet1_2015 excel
Forest Residue	GREET.net	HTL, Pyrolysis	Tews et al., 2014

GREET.net

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET.net) framework (version 1.3.0.10631 .net and database 12707) developed by ANL is used to perform calculations in a systematic way. Pathways in the scope of this research that are not available in the GREET.net database are developed in the GREET.net framework based on public available data. The GREET.net model is used both as a database and a calculation platform. Key parameters are identified and default GREET.net values are updated with recent information in literature when available.

Emissions from fertilizer use

Fertilizer induced N₂O emissions due to energy crop productions are included in the GREET.net model (Wang et al., 2007). The fertilizer inputs and the associated soil emissions of default pathways are based on public literature and calculations from ANL. These studies apply different methods to calculate soil emissions. For example, soil emissions associated with camelina are adopted from the Intergovernmental Panel for Climate Change (IPCC) (Shonnard et al., 2010). Emissions associated with jatropha are calculated with IPCC Tier 1 method (Stratton et al., 2010) and poplar, willow, forest residue, corn stover, corn and sugarcane are based on calculations performed by ANL in GREET

excel model (GREET1_2015). The N₂O soil emissions induced by sugar beet farming are adopted from the WTW analysis of JEC, and are based on IPCC Tier 3 (Edwards et al., 2014). Smeets et al. (2009) report large variations of total GHG emissions from biofuel production due to the effects of nitrogen fertilizers. A large range of 10% - 80% is found for the contribution of N₂O emissions in total GHG emissions. Different calculation approaches result in different estimates of N₂O soil emissions due to fertilizer application (Smeets et al., 2009). The emission factors are subject to the large uncertainties associated with these calculation methods (Stratton et al., 2010). While the focus of this work is not to access uncertainty in these calculation methods, the reader should be aware of the existence of this uncertainty and that their impact is larger for pathways where significant amounts of nitrogen fertilizers is used.

Transportation parameters

Several transportation modes are used in GREET.net. The pathways in the scope of this research include heavy-duty trucks, locomotives and barges. The document of Dunn et al., 2013 reports energy intensity and emissions parameter assumptions associated with transportation used in GREET.

The energy intensity for goods transport by rail is based on data reported to the Surface Transportation Board of the United States Department of Transportation (DOT). Emission factors are based on values from EPA. The energy intensity and emissions factors for Heavy-Duty trucks are based on EPA's Motor Vehicle Emission Simulator (MOVES) model. GREET includes a Medium Heavy-Duty Truck and a Heavy Heavy-Duty truck. The energy intensity and emission values for Barge transport is based on research by the Bureau of Transportation statistics and the Department of Energy.

Transportation distances and mode shares are based on the Freight Analysis Framework (FAF) model of the DOT. The payloads and transport parameters can be found in the Greet.

Fossil reference

To the end of calculating GHG emissions savings of biofuel pathways a fossil reference value must be defined. No fossil reference for RJF exists in the RED or the RFS. Therefore, the fossil reference used in this research is based on the default conversion pathway of crude oil to conventional jet fuel in GREET.net. The lifecycle GHG emissions associated with conventional jet fuel production are 82 gCO₂e/MJ Jet fuel. This includes the TTW stage of combustion the fuel in the aircraft.

3.1.5 Hydrogen use in RJF conversion pathways

To the end of showing the impact of hydrogen use on GHG performance of RJF pathways, the influence of different hydrogen production techniques is assessed. The default hydrogen production pathway in GREET.net is hydrogen via steam methane reforming (SMR) of natural gas (Elgowainy et al., 2013). All calculations for this research that include hydrogen inputs use hydrogen production via SMR of natural gas in the base case. To show the impact of hydrogen production processes on GHG performance of RJF pathways two other hydrogen production pathways are assessed for pathways

with hydrogen inputs. These pathways are: hydrogen production via electrolysis using renewable electricity (from wind, solar and biogenic waste), and hydrogen production via the gasification of biomass (switchgrass). The impact assessment of hydrogen production processes is calculated on energy allocation basis. All hydrogen production pathways are available in GREET.net and based on H2A model version 3.0 from National Renewable Energy Laboratory with support from the DOE Fuel Cell Technologies Office (FCTO) (DOE, 2015).

3.1.6 Functional unit and carbon dioxide equivalent

GHG emissions are assessed and reported on the basis of per-unit energy jet fuel produced.

The lifecycle GHG emissions are presented using the unit gCO₂e/MJ product (LHV dry mass). The GHG emissions considered are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) using their 100-year global warming potentials, which are 1, 25 and 298 respectively based on a 100-year time window (Elgowainy et al., 2012). The CO₂ equivalent (CO₂e) for GHG is calculated within the GREET.net framework with the formula presented below.

$$CO_2e = (CO_2 + GWP_{CH_4} \cdot CH_4 + GWP_{N_2O} \cdot N_2O) \quad \text{Equation 1}$$

3.2 HEFA Jet Fuel from renewable oils

Renewable oils from biomass feedstocks can be processed into fuels that have properties similar to conventional jet fuels (Stratton et al., 2010). The processing of renewable oils to RJF involves hydro treatment to deoxygenate the oil with subsequent hydrocracking to create a range of hydrocarbons such as naphtha, jet, and diesel fuels (Elgowainy et al., 2012; Hileman et al., 2009). In this research it is assumed that the biomass feedstocks produce renewable oils with similar properties. Therefore, first the hydroprocessing of renewable oil to produce HEFA RJF is discussed following by a description of the cultivation and oil extraction stages of the separate pathways.

Three non-food competing feedstocks are considered in this research. These are jatropha, camelina and Used Cooking Oil (UCO). Jatropha is a small tree which can grow without irrigation in a wide variety of rainfall regions (Stratton et al., 2010). The jatropha fruit consists of an outer capsule containing two or three seeds. Each seed has a shell and a kernel, which contains oil. Jatropha plants have higher oil yields than many other oil yielding crops. The husk and the seed shells result in co-products, which can be utilized for fertilizers, power generation, animal feed or biogas.

Camelina is an oilseed crop which is well adapted to cultivation in low temperature regions (Shonnard et al., 2010). Camelina is relatively easy to grow as it needs fewer inputs compared to most other oil crops.

Used Cooking Oil (UCO) consists of collected waste cooking oils based on a mixture of vegetable oils (Seber et al., 2014). UCO is first filtered and subsequently rendered to remove water the product of this process is called 'yellow grease'. UCO is particularly interesting as the oil that is primarily produced for cooking can have a second purpose as fuel and, in theory, reduces GHG emissions and can be economically reasonable. Instead of cultivating oil crops UCO can be "recycled" as fuel. Moreover, in the EU, the use of UCO derived fuel is high due to double counting towards the 10% blending target (Chiaramonti et al., 2014).

3.2.1 HEFA process

The HEFA process in GREET.net for production of vegetable oils to RJF is originally based on the study of Stratton et al. (2010) and the UOP hydrodeoxygenation process. (Elgowainy et al., 2012; Huo et al., 2008). The UOP process is currently the most well-developed process for RJF from vegetable oils. The primary product of the UOP process is 'green diesel'. Additional hydro processing is needed for the production of Jet fuel instead of diesel (Stratton et al., 2010). Compared to diesel production this requires extra hydrogen and power inputs. The inputs for the process are given in Table 6.

Table 6 HEFA process inputs and co-products

	Unit	Amount	Source
Renewable oil	MJ/MJ Jet	1.17	REET.net
Natural gas	MJ/MJ Jet	0.18	REET.net
Electricity	MJ/MJ Jet	4.98E-03	REET.net
Gaseous hydrogen	MJ/MJ Jet	0.15	REET.net
<i>Co-products</i>			
Propane fuel mix	MJ/MJ Jet	0.10	REET.net
Naphtha	MJ/MJ Jet	0.14	REET.net

3.2.2 HEFA RJF from jatropha oil

The jatropha pathway input data in REET.net is based on the research of Stratton et al., 2010. Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of jatropha

The inputs required for growth are diesel fuel for tractor and irrigation pump and mineral fertilizers in the form of nitrogen, phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O) (Elgowainy et al., 2012). The inputs are given in Table 7.

Table 7 Cultivation inputs for growth of jatropha

	Unit	Amount	Source
K_2O	g/kg seed	40.24	REET.net
P_2O_5	g/kg seed	13.99	REET.net
N	g/kg seed	36.58	REET.net
Diesel	MJ/kg seed	1.50	REET.net

Transport of jatropha to oil extraction plant

The transport of jatropha oil goes in two phases. The jatropha is transported from the jatropha field to Jatropha stacks with a Medium Heavy-Duty Truck and from the stacks to the oil extraction plant with a Heavy Heavy-Duty Truck. Both Trucks are defined in REET.net. The backhaul travel is accounted for. The distances are given in Table 8.

Table 8 Transport inputs for Jatropha to oil extraction plant

Distance	Unit	Amount	Source
From field to stacks	km	16	GREET.net
From stacks to plant	km	64	GREET.net

Oil extraction from jatropha

The oil extraction process requires heat from natural gas and hexane as oil extraction solvent (Elgowainy et al., 2012). The shells and husks co-products are combusted for electricity and result in an excess output of electricity. See Table 9.

Table 9 Jatropha oil extraction inputs and co-products

	Unit	Amount	Source
Jatropha Seed	g/MJ oil	74.36	GREET.net
Natural gas	MJ/MJ oil	4.9E-02	GREET.net
Hexane	MJ/MJ oil	4.7E-03	GREET.net
<i>Co-product</i>			
Electricity	MJ/MJ oil	0.34	GREET.net

Transport of jatropha oil to renewable jet fuel plant

The transport of jatropha oil to the jet fuel plant is based on default values in GREET.net (Elgowainy et al., 2012). The transport is divided between barge, rail and truck transport. The shares and distances are given in Table 10

Table 10 Transport inputs for jatropha oil to jet fuel plant

	Unit	Share	Amount	Source
Barge	km	40%	837	GREET.net
Rail	km	20%	1127	GREET.net
Heavy Heavy-Duty Truck	km	40%	129	GREET.net

3.2.3 HEFA RJF from camelina oil

The camelina pathway input data in GREET.net is based on the research of Shonnard et al., (2010). Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of camelina

The inputs required for growth are diesel fuel for tractor and irrigation pump and mineral fertilizers in the form of nitrogen, P₂O₅ and K₂O (Elgowainy et al., 2012). The inputs are given in Table 11.

Table 11 Cultivation inputs for growth of camelina

	Unit	Amount	Source
K ₂ O	g/kg seed	11.6	GREET.net
P ₂ O ₅	g/kg seed	17.4	GREET.net
N	g/kg seed	43	GREET.net
Diesel	MJ/kg seed	1.18	GREET.net

Transport of camelina to oil extraction plant

The transport of camelina oil goes in two phases and is the same as the jatropha transport to the oil extraction plant. The camelina is transported from the camelina field to camelina stacks with a Medium Heavy-Duty Truck and from the stacks to the oil extraction plant with a Heavy Heavy-Duty Truck. Both Trucks are defined in GREET.net. The backhaul travel is accounted for. The distances are given in Table 12.

Table 12 Transport inputs for camelina to oil extraction plant

Distance	Unit	Amount	Source
From field to stacks	km	16	GREET.net
From stacks to plant	km	64	GREET.net

Oil extraction from camelina

Input parameters and co-products for camelina oil extraction are given in Table 13. The oil extraction process requires heat from natural gas and hexane as oil extraction solvent (Elgowainy et al., 2012; Shonnard et al., 2010). The co-product of the process is camelina meal. The camelina meal is assumed to be a substitute for soybean meal as an animal feed and is therefore not burned for electricity production (Shonnard et al., 2010).

Table 13 Camelina oil extraction inputs and co products

	Unit	Amount	Source
Camelina Seed	g/MJ oil	74.36	GREET.net
Natural gas	MJ/MJ oil	3.1E-02	GREET.net
Hexane	MJ/MJ oil	2.7E-03	GREET.net
Electricity	MJ/MJ oil	2.3E-03	GREET.net
Diesel	MJ/MJ oil	1.7E-02	GREET.net
<i>Co-product</i>			
Camelina meal	g/MJ oil	47.79	GREET.net

Transport of camelina oil to renewable jet fuel plant

The transport of camelina oil to the jet fuel plant is based on default values in GREET.net (Elgowainy et al., 2012). The transport of camelina oil is divided between rail and truck transport. The shares and distances are given in Table 14.

Table 14 transport of camelina oil to jet fuel plant

	Unit	Share	Amount	Source
Rail	km	33%	1126.54	REET.net
Heavy Heavy-Duty Truck	km	67%	128.75	REET.net

3.2.4 HEFA RJF from used cooking oil

The UCO pathway input data is based on research and reports of Seber et al. (2014), López et al., (2010) and the California Environmental protection Agency (2011). The UCO to RJF was not yet available in the REET.net database and is therefore developed into the REET.net model to perform the WTP calculations. Transportation, electricity, displaced pathways and resource parameters are all default values in REET.net and the result of research conducted at ANL. It is assumed that the rendered UCO (yellow grease) entails similar properties (e.g. heating values) as the renewable vegetable oils from jatropha and camelina (Seber et al., 2014) as it is a bio-derived lipid as well. The HEFA process inputs can therefore be considered the same for UCO as for jatropha and camelina.

Collection and transportation of used cooking oil

The GHG emissions emitted during the collection of UCO from commercial kitchens in the US were assumed negligible (CEPA, 2011; López et al., 2010; Seber et al., 2014). The transport parameters of UCO collection locations to the rendering plant are given in Table 15. The distance between the origin of the UCO and the rendering plant is an average value resulting of a survey from U.S rendering plants (n=19) (López et al., 2010). The properties (e.g. fuel consumption and fuel source) of the heavy-duty trucks from the research survey are similar to the heavy-heavy duty trucks defined in REET.net. The payload of the trucks is an average of the results (n=26) as well and is 16 ton UCO per truck.

Table 15 UCO transport to rendering plant

	Unit	Share	Amount	Source
Heavy-Heavy Duty truck	Km	100%	156	(López et al., 2010)

Rendering of used cooking oil

The rendering process requires heat which is generated with a natural gas industrial boiler. As only water is removed from the UCO the process doesn't have any co-products. The inputs are shown in Table 16.

Table 16 Rendering inputs

	Unit	Amount	Source
UCO	kg/kg yellow grease	1.66	(López et al., 2010)
Natural gas	MJ/kg yellow grease	1.46	(Seber et al., 2014)
Electricity	MJ/kg yellow grease	0.15	(Seber et al., 2014)

Transport of yellow grease to renewable jet fuel plant

The transportation of yellow grease to the RJF plant is based on the study of Seber et al., (2014). The transportation parameters are given in Table 17. The payload of the truck is 24 ton, which is similar to the default payload of trucks in GREET.net transporting camelina and jatropha oil.

Table 17 transport of yellow grease to jet fuel plant

	Unit	Share	Amount	Source
Heavy Heavy-Duty Truck	km	100%	80	GREET.net

3.3 FT Jet fuel from cellulosic biomass

FT jet fuel can be produced from a variety feedstock sources, which include fossil feedstocks and biomass (Elgowainy et al., 2012). In this research only FT Jet Fuel from biomass is assessed. The process involves the production of syngas via gasification of cellulosic biomass, the conversion of syngas and additional hydrocracking to maximize production of jet fuel. Co-products that emerge from the gasification are internally used to produce hydrogen for hydrocracking.

Four types of cellulosic biomass are considered. These are poplar, willow, corn stover and forest residue. Poplars are among the fastest-growing trees and are well suited for the production of biofuels, paper and pulp (Sannigrahi et al., 2010). Due to the relative ease of its genetic manipulation enhanced chemical properties for efficient conversion to biofuels can be created. Poplar grows in a wide variety of regions.

Willow is a tree that has several characteristics that make it an ideal feedstock for biofuel production. These include high yields in few years, the ease of vegetative propagation, a broad genetic base, a short breeding cycle and the ability to resprout after multiple times (Volk et al., 2004).

Corn stover is the residual stalk and leaf material left on the field following corn harvest. Farmers leave stover on the field to reduce top soil loss, and to return carbon and nutrients to the soil (Kendall & Yuan, 2013). Some portion of the corn stover can be removed without any significant effect on soil loss. The loss of nutrients however is increasing demand for fertilizers during the growth season, which is incorporated in the calculations.

Forest residue includes logging residues, removals from the forest as a result of pre-commercial thinning, land clearing, changes in land use and mill residue (Xie et al., 2011) Forest residue requires

no fertilizers and GHG emissions from energy use in collection of forest residue are often very small (Stratton et al., 2010).

3.3.1 Fischer-Tropsch process

The FT pathway used in this research is available in the Greet.net database and is based on Stratton et al., (2010) and Xie et al., (2011). For the biomass to FT RJF a self-sufficient biomass-to-liquid (BTL) plant was assumed (Stratton et al., 2010). Part of the biomass feedstock is therefore used to meet internal process energy needs with excess electricity produced for export. The plant is based on a recycling design. In the recycling design, the unconverted syngas from FT reactors is recycled back into them for additional conversion (Xie et al., 2011). The final off-gas from the reactor is used for electricity production. The process efficiency is an important parameter as it can have a significant effect on the GHG emissions resulting from the process. The input parameters for the FT process are given in Table 18.

Table 18 Inputs and output of Fischer-Tropsch process

	Unit	Amount	Source
Process efficiency	%	46.20	GREET1_2015
Biomass	MJ/MJ Jet	0.46	GREET1_2015
<i>Co-products</i>			
Electricity	MJ/MJ Jet	0.12	GREET1_2015

3.3.2 FT RJF from poplar

The poplar pathway input data is available in GREET.net. Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of poplar

The inputs required for growth of poplar are diesel fuel for the tractor and the irrigation pump and mineral fertilizers in the form of nitrogen, calcium carbonate (CaCO_3), P_2O_5 and K_2O , also herbicides are added. The inputs are given in Table 19.

Table 19 Cultivation inputs for growth of Poplar

	Unit	Amount	Source
CaCO_3	g/kg poplar	2.16	GREET.net
K_2O	g/kg poplar	1.83	GREET.net
P_2O_5	g/kg poplar	0.91	GREET.net
N	g/kg poplar	2.74	GREET.net
Herbicides	g/kg poplar	0.14	GREET.net
Diesel	MJ/kg poplar	0.23	GREET.net

Transport of poplar to FT plant

The poplar is transported from the field to the FT plant with a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The distance is given in Table 20.

Table 20 Transport inputs for poplar to FT plant

Distance	Unit	Amount	Source
From field to plant	km	80	GREET.net

3.3.3 FT RJF from willow

The willow pathway input data is available in GREET.net. Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of willow

The inputs required for growth of willow are diesel fuel for the tractor and the irrigation pump and mineral fertilizers in the form of nitrogen and also herbicides are added. The cultivation process requires very small inputs of electricity and natural gas. The inputs are given in Table 21.

Table 21 Cultivation inputs for growth of willow

	Unit	Amount	Source
N	g/kg willow	2.58	GREET.net
Herbicides	g/kg willow	0.03	GREET.net
Electricity	MJ/kg willow	3.65E-04	GREET.net
Natural gas	MJ/kg willow	4.23E-07	GREET.net
Diesel	MJ/kg willow	0.16	GREET.net

Transport of willow to FT plant

The willow is transported from the field to the FT plant with a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The distance is given in Table 22.

Table 22 Transport inputs for poplar to FT plant

Distance	Unit	Amount	Source
From field to plant	km	80	GREET.net

3.3.4 FT RJF from corn stover

The corn stover pathway input data is available in GREET.net. Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of corn stover

The inputs required for growth of corn stover are diesel fuel for the tractor and the irrigation pump and mineral fertilizers in the form of nitrogen, P₂O₅ and K₂O. The field treatment and drying of corn stover requires High-Density Polyethylene (HDPE) which is taken into account in the calculation. The emissions associated with the production of HDPE are incorporated within the GREET model. The inputs are given in Table 23.

Table 23 Cultivation inputs for growth of corn stover

	Unit	Amount	Source
K ₂ O	g/kg corn stover	13.64	GREET.net
P ₂ O ₅	g/kg corn stover	2.27	GREET.net
N	g/kg corn stover	7.96	GREET.net
Diesel	MJ/kg corn stover	0.24	GREET.net
HDPE	g/kg corn stover	0.34	GREET.net

Transport of corn stover to FT plant

The corn stover is transported from the field to the FT plant with a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The distance is given in Table 24.

Table 24 Transport inputs for corn stover to FT plant

Distance	Unit	Amount	Source
From field to plant	km	153	GREET.net

3.3.5 FT RJF from forest residue

The forest residue pathway input data is available in GREET.net. Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of forest residue

The only input for forest residue is diesel fuel for the tractor that collects the forest residue. The input parameter are given in Table 25.

Table 25 Cultivation inputs for Forest residue

	Unit	Amount	Source
Diesel	MJ/kg forest residue	0.14	GREET.net

Transport of forest residue to FT plant

The forest residue is transported from the field to the FT plant with a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The distance is given in Table 26..

Table 26 Transport inputs for forest residue to FT plant

Distance	Unit	Amount	Source
From forest field to plant	km	144	GREET.net

3.4 DSHC RJF from sugars

Via the DSHC process, sugars can be directly converted to hydrocarbons by the fermentation of sucrose and subsequent refining (Klein-Marcuschamer et al., 2013). In this research only sugarcane as feedstock for the DSHC process is considered. Based on flowsheet models from Klein-Marcuschamer et al. (2013) the process is developed into GREET.net. The flowsheet models are based on the DSHC process developed by Amyris.

Sugarcane plants are primary feedstocks for the production of sugar and ethanol. Sugarcane bagasse can serve as sources of process heat and power generation, which can be internally used (Chum et al., 2011). The sugarcane plant grows in warm temperate to tropical regions.

3.4.1 DSHC process

The DSHC process is a multi-stage process consisting of a fermentation step and a refining step. The main output of the DSHC process that is adopted from Klein-Marcuschamer et al. (2013) is molasses. The study of the scholars involves two separate processes, the sugarcane milling and a fermentation (DSHC) process. In this research assumptions are made in line with default GREET.net pathways. Sugarcane milling is a preparation process in the biomass to fuel conversion. Many of the preparation processes in GREET.net are already included in the total mass and energy balances of the main process (e.g. sugarcane to ethanol). To the end of comparing fuel pathways and show important differences between the pathways several side assumptions such as feedstock preparation are the same along all the pathways considered in the research. Therefore it is assumed that the sugarcane milling is part of the entire DSHC process. In the original study from Klein-Marcuschamer et al. (2013) sugarcane molasses is the main input of the DSHC process. In this research we assumed sugarcane as the main input of the DSHC process. Appropriate calculations are carried out for determining the sugarcane input for the process, considering the percentage of sucrose into sugarcane.

The sugarcane feedstock is assumed to be dedicated for biofuels and therefore all sugars from the sugarcane are converted to hydrocarbons. The bagasse that is a co-product of sugarcane milling is used for power generation of the process and excess electricity is exported. The inputs of the DSHC process are provided in Table 27.

Table 27 Inputs and yields for sugarcane to DSHC RJF

	Unit	Amount	Source
Yeast	g/MJ Jet	1.41E-06	(Klein-Marcuschamer et al., 2013)
Sodium chloride	g/MJ Jet	9.95	(Klein-Marcuschamer et al., 2013)
Sodium hydroxide	g/MJ Jet	0.23	(Klein-Marcuschamer et al., 2013)
Ammonium hydroxide	g/MJ Jet	2.59	(Klein-Marcuschamer et al., 2013)
Diammonium phosphate	g/MJ Jet	0.63	(Klein-Marcuschamer et al., 2013)
Gaseous hydrogen	g/MJ Jet	4.33	(Klein-Marcuschamer et al., 2013)
Glucose	g/MJ Jet	22.49	(Klein-Marcuschamer et al., 2013)
Sulfuric acid	g/MJ Jet	11.70	(Klein-Marcuschamer et al., 2013)
Sugarcane	g/MJ Jet	1.72	(Klein-Marcuschamer et al., 2013)
<i>Co-products</i>			
Electricity	MJ/MJ Jet	0.024	(Klein-Marcuschamer et al., 2013)
Diesel	MJ/MJ Jet	0.15	(Klein-Marcuschamer et al., 2013)
Naphtha	MJ/MJ Jet	0.54	(Klein-Marcuschamer et al., 2013)

3.4.2 DSHC RJF from Sugarcane

The sugarcane production for ethanol pathway is available in GREET.net and is used as input for the DSHC process. Transport, electricity, displaced pathways and resource parameters are all default and the result of research conducted at ANL.

Cultivation of sugarcane

The inputs required for growth of sugarcane in Brazil are diesel and gasoline for the tractor and natural gas for the irrigation pump and mineral fertilizers. Sugarcane straw is burned on the field causing GHG emissions to the atmosphere. The inputs are given in Table 28.

Table 28 Cultivation inputs for sugarcane

	Unit	Amount	Source
K ₂ O	g/kg sugarcane	1	GREET.net
P ₂ O ₅	g/kg sugarcane	0.3	GREET.net
N	g/kg sugarcane	0.8	GREET.net
CaCO ₃	g/kg sugarcane	5.2	GREET.net
Herbicides	g/kg sugarcane	0.045	GREET.net
Insecticides	g/kg sugarcane	0.0025	GREET.net
Sugarcane straw for field burning	kg/kg sugarcane	0.017	GREET.net
Diesel	MJ/ton sugarcane	38.39	GREET.net
Natural Gas	MJ/ton sugarcane	21.55	GREET.net
Liquefied petroleum gas	MJ/ton sugarcane	18.84	GREET.net
Gasoline	MJ/ton sugarcane	12.33	GREET.net
Electricity	MJ/ton sugarcane	9.02	GREET.net

Transport of Sugarcane to DHSC plant

The sugarcane is transported from the field to the DSHC plant using a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The transport parameters are based on the default GREET.net transport of sugarcane to a Brazilian ethanol plant. It is assumed that the distance is the same in the US context. The distance is given in Table 29.

Table 29 Transport inputs for sugarcane to DSHC plant

Distance	Unit	Amount	Source
From field to plant	km	19.31	GREET.net

3.5 ATJ RJF from sugars

The ATJ process involves converting ethanol from sugars to RJF. The process involves a dehydration, oligomerization and hydrotreating (Staples et al., 2014). The data inputs for ATJ are based on the ATJ pathway available in the GREET1_2015 excel model which is based on internal research from ANL. The process that is modelled is industry wide accepted similar to the upgrading process described by Staples et al. (2014). In this research three feedstocks for ethanol are considered: sugarcane, sugar beet and corn.

The cultivation and transport process for sugarcane is the same as described for the DSHC RJF pathway (in section 3.4.2 cultivation of sugarcane). Sugar beet is taken into this research as this can be a potential feedstock for ethanol production in Europe (Edwards et al., 2014). Sugar beet is a high yield crop. It produces carbohydrate already in the form of sugar and is easily crushed and mashed for fermentation. The sugar beet pulp co-product from the fermentation process can both be used as animal feed substitute or to combust them for power generation. The cultivation of corn is based on a default pathway available in GREET.net.

3.5.1 ATJ Process

The ATJ process is an industry wide accepted process of upgrading ethanol to biofuels as diesel and Jet fuel (Staples et al., 2014). The input parameters for the process are given in Table 30. The pathway is developed into GREET.net.

Table 30 Inputs and outputs for ATJ process

	Unit	Amount	Source
Ethanol	MJ/MJ Jet	1.49	REET1_2015
Gaseous hydrogen	g/MJ Jet	0.68	REET1_2015
Catalyst for hydrotreating	g/MJ Jet	0.064	REET1_2015
Catalyst for Oligomerization	g/MJ Jet	0.043	REET1_2015
Electricity	MJ/MJ Jet	0.033	REET1_2015
<i>Co-products</i>			
Diesel	MJ/MJ Jet	0.12	REET1_2015
Naphtha	MJ/MJ Jet	0.21	REET1_2015

3.5.2 ATJ RJF from sugarcane ethanol

The ATJ RJF from sugarcane pathway is based on the same feedstock cultivation pathway as used for the DHSC pathway. The sugarcane to ethanol pathway is available in GREET.net and based on research performed by ANL. Distributed ethanol from sugarcane is the main input for the ATJ process. Three major steps are important in the pathway. First, the cultivation of sugarcane, secondly the fermentation of sugarcane to ethanol, thirdly the upgrading of ethanol to RJF.

Cultivation and transportation of sugarcane

The input parameters for sugarcane cultivation and transportation of the sugarcane are provided in section 3.4.2. Instead of the sugarcane being transported to a DSHC plant the sugarcane is transported to an ethanol plant. The same parameters however apply as it is assumed that ethanol and DSHC plants are both being built nearby the sugarcane fields.

Sugarcane to ethanol conversion

The sugarcane conversion is a process in which sugarcane is fermented to ethanol. Power and heat generated from sugarcane bagasse are used internally. The enzyme and yeast use is not available in GREET.net as the reference study of Wang et al. (2012) did not have data available and assumed that their effect on sugarcane WTP GHG emissions are small, given that their effects on corn ethanol are small. The input data of the process is given in Table 31.

Table 31 Input data sugarcane to ethanol

	Unit	Amount	Source
Sugarcane	g/MJ ethanol	579.89	GREET.net
Sugarcane straw (internal)	g/MJ ethanol	36.01	GREET.net
Sugarcane bagasse (internal)	g/MJ ethanol	89.40	GREET.net
Residual oil	g/MJ ethanol	3.93E-03	GREET.net

Ethanol transport to ATJ plant

The ethanol is transported from the ethanol plant to the ATJ plant with a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The parameters are based on the transport process from an ethanol plant to a distribution point in GREET.net. As the main input for the ATJ plant is assumed to be distributed ethanol this transportation process is deemed appropriate. The distance is given in Table 32.

Table 32 Transport of ethanol to ATJ plant

	Unit	Amount	Source
Heavy Heavy-duty truck	Km	129	GREET.net

3.5.3 ATJ RJF from sugar beet ethanol

The sugar beet to ethanol pathway is based on the Well-To-Wheel study performed by JRC, EUCAR and CONCAWE (Edwards et al., 2014). The distributed ethanol from sugar beet is the main input for the ATJ process. Three major steps are important in the total pathway. First, the cultivation of sugar beet, secondly, the sugar beet is fermented to ethanol, thirdly, the distributed ethanol is upgraded to Jet fuel.

Cultivation of sugar beet

The inputs required for growth of sugar beet are diesel fuel for the tractor and the irrigation pump and mineral fertilizers in the form of nitrogen, P₂O₅, K₂O, CaO, and also herbicides are added. The inputs are given in Table 33.

Table 33 Cultivation inputs for growth of sugar beet

	Unit	Amount	Source
N	g/kg sugar beet	6.92	(Edwards et al., 2014)
P ₂ O ₅	g/kg sugar beet	3.47	(Edwards et al., 2014)
K ₂ O	g/kg sugar beet	7.84	(Edwards et al., 2014)
CaO	g/kg sugar beet	23.24	(Edwards et al., 2014)
Herbicides	g/kg sugar beet	0.08	(Edwards et al., 2014)
Diesel	MJ/kg sugar beet	0.37	(Edwards et al., 2014)

Transport of sugar beet to ethanol plant

Sugar beet is transported from the field to an ethanol plant by a heavy-heavy duty truck that has similar properties as the truck that is defined in GREET.net. Therefore the same characteristics for the heavy heavy-duty truck are used. The distance of transportation is given in Table 34.

Table 34 Transport of sugar beet to ethanol plant

	Unit	Amount	Source
Heavy Heavy-duty truck	Km	30	(Edwards et al., 2014)

Sugar beet to ethanol conversion

The sugar beet conversion is a process in which sugar beet is fermented to ethanol. The enzyme and yeast use is not available in the data from Edwards et al. (2014). Therefore similar assumptions as for the sugarcane to ethanol conversion process are made. Natural gas is needed as input for steam production. The co-product sugar beet pulp is assumed to be used as animal feed. The input data of the process is given in Table 35.

Table 35 Input data sugar beet to ethanol

	Unit	Amount	Source
Sugar beet	g/MJ ethanol	112.88	(Edwards et al., 2014)
Electricity	MJ/MJ ethanol	0.04	(Edwards et al., 2014)
Natural gas	MJ/MJ ethanol	0.12	(Edwards et al., 2014)
<i>Co-product</i>			
Sugar beet pulp	kg/MJ ethanol	0.028	(Edwards et al., 2014)

Ethanol transport to ATJ plant

The ethanol is transported from the ethanol plant to the ATJ plant with a Heavy Heavy-Duty Truck. The backhaul travel is accounted for. The parameters are based on the transport process from an ethanol plant to a distribution point in GREET.net. As the main input for the ATJ plant is assumed to be distributed ethanol this transportation process is deemed appropriate. This is the same assumption as made for the ATJ (sugarcane). The distance is given in Table 36.

Table 36 Transport of ethanol to ATJ plant

	Unit	Amount	Source
Heavy Heavy-duty truck	Km	129	GREET.net

3.5.4 ATJ RJF from corn ethanol

The corn to ethanol pathway is based on the pathway that is available in GREET.net. Distributed ethanol is considered as the feedstock for ATJ RJF from sugarcane. Three major steps are important in the total pathway. First, the cultivation of corn, secondly the fermentation of corn to ethanol, thirdly the distributed ethanol is upgraded to Jet fuel. Three different fermentation processes exist in the U.S. All three processes are used to produce fuel ethanol.

Cultivation of corn

The inputs required for growth of corn are diesel fuel and gasoline for the tractor and the irrigation pump, LPG and Natural gas for heating, mineral fertilizers in the form of nitrogen, P₂O₅, K₂O, CaCO₂, and also herbicides and insecticides are added. The inputs are given in Table 37.

Table 37 Cultivation inputs for growth of sugar beet

	Unit	Amount	Source
N	g/kg Corn	15.86	GREET.net
P ₂ O ₅	g/kg Corn	5.46	GREET.net
K ₂ O	g/kg Corn	5.67	GREET.net
CaCO ₂	g/kg Corn	43.07	GREET.net
Herbicides	g/kg Corn	0.28	GREET.net
Insecticides	g/kg Corn	2.36E-03	GREET.net
Diesel	MJ/kg Corn	0.19	GREET.net
Liquefied Petroleum Gas	MJ/kg Corn	0.07	GREET.net
Gasoline	MJ/kg Corn	0.06	GREET.net
Natural gas	MJ/kg Corn	0.05	GREET.net
Electricity	MJ/kg Corn	0.02	GREET.net

Transport of corn to ethanol plant

Corn is transported from the field to corn stacks by means of a heavy-heavy duty truck. From the stacks to the ethanol plant the corn is transported by a medium-heavy duty truck. The distances of transportation are given in Table 38.

Table 38 Transport of corn to ethanol plant

	Unit	Amount	Source
From corn field to Stacks with Heavy Heavy-duty truck	Km	64	GREET.net
From stacks to ethanol plant with medium heavy-duty truck	Km	16	GREET.net

Corn to ethanol conversion

The sugar beet conversion is a process in which sugar beet is fermented to ethanol. Three different fermentation processes are used in the U.S. These processes include dry mill ethanol production without corn oil extraction, dry mill ethanol production with corn oil extraction, and wet mill ethanol production, which respectively produce 18.23%, 72.91% and 8.87% of the total produced ethanol. The input data of the processes is given in Table 39.

Table 39 Input data corn to ethanol

	Unit	Amount			Source
		1	2	3	
Corn	g/MJ ethanol	107.58	106.73	115.12	GREET.net
Alpha Amylase	g/MJ ethanol	0.03	0.03	0.03	GREET.net
Glucosyl Amylase	g/MJ ethanol	0.07	0.07	0.07	GREET.net
Yeast	g/MJ ethanol	0.03	0.03	0.04	GREET.net
Sulfuric Acid	g/MJ ethanol	0.22	0.22	0.23	GREET.net
Ammonia	g/MJ ethanol	0.22	0.22	0.23	GREET.net
Sodium hydroxide	g/MJ ethanol	0.27	0.27	0.29	GREET.net
Calcium oxide	g/MJ ethanol	0.13	0.35	0.14	GREET.net
Natural Gas	MJ/MJ ethanol	0.29	0.29	0.45	GREET.net
Electricity	MJ/MJ ethanol	0.03	0.034		GREET.net
Coal	MJ/MJ ethanol	2.00E-03	0.03	0.17	GREET.net
<i>Co-product</i>					
DGS	g/MJ ethanol	31.74	30.36	-	GREET.net
Corn oil	MJ/MJ ethanol	-	0.04	0.21	GREET.net
CGM	g/MJ ethanol	-	-	6.87	GREET.net
CGF	g/MJ ethanol	-	-	29.74	GREET.net

(1) Dry mill ethanol production w/o corn oil extraction, (2) Dry mill ethanol production w/ corn oil extraction, (3) wet mill ethanol production

Ethanol transport to ATJ plant

The ethanol is transported from the ethanol plant to the ATJ plant by a heavy heavy-duty truck. The backhaul travel is accounted for. The distances are given in Table 40.

Table 40 Transport of ethanol to ATJ plant

		Unit	Amount	Source
From ethanol plant to RJF plant	Heavy Heavy-duty truck	Km	129	GREET.net

3.6 HTL and Pyrolysis from forest residue

The HTL and Pyrolysis from forest residue pathways are based on data from research from Pacific Northwest National Laboratory on Biomass direct liquefaction options (Tews et al., 2014). The pyrolysis and HTL processes have similar characteristics and are therefore discussed in the same section. The data from Tews et al. (2014) is based on plants with in-situ production. In this research, however, most of the pathways are assumed to have ex-situ hydrogen production. To show the effect of both in-situ and ex-situ hydrogen production and comparison reasons, this is included in the assessment.

3.6.1 Forest residue feedstock cultivation and transport

The forest residue feedstock and transport inputs for the HTL and Pyrolysis processes are adopted from the GREET.net model and are the same inputs that are used as input for the FT RJF from forest residue pathway that is discussed in section 3.3.5.

3.6.2 HTL process

The HTL process is a process that is defined by five major steps: feedstock pre-treatment, HTL, hydrotreating, internal hydrogen production and wastewater treatment (Tews et al., 2014). In this research the individual processes at the HTL plant are considered as one big process from which the inputs and outputs are used in the process that is developed in the GREET.net model.

HTL in-situ hydrogen production

In this process, off-gases from the HTL process and the anaerobic digestion of wastewater are used as input for the on-site hydrogen production plant (Tews et al., 2014). Hydrogen is used in the hydrotreating process. Fuel gas from the hydrogen production plant is used internally for heating the HTL process.

The process described in the research of Tews et al (2014) is focused on diesel as main output and reports a hydrocarbon yield of 27% (6.35/23.15 kg/s). The HTL process and hydrocarbon yields by Tews et al. 2014 are compared with research from Utrecht University and TU Delft by Tzanetis et al. (forthcoming) on RJF from biomass via liquefaction. The latter reports hydrocarbon yields including jet fuel yields. Therefore the mass allocation factors of Tzanetis et al. (forthcoming) are used to calculate the jet fuel and co-product yield as if the process of Tews et al. (2014) were to produce Jet fuel instead of diesel as main output. Using a renewable diesel production process as a proxy for jet fuel processes is a common practice because the lack of publically available data for jet fuel production pathways (e.g. studies using proxy's: Elgowainy et al., 2012; Forman & Unnasch, 2015). Moreover, jet

or diesel fuels have similar characteristics and production processes. Input parameters for the process are given in Table 41.

Table 41 Inputs for HTL with in-situ hydrogen production

	Unit	Amount	Source
Forest residue	g/MJ RJF	206.65	(Tews et al., 2014)
Electricity	MJ/MJ RJF	0.21	(Tews et al., 2014)
Diesel	MJ/MJ RJF	3.1E-03	(Tews et al., 2014)
<i>Co-product</i>			
Gasoline	MJ/MJ RJF	0.59	(Tews et al., 2014; Tzanetis et al., forthcoming.)
Diesel	MJ/MJ RJF	0.30	(Tews et al., 2014; Tzanetis et al., forthcoming.)
Heavy oil	MJ/MJ RJF	0.60	(Tews et al., 2014; Tzanetis et al., forthcoming.)

HTL ex-situ hydrogen production

Due to a lack of data for the ex-situ hydrogen production scenario several configuration assumptions had to be made. Based on the available data the in-situ hydrogen plant is extracted from the mass and energy balances (Tews et al., 2014). The absence of power demand of the hydrogen plant is taken into account and off-gases from the conversion process anaerobic digestion of water are used to generate electricity and heat which are internally used. Excess electricity is exported. The electricity yield from off gasses is based on energy balance and efficiency of the gas turbine. The hydrogen input for the hydrotreating process is replaced by external hydrogen production via SMR of natural gas. The new Input parameters are given in Table 42.

Table 42 Inputs for HTL with ex-situ hydrogen production

	Unit	Amount	Source
Forest residue	g/MJ RJF	206.65	(Tews et al., 2014)
Gaseous hydrogen	g/MJ RJF	2.68	(Tews et al., 2014)
Electricity	MJ/MJ RJF	0.053	(Tews et al., 2014)
Diesel	MJ/MJ RJF	3.1E-03	(Tews et al., 2014)
<i>Co-product</i>			
Gasoline	MJ/MJ RJF	0.59	(Tews et al., 2014; Tzanetis et al., forthcoming)
Diesel	MJ/MJ RJF	0.30	(Tews et al., 2014; Tzanetis et al., forthcoming)
Heavy oil	MJ/MJ RJF	0.60	(Tews et al., 2014; Tzanetis et al., forthcoming)

3.6.3 Pyrolysis process

The pyrolysis process includes pre-treatment of feedstock, fast pyrolysis and upgrading into hydrocarbon fuels. The char is internally used for heat which is generated in a char fired boiler (Tews et al., 2014).

In this research the individual processes at the pyrolysis plant are considered as one big process from which the inputs and outputs are used in the process that is developed in the GREET.net model.

Pyrolysis in-situ hydrogen production

In this process off-gases from the pyrolysis process and the upgrading process are used as input for the on-site hydrogen production plant (Tews et al., 2014). Hydrogen is used in the upgrading process. Fuel gas from the hydrogen production plant is used internally for heating the pyrolysis process. Similar assumptions are made for the jet fuel yields in the HTL process as in section 6.2.1. The differences in yields between the pyrolysis plant and HTL plant are taken into account. The hydrocarbon yield for the pyrolysis process is 24% (5.6/23.15 kg/s) of hydrocarbon liquids. Input parameters for the process are given in Table 43.

Table 43 Inputs for pyrolysis with in-situ hydrogen production

	Unit	Amount	Source
Forest residue	g/MJ RJF	234.33	(Tews et al., 2014)
Electricity	MJ/MJ RJF	0.27	(Tews et al., 2014)
Diesel	MJ/MJ RJF	3.52E-03	(Tews et al., 2014)
<i>Co-product</i>			
Gasoline	MJ/MJ RJF	0.59	(Tews et al., 2014; Tzanetis et al., forthcoming.)
Diesel	MJ/MJ RJF	0.30	(Tews et al., 2014; Tzanetis et al., forthcoming.)
Heavy oil	MJ/MJ RJF	0.60	(Tews et al., 2014; Tzanetis et al., forthcoming.)

Pyrolysis ex-situ hydrogen production

The same assumptions as for the HTL process are made regarding the pyrolysis process with ex-situ production. Input parameters are given in Table 44.

Table 44 Inputs for pyrolysis with ex-situ hydrogen production

	Unit	Amount	Source
Forest residue	g/MJ RJF	234.33	(Tews et al., 2014)
Gaseous hydrogen	g/MJ RJF	8.10	(Tews et al., 2014)
Diesel	MJ/MJ RJF	3.52E-03	(Tews et al., 2014)
<i>Co-product</i>			
Gasoline	MJ/MJ RJF	0.59	(Tews et al., 2014; Tzanetis et al., n.d.)
Diesel	MJ/MJ RJF	0.30	(Tews et al., 2014; Tzanetis et al., n.d.)
Heavy oil	MJ/MJ RJF	0.60	(Tews et al., 2014; Tzanetis et al., n.d.)
Electricity	MJ/MJ RJ	0.09	(Tews et al., 2014)

4 Results

In this section the results of the WTP_r calculations from the GREET.net model are given for both the energy allocation method and the displacement method. The base case results, the sensitivity analysis and the influence of different hydrogen production processes are described.

4.1 GHG performance of RJF conversion pathways

Base case results are calculated with different co-product treatment methods. The corresponding WTP_r results for both methods are given in Table 45 and shown in Figure 4. Figure 4 is a representation of the distribution of GHG emissions along all stages of the different pathways and the savings under regulations. The tables give the GHG emission results per stage, the total WTP_r GHG emission results, and the savings compared to the fossil fuel comparator. Total GHG savings range between 32% and 91% when GHG emissions are allocated to the products based on energy content. Saving results calculated with the displacement method range between -9% and 114% (excluding HEFA (Camelina)). The total WTP_r GHG emissions are represented by the blue bars in the displacement graph and by the total of the stacked bars in the energy allocation graph.

The ATJ (Corn) pathway shows the highest WTP_r GHG emissions in both methodological approaches. 55 g CO₂e/MJ RJF with the energy allocation method and 89 gCO₂e/MJ RJF with the displacement method. Overall, the FT conversion pathways show the best GHG performance in both approaches. WTP_r GHG emissions range from 8 - 11 g CO₂e/MJ RJF with energy allocation and -4 - -11 g CO₂e/MJ RJF with displacement depending on the type of feedstock.

The relatively good performance of FT conversion pathways can mainly be explained by the lack of pre-conversion processes and the self-sustaining FT conversion process. Due to the fact that the FT plant in this research uses part of the biomass input for internal heat, hydrogen and electricity for the process, the emissions are very low (0.1 g CO₂e/MJ RJF).

HEFA (Camelina, Jatropha) and ATJ conversion processes show relatively large GHG emissions associated with the feedstock cultivation stage 21 - 29 g CO₂ / MJ RJF and 15 - 20 g CO₂ /MJ RJF respectively with energy allocation. With displacement the feedstock cultivation processes show relatively high emissions as well. The high emissions associated with jatropha and camelina can be explained by the larger input of fertilizers and the related N₂O emissions: 37 g/kg jatropha seed and 43 g/kg camelina seed compared to the average nitrogen input for feedstocks in this scope of 14 g/kg feedstock. Also, extraction yields for vegetable oil are relatively low. Furthermore, the extra pre-conversion processes result in more required feedstock per MJ RJF output compared to the other conversion pathways.

The ex-situ hydrogen production via SMR of natural gas in some of the conversion pathways result in significant GHG emissions. DSHC and Pyrolysis processes have relatively large GHG emissions associated with hydrogen due to their large hydrogen demand of respectively 4.33 and 8.10 g/MJ RJF compared to 0.68 g/MJ RJF for ATJ and 0.15 g/MJ RJF for HEFA.

Table 45 WTPr GHG emissions (in g CO₂e/MJ RJF) for RJF conversion pathways calculated with energy allocation method and displacement method.

Energy allocation method								
	Feedstock cultivation	Pre-Conversion	Transport to RJF plant	Conversion to RJF	Hydrogen	Co-product credit	Total GHG emissions	GHG performance (savings)
HEFA (UCO)	1	3	1	11	11		27	67%
HEFA (Camelina)	21	3	0.5	11	11		46	44%
HEFA (Jatropha)	29	3	1	11	11		54	34%
FT (Willow)	7			0.1			8	91%
FT (Poplar)	8			0.1			8	90%
FT (Corn Stover)	11			0.1			11	86%
FT (Forest residue)	5			0.1			5	94%
DSHC (Sugar cane)	8			19	28		55	32%
ATJ (Sugar cane)	15	4	1	3	7		29	64%
ATJ (Sugar beet)	20	6	1	3	7		37	55%
ATJ (Corn)	19	24	1	3	7		55	33%
HTL (Forest Residue in-situ H ₂)	4			13			17	79%
HTL (Forest Residue ex-situ H ₂)	4			3	12		20	76%
Pyrolysis (Forest Residue in-situ H ₂)	5			18			23	72%
Pyrolysis (Forest Residue ex-situ H ₂)	5			0.2	35		40	51%
Displacement method								
HEFA (UCO)	2	4	1	13	14	-4	29	65%
HEFA (Camelina)	43	5	1	13	14	-114	-39	148%
HEFA (Jatropha)	47	4	1	13	14	-60	20	76%
FT (Willow)	8.4			0.1		-17	-9	110%
FT (Poplar)	9.0			0.1		-17	-8	110%
FT (Corn Stover)	13			0.1		-17	-4	105%
FT (Forest residue)	6			0.1		-17	-11	114%
DSHC (Sugar cane)	14			33	48	-15	80	3%
ATJ (Sugar cane)	20	5	1	5	8	-5	34	58%
ATJ (Sugar beet)	36	11	1	5	8	-23	38	53%
ATJ (Corn)	33	65	2	5	8	-24	89	-9%
HTL (Forest Residue in-situ H ₂)	11			32		-27	15	81%
HTL (Forest Residue ex-situ H ₂)	11			8	30	-27	21	74%
Pyrolysis (Forest Residue in-situ H ₂)	12			52		-27	26	68%
Pyrolysis (Forest Residue ex-situ H ₂)	12			0.5	90	-40	63	23%

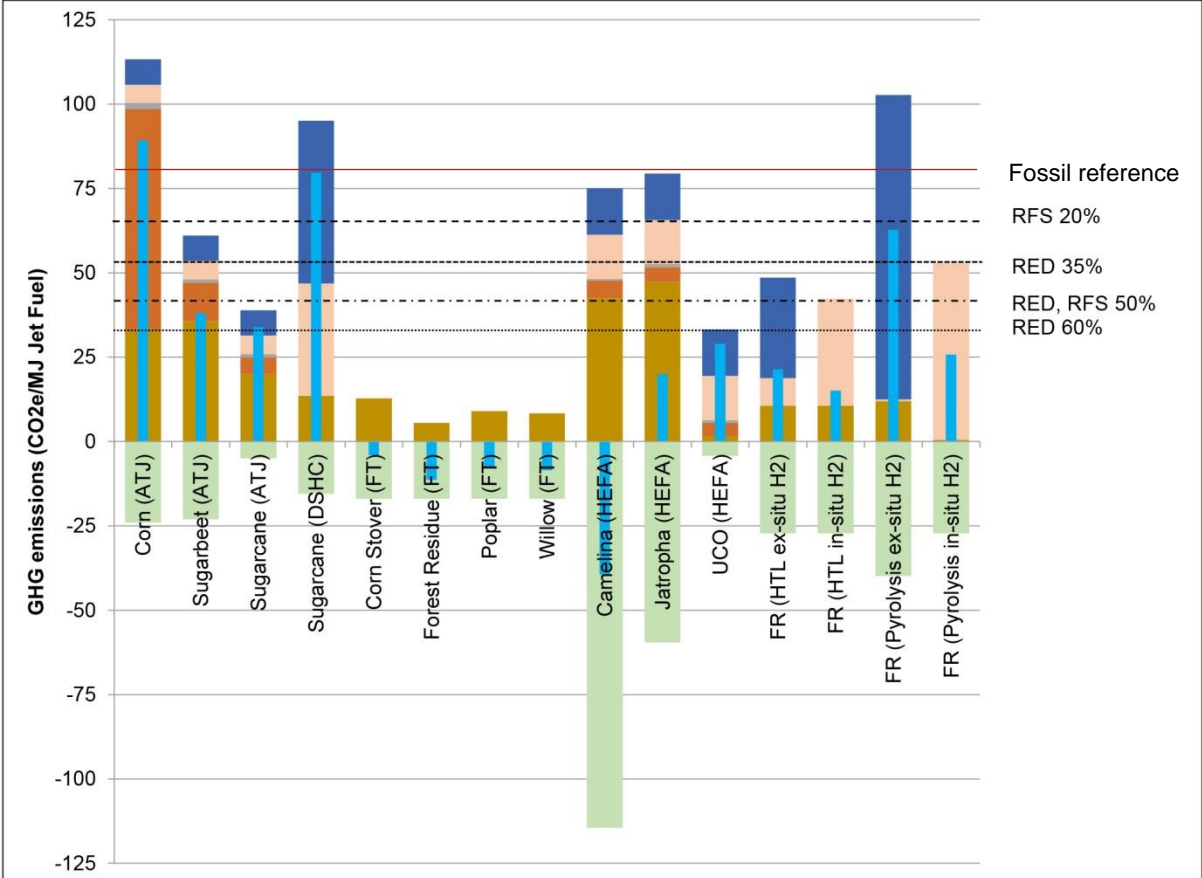
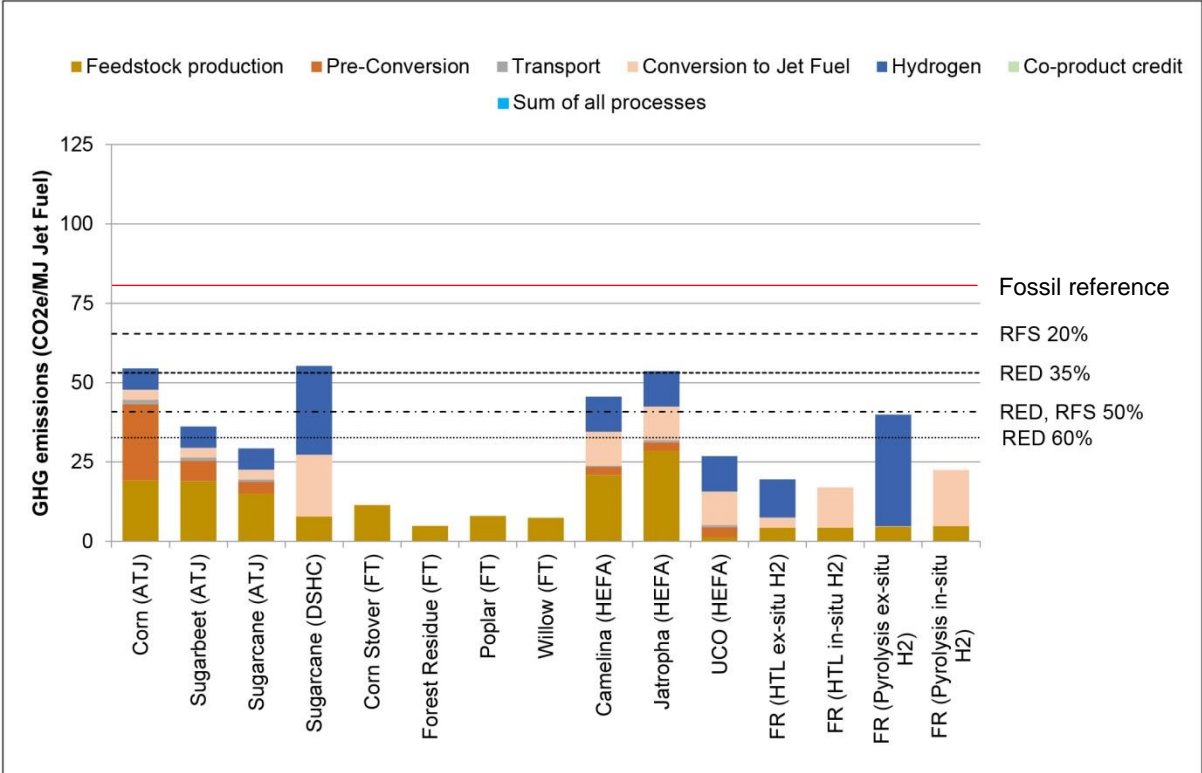


FIGURE 4 GHG EMISSIONS FOR RJJ PATHWAYS CALCULATED WITH ENERGY ALLOCATION (UPPER GRAPH) AND DISPLACEMENT METHOD (LOWER GRAPH).

4.2 Influence of co-product treatment approaches

In Figure 4 it is shown that, compared to the savings calculated with energy allocation, some pathways have considerable larger saving when calculated with the displacement method. This is the case with HEFA (Jatropha), HEFA (camelina), all FT conversion pathways and HTL (in-situ). It is argued, that the calculation of HEFA (camelina) would give distorted results as the oil extraction yields are very low compared to the yields of the co-product (camelina meal). This distortion is confirmed in the results and shown in figure 4, as the displacement method gives extremely large GHG savings due to large co-product credits. Figure 5 shows the impact of different co-product handling methods on the results of HEFA (camelina). Besides the displacement and energy allocation method, the pathway is calculated with a hybrid method as well. The main difference between the three results is that the displacement method gives large co-product credits for the production of camelina meal, while the hybrid and the energy allocation approach allocate the larger part of the emissions to the camelina oil due to its higher energy content and higher market value.

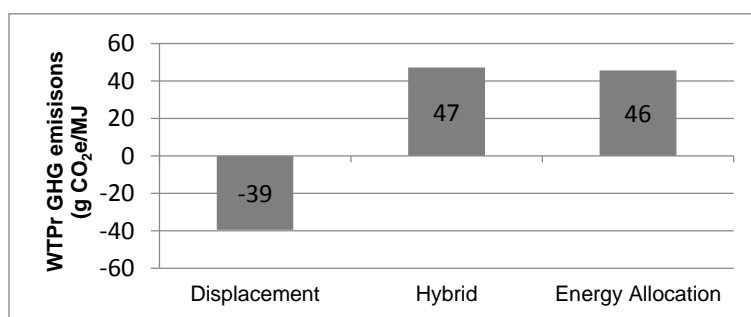


FIGURE 5 IMPACT OF CO-PRODUCT HANDLING METHOD ON HEFA (CAMELINA)

Other pathways show considerable higher emissions, and therefore less savings, when calculated with the displacement method. In the displacement method all emissions are allocated to the main output of a process and credits are given for the co-products. In the case of higher emissions, the gained credits do not off-set the extra emissions that are allocated to the main product.

4.3 Evaluating RJF pathways against reference and regulations

As shown in Figure 4 and Table 45, the WTPr GHG emissions and the related savings compared to the fossil fuel reference differ with the applied allocation or displacement methods. In the figure the saving thresholds for biofuels in order to comply with the regulations are drawn. Four lines are drawn, which correspond to different saving thresholds. The red line gives the lifecycle emissions of the conversion of conventional jet fuel. The line "RFS 20%" corresponds to the 20% saving threshold for renewable fuels under the RFS. The line "RED 35%" corresponds to the 35% saving threshold for biofuel under the RED effectual until December 31th 2016. The line "RED, RFS 50%" corresponds to 50% saving threshold for advanced biofuel and biomass based-diesel under the RFS and for biofuel under the RED effectual from January 1st 2017. This is for this research the most relevant line as some pathways are still in a testing phase and they have to meet future thresholds and nearly all of the pathways have to qualify for 'advanced biofuels' under the RFS. The final line "RED 60%"

corresponds to 60% saving threshold which will be effectual under the RED from January 1st 2018. It is important to re-state that the RED requires GHG emissions associated with biofuel conversion pathway to be calculated with energy allocation and RFS focusses on the displacement method. In order to show the influence of the two methods on results and biofuel pathway endorsement under the regulations these lines are drawn in both graphs. Pathways that do not qualify under the RED 50% are:

- ATJ (Corn): 33% savings
- DSHC (Sugar cane): 32% savings
- HEFA (Camelina): 44% savings
- HEFA (Jatropha): 34% savings

Except for ATJ (Sugar beet) and Pyrolysis (ex-situ) all other pathways will qualify under the future 60% GHG emission threshold.

Several pathways do not qualify under the 50% savings threshold of the RFS. These are:

- ATJ (Corn): -9% savings
- DSHC (Sugar cane): 3% savings
- Pyrolysis (FR ex-situ H₂): 28% savings

HEFA (Jatropha) and HEFA (Camelina) conversion pathways would comply with the RFS savings threshold due to the awarded co-product credits.

4.4 Sensitivity Analysis

A sensitivity analysis is performed to determine the impact of the hydrogen input, fertilizer input and RJF yields on final results. Hydrogen is reported to have large influence on both environmental and techno-economic performance of RJF pathways (de Jong et al., 2015; Han et al., 2013). Fertilizer use cause potentially large GHG emission due to especially N₂O emissions from nitrogen fertilizers (Stratton et al., 2010). RJF yield sensitivity is taken into account as yields can be reported more positive by biofuel producers and likely RJF yields will increase in the future due to process improvements. A single-point sensitivity analysis is conducted for all individual parameters in a base, an optimistic and a pessimistic scenario. Also, a simultaneous analysis of all pessimistic or optimistic values is done.

Yield range for HEFA pathways are based on the study of Stratton et al. (2010). All the other ranges for RJF yields are based on upper and lower values reported in a study of de Jong et al. (2015). Due to the absence of multiple references for ATJ RJF and DSHC RJF a yield of $\pm 5\%$ for ATJ is used by the scholars. The theoretical yield. 50% of the theoretical yield is used for DSHC (de Jong et al., 2015). Based on the same research of de Jong et al. (2015), hydrogen input is varied between -25% and +50%. Different ranges for fertilizer use can be found in public literature, however there is no consensus on this subject. Based on a discussion with experts from ANL a $\pm 20\%$ for fertilizer inputs is chosen. The ranges are given in Table 46. The sensitivity analysis is carried out on basis of the energy allocation method as this method produces more reliable results and is less subject to the influence of assumptions and uncertainty.

Table 46 Parameter ranges for sensitivity analyses

Parameter	Pessimistic	Optimistic	Source
FT yield	76%	129%	(de Jong et al., 2015)
HEFA yield	98%	102%	(Stratton et al., 2010)
DSHC yield	83%	167%	(de Jong et al., 2015)
ATJ yield	95%	105%	(de Jong et al., 2015)
Pyrolysis yield	71%	161%	(de Jong et al., 2015)
HTL yield	71%	142%	(de Jong et al., 2015)
Fertilizer	120%	80%	-
Hydrogen	150%	75%	(de Jong et al., 2015)

4.4.1 Results of sensitivity analysis

Figure 6 shows the result of the sensitivity analysis. It is shown that the conversion pathways are particularly sensitive to variations in yields and hydrogen inputs. Only HEFA processes do not show large uncertainty caused by yields, which can be explained by the relatively small variation that is considered for HEFA yields ($\pm 2\%$). The impact of yield and hydrogen input is very prominent in the DSHC and the Pyrolysis (ex-situ hydrogen) processes. In all pathways that include external hydrogen inputs, hydrogen is produced via steam methane reforming, which causes considerable GHG emissions. The variation in nitrogen input has the most impact on GHG emissions of all fertilizers.

This is mainly due to the N₂O emissions associated with nitrogen fertilizer inputs. Other fertilizers have shown very small impacts and are therefore not presented in this figure.

Using pessimistic assumptions, HTL can have higher GHG emissions than pyrolysis. DSHC can have middle-range GHG emissions in an optimistic scenario, but can also give the highest GHG emissions of all pathways in a pessimistic scenario, due to large hydrogen inputs. Overall, FT, HTL and Pyrolysis (in-situ H₂) pathways are still among the pathways with the best GHG performance. ATJ (sugarcane and sugarbeet) show similar variations and cover middle-range GHG emissions together with HEFA (UCO). The highest ranges of emissions are found for HEFA (Jatropha and Camelina), DSHC (sugarcane), ATJ (corn) and Pyrolysis (external Hydrogen).

4.5 Influence of hydrogen production pathways.

Figure 7 shows the sensitivity of WTP_r GHG emissions to different hydrogen production processes. The sensitivity to hydrogen input parameter variation is represented by error bars. The default hydrogen production by SMR from natural gas is represented by the black coloured bars. The orange coloured bars represent the hydrogen production from biomass gasification and the green bars represent hydrogen production from electrolysis with renewable electricity. The total WTP_r emissions of the pathways are given by the striped bars.

The analysis shows that GHG emissions associated with hydrogen production from biomass gasification are about 50% of the GHG emissions associated with the default production process. GHG emissions emerge from the production of biomass, in the gasification process from energy inputs and the transportation and compressing processes. When hydrogen is produced via electrolysis from renewable electricity, the GHG emissions associated with hydrogen are very small in relative terms. GHG emissions in this process emerge from the use of US mix electricity in the compressing stages.

It is noteworthy that the uncertainty of results increases when parameter input values are relatively large. This concerns especially the Pyrolysis and DSHC pathways, but also to a lesser extent for HEFA pathways.

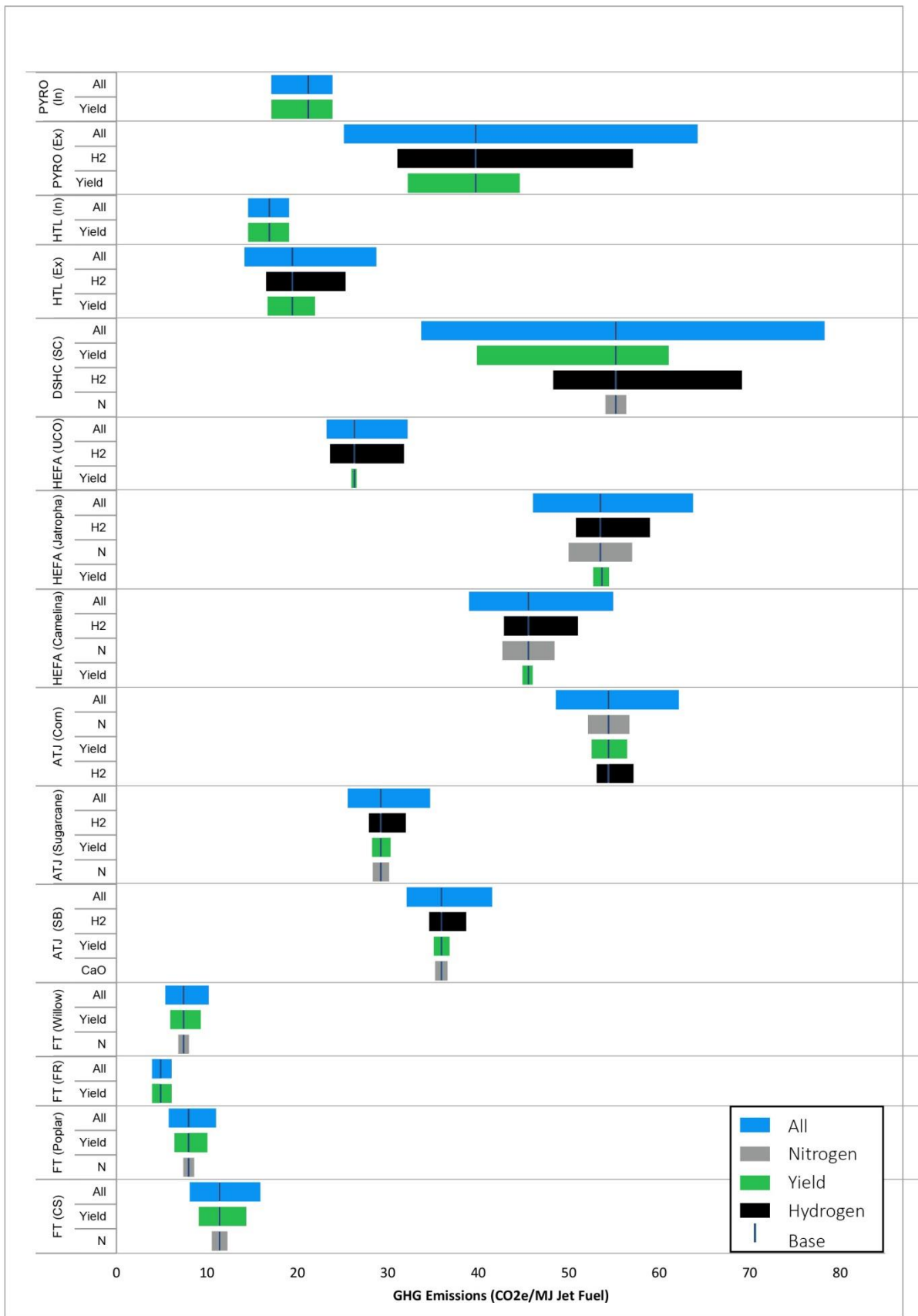


FIGURE 6 SENSITIVITY ANALYSIS

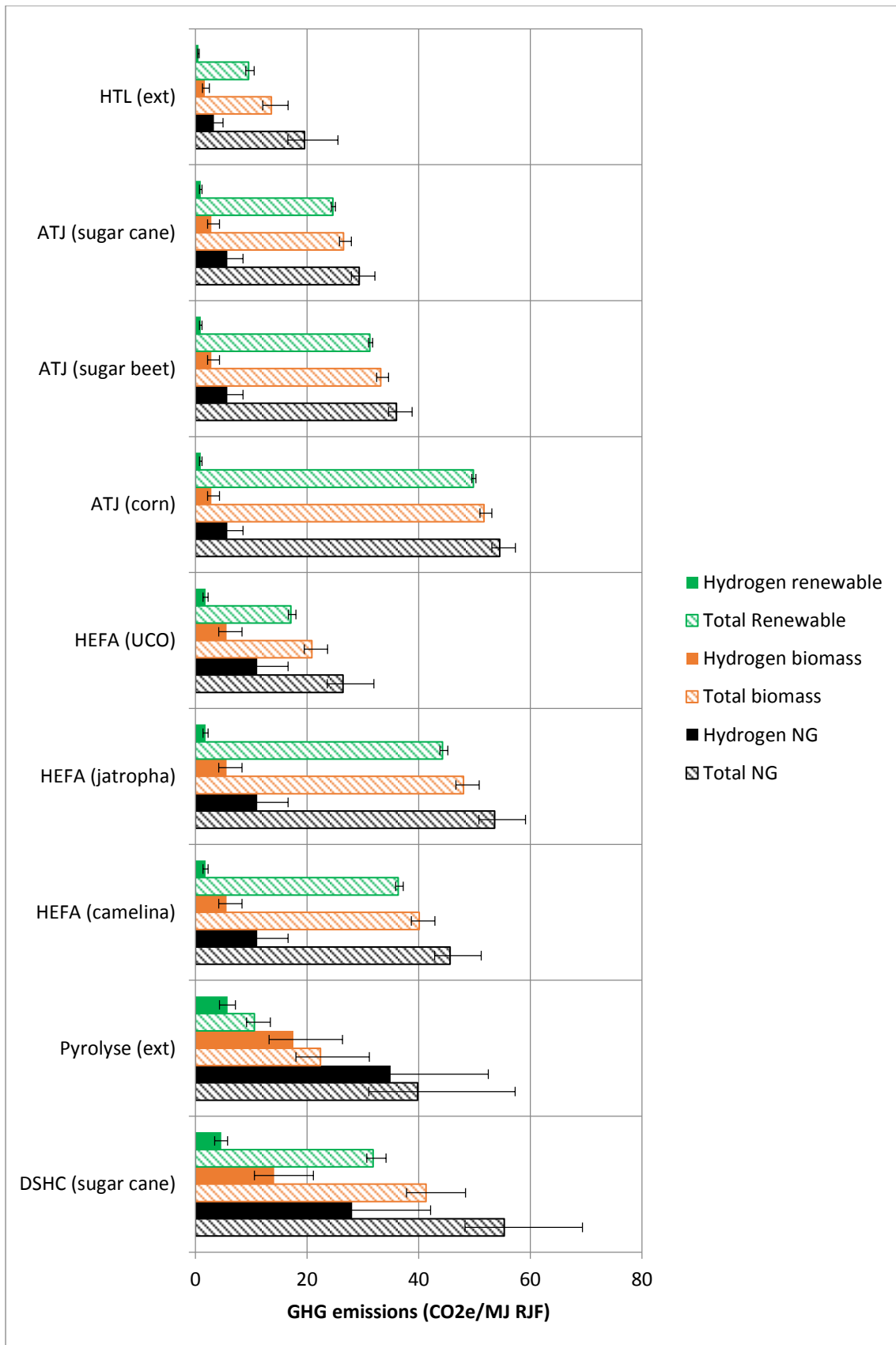


FIGURE 7 SENSITIVITY OF WTPR EMISSIONS TO DIFFERENT HYDROGEN PRODUCTION PROCESSES. TOTAL WTPR GHG EMISSIONS WITH DIFFERENT HYDROGEN PRODUCTION TECHNOLOGIES ARE REPRESENTED IN THE STRIPED BARS.

5 Discussion

The use of bio based fuels in aviation provides opportunities to reduce lifecycle GHG emissions, fuel costs and dependence on fossil fuels. In recent years research towards bio based or renewable jet fuels has increased¹. Research in this area is expanding as international aviation organizations have pin-pointed RJF as solution for reducing GHG emissions and more RJF fuel products have been certified in recent years (ASTM, 2016). The results in this research are based on most recent developments in the research area. This section covers data input quality and assumptions, methodological choices, applicability of results and a small comparison of results with other studies.

5.1 Data input quality

There are numerous pathways developed to produce drop-in bio based fuels for aviation. One can consider different feedstocks, pretreatment technologies, conversion technologies and transport options. Choices need to be made regarding the configuration of these pathways. These choices can be made based on the region where the fuel is used, techno-economical aspects of the fuel pathway, environmental impacts and many more aspects. Several pathways are only theoretically developed or a result of lab scale experiments (Mawhood et al., 2015). Results from these studies are often hard to compare due to poor documentation of choices in research or different applied methodologies.

Since, RJF production is just in an early stage (Mawhood et al., 2015) not much process data is publically available to calculate GHG emissions associated with RJF production. Data that is available is often coming from a single source. HEFA and FT pathways are widely documented, while other pathways are just documented a few times. This naturally imposes limitations on the generalizability and comparability of results and uncertainty increases. This uncertainty is shown in the sensitivity analysis where large ranges for parameters resulted in large differences in the final results and GHG emissions associated with the different parameters. This research is however, to the best of our knowledge, the first research that compares GHG emissions from relevant RJF conversion pathways and promising feedstocks, based on coherent assumptions and co-product treatment methods. Due to this coherent approach, of varying only essentially different parameters between the conversion pathways and keeping other parameters (e.g. electricity mix, transport emissions) the same, uncertainty in the comparison is limited.

Much difference exists in the way data is documented among literature and also in the GREET.net database. For example, FT processes in GREET.net and the reference study from (Stratton et al., 2010) are considered a 'black-box' in which hydrogen, heat and electricity is produced for internal use, while the energy balances and mass balances for DSHC, HTL and pyrolysis are well documented and values for internal products and processes are available. It should be noted that FT processes in general are widely documented and that one can assume that the processes in

¹ Based on a document count in Scopus on April 28th, 2016. Combined result of search terms: biofuel AND aviation, renewable fuel AND aviation. 2004-2008: 4, 2010: 4, 2011: 9, 2012: 1, 2013: 15, 2014: 7, 2015:15. Total: 59.

REET.net are representative. This same practice is however seen in many studies and therefore limitations to a detailed comparability of processes exist.

The pathways for pyrolysis and HTL are based on production pathways for fuels in automotive vehicles. As jet fuel requires further upgrading than diesel it can be expected that extra power and hydrogen inputs are required (Elgowainy et al., 2012). It is however assumed that the extra generated GHG emissions are minimal and therefore no extra inputs are incorporated in the pathways. This assumption is consistent with other studies in the RJF research area where biodiesel production pathways are used as proxy for bio based jet fuel (Elgowainy et al., 2012).

Due to a lack of data for ex-situ hydrogen production scenarios for HTL and Pyrolysis, several configuration assumptions had to be made. Based on the available data from Tews et al. (2014), the in-situ hydrogen plant is extracted from the process. This can be considered as a theoretical exercise and one could question if this theoretical process is practically feasible. However, given the lack of data, these assumptions and the following calculations give an opportunity to include pyrolysis and HTL with ex-situ hydrogen production in the comparison.

5.2 Practical applicability and limitations

All default processes (e.g. feedstock/electricity/hydrogen production, transport, and conversion) are developed in REET.net in the U.S. context. The conversion pathways considered in this research are therefore analyzed in a U.S. context as well. One can argue that mass and energy balances of conversion processes are independent of their regional context. It, however, varies per world region, which feedstocks are available, what the electricity mix is, how displaced products are produced, which types of transportation processes are used, how fertilizers and other inputs are produced etc. Therefore, one should be careful by translating pathways in their current configurations in this research to other world regions than the US. A theoretical pathway is developed based on sugar beet ethanol, which cultivation data inputs are adopted from an EU context, the transport vehicle and electricity assumptions, however, are all default REET.net assumptions. The pathway can therefore only be considered as a theoretical exercise to show the influence of different feedstocks for ATJ processes.

The geographical context also influences the applicability of the results under the RED and RFS. This mainly has to do with LUC effects. As LUC effects depend on the types of land the feedstock is cultivated and the type of land for cultivation of the product that is displaced. The RED and RFS apply only for fuels that are consumed in respectively the EU or the US. This means that fuels that are produced in the US must qualify under the RED when used in the EU. Under the RFS the EPA undertakes the GHG calculations, which are based on typical values. This means that results from this research can be different than results from EPA fuel pathways due to difference in data assumptions and data availability.

LUC effects attributable to biomass cultivation can significantly dominate the GHG performance of biofuels as is demonstrated by Staples et al. (2014). The tools and methods for calculation of DLUC

and ILUC are still heavily debated (Edwards et al., 2014) and are therefore not considered in this research.

Both the RED and the RFS require GHG emissions associated to storage and distribution to be included in the lifecycle GHG emissions. This research doesn't include the storage and distribution stage and does not include LUC effects as these depend very much on the location of feedstock cultivation and the RJF end users. To include LUC and transport and distribution would compromise the generalizability and comparability of this research' comparison. Moreover ILUC effects can only be assessed in a consequential LCA.

A full lifecycle environmental impact assessment would require other environmental impact categories to be included as well. This research focus on the performance of conversion pathways based on the global warming potential of GHG emissions within a 100-year time frame. Energy use in the conversion pathways is included in the pathways to calculate GHG emissions. The energy use is however not assessed and therefore no conclusions can be drawn for energy use of the pathways. Other categories to assess the environmental impact of conversion pathways include acidification, eutrophication-, photochemical ozone creation-, human toxicity-, abiotic depletion -potentials and the effect of particulate matter (Chum et al., 2011). Other impacts of biofuel production concern water consumption (ICAO, 2010) and albedo changes due to LUC (Caiazza et al., 2014). A lot of these parameters are very location specific and therefore difficult to include in a general comparison,

5.3 Methodological assumptions

The underlying calculation algorithms of the GREET.net model are based on LCA methodology principles. The LCA methodology is widely accepted among academics, companies and policy makers as calculation methodology for environmental impact of production processes. Due to its complexity and wide variety of methodological choices, the results of LCA are often different even for apparently the same pathways.

In recent years, the terms WTW and WTWa are increasingly used to define the boundaries of biofuel production systems for respectively road and aviation transport. This research is focused on the WTPr GHG emissions of RJF production as storage and distribution stages are not included. The TTTW stage is especially relevant in road transport context as there is a lot of difference in GHG performance of vehicles (Edwards et al., 2014). Less difference in GHG performance of aircrafts exists in aviation context. There are, however, other emissions that effect air quality or global climate change that can be considered such as particulate matter, volatile organic compounds, sulfur oxides, nitrogen oxide, carbon monoxide, black carbon and water vapor (Elgowainy et al., 2012).

In literature, a lot of discussion exists on the subject of allocation methodologies. The difference in applied methodologies is at the root of challenges regarding the comparability of lifecycle environmental impact results. The displacement methodology is often argued to be the preferred method for co-product treatment as it tends to give a realistic presentation of what happens with co-products from industrial processes.(ISO, 2006b; Michael Wang et al., 2011). This is also the reason why pathways in the RFS require to be calculated with this methodology. Problems arise when one

has to make assumptions for displaced products and ratios. These decisions are often very case-dependent and market-sensitive. LUC effects further increase the complexity of this methodology. For this reason, a lot of allocations are based on physical relations between multiple process outputs. The energy allocation methodology is not always suitable for non-fuel products. Therefore, a hybrid approach between multiple non-fuel and fuel products is proposed increasingly. In this approach non-fuel products are allocated based on market-values and fuel-products based on energy allocation. This research included the market value allocation for non-fuel products of HEFA (camelina). The market values are however subject to economic disturbances and results are therefore only valid until a next economic disturbance occurs. Due to multiple analyses with different co-product treatment methodologies this research gives insight in the effect of co-product methodology on GHG performance of RJF fuels and conclusions can be drawn in different regulatory contexts.

Due to a lack of a fossil comparator in the regulations, the fossil fuel comparator in this research is based on the crude oil to conventional jet fuel pathway in GREET.net. The achieved savings depend on the comparator and are therefore subject to change as no official value is defined. However, the data in GREET.net for the conventional jet fuel pathway is assumed reliable and the official (to be defined) comparator is expected not to differ much as it is already similar to diesel and gasoline lifecycle GHG emissions.

5.4 Results

Various factors influence the WTP_r results. The most influential parameters (hydrogen, yield and fertilizers inputs) are taken into account in a sensitivity analysis. Other factors that can influence the results are differences into documented heating values, transport losses, transport efficiencies, conversion conditions etc. The differences caused by these parameters are however reported to be very small, which is also seen in this research.

It is difficult to make a good comparison of this study's results to results from other LCA studies on GHG emissions of RJF conversion pathways as not all studies include the same methodological choices and assumptions. A simple comparison with existing research only based on similar co-product treatment methods is shown in Table 47. It should be noted that the difference in displacement assumptions between the researches are not assessed and the comparison with other research only serves to show if results are reliable and plausible. It is shown that FT and HEFA (jatropha) and HEFA (camelina) pathways in Han et al. (2013) results are similar compared to this study. This similarity is the result of the fact that the pathways in Han et al. are calculated with the GREET.net model and same data assumptions as well. Difference can exist in the fact that this study does not include the TTW stage and the study of Han et al. 2013 does. Furthermore, the DSHC pathway shows similar results when calculated with displacement. The ATJ (sugarcane) GHG emissions are the most deviated from other research, which is caused by the difference in awarded credits between Seber et al. (2014) and this study. The difference in results with HTL and Pyrolysis can be the result of difference in calculation methods and methodological assumptions. The main differences come from the GHG emissions from the pre-processing step. The remaining pathways

show similar results that lie in the uncertainty range of this research. The comparison with other studies shows that the results of this study are in a plausible range.

Table 47 Comparison of this study's result with lifecycle GHG emissions reported by other studies

Author [ref]	Technology	Feedstock	Methodology remarks	Co-product treatment	Emissions reported in g CO ₂ e /MJ RJF	Emissions calculated in this research gCO ₂ e/ MJ
(Cox et al., 2014)	DSHC	Sugar cane		Displacement	80	80
(Han et al., 2013)	FT	Corn stover	Results vary with different production efficiencies and electricity shares in output	Energy allocation	~ 8 - 11	11
				Displacement	~ -22 - 11	-4
(Han et al., 2013)	HEFA	Jatropha		Energy allocation	~ 55	54
(Bailis & Baka, 2010)	HEFA	Jatropha	Values for displacement vary with different scenarios	Energy allocation	40	54
				Displacement	-134 – 63	-60
(Han et al., 2013)	HEFA	Camelina		Energy allocation	~ 46	46
(Shonnard et al., 2010)	HEFA	Camelina	Results vary with different fertilizer calculation methods	Energy Allocation	18.04 – 26.99	46
(Seber et al., 2014)	HEFA	UCO		Energy allocation	19.4	27
(Staples et al., 2014)	ATJ (Advanced Fermentation)	Sugar cane		Displacement	-4.9	39
(Staples et al., 2014)	ATJ (Advanced Fermentation)	Corn grain		Displacement	50.1 - 117.4	89
(Tews et al., 2014)	Pyrolysis Diesel (in-situ)	Forest Residue		Energy Allocation	34.0	23
(Tews et al., 2014)	HTL Diesel (in-situ)	Forest Residue		Energy Allocation	27.3	17

Depending on the pathways and process outputs the results show differences between the co-product treatment approaches. The displacement approach shows large difference in GHG performance compared to the energy allocation approach when co-product amounts of non-fuel products are relatively large. Energy allocation with non-fuel products is based on energy values from a nutritional context and can differentiate from values based on heat of combustion (Wang et al., 2011). A better method for allocation is based on economic value of the output products. HEFA (camelina) is calculated with a hybrid economic/energy value allocation approach as well, which gives a more realistic GHG performance compared to other literature. The results from the economic allocation and energy allocation with HEFA (camelina) are shown to be very similar.

The sensitivity of GHG emissions to the yield is relatively large and can significantly influence the merit order and therefore the qualification of a pathway under the regulatory regimes. It is likely that with future technology improvements yields will be larger, which results in better GHG performance of conversion pathways. Also in many pathways hydrogen inputs are larger than theoretically necessary. This implicates that improvements can be made in hydrogen production.

6 Conclusion

The aviation industry has embraced the production and use of RJF combined with the deployment of GMBM as one of the solutions to bring down GHG emissions from aviation. An increasing amount of research is done on the subject of RJF as there is a need to know environmental performance of RJF pathways. The goal of this study was to compare GHG performance of different RJF conversion pathways. To this end a Well-to-Product assessment has been conducted on the GHG performance of different RJF conversion pathways. The GHG performances are calculated in a coherent way in the GREET.net model, so that the impacts of key differences between the pathways emerge. Included in the assessment are different co-product treatment procedures, different feedstocks, different conversion processes and different hydrogen production technologies. The qualification of GHG performance of pathways under the RED and RFS regulations is assessed.

The highest GHG performance was found for FT conversion pathways, of which FT (forest residue) has the highest performance (5 (energy allocation) / -11 (Displacement) g CO₂ /MJ RJF). The conversion pathways with the lowest GHG performance are found to be DSHC from sugarcane (55 / 80 g CO₂ / MJ RJF) and ATJ from corn (55 / 89 g CO₂ / MJ RJF). Depending on the combination of feedstocks and conversion processes, GHG performances of HEFA pathways differ between 27 - 54 g CO₂ /MJ RJF (energy allocation) or -39 - 29 g CO₂ /MJ RJF (displacement), for ATJ pathways from sugar beet or sugar cane between 29 - 37 g CO₂ /MJ RJF (energy allocation) or 34 - 38 g CO₂ /MJ RJF (displacement), for HTL pathways between 17 – 20 g CO₂ /MJ RJF (energy allocation) or 15 – 21 g CO₂ /MJ RJF (displacement), and for Pyrolysis 23 – 40 g CO₂ /MJ RJF (energy allocation) or 26 – 63 g CO₂ /MJ RJF (displacement).

Considerable difference is found in generated GHG performance results due to the impact of different co-product treatment methods. The displacement approach gives the most extreme GHG performance results for pathways with large non-fuel co-product outputs. The outputs of HEFA (camelina) are besides the energy allocation and displacement methods also allocated based on economic value of output products. The displacement method gave distorted results, while the allocation methods showed good agreement with each other, generating similar results.

Key processes that influence the GHG performance of pathways are the feedstock cultivation, pre-conversion (such as oil extraction from oil crops) and main conversion processes. Lignocellulosic feedstocks tend to have lower GHG emissions associated with their cultivation due to smaller fertilizer inputs compared to oil and sugar crops. Production processes with low production yields of RJF need relatively larger feedstock inputs and therefore increase GHG emissions associated with feedstock cultivation. The performance of conversion pathways with ex-situ hydrogen inputs increases with lower hydrogen inputs or with less GHG emission intensive hydrogen production processes.

As the results are calculated within the geographical context of the US, there are certain limitations to comparing this study's results to the same conversion pathways in an EU context or that of another world region. Difference will exist in fertilizers input, feedstock availability, transport parameters and

GHG emissions associated with electricity production or material inputs. The most important parameters hydrogen, yield and fertilizer show different variations among the pathways and it can be expected that when pathways are considered in different geographical contexts that results will be in the uncertainty range of this study as difference in fertilizer input is assessed in the sensitivity analysis and production yields and required hydrogen inputs are not location specific. Other parameters are of less influence and can be expected to have little variety between locations.

This research, however, gives insight in distribution of GHG emissions among the different production stages in the different pathways and the GHG performance of a series of proven and potential conversion pathways. Pyrolysis and HTL processes are both still in an experimental phase, but the results for HTL and Pyrolysis are promising.

This study reconfirms the difference in results caused by different co-product treatment approaches. The RED and RFS both require different approaches and therefore there is a difference in the pathways that qualify under the two standards. The savings of conversion pathways compared to the fossil reference depend on the lifecycle GHG emissions of the fossil fuel production, which can be calculated according different methods as well. The displacement method can generate distorted results, which gives difficulties to assess the qualification of a pathway under the regulations.

The results of this study show that a clear ranking of conversion pathways can only be made for pathways that are based on coherent data inputs and the same co-product treatment method. As the aviation sector operates on a global scale, it is important to establish a globally accepted standard for qualifying conversion pathways. Moreover, assessing GHG performance within a coherent approach that excludes uncertainties do to different co-product assumptions is essential for the deployment of GBMB and the success of RJF in aviation.

In context of the current debate on RJF sustainability and GHG performance assessment strategies, there is a need to improve insight in energy and material balances of promising conversion processes as data availability is still scarce. This study shows that a wide variety can be found in GHG performance for RJF pathways. It is therefore important that research is directed towards the assessment of GHG performance from individual pathways calculated within a framework of globally accepted standardized assumptions. Before GMBM can be deployed, the impact of geographical context on GHG performance needs to be assessed. As hydrogen consumption in processes imposes large GHG emissions, research can be conducted on the GHG performance and techno-economic feasibility of hydrogen production pathways.

7 References

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Appendix A: energy and economic values

Resource	LHV value	Source
Camelina meal	13,4 MJ/kg dry	GREET.net
Camelina oil	37,2 MJ/kg dry	GREET.net
Jatropha oil	37,2 MJ/kg dry	GREET.net
Used Cooking Oil	37,2 MJ/kg dry	CEPA, 2011
RJF	33,4 MJ/L	GREET.net
Naphtha	31,1 MJ/L	GREET.net
Propane	48,0 MJ/L	GREET.net
Biodiesel	33,3 MJ/L	GREET.net
Ethanol	29.7 kj/g	GREET.net
Sugar beet pulp	12,5 MJ/kg dry	Kelly, 1983
DGS	21,4 MJ/kg dry	Feedipedia
CGM	21,4 MJ/kg dry	Feedipedia
CGF	18,8 MJ/kg dry	Feedipedia

Resource	Market value (\$/lb. dry)	Source
Camelina meal	0.018	GREET.net
Camelina oil	0.384	GREET.net