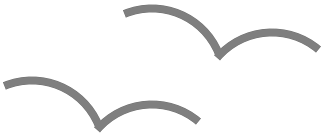

Plant + Boom = Boat + Vroom

A comparative technoeconomic and environmental assessment of marine biofuel production in Brazil and Scandinavia using residual lignocellulosic biomass and thermochemical conversion technologies.

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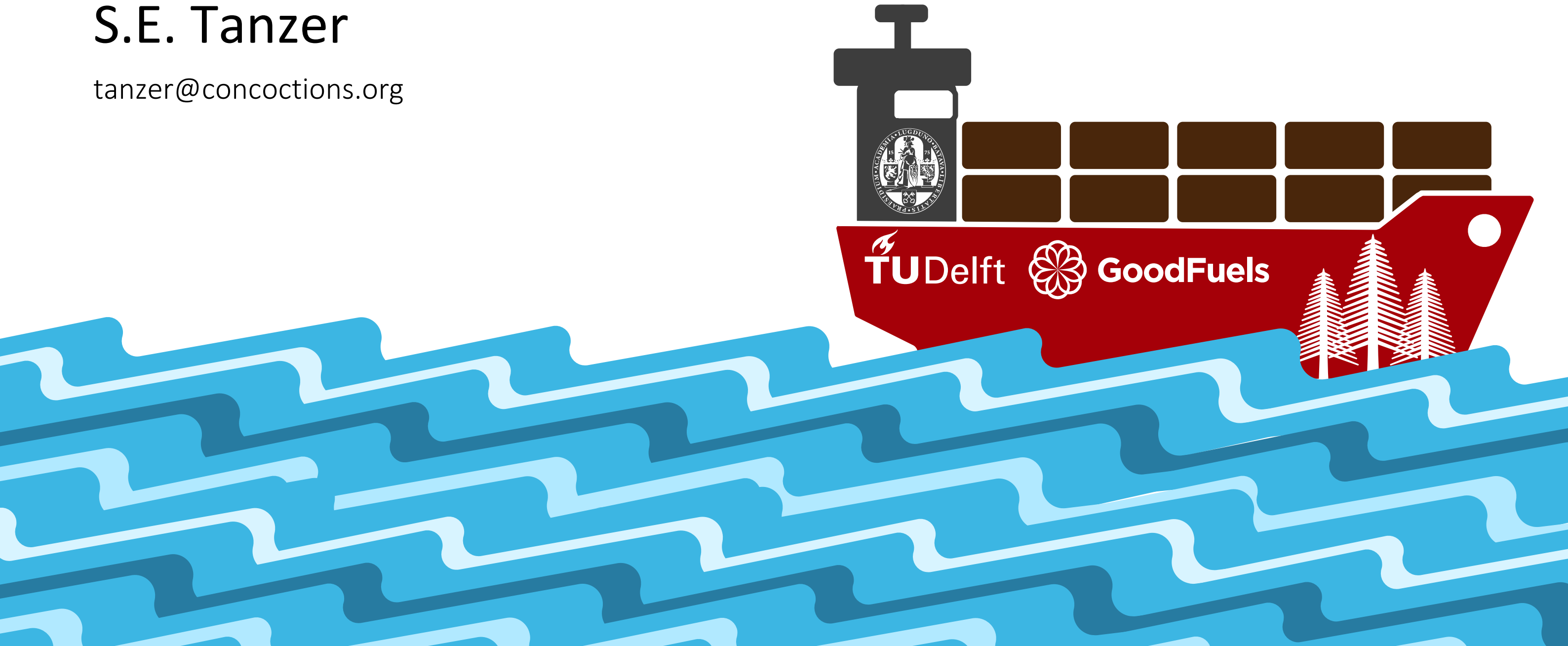

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A comparative technoeconomic and environmental assessment of marine biofuel production in Brazil and Scandinavia using residual lignocellulosic biomass and thermochemical conversion technologies.

By

S.E. Tanzer

in partial fulfilment of the requirements for the degree of

Master of Science
in Industrial Ecology

at the Delft University of Technology and Leiden University,
and was defended publicly on Thursday July 18, 2017 at 2:00 PM.

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This thesis was slightly modified from the original version with permission of the supervisors.

The data model used in this thesis is available at **http://concoctions.org/biofuel/**
An electronic version of this thesis is available at **http://repository.tudelft.nl/**

Preface

Twelve years ago, I wrote a painfully earnest college application essay about what I thought was the center of my academic career, and possibly my life, at the time: not the search for the right answers, but the search for the right questions. A bad question may have an easy answer, but that answer takes us nowhere. A good question may have no answer, but will lead to other good questions, some of which will have good answers. Twelve years ago, my most important question was: *What university will best help me develop the skills necessary to ask good questions?*

Eight years ago, I never thought I would stop asking questions, but I also thought that I would never go back to school. At the time, my most important question was: *What can I learn from this job as a software project manager?*

Three years ago, my most important question was: *How can I use what I've learned in this job to contribute more to society?*

Two and a half years ago, my most important question was: *Will you marry me?*

Two years ago, I started the Industrial Ecology master's program to confront the large and difficult question of: *What can modern human society realistically do to tread more lightly on the planet that we're already rapidly damaging?* It's a good question, and one that I am grateful that I have spent the past two years living with it and asking many smaller questions that it engendered.

Five months ago, I began this thesis with the question: *What is the estimated economic and environmental performance of marine biofuels made from lignocellulosic feedstocks via thermochemical conversion technologies in the context of biofuel supply chains in Brazil and Scandinavia?* Along the way, I found some answers and many more questions. Today, I am near the end of that thesis, near the end of my master's, and near the start of a PhD.

For the next four years, I will live with the question of: *Is possible for large industries to be carbon negative through the use of bioenergy and carbon capture and sequestration?* I will continue to live with the question that I started my master's with, for which I am deeply grateful. I expect to get no closer to an answer, but hopefully along the way I will find some good small questions with good small answers, and some even larger questions to live with for the years to come after that.

July 11, 2017

TABLE OF CONTENTS

Abstract

This thesis compares the performance of hypothetical biorefineries in Brazil and Scandinavia that produce biofuel for use in large marine vessels using one of three thermochemical technologies—hydrothermal liquefaction (HTL), fast pyrolysis with hydrodeoxygenation (FP), and gasification with Fischer-Tropsch synthesis (GFT)—and one of ten lignocellulosic residues from forestry and agriculture. The biorefineries were modeled using black-box mass balances for biofuel production and electricity and heat cogeneration. The results of this model, along with local costs factors, were used to estimate the economic performance of biorefineries in each country where each feedstock is available. Estimates of capital expenses, operating expenses, and annual earnings were used to calculate the minimum selling price of the biofuel, which is used as an indicator of economic performance. The environmental performance of each combination was estimated using the indicators of life cycle greenhouse gas emissions, sulfur dioxide emissions, nitrogen oxide emissions, and non-renewable energy use. The economic and environmental indicators for each feedstock-technology-country combination are compared to each other and also compared to reference values for other marine emission-reducing technologies, including liquid natural gas, emission scrubbers, and soy biodiesel. The results are subject to sensitivity analysis to determine the influence of uncertainty of capital costs, feedstock costs, biorefinery scale, biorefinery siting, biorefinery configuration, biofuel yields, biofuel blending, and environmental impact allocation.

The biofuels modeled in this study have significantly lower life cycle greenhouse gas and sulfur dioxide emissions and non-renewable energy use than those of heavy fuel oil, but have higher life cycle nitrogen oxide emissions, due to the lower quality of the fuel produced and combusted. Economically, none of the biofuels are competitive with current fossil fuel prices when estimated with the scale and cost factors in this study. The feedstock-technology-country combinations with the lowest minimum biofuel selling price, when considered as a ratio to the current local price of marine gas oil, are the hydrothermal liquefaction of barley straw in Sweden, and the fast pyrolysis of corn stover and rice residues in Brazil. Each of those combinations has a minimum biofuel selling price ratio of 3.2 times that of marine gas oil. Performance trends between technologies and feedstocks are weak, and superior economic performance does not correlate with superior environmental performance.

Acknowledgements

I would like to thank my supervisors Dr. John Posada Duque, Dr. Andrea Ramirez-Ramirez, and Mr. Sjors Geraedts for their support and insight throughout this thesis project, as well as their consistently prompt and thorough feedback on my progress. I am also grateful to B Daniel Roth Fairchild, who was a sounding board for many problems and ideas, and who read my draft reports and provided many helpful comments and edits. Finally, I would like to thank my parents, Bruce Tanzer and Ana Gabriela Anaya, and my husband, Tai Zen Sassen-Liang, for making sure that I remembered to eat occasionally.

Abbreviations

A – I	
BR	Brazil
C	degrees Celsius
C_2 - C_4	light hydrocarbons (C_2H_n -> C_4H_n)
CapEx	Capital Expenses
CEPCI	Chemical Engineering Plant Construction Index
CO_2-eq	Carbon dioxide equivalent
DE	Denmark
EEA	European Environmental Agency
ECA	Emission Control Area
ECN	Energy Research Centre Of The Netherlands
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FAME	Fatty Acid Methyl Ester
FCI	Fixed Capital Investment
FERC	Federal Energy Regulatory Commission
FI	Finland
FP	Fast Pyrolysis
GDP	Gross Domestic Product
GFT	Gasification with Fischer-Tropsch synthesis
GHG	Greenhouse Gasses (CO_2, CH_4, N_2O)
GJ	Gigajoule (10^9 joules)
GWP	Global Warming Potential
GWP_{bio}	Global Warming Potential of Biogenic emissions
HDO	Hydrodeoxygenation
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
HIP	Horizontal International Project
HT	Hydrotreatment
HTL	Hydrothermal Liquefaction
ICS	International Chamber Of Shipping
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
IRR	Internal Rate Of Return

K – Z	
K	degrees Kelvin
kg	Kilogram
kJ	Kilojoule
kWh	kilowatt hour
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LNG	Liquid Natural Gas
LSHFO	Low Sulfur Heavy Fuel Oil
M USD	Million US Dollars
MEA	Monoethanolamine
MFSP	Minimum Fuel Selling Price
MGO	Marine Gas Oil
MJ	Megajoule (10^6 Joules)
MWh	Megawatt Hour
NECA	Nitrogen Emission Control Areas
NO	Norway
NPV	Net Present Value
NREL	National Renewable Energy Laboratory (USA)
NREU	Non Renewable Energy Use
OpEx	Operating Expenses
PJ	Petajoule (10^{15} joules)
PNNL	Pacific Northwest National Laboratory (USA)
RFO	Residual Fuel Oil
RPM	Revolution Per Minute
SE	Sweden
SECA	Sulfur Emission Control Area
t	metric tonnes (1000 kg)
TCI	Total Capital Investment
TEA	Technoeconomic Assessment
TPEC	Total Purchased Equipment Costs
ULS	Ultra Low Sulfur
USD	US Dollars

1 Introduction

Over 80% of global trade travels by ship (UNCTAD 2015). Every year, seafaring vessels consume 300 million tonnes of low-quality diesels and heavy fuel oils (INSEE 2012). These “bunker fuels” have high concentrations of sulfur and nitrogen (Vermeire 2012), which are released into the atmosphere when combusted. Maritime trade is responsible for 2-4% of global emissions of carbon dioxide, 4-9% of sulfur dioxide, and 10-13% of nitrogen oxide (Smith et al. 2014).

Until recently, conversations on reducing maritime trade’s environmental impacts focused on preventing pollution from ship cargo or wastes. The International Convention for the Prevention of Pollution from Ships, or MARPOL convention was originally ratified in 1973, but only in 2005 were “Sulfur Emission Control Areas” established which strictly limit the sulfur emissions by ships in highly populated coastal waters (IMO 2016). While in SECAs, ships are required to use expensive low-sulfur fuel or exhaust scrubbers to remove pollutants (UNCTAD 2015).

Forthcoming regulation, finalized in October 2016, will drastically decrease the sulfur content of fuel used in open waters from 3.5% to 0.5%, starting in 2020 (ICS 2016). The International Maritime Organization (IMO) has also committed to developing comprehensive greenhouse gas reduction plan by 2018 for implementation in 2023. Together, these forthcoming regulations set the stage for a dramatic shift in how maritime vessels are fueled.

While many shippers responded to current MARPOL regulation by switching to low-sulfur diesel fuels when in SECAs (UNCTAD 2015), volatility in oil prices and concerns about future availability of sufficient low-sulfur petroleum fuel (Pedersen 2016) have led to increased interests in alternative fuels, such as liquid natural gas and biofuels. Biofuels could potentially operate as “drop-in” fuels that require no major changes to ship engines or fuelling infrastructure. Biofuels also could be a renewable resource if carefully managed; allowing for distributed production of feedstock; containing near-zero sulfur, and having lower supply chain carbon dioxide emissions.

Current biofuel research focuses on their applications as replacements for highly refined fuels such as gasoline (Jones et al. 2009; Tews et al. 2014), road diesel (Dai et al. 2015; Shahid and Jamal 2008; Sharma et al. 2008) and jet fuel (Alves et al. 2016; Blakey et al. 2011; Faaij and van Dijk 2012; Rye et al. 2010; da Silva 2016). The lower quality fuels used in marine engines have received less attention. Additionally, the massive quantity of marine fuel used by a single ship engine make it more difficult to transition from lab scale to commercialized pilots. These high research and development costs paired with the fuel price sensitivity of shipping companies make cost-competitiveness a particular challenge for marine biofuels. However, interest in marine biofuels is rising, and the 2017 ISO standard for marine fuels (ISO-8217) introduced an annex with specification for 7% blends of oil-derived biofuels into fossil marine fuels (Einemo 2017).

Current biofuel production is dominated by fuels made from starchy or oily food crops, which are easy to convert into alcohol or oil based fuels (AFDC 2016). However, the ethical issues of using food for fuels has led to the increased interest in inedible biomass biofuel feedstocks (Sims et al. 2008). Inedible biomass is usually lignocellulosic; made of tough long-chain molecules that are difficult to convert into liquid biofuels. However, lignocellulosic biomass, including residues from agriculture and forestry, is abundantly available (Searle and Malins 2013a; Baruya 2015; Ferreira-Leitao et al. 2010), which makes it an attractive potential feedstock for biofuel development.

The technological and economic potential of lignocellulosic marine biofuels has been assessed on a broad level for US and European markets (Adom et al. 2013; Florentinus et al. 2012; McGill et al. 2013; Moirangthem 2016; Nayyar 2010; Opdal and Hojem 2007; Zhou et al. 2003). Additionally, engine testing of specific marine biofuel blends has been conducted predominantly using food-crop biofuels, including testing of a sugar-derived biodiesel blend tested by the US Maritime Administration, (Risley and Saccani 2013); testing of soy biodiesel by the Washington State Ferry System, and the testing of palm-oil biodiesel by the Royal Caribbean Cruises (Nayyar 2010). In 2016, testing of a wood residue biofuel in a joint venture by GoodFuels, Boskalis, and UPM (GoodFuels 2016) was one of the first large scale tests of lignocellulosic biofuels in marine engines.

However, there is a dearth of intermediate-level comparisons of feedstocks, technologies, and regions for lignocellulosic marine biofuels. Additionally, little consideration has been given to long-term scaling how current technological and economic uncertainties can affect concerns of large-scale implementation.

1.1 Research Aim

The goal of this research is to assess the possible economic and environmental performance of marine biofuels produced from different residual lignocellulosic feedstocks and thermochemical conversion technologies in the context of biofuel supply chains in Brazil and Scandinavia and then evaluate their technical and economic uncertainties in the context of potential commercial implementation.

Specifically, this thesis addresses the **research questions**:

1. *What is the estimated economic and environmental performance of marine biofuels made from lignocellulosic feedstocks via thermochemical conversion technologies in the context of biofuel supply chains in Brazil and Scandinavia?*
    i. What inputs and processes are needed to convert each feedstock into a biofuel that can operate in slow-speed marine diesel engines?
    ii. What are the estimated yields and profitability of the marine biofuels and their coproducts?
    iii. What are the estimated life cycle air emissions of greenhouse gases, sulfur dioxide, and nitrogen oxides, and the estimated life cycle non-renewable energy use for selected combinations?

2. *For the best performing combinations, how do the technoeconomic uncertainties in the supply chain constrain the possibility of large-scale implementation?*

To answer these questions, the following methodology is used:

1. Estimation of the supply of ten lignocellulosic feedstocks (**Table 1**) and marine fuel demand in Brazil, Denmark, Finland, Norway, and Sweden.
2. Mass balances of three biofuel production pathways for each feedstock: hydrothermal liquefaction (HTL), fast pyrolysis with hydrodeoxygenation (FP), and gasification followed by Fischer-Tropsch synthesis (GFT).
3. Estimation of biorefinery utility needs, including water, waste treatment, heat, electricity, and hydrogen.
4. Estimation of biorefinery capital expenses, operating expenses and sales revenue.

5. Estimation of the greenhouse gas emissions (CO_2, CH_4, N_2O), sulfur dioxide (SO_2) emissions, nitrogen oxide (NO_x) emissions, and non renewable energy use (NREU) throughout the biofuel supply chains, including feedstock production, feedstock transport, biofuel production, and biofuel combustion.
6. Sensitivity analysis of the economic, technological, and environmental impact parameters used in the study.
7. Comparison of biofuel's estimated economic and environmental impact indicators with those of fossil marine fuel and other emissions reducing technologies, including exhaust scrubbers, liquid natural gas, ultra low sulfur fossil fuels, and biodiesel.
8. Discussion of how the uncertainties throughout the biofuel supply chains affect the potential implementation of large-scale marine biofuel production.

Table 1. Biofuel feedstocks considered in this study.

Forestry Feedstocks	Grain Feedstocks	Sugar crop Feedstocks
Eucalyptus residues	Barley straw	Sugarcane bagasse
Pine residues	Corn stover	Sorghum bagasse
Spruce residues	Rice straw and husks	Sugar beet pulp
	Wheat straw	

This project was conducted over twenty-three weeks by a single master's student in fulfillment of the thesis requirement of the program of Industrial Ecology at Leiden University and Delft Technical University. The research was supervised by Assistant Professor Dr. ir. John Posada Duque of the Department of Biotechnology at TU Delft and Professor Dr. ir. Andrea Ramirez-Ramirez at the Faculty of Technology, Policy, and Management at TU Delft. Mr. Sjors Geraedts of GoodFuels provided additional guidance as an external supervisor.

The report is supplemented by a spreadsheet available at **concoctions.org/biofuel**.

1.2 The Horizontal International Project

This study builds on research conducted at TU Delft for the Horizontal International Project (HIP), a multinational collaboration to evaluate the economic, environmental, and social impacts of producing biojetfuel and other biochemicals in Brazil from a full supply chain perspective.

HIP has two phases. **Phase one** identifies promising biofuel production pathways using economic, environmental, and social performance indicators, looking at combinations of feedstocks, technologies, production scales, regions, and supply chain configurations, assuming an annual demand scenario of 208.9 kilotonnes of biojetfuel (Duque et al. 2016).

After the most promising supply-chain options have been selected, **phase two** will analyze their sustainability and feasibility in specific technological combinations, and develop methodology for social impact criteria and biorefinery sustainability assessment. The intended result is a sustainability ranking of biojetfuel supply chains in Brazil and the development of a methodological model for "integral sustainability" evaluation of bioproduct value chains (Duque et al. 2016).

1.2.1 Prior work

Three studies conducted by TU Delft researchers under HIP provided a foundation for this study:

1. **Alves (2015)** conducted a broad technoeconomic assessment comparing a variety of biojetfuel production technologies, coproducts, and feedstocks available in Brazil. The study performs refinery-level mass balances and economic assessments, based on the yield and production costs data from literature.
2. **da Silva (2016)** built on Alves's results to construct process models for thermochemical and biochemical conversion pathways of eucalyptus, pine, coffee, rice, macauba, and camelina into biojetfuel and biochemical coproducts. The models were based on a literature review of biorefining process design, and were used to conduct a unit process-level technoeconomic analysis of each combination. The most promising combinations were modeled in greater detail using the chemical process optimization software Aspen Plus to refine their yields and costs. The life cycle greenhouse gas emissions and non-renewable energy use of the most promising combinations were also estimated.
3. **Santos (2016)** used a similar methodology as da Silva to explore the thermochemical and biochemical conversion of sugarcane and sorghum crops in an integrated first-generation (sugar) and second-generation (lignocellulosic) biorefinery.

In Santos (2016) and da Silva (2016), the economic potential of each combination was calculated using the indicators:

i. **Gross profit**, which is the difference of the annual sales revenue from biorefinery products minus the variable costs of feedstocks, process chemicals, utilities, and waste processing.

ii. **Minimum fuel selling price** (MFSP), which is the price for biofuel where the biofuel sales revenue minus coproduct sales and operating expenses is zero.

Combinations with the best economic potential were also evaluated using environmental impact indicators:

iii. **Greenhouse gas emissions** (GHG), specifically carbon dioxide, methane, and nitrogen dioxide, estimated over the biofuel's life cycle, including feedstock production, biofuel production including utility and chemical inputs, transport, and use, including all upstream impacts of process inputs.

iv. **Non-renewable energy** use (NREU), estimated over the biofuel's life cycle, including feedstock production, production electricity and gas use, and transportation.

1.3 GoodFuels Marine

GoodFuels is a Netherlands-based company that facilitates the development and marketing of "drop-in" biofuels for marine, road, and rail applications. They bring together producers of promising biofuels, potential consumers, such as ports and shipping companies, and third parties, such as engine manufacturers. Their expertise includes the biofuel production and testing, environmental impact assessment, market research, marketing, and compliance.

1.4 This study in context

This thesis builds on the methodology and data used in HIP, supplemented by additional literature data and the marine biofuel expertise of GoodFuels to provide a cross-sectional analysis of advanced biofuel pathways in Brazil and Scandinavia. **Figure 1** visualizes this study in relation to the ongoing projects of HIP and Good Fuels.

Compared to prior work, as in **Table 2,** this study considered more feedstocks than da Silva and Santos, but only lignocellulosic residues and with fewer conversion technologies. The regional context was expanded to include five Scandinavian countries. Da Silva's thermochemical process model was the template for this study's models, adapted for other feedstocks and the different specifications of marine fuels. The technoeconomic assessment (TEA) was considered at a unit-process level, as opposed to the black-box refinery level in Alves or the detailed chemical process modeling in da Silva. The environmental indicators were expanded to include nitrogen oxides and sulfur dioxide, which are the focus of maritime air pollution regulation. This study made efforts to validate and improve the data and assumptions from prior work and provide data in a portable and transparent format for future use.

Figure 1. The Horizontal International Project, GoodFuels, and this study .

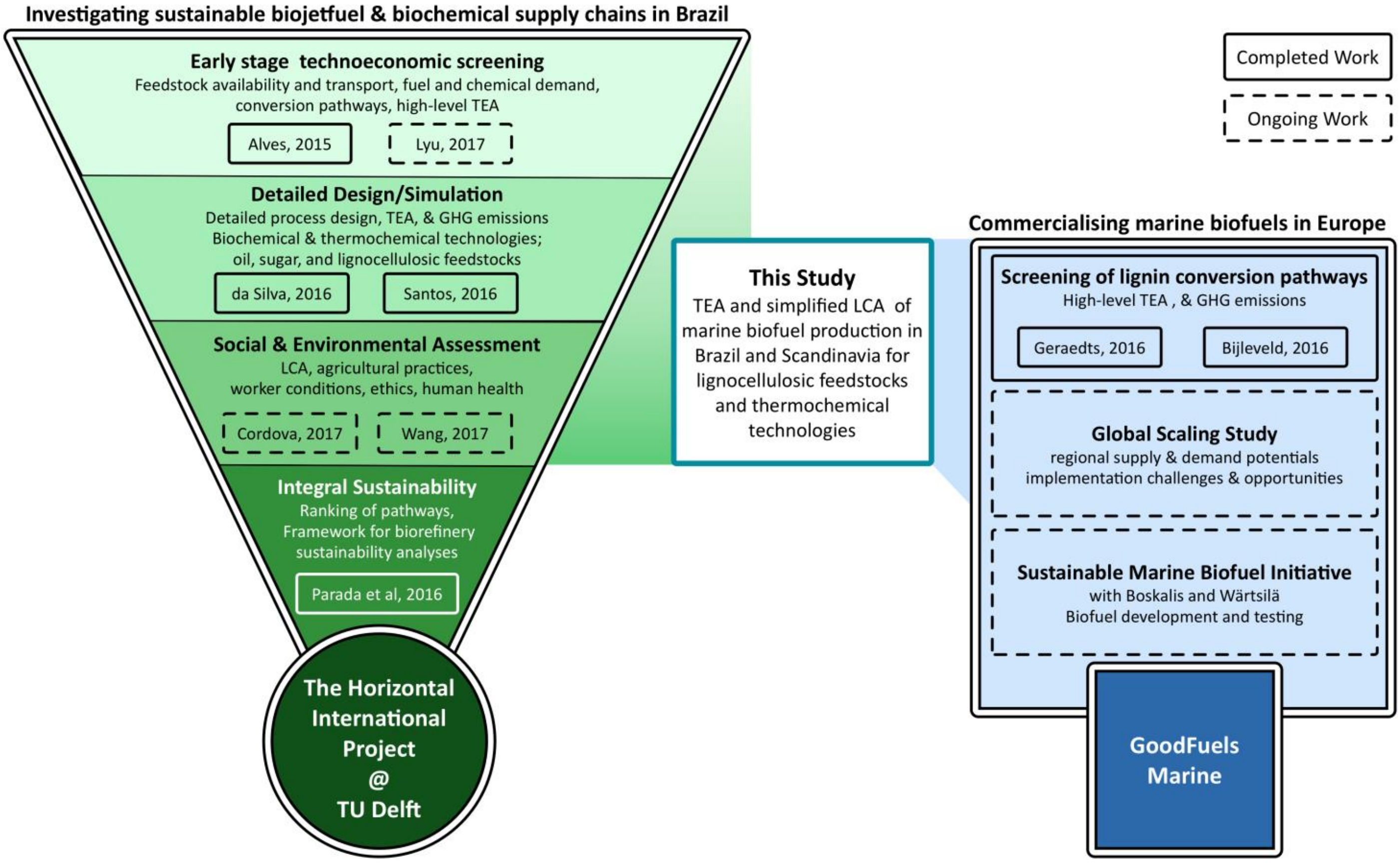


Table 2. Comparison of main parameters considered in this study and three TU Delft HIP studies.

	This study	Alves	da Silva	Santos
Year of completion	**2017**	2015	2016	2016
Regions	**Brazil Scandinavia**	Brazil	Brazil	Brazil
Primary product	**Marine biofuel**	biojetfuel	biojetfuel	biojetfuel
Coproducts	**electricity**	9 chemicals, 4 fuels, 6 oils and cakes	electricity, 2 sugars, 3 fuels, 2 cakes and oil	electricity, 4 chemicals, 2 fuels,
Feedstocks	**10 lignocellulosic**	7 lignocellulosic 4 oil, 2 sugar	4 lignocellulosic, 1 oil	2 lignocellulosic, 2 sugar
Technologies	**3 thermochemical**	5 pretreatments, 2 biochemical, 3 thermochemical	5 pretreatments, 4 thermochemical	9 pretreatments, 3 biochemical, 2 thermochemical
Level of process modeling	**unit process**	refinery	unit process and stoichiometric	unit process
Economic performance indicators	**CapEx, OpEx, MFSP**	NPV, IRR	gross profit, CapEx, OpEx, earnings, MFSP	CapEx, OpEx, MFSP
Environmental performance indicators	**GHG, SO_2, NO_X, NREU**	—	GHG, NREU	GHG

2 Context

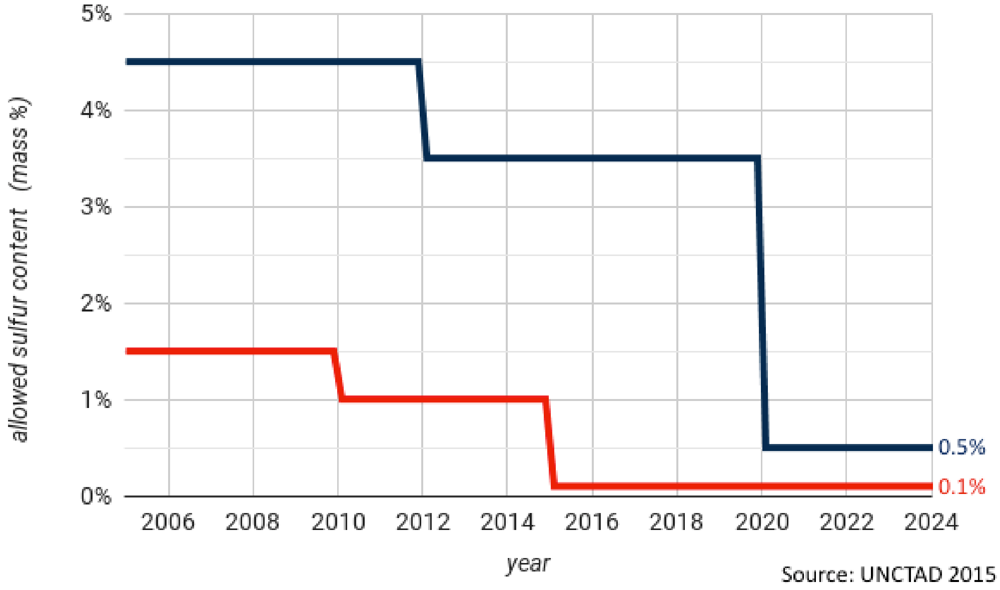
2.1 Maritime Shipping & Emissions Regulations

In terms of energy use and carbon dioxide emissions per ton–kilometer, maritime shipping is the most efficient method of freight transport. Maritime shipping transports 90% of global freight, consuming less than a third of the energy used by freight transport worldwide (EIA 2016). Perhaps for this reason, reducing air pollution emissions from marine vessels has been seen as less urgent until recently. While the automotive and aviation industries, which are more energy and carbon emissions intensive, have been working to reduce emissions for several decades (Lee et al. 2001; Nesbit et al. 2016), this conversation is new to marine transport. The first study of greenhouse gas emissions of maritime shipping was not conducted until 2000, and until 2005 all environmental regulation focused on preventing spillage of cargo or waste (IMO 2017a).

In 2005, the first major emission regulations established (ECG 2013), a progressively decreasing cap on fuel sulfur content (**Figure 2**), initially of 4.5% by mass. In 2012, the allowed sulfur content was reduced to 3.5%, which will further drop to 0.5% in 2020. **Emission control areas (ECAs)** (**Figure 3**) were established in heavily populated coastal regions where the cap was 1.5% in 2005 and 0.1% after 2015.

That regulation also capped nitrogen oxide emissions, with the cap dependent on the ship's year of construction and engine speed (IMO 2017b). The ECAs in North American waters also more stringently restrict NO_x emissions from new ships. Emissions of ozone-depleting chlorofluorocarbons were entirely prohibited.

Figure 2. Limits on marine fuel sulfur content for **open waters** and **emission control areas**.



Source: UNCTAD 2015

Figure 3. **Established** and **potential** emission control areas.

Source: IMO 2016

The decision to implement the 0.5% sulfur cap in 2020 instead of 2025 was finalized in October 2016, and there is uncertainty about how the refining and shipping industries will respond. The simultaneous announcement of a greenhouse gas reduction plan, to be developed by 2018 and implemented by 2023, further complicates the future of marine fuels. There are several competing options for compliance with upcoming regulations, including:

- **ultra low sulfur (ULS) fossil fuels**, which are already in production and can operate in existing ship engines (Moirangthem 2016). While the IMO predicts that refineries will produce them in sufficient quantity (CE Delft 2016), competing studies are more pessimistic and predict that low-sulfur fuel will not be profitable enough and fuel prices will rise sharply (Molloy et al. 2016). Additionally, ULS fossil fuels do not reduce greenhouse gas emissions, and the removal of sulfur increases the energy intensity of the supply chain.

- **liquid natural gas (LNG)**, which has been in use since 2000. Besides having a near-zero sulfur content, LNG reduces CO_2 and NO_x emissions, though the CO_2 emission reductions are offset by increased CH_4 emissions (Brynolf et al. 2014). While the technology is proven, it requires new or retrofitted engines, double the storage space of fossil fuels, and specialized refueling services (Moirangthem 2016). As of 2016, 77 LNG-powered ships are operational, the majority in Norway, with 85 on order (DNV-GL 2016). LNG is available in 28 ports worldwide, primarily in Europe, and only in Buenos Aires in South America (WPCI 2017).

- **exhaust scrubbers**, which remove SO_2, NO_X, CO_2 and/or particulate matter at the ship's tailpipe. SO_2 scrubbers are considered a novel technology, and globally only 80 active scrubbers are installed, with another 300 on order (Boer and Hoen 2015). Scrubbers are capable of removing over 90% of SO_2 emissions, but increase fuel use per ton-kilometer. Scrubbers are expensive and are primarily cost-effective when there is a high price differential between high-sulfur and low-sulfur fuels (Boer and Hoen 2015). CO_2 scrubbers are experimental, and the challenge of safely storing the CO_2 needs to be addressed (Wang et al. 2017).

- **biofuels**, some of which can be used in existing engines and infrastructure. Biofuels typically have a near-zero sulfur content, reduce fossil-based CO_2 emissions, and are less toxic if spilled, but can be more expensive, difficult to store, and affect engine performance (Florentinus et al. 2012). Several biofuels are being tested, including biomethanol, liquid biogas, and biodiesels from oil, algal, feedstocks, and lignocellulosic feedstocks (Moirangthem 2016; GoodFuels 2016), but none are available as a common bunkering fuel.

2.2 History of Liquid Biofuels in Transportation

The first diesel engine, invented by Rudolf Diesel in 1897 to replace the steam engine, ran on fuel derived from peanut oil (Jansen 2012). Jansen also relates that when Henry Ford developed the Model T in 1908, it was designed to run on corn ethanol as well as petroleum. Over the next couple of decades, the decreasing cost of fossil fuels and the US Prohibition ban on alcohol distillation paved the way for fossil fuels to dominate transportation energy in the 20th century.

However, shortages of fossil fuels during the World Wars and the geopolitical crises of the 1970s meant that biofuels were never far out of the picture. As described in *The History of Biofuels* (Kovarik 2013), in the 1980s both the US and Brazil invested heavily in bioethanol production following extended turmoil in the Middle East that led to unreliability in the gasoline supply. However, the subsequent fall of fossil fuel prices led to slowing biofuel production in the US until the early 2000s, when the conversation turned to long-term fuel security and the environmental impacts of fossil fuels. Brazil, however, continued investing in biofuels, particularly ethanol from sugarcane, and is currently the world leader in biofuel policy and production.

Current biofuel production is dominated by **first-generation biofuels,** which are made from crops grown with the same agricultural attention as food. Feedstock crops have a high sugar or oil content, such as corn, potatoes, sugar cane, soy, peanuts, and palm fruit (AFDC 2016). Starchy feedstocks are fermented and distilled into ethanol, which is purified and blended with gasoline. Oil feedstocks are reacted with alcohol to remove unwanted chemicals and then refined into biodiesel. While biodiesel can be used directly in diesel engines, both bioethanol and biodiesel are usually blended with fossil fuels.

First-generation biofuels, however, are heavily criticized. The “food vs. fuel debate” argues that the large-scale production of biofuel feedstocks causes rising food prices and food shortages. Their potential as a sustainable fuel source is also confounded by their reliance on fossil fuel-based production methods and nonrenewable fertilizers, and the acceleration of land use change (e.g. from forest to farmland) that results in increased net greenhouse gases emissions and biodiversity loss (Sims et al. 2008). The concern over land use change has led the EU to restrict how much first-generation biofuels can count towards renewable energy targets (European Commission 2012).

Due to these complications, biofuels made from agricultural, industrial, or municipal wastes have gained research and commercial attention. Fuels from residual sources are considered to sidestep the land use change and food competition dilemmas of first-generation biofuels (European Commission 2012). The feedstocks used for these **second-generation biofuels** are “woody,” e.g. straw, bagasse, or forestry residues, or “dirty,” e.g. used cooking oil or municipal sewage, and require extensive processing to convert them into usable biofuels. Woody feedstocks are lignocellulosic and need to chemically treated or subject to intense heat to allow their cellulose and lignin to decompose into biofuels. Waste oils must be cleaned before they can be converted into biodiesel, and waste sludge is usually fermented into a gas that is catalyzed into biofuel. Second-generation biofuels are in the early stages of commercialization, and lignocellulosic ethanol is the most developed, with 14 operational commercial demonstration plants (UNCTAD 2016).

Beyond concerns of feedstock sustainability and technological feasibility, biofuels must also confront the existing fuel infrastructure, which is designed for liquid petroleum fuels. Pure ethanol, the most abundant biofuel under production, cannot be used in regular gasoline engines, but is limited to a 10-15% blend (EIA 2017a). Higher ethanol contents require specially designed flexible-fuel vehicles (Joseph 2013). Biodiesels, in contrast, can be used directly in convention diesel engines, but its performance, especially in cold weather, may vary (AFDC 2016).

2.3 Marine Fuels

Large seafaring vessels typically use compression-ignition diesel engines, in which air is compressed by a piston, and fuel is injected into the heated air pocket, where it spontaneously combusts, pushing the piston away, thus transferring the fuel's energy into a crankshaft that turns a propeller that moves the ship (Taylor 1983).

The most common marine fuels, as explained by McGill et al (2013), are **marine gas oil** (MGO), a distillate fuel with properties similar to road diesel with higher impurities, and **residual fuel oil** (RFO), composed of long-chain hydrocarbons and contaminants left over from petroleum distillation. RFO is viscous and requires pre-heating. **Intermediate fuel oils** (IFO) are blends of MGO and RFOs and are classified by their viscosity. IFO-380 is an intermediate fuel oil with a kinematic viscosity of 380 mm^2/s (at 50C) and accounts for 63% of marine fuel use. MGO accounts for a further 23%, and RFOs for 10%. RFOs and IFOs are often both referred to as **heavy fuel oils** (HFO).

Standardization of marine fuels is set out in ISO 8217, and each classification has specific parameters, **Table 3**. As described by Vermeire (2012), it must have specific **density**, **viscosity**, and maximum **pour point** to ensure it will flow through the engine at an expected rate; it must have a specific minimum **flash point** to ensure it will only ignite at the expected temperature; and it must contain a limited number of contaminants, such as **water** and **sulfur**, to ensure that it will function correctly in the engine and accord with MARPOL regulations. Since the sulfur content affects the lubricity of the fuel, the use of low sulfur fuels affect engine operating procedures and maintenance.

Table 3. Properties of different fuel types.

Fuel Type	Carbon Chain Length	Heating Value (MJ/kg)	Density At 15C (kg/m^3)	Maximum Pour Point	Minimum Flash Point	Kinetic Viscosity (mm2/s)	Sulfur Content	Water Content
DMA (Marine gas oil)	10-20	43	890	-6/0C	60C	6000 at 40C	1.5%	—
IFO-380 (Intermediate fuel oil)	12-70	42	991	30C	60C	<380 at 50C	3.5%	0.5%
RMK-500 (Residua fuel oil)	20-70	40	1010	30C	60C	—	3.5%	0.5%
Jet Fuel A (for reference)	8-16	43	775-840	—	38C	Unspecified	0.3%	0.003%

Sources: Exxon Mobil Aviation 2005; Rodrigue et al.; Ronneau 2004; Santos 2016; Vermeire 2012; Bengtsson et al. 2011

2.3.1 Marine Biofuels

Only in 2017 did ISO standards add a provision for biofuels, with a specification allowing for a maximum of 7% oil-derived biodiesel blended into petroleum fuels (Einemo 2017). However, the lack of guarantee by regulatory agencies and engine manufacturers of the quality and safety of biofuels represent substantial reservations of the marine transport industry, which are only beginning to be addressed by testing and standards development. As detailed by Nayyar (2010), marine biofuels must be:

- tested and guaranteed to work with existing ship engines.
- miscible with existing fuels, without the potential for separation or spoilage.
- immiscible with water, which could cause microbial contamination, engine starting issues, or fuel spoilage.
- stable for long-term storage without deterioration in quality.
- guaranteed to comply with environmental regulations.
- cost-competitive with other fuelling options.
- readily available in sufficient quantity and consistent quality.

There are no biofuels that meet these specifications and are also in widespread commercial use. Private ship companies have successfully tested biodiesels, but with mixed results (Florentinus et al. 2012). The sugar-based biodiesel blend tested by the US Maritime Administration was successfully overwintered and is approved for use in diesel-electric engines (Risley and Saccani 2013). Also in the US, ten vessels owned by the Great Lakes Environmental Research Laboratory are fuelled by 100% soy biodiesel (GLERL 2017). Second-generation marine biofuel availability is more recent. At the end of 2016, GoodFuels announced the commercial availability of a wood-residue biodiesel produced by the Finnish company UPM, after extensive testing on a Boskalis dredger (GoodFuels 2016).

2.3.2 Marine Fuel Prices

In the maritime shipping industry, a single fueling can cost millions of dollars (UNCTAD 2015). Marine fuel prices, **Table 4**, are highly volatile, varying not just with crude oil prices, but also with the port of sale, shipping demand, distributer, and demand for other fuels. Low-quality heavy fuel oils are historically substantially cheaper than distillate fuels, **Figure 4**, which can be up to twice as expensive as HFOs, roughly equal to the price of jet fuel.

For SECA compliant fuel, the "low sulfur premium" has fluctuated widely, averaging 20 USD per tonne in the past 30 years, peaking at 75 USD/tonne in 2008 (Mazraati 2011). In the past year (March 2016-2017), the premium has been zero or negative (Ship & Bunker 2017), due to low demand. However, the predicted premium when 2020 sulfur cap comes into effect range from 10% to 100% of the current price of heavy fuel oil (ICS 2016; Molloy et al. 2016).

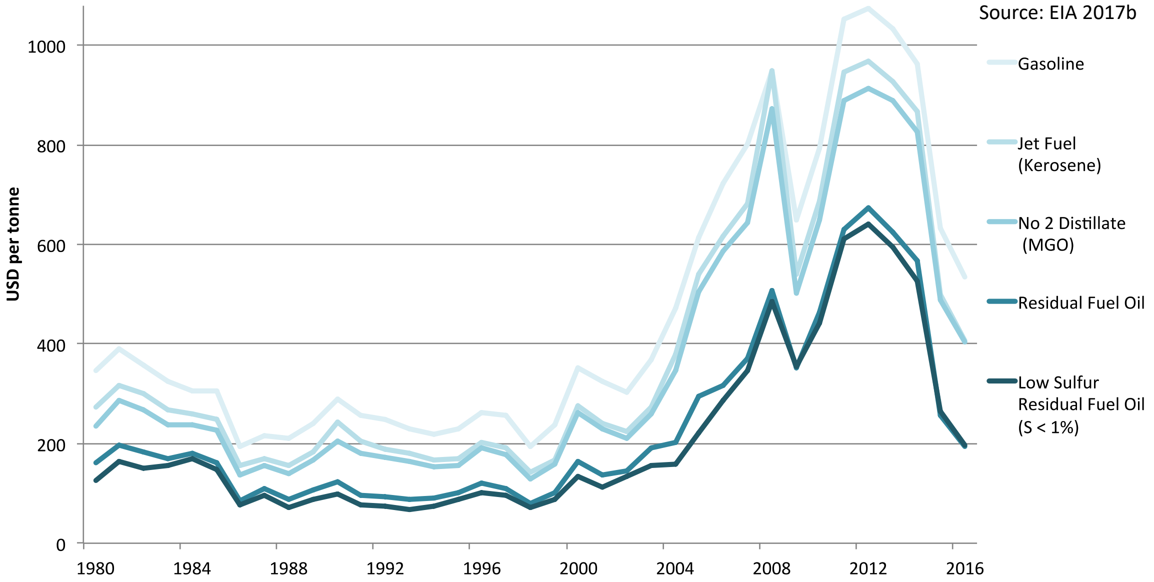
Table 4. Fuel prices, March 31 2017, in USD 2017 per metric tonne.

Country (Port)	Heavy Fuel Oils		Distillate Fuels		Jet Fuel
	IMO-380	IMO-180	MGO	LSMGO	Jet-A
Brazil (Santos)	300	331	671		513
Brazil (Tubarao)	309	340	691		
Netherlands (Rotterdam)	286	322	455	451	501
Sweden (Gothenborg)	291	328	n.a.	496	
Norway (Bergen)	n.a.	n.a.	n.a.	489	

n.a.: not available

Sources: Ship & Bunker 2017; IATA 2017

Figure 4. Historic US wholesale fuel prices, in USD per tonne.



Source: EIA 2017b

2.4 Regional Context

The economic viability and environmental impacts of marine biofuel production depend on where the biofuel is produced. The agricultural and forestry sectors, and related manufacturing industries, inform the type and quantity of available feedstocks. The climate and soil influence what crops can be grown, and the existing bioenergy industry determines the available infrastructure and expertise. Additionally, laws and regulation define relevant taxes or credits, environmental mandates, and other incentives or drivers to the bioenergy sector.

This study considers biofuel production in Brazil, Denmark, Finland, Norway, and Sweden, whose major relevant statistics are compared in **Table 5**. Brazil is eight times larger in area, population, cereal production, and liquid biofuel production than the whole of Scandinavia. However, on a per capita basis, Scandinavian countries have a larger gross domestic product (GDP), more maritime as cargo throughput, and higher marine fuel demand. Denmark also has a higher density of cereal production, and Norway a higher density of forestry, than Brazil. Sweden also produces a larger per capita quantity of liquid biofuels than Brazil.

Table 5. Comparison of key statistics of the countries considered in this study.

	Brazil	Denmark	Finland	Norway	Sweden	Source(s)
Area, in thousands of sq. km.	8 500	43	338	324	450	CIA 2017
Population, 2016, in millions	206	5.6	5.5	5.3	9.9	CIA 2017
GDP per capita, 2016, In USD/person	\$15 200	\$46 600	\$41 800	\$69 300	\$49 700	CIA 2017
Cereals crop production, 2014 in millions of tonnes	101	10	4	1	6	FAO 2016
Sugar crop production, 2014, in millions of tonnes	738	3	0.6	n/a	2	FAO 2016
Forestry crop production 2014, in millions of m^3, underbark	256	3.5	5.7	12	7.3	FAO 2016
Maritime cargo throughput, in millions of tonnes	931 (2013)	92 (2014)	89 (2015)	206 (2015)	133 (2015)	ANTAQ 2013; Statistics Denmark 2017; Finnish Transport Agency 2015; Statistics Norway 2017; Transportföretagen 2016
Marine fuel demand, 2014, in petajoules	154.0	32.8	4.3	6.4	76.0	IEA 2016
Bioenergy share in energy mix	27.7%	23.6%	26.7%	4.7%	23.5%	Bacovsky et al. 2016
Liquid biofuel production, 2014, in petajoules	584	12	17	6	37	Bacovsky et al. 2016

2.4.1 Brazil

Brazil is a tropical country with large agriculture and bioenergy sectors. In 2015, Brazil produced 25% of the global bioethanol supply and the world leader in biofuel policy (RFA 2015). Sugar bioethanol has been blended into gasoline since 1977. The current blend ratio is 25-27% ethanol, and flexible-fuel cars, which can use higher blends, account for over two-thirds of the light-duty vehicle fleet (Barros 2015). Biodiesel has also been blended into fossil diesel since 2008, currently at a 7% ratio, and will increase to 10% in 2020 (Barros 2015). By 2012 Brazil had reduced its greenhouse gas emissions 41% relative to 2005 levels, and has committed to reduce them a further 2% by 2030 (Bacovsky et al. 2016). However, Amazon deforestation is a major issue, and Brazil has pledged promote second-generation biofuels and increase enforcement of the Law on the Protection of Native Forests (Bacovsky et al. 2016).

Brazilian ports saw a maritime cargo throughput of nearly one billion tonnes in 2013. However, marine fuel prices are particularly high in Brazil (**Table 4**), and Brazil is actively pursuing alternative marine fuels, including liquid natural gas (Alisson 2016) and biofuels (Duque et al. 2016).

2.4.2 Denmark

Denmark is the smallest country in this study but has the highest per-capita grain production and a history of producing bioenergy from straw. The Danish government is striving for fossil fuel independence by 2020, and has implemented feed-in tariffs on renewable energy sources, tax incentives for renewable energy vehicles, and biofuel blending quotas (Bacovsky et al. 2016). Notably, Denmark is the first country to mandate a blending quota for second-generation biofuels in transportation, which will start at a modest 0.9% in 2020 (Flach et al. 2016).

Denmark has a high marine fuel demand per capita, and the first pilot plant dedicated to marine biofuel production was constructed in 2013, as a collaboration between Steeper Energy and Aalborg University (Steeper Energy 2017a).

2.4.3 Finland

Finland has the fastest growing biofuel industry in Scandinavia, and particularly for thermochemical conversion of its abundant forestry residues, supported by carbon taxes on fossil fuels and biofuel subsidies. In 2014, over 20% of transport energy was from biofuels (Bacovsky et al. 2016). That 20% is a partially inflated figure due to the high proportion of second-generation biofuels, which the EU allows to be double-counted in renewable energy reporting, as a promotional incentive (Olsen et al. 2013).

Wartsila, UPM, and Boskalis, companies collaborating with GoodFuels to produce marine biofuels from wood residues, are all Finnish. Finland, however, is not a maritime country and has the lowest per-capita maritime cargo throughput and fuel demand. If substantial marine biofuel were produced in Finland, it would need to be exported.

2.4.4 Norway

Norway is home to a large number of shipping companies, which would benefit from the availability of clean marine fuels. However, Norway is also a major exporter of fossil fuels, due to its reserves in the North Sea (International Energy Agency 2016) and between 2006 and 2010, it had the slowest growth of biofuel use in Scandinavia (Olsen et al. 2013). It produces the least biofuel in Scandinavia and its transport bioenergy target is the EU mandated minimum of 10%. Norway’s primary policy tool for promoting renewable energy is a quota system (Bacovsky et al. 2016). Tax policies have been mixed, with a 2006 tax exemption for biofuels later rescinded for biodiesels (Olsen et al. 2013).

Despite having a large per-capita maritime cargo throughput, Norway has a low marine fuel demand (**Table 5**). However, it also has the largest forestry sector in Scandinavia, suggesting high feedstock availability.

2.4.5 Sweden

Sweden has already met its 2020 renewable energy targets of 49% of total energy and 10% of transport energy use (Bacovsky et al. 2016). Sweden has also committed to vehicular fossil fuel independence by 2030 (Olsen et al. 2013). Sweden’s bioenergy sector is well developed for heating and transportation, and produces 30% more liquid biofuel per capita than Brazil. Biofuels are exempt from the energy and carbon taxes levied on fossil fuels (European Biofuels Technology Platform 2015). However, most of Sweden’s biofuels are first-generation, and the tax exemptions are being revised to comply with EU restrictions on incentives for food-crop biofuels (Bacovsky et al. 2016).

Sweden has the largest per capita marine fuel demand of the countries considered, and Gothenburg is the largest fuelling port in Scandinavia. The port is working to reduce its environmental impacts and offers liquid natural gas fuelling services and onshore power supplies for docking ships (Gothenburg Port Authority 2017).

2.5 Feedstocks

The primary lignocellulosic feedstocks used for second-generation biofuels are agricultural and forestry residues, such as bagasse, straw, bark, and branches (Alves et al. 2016). Lignocellulosic biomass's energy is stored in long chain carbohydrate molecules in plant cell walls. This makes them difficult to convert into liquid biofuels, and substantial energy is needed to release the energy trapped in the complex molecules.

The major components of lignocellulosic biomass that affect its ability to be converted into biofuel include:

- **cellulose**, which is a linear chain of glucose molecules that provide structure and strength (Jansen 2011).
- **hemicellulose,** which consists of non-linear linkages of sugars. (Singh et al. 2015).
- **lignins**, which are large, complex polymers of alcohols, responsible for the resilience and flexibility of plant cell walls. They bind cellulose and hemicellulose together, and are difficult to decompose (Dai et al. 2015).
- **water**, which reduces the energy density of a feedstock, reduces storage stability, and interferes with combustion (Gupta and Demirbas 2010). Drying is an initial step of many biorefining processes, and can be highly energy intensive, depending on the method used and the feedstock's initial moisture content
- **ash**, which consists of the non-combustible minerals that are not available for conversion into biofuel. Volatile metals in the ash can contaminate biofuels or processing equipment (Gupta and Demirbas 2010).

The lignocellulosic feedstocks in this study are grouped into three categories, each discussed in more detail below:

- **forestry residues**, which have a higher lignin content and lower ash content than grain or sugar crop residues (ECN 2012). They are not subject to harvest seasonality like agricultural residues, but their slow drying speed makes it difficult to reduce their moisture content before transport. (Hoyne and Thomas 2001).
- **grain residues**, which have a higher hemicellulose content than forest residues, and dry quickly in the field. Grain residues tend to have high ash content, which can reduce biofuel yields.
- **sugar crop residues**, which are available abundantly in Brazil, and are currently discarded or combusted to generate heat and electricity used in the bioethanol plants where they are processed.

2.5.1 Forestry Residues

Forestry residues include bark, small branches, chips, stumps and broken logs that would have otherwise been left in the forest or discarded, beyond the amount necessary to protect soil quality. In non-commercial forests, thinning and removal of excess residues is also necessary to prevent forest fires. Residues from wood manufacturing, such as sawdust, wood chips, and wood pulp are another sources of feedstock.

There are many experimental studies and technoeconomic analyses on the conversion of forestry crops to biofuels (Jones et al. 2009; Tews et al. 2014; Gregoire and Bain 1994; Ghodke et al. 2015; Phillips et al. 2011), Additionally, multiple pilot biorefineries that use forestry feedstocks are currently operational or under development (GoodFuels 2016; Rudloff 2008; Steeper Energy 2017b).

The forestry feedstocks considered in this study are the residues of:

- **eucalyptus**, which is a subtropical genus of hardwood trees, originating in Australia. In Brazil, eucalyptus is a common plantation crop, due to its fast growth rate and value as building material and fuel (Couto et al. 2011).

- **pine**, which is cultivated in all countries considered. In Scandinavia, the cold-tolerant Scots Pine is the most common species, while sub-tropical species, such as the Caribbean pine, are common in Brazil (Iqbal et al. 2016; TRAFFIC).
- **spruce**, which is hardy, fast growing, and has long fibers that make it the primary input for the paper industry in Scandinavia (Demirbas, 2010). Spruce is the dominant forestry crop in Denmark, Norway, and Sweden.

2.5.2 Grain Residues

Grain dominates global agricultural production. Grains are the seeds of domesticated grasses, and 30-60% of their mass is straw and husks. These residues are not digestible by humans and are used as animal feed, burnt for energy, or discarded. The grain residues considered in this study are from the world's four dominant cereal crops:

- **barley straw**, which is the residue of the hardy and nutritious grain grown in Brazil in the winter and Scandinavia in the summer.
- **corn stover**, which consists of the corn's stalks, husks, and cobs. Corn (maize) is the most abundant cereal crop in the world (FAO 2004) and there has been substantial interest in corn stover as a biofuel feedstock. Brazil is the third largest producer of corn, with 52 million tonnes of corn harvested annually (Ferreira-Leitao et al. 2010).
- **rice straw and husks**, which, unlike the other residues considered, do not need to remain in the field to protect soil quality, thus maximizing its potential residue yield (Ferreira-Leitao et al. 2010). Rice, however, is very labor and water intensive (FAO 2004). Rice straw also has a high ash content (15-20% of dry weight), which can complicate biofuel production. Rice is not grown in Scandinavia.
- **wheat straw**, which is available in all countries considered, with a high residue-to-crop ratio (Ferreira-Leitao et al. 2010).

2.5.3 Sugar crop residues

Over 170 million tonnes of sugar are produced globally, and Brazil is the largest producer. Sugar crops must be processed quickly to avoid spoilage, limiting their season of biofuel production. The sugar crop residues considered in this study are:

- **sugarcane bagasse**, which is the pulp remaining after pressing the sugary liquid from the cane, accounts for 28% of the sugarcane's mass. Sugarcane has been the heart of Brazilian agriculture since the colonial era, and today half of all Brazilian sugar is converted to bioethanol (USDA 2016). Over 600 million tonnes of cane, producing over 37 million tonnes of sugar, is harvested in Brazil every year (Alves 2015).
- **sorghum bagasse**, which is the residual pulp from the sugar bearing grass imported to Brazil from Africa in the 1970s (Santos, 2016). Currently, sorghum accounts for less than 0.03% of Brazil's sugar crop (FAO 2016), although there has been substantial speculation about its use as a complementary energy crop as it has a similar composition to sugarcane and a non-overlapping harvest season (Schaffert and Gourley 1982).
- **sugar beet pulp**, which is the residue of the only sugar crop available in Scandinavia. The sugar beet was aggressively cultivated in the 1800s to reduce European dependence on tropical sugarcane. Beet sugar accounts for 20% of global sugar production (FAO Investment Centre Division 2009).

2.6 Conversion Technology

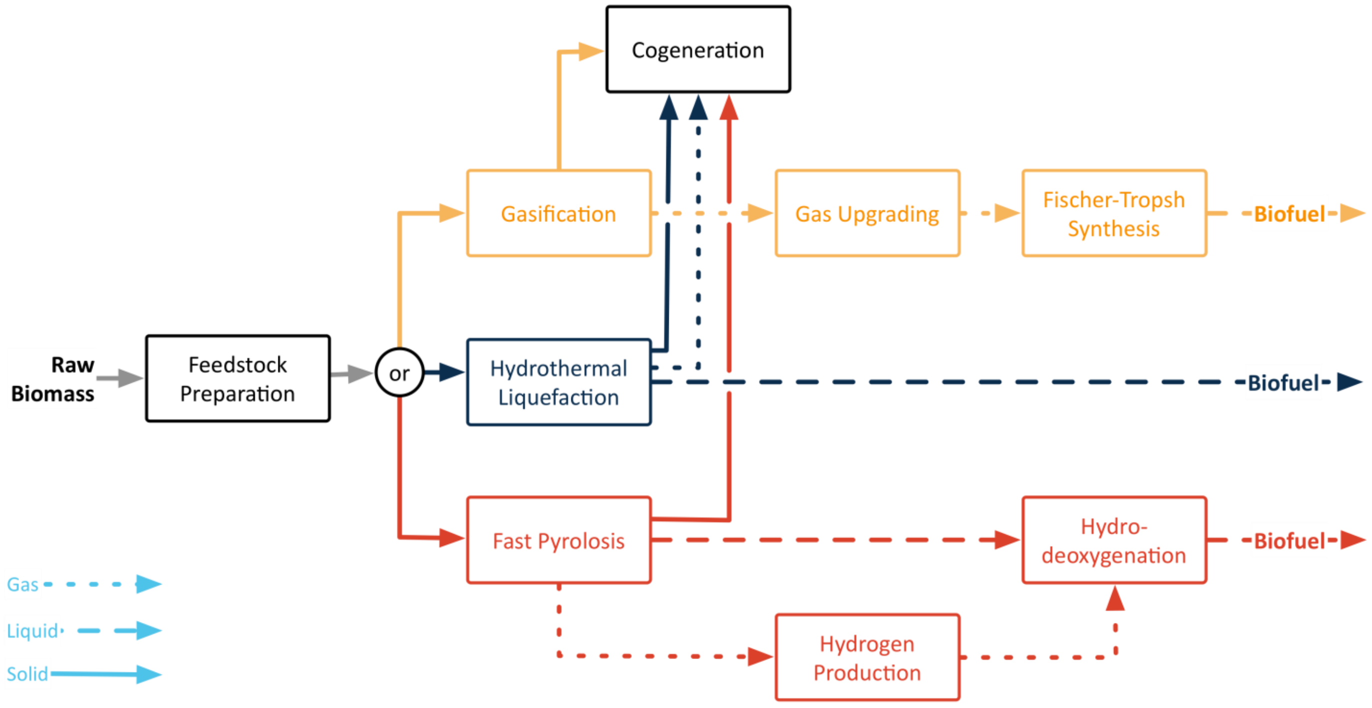
Thermochemical biofuel production deconstructs the feedstock's complex organic molecules into solid, liquid, and gaseous fractions via the application of heat and pressure. The production of fossil fuels by the earth is also predominantly a thermochemical process, where the application of heat and pressure over thousands or millions of years converts buried biomass into coal, oil, and natural gas (Sato 1991). Thermochemical biofuel production seeks to replicate the outcome of geologic petroleum production, but in a much shorter timeframe.

Thermochemical biofuel production differs from biochemical biofuel production, which uses microorganisms or enzymes to deconstruct biomass into alcohols and other useful chemicals. In this study, three thermochemical biofuel production technologies, summarized in **Figure 5**, are considered:

- **hydrothermal liquefaction** (HTL), which decomposes biomass in a high-pressure, water-saturated environment, producing a crude-oil-like substance. It is still an experimental technology, that is only operational on a pilot scale, though a commercial-scale demonstration plant is currently under construction in Denmark (Steeper Energy 2017a).
- **fast pyrolysis and hydrodeoxygenation** (FP), which decomposes biomass with high heat in the absence of oxygen. The liquid fraction is then separated and reacted with hydrogen to reduce its water content by removing oxygen molecules.
- **gasification and Fischer-Tropsch synthesis** (GFT), which combusts biomass to produce a gas, which is cleaned and reacted with a catalyst that promotes the formation of hydrocarbon molecules. GFT is a technology that is mature for coal gas and natural gas, and is in the early stage of commercialization for biomass.

In all cases, the reaction products unused for biofuel production (e.g. char) are combusted to generate heat and electricity for the biorefinery. For fast pyrolysis, hydrogen for hydrodeoxygenation is also produced from the gas fraction.

Figure 5. Thermochemical biofuel production pathways considered in this study.



2.6.1 Hydrothermal Liquefaction

As described by (Zhang 2010), during hydrothermal liquefaction small pieces of biomass are saturated with a solvent, such as subcritical or supercritical water, and reacted under pressure, with or without the use of a catalyst, to decompose lignin and other long-chain molecules into gas, liquid, and char fractions. The liquid phase is then separated into water-soluble and oil-soluble fractions. The latter is often called a “biocrude,” and has a low oxygen content, is miscible with petroleum, and can be used directly in diesel engines (Nabi et al. 2015) or upgraded, such as via hydrodeoxygenation, and separated into higher quality fuels (Ramirez et al. 2015).

Hydrothermal liquefaction yields are affected by:

- **temperature**, with intermediate temperatures (300-350C) having the highest biocrude yields. Higher temperatures produce more gas and char, whereas temperatures below 280C lead to lower overall yields due to incomplete degradation of lignin and cellulose (Akhtar and Amin 2011).
- **solvent-to-feedstock ratio**, with higher ratios resulting in lower char and gas yields, but increased costs. Too little solvent inhibits the reaction, causing it to behave like pyrolysis (Akhtar and Amin 2011).
- **lignin** content of the feedstock, which decreases biocrude yields (Akhtar and Amin 2011).
- **recycling of the water-soluble fraction** into the reactor feed, which allows for unreacted biomass to be converted, increasing biocrude and solid yields (Zhu et al. 2015).

Heating rate, pressure, and residence time must also be optimized, but their effects are smaller and dependent on other operating conditions.

Hydrothermal liquefaction is the least developed technology considered in this study and high uncertainties exist pertaining to yield, and the biocrude’s viscosity, energy content and moisture. The largest operational HTL plant is a pilot plant in Denmark that produces one-half barrel of biocrude per day (Steeper Energy 2017b).

2.6.2 Fast Pyrolysis

Fast pyrolysis is the rapid heating of finely ground, dried biomass to a temperature between 450-800C in the absence of oxygen to decompose it into gaseous, liquid, and char fractions (Bridgwater 2012). Fluidizing agents, such as gas and sand allow heat to distribute quickly to the biomass, as reactor residence times are between 0.5 and 3.0 seconds (Bridgwater 2012). The char fraction can be then combusted for the generation of heat and electricity (Baskar et al. 2012). The liquid fraction is called “pyrolysis oil” and is acidic, rich in oxygenated hydrocarbons, has an energy content of 15-22 MJ per kilogram, and has a water content of 14-33% that is not easily separable (Sadeghinezhad et al. 2014). The high water content means that the pyrolysis oil is not stable for long-term storage, and must be combusted immediately. To produce high quality fuels, the pyrolysis oil must be deoxygenated, such as via hydrodeoxygenation, catalytic cracking, or steam reforming (Zhang et al. 2007).

As outlined by Kan et al (2016) and Bridgwater (2012), fast pyrolysis yields are affected by:

- **reaction temperature**, with liquid yield maximized around 500C. Higher temperatures result in larger gas yields, lower temperatures in larger char yields.
- **cellulose and hemicellulose** content of the feedstock, which increases the liquid yield.

- **lignin** content of the feedstock, which increases char yield and leads to a decrease in the water content of the pyrolysis oil, thus increasing its viscosity.
- **particle size** of the feedstock, which allow for faster heat transfer and higher liquid yields as it decreases. However, oil yields do not improve with particle sizes below 1mm.

Fast pyrolysis of biomass has been under development for over thirty years, and in the past decade commercial pyrolysis oil plants have been constructed (Bridgwater 2012). An Ensyn plant in Canada, commissioned in 2006, produces over eleven million liters of pyrolysis oil per year; Fortum has operated a pyrolysis oil and combined heat and power plant in Finland since 2013 (Fortum 2016); and Empyro commissioned a fast pyrolysis plant in the Netherlands in 2015 (BTG-BTL 2017). There is currently no production of upgraded fuel from pyrolysis oil, though the development of an economically feasible hydrotreated pyrolysis fuel is a major research goal of the Pacific Northwest National Laboratories in the US (Jones et al. 2016).

2.6.3 Gasification with Fischer-Tropsch Synthesis

During gasification, biomass is decomposed by high heat (700-900C) in the presence of oxygen and/or steam, to produce a synthesis biogas, or “syngas”, rich in hydrogen and carbon oxides, as char, and small quantities of liquid. The syngas is cleaned and fed into a **Fischer-Tropsch** (FT) reactor, which uses catalysts, such as cobalt or iron, to “grow” hydrocarbon chains by combining the gas’s component molecules (Baskar et al. 2012). Some of the influencing factors on GFT yields are:

- **lignin** content of the feedstock, which decreases syngas yield (Hanaoka et al. 2005).
- **ash** content of the feedstock, which can cause sintering in the FT reactor. (Moilanen et al. 2014).
- **gasification temperature**, with higher temperature increasing syngas yields (Kurkela et al. 2014).
- **fluidizing medium** used in gasification, with oxygen and steam-reacted syngas having higher energy contents, and air-reacted syngas having the lower energy contents (Salami 2012).
- **hydrogen-carbon monoxide ratio** of the syngas, which influences the length of the hydrocarbons generated during FT synthesis (Baskar et al. 2012). After cleaning, the syngas is often subject to additional processes to improve the H-CO ratio, such as a water-gas shift or steam methane reforming.
- **Fischer-Tropsch synthesis temperature**, with lower temperatures favoring larger hydrocarbons (Swanson et al. 2010).
- **Fischer-Tropsch synthesis catalyst**, with cobalt catalysts favoring larger hydrocarbons and iron favoring shorter ones (Swanson et al. 2010).

Gasification with Fischer-Tropsch synthesis is the most mature of the technologies considered. GFT was first described in the 1920s, and was commercialized for the production of liquid fuels from natural gas and coal gas during oil shortages in Germany during WWII (Stranges 2007). However, commercialization of biomass GFT is limited. A 72 tonne per day demonstration plant is operational in France (IFPEN 2016) and a 24 tonne per day pilot plant is operational in Germany (KIT 2016). A commercial scale Fischer-Tropsch plant that uses a combined feedstock of natural gas and landfill gas has been constructed and is undergoing product testing in the US (Velocys 2017).

3 Methodology

While other work in HIP focuses on the production of biojetfuel, along with coproduct fuels and biochemicals, this report addresses the direct thermochemical conversion of lignocellulosic biomass residues to marine biofuels. The analysis is intermediate to that of Alves's (2015) and da Silva's (2016) work, considering the conversion processes at a unit process black-box level rather than a refinery-black-box or unit process stoichiometric level. The economic model similarly is intermediate, scaling costs for process sections, rather than the whole plant or individual pieces of equipment.

Whenever possible, existing HIP data and conventions were used, and efforts were made to validate prior work.

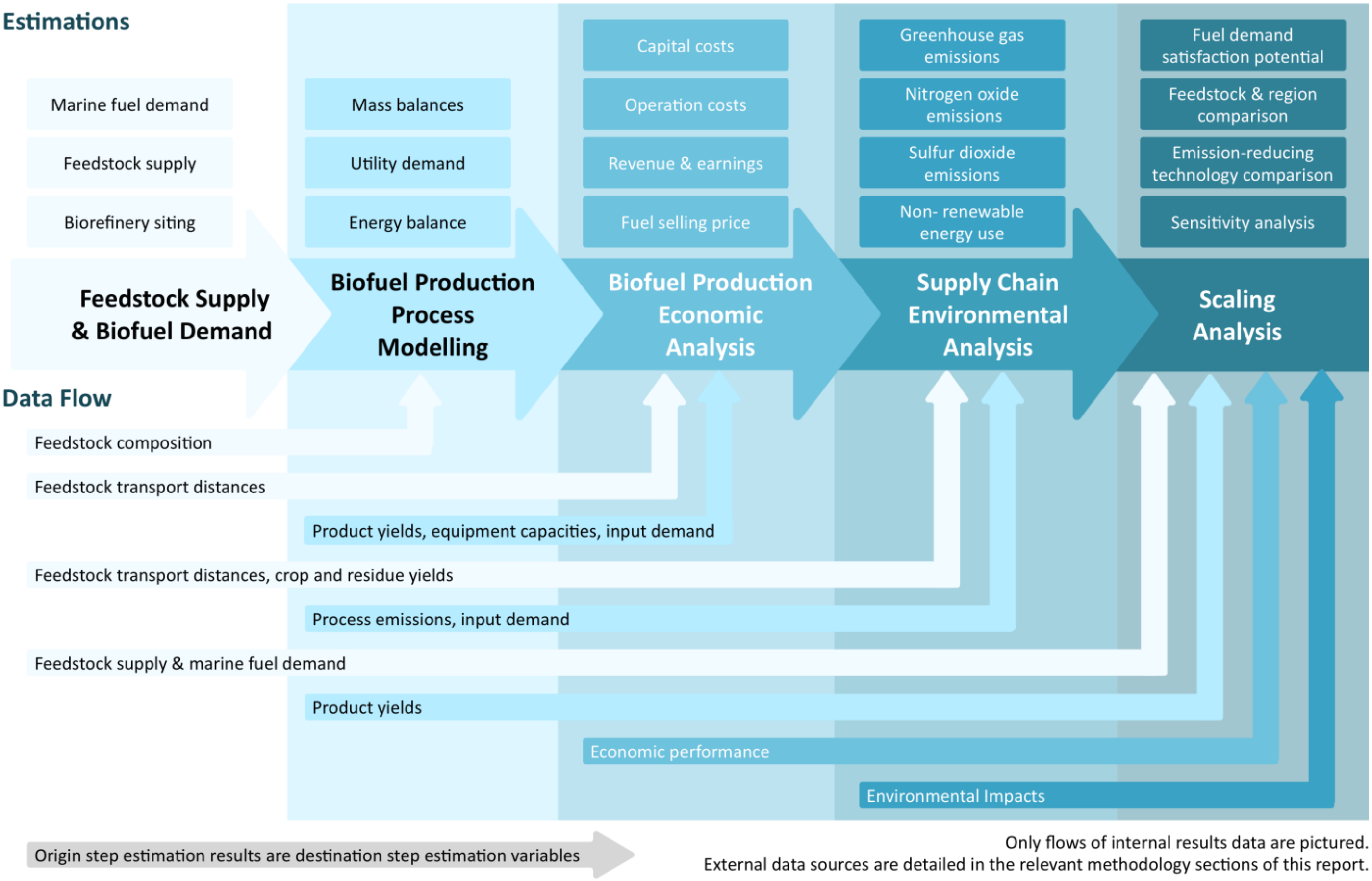
Figure 6 provides an overview of the methodology used in this study. The main steps were:

1. **Estimation of the feedstock supply and marine fuel demand** for each country considered.
2. **Technological modeling of biofuel production processes** for all three technologies, including mass balances and estimation of utility needs.
3. **Estimation of economic performance of the hypothetical biorefineries**, including capital investment for plant construction, annual operating costs, annual sales revenue and earnings, and the break-even biofuel selling price.
4. **Estimation of life cycle environmental impacts of biofuel production and use**, including greenhouse gas emissions (CO_2, CH_4, N_2O), SO_2 emissions, NO_x emissions, and non-renewable energy use. The life cycle includes feedstock production, feedstock transport, biofuel production, and biofuel combustion.
5. **Comparison of technology-feedstock-region combinations** including their ability to satisfy demand and their economic and environmental performance indicators. These indicators are also compared to other technologies for reducing marine fuel emissions, including natural gas, low sulfur HFO, soy biodiesel, and exhaust scrubbers.

Estimations made in earlier steps were used for input into later ones, though not always sequentially. The major flows of internal results data are visualized in **Figure 6**.

Methodological and data transparency is keystone of this study, and all data, variables, and calculations are available, with in-line documentation and citations, in a free spreadsheet software, Google Sheets, at **concoctions.org/biofuel**.

Figure 6. Overview of thesis methodology.



3.1 Feedstock Availability

Alves (2015) and da Silva (2016) estimate residue availability using land productivity and land area of production. However, due to the number of feedstocks considered, this study extrapolates from existing production statistics. Da Silva also investigates the availability in specific Brazilian states, while this study focuses on national availability.

The availability of ten lignocellulosic residues (**Table 1**) was estimated using national crop statistics and residue yields from literature. 2020 is the target year of production, which is when the new marine fuel sulfur restrictions go into effect. Feedstocks in each country that are available in sufficient quantity to supply the biorefinery (defined in **3.2**), continue to process modeling and economic and environmental analyses.

3.1.1 Residue Availability

For each feedstock available in each country (**Table 6**), national crop production data from 2000-2014 was used to project 2020 crop production via a least squares regression. FAO statistics (FAO 2016) were used for all grain and sugar crop estimations, while national statistics were needed for forestry estimations. Forestry production data in cubic meters was converted to tonnes using green wood densities, **Table 7**, and standardized to overbark measurements at a ratio of 1.12:1 overbark-to-underbark (Forestry Commission, 2015). Other differences in forestry reporting (e.g. the inclusion of stumps or minimum branch size) were not considered. For pine and eucalyptus in Brazil, species-specific crop production data was not available. Instead, the 2020 production estimates from da Silva (2016) were used.

Table 6. Feedstock availability by country.

Feedstock	Brazil	Denmark	Finland	Norway	Sweden
Eucalyptus	■	No	No	No	No
Pine	■	■	■	■	■
Spruce	No	■	■	■	■
Barley	■	■	■	■	■
Corn	■	■	No	No	No
Rice	■	No	No	No	No
Wheat	■	■	■	■	■
Sugarcane	■	No	No	No	No
Sorghum	■	No	No	No	No
Sugar beet	No	■	■	No	■

Shaded cells indicate that a feedstock is grown In that region.

Table 7. Wood densities.

Wood (common name)	Density of green wood (wet mass / wet volume)	Basic specific gravity (dry mass / wet volume)
Eucalyptus	830 kg / m^3	480 kg / m^3
Pine	870 kg / m^3	436 kg / m^3
Spruce	930 kg / m^3	420 kg / m^3

Source: Miles and Smith 2009

The projected crop production was multiplied by crop-to-residue ratios from literature, **Table 8**, to estimate the total residue production. 50% of grain residues and 14% of forestry residues (da Silva 2016) were assumed to remain in the field to protect soil quality and prevent erosion (Holm-Nielsen 2016). Rice straw is not used to protect soil quality and therefore 100% of rice was assumed available (Ferreira-Leitao et al. 2010). In the case of industrial residues (sugar crops and about 50% of forestry residues), no losses were assumed. Losses from feedstock storage, which depend on climate and storage conditions, were beyond the scope of this study.

Table 8. Residue feedstocks considered in this thesis.

Feedstock	Location	Residue Yield[2], tonnes/hectare					Residue-to-Crop Ratio	Sources
		BR	DK	FI	NO	SE		
Forestry residues								
Eucalyptus residues	Forest, mill	15.3	—	—	—	—	0.49	da Silva 2016
Pine residues	Forest, mill	12.2	2.5	2.5	2.0	3.6	0.50 / 0.70 [1]	da Silva 2016; Searle and Malins 2013b; Pukkala et al. 2009; Øyen 2011
Spruce residues	Forest, mill	—	3.7	3.7	2.1	3.8	0.70	Searle and Malins 2013b; Pukkala et al. 2009; Øyen 2011
Grain residues								
Barley straw	Field	1.7	3.5	2.2	2.5	2.9	1.2	Adolfsson 2005; FAO 2016
Corn stover	Field	2.4	3.6	—	—	—	1.0	Ferreira-Leitao et al. 2010; Alves 2015; FAO 2016
Rice straw & husk	Field	1.7	—	—	—	—	0.47	da Silva 2016; Alves 2015; FAO 2016
Wheat straw	Field	1.7	5.1	2.7	3.2	4.7	1.3	Adolfsson 2005; Alves 2015; FAO 2016
Sugar residues								
Sugarcane bagasse	Mill	15.8	—	—	—	—	0.28	Santos 2016a; Alves 2015; FAO 2016
Sorghum bagasse	Mill	0.8	—	—	—	—	0.75	Santos 2016a; Alves 2015; FAO 2016
Sugar beet pulp	Mill	—	2.9	1.9	—	2.5	0.1	FAO Investment Centre Division 2009; FAO 2016

1: (Brazil / Scandinavia). All other values are for all regions.

2: Including both forest and mill residues for forestry feedstocks. The large difference between Brazilian and Scandinavian forestry yields is a product of different forestry management practices.

Lignocellulosic residues have other applications, such as direct combustion bioenergy and animal husbandry (Iqbal et al. 2016). To account for feedstock use competition, 30% of residues removed from the field or mill are assumed to be unavailable. Taken all together, the available residues calculation can be expressed as **Equation 1**.

Equation 1. Residue availability

$$Available\ Residues = Projected\ Crop \times Residue{:}\ Crop\ Ratio \times (1 - Soil\ Protection\ Fraction) \times (1 - Competing\ Use\ Fraction)$$

3.1.2 Residue Composition

The composition of feedstocks varies with region, varietal, growing conditions, and season. For this study, average values from the ECN Phyllis 2 database for biomass and waste (ECN 2012) were used for feedstock composition, **Table 9**. Moisture content was assumed to be that of fresh residues. Grain residues dry rapidly after harvest, achieving an equilibrium moisture of 8-18% (Coignac 2013). Forestry residues take months to dry (Phanphanich and Mani 2010), and their moisture content is around 50%. For sugarcane and sorghum, the moisture of bagasse at the mill was used. For sugar beet, data for wet pulp was unavailable so the dry pulp moisture level was used.

Table 9. Feedstock compositions used in this thesis.

Feedstock	Moisture	Cellulose	Hemicellulose[1]	Lignin	Ash	Sulfur	Nitrogen	Density[2]	HHV
Unit	% mass	% dry mass						kg/m^3	MJ/kg
Forestry residues									
Eucalyptus	42%	43%	18%	25%	1.5%	0.04%	0.30%	830	20.0
Pine[3]	50%	42%	27%	28%	0.5%	0.08%	0.17%	870	20.7
Spruce	50%	42%	22%	27%	1.0%	0.02%	0.15%	930	20.0
Grain residues									
Barley	8%	44%	23%	17%	5.0%	0.14%	0.80%	190	19.0
Corn	15%	37%	29%	15%	6.0%	0.10%	0.75%	190	19.0
Rice	15%	37%	24%	13%	18.0%	0.14%	1.00%	190	18.8
Wheat	15%	37%	37%	18%	7.0%	0.15%	0.70%	190	19.4
Sugar residues									
Sugarcane	54%	35%	36%	21%	3.5%	0.10%	0.40%	180	19.3
Sorghum	54%	36%	26%	9%	7.0%	0.20%	1.50%	180	19.2
Sugar beet	10%	25%	37%	3%	5.0%	0.15%	1.70%	560	18.2

Source: ECN 2012

1: hemicellulose includes pectin

2: density of wet residues, as delivered to the biorefinery

3: Pine species in Brazil and Scandinavia have a similar composition, and were modeled as a single feedstock.

3.2 Biorefinery

The hypothetical biorefineries in this study produce a single undistilled "biocrude" for use as marine biofuel. The high price of marine gas oil (**Table 4**) led to the decision to exclude other fuel cuts, which require additional fuel upgrading and separation expenses. A variant model including fuel cuts is addressed as a sensitivity analysis.

An integrated cogeneration plant produces heat and electricity for use in the biorefinery and excess electricity is sold to the grid. If necessary, hydrogen is also produced on-site, with any excess burnt in the cogeneration plant. No other coproducts are considered. If the non-biofuel reactor outputs generate insufficient heat, electricity, or hydrogen, natural gas is purchased to fulfill the remaining demand.

The biorefinery was assumed to have a 15-year lifespan.

3.2.1 Scale

The biorefinery was assumed to process 500 dry tonnes of feedstock per day. This is in contrast to da Silva (2016) and PNNL (Jones et al. 2009, 2013; Tews et al. 2014; Tews and Elliott 2014), who use a scale of 2000 dry tonnes per day. However, 500 tonnes is the capacity of current and planned thermochemical biorefineries (2.6) and was considered a more realistic scale for near-term construction. Different refinery scales are explored in the scaling analysis.

3.2.2 Operating days

Each feedstock has a different harvest season and storage needs, resulting in different biorefinery operating intervals (**Table 10**). Forestry residues can be harvested throughout the year (de Jong and Jungmeier 2015), while grain residues generally have two harvests of two months per year (USDA 1994), but their residues can be easily dried and stored. Sugarcane and sorghum have long (5-6 months) harvest seasons (USDA 1994), but bagasse is highly perishable, thus limiting the potential biorefinery operating time to their harvest season.

Table 10. Seasonality of feedstocks and biorefinery operating intervals.

Feedstock	Harvest period	Storable?	Refinery Operating Time
Forestry Residues			
Eucalyptus	Year round	n/a	330 days/year
Pine	Year round	n/a	330 days/year
Spruce	Year round	n/a	330 days/year
Grain Residues			
Barley	3-4 months	Yes	330 days/year
Corn	4 months	Yes	330 days/year
Rice	4 months	Yes	330 days/year
Wheat	3-4 months	Yes	330 days/year
Sugar Residues			
Sugarcane	6 months	No	180 days/year
Sorghum	5 months	No	150 days/year
Sugar beet	4 months	3-6 months	240 days/year

3.2.3 Siting

Local availability of feedstock was determined by using regional crop statistics for each country (**Table 11**). Regional production in 2020 was assumed to follow the same trend as national production. To ensure an adequate density of feedstock supply, the biorefinery's feedstock demand must be satisfied by a single region. If there is not a single region capable of supplying the biorefinery, the feedstock is excluded from further consideration for that country. As a note, the size of administrative regions in Brazil are much larger than those in Scandinavia, which is a limitation of this method, but density mapping of feedstock production was beyond the scope of this study.

In this study, the biorefinery was assumed to be located halfway between the center of the chosen supply region and the nearest large ports (**Table 40**). When multiple regions could supply the feedstock, a single site was picked based on distance to and size of the closest port. For sugar residues in Brazil, the presence of sugar mills in the supply region was also considered (Gismaps 2017). The distance between the port and the biorefinery was calculated using Google driving directions. If the distance from the feedstock source and biorefinery is shorter than the radius of the minimum area needed to supply the required residue yield, derived from **Table 8**, the radius of the minimum area is used instead.

Table 11. Regional crop production data sources, by country.

Country	Source
Brazil	IBGE 2006
Denmark	Statistics Denmark 2017
Finland	Statistics Finland 2017
Norway	Statistics Norway 2017
Sweden	Statistics Sweden 2017

3.3 Process Modeling

Three thermochemical biofuel production methods were modeled: hydrothermal liquefaction (HTL), fast pyrolysis with hydrodeoxygenation (FP), and gasification with Fischer-Tropsch synthesis (GFT). Mass balances and utility demand estimations were made for biofuel production and for pretreatment, heat and electricity cogeneration, air separation, and hydrogen production to determine the yields of biofuel, electricity, flue gases, and wastewater, as well as demand for chemicals, water, heat, electricity, hydrogen, and waste treatment services. Catalyst consumption was not explicitly considered in the model, due to the high variability in their use.

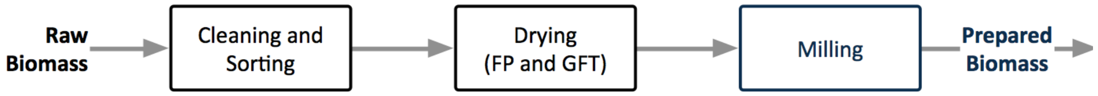
The mass balances used a unit process black-box model based on da Silva (2016), which was based on a comparative technoeconomic assessment of forest residue HTL and FP from PNNL (Tews et al. 2014) and a technoeconomic assessment of corn stover GFT at the National Renewable Energy Laboratory (NREL) in the US (Swanson et al. 2010). The model used literature yields for each feedstock/technology combination. Whenever possible, yield composition and process conditions are those from the yield source. When the data was incomplete from the yield source, an assumption was made based on the most similar combination for which data was available. This method is in contrast to da Silva who assumed the same conditions across feedstocks but adjusted yield data based on other source literature. Besides different biofuel yields, this leads to differences in utility estimations and inputs demand, and thus the expenses and emissions.

These models were used to estimate purchased equipment capacities, the variable costs, and sales revenue. The input demand, yields, and process emissions are also used in the environmental analysis. Complete process modeling parameters and assumptions used for each feedstock and technology are available in the accompanying spreadsheet.

Percentages in the methodology section are mass percentages unless explicitly mentioned otherwise.

3.3.1 Feedstock Pretreatment

Figure 7. Feedstock pretreatment, as modeled.



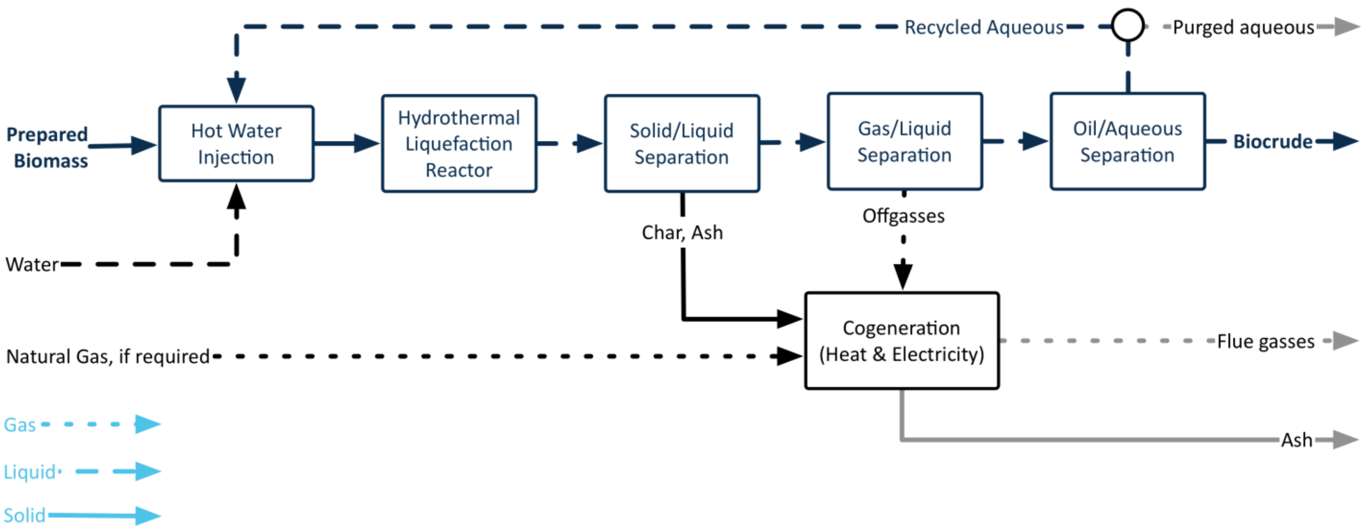
When the feedstock arrives at the biorefinery, it is cleaned, sorted, and then treated to improve its performance in the biofuel reactors, **Figure 7**. For FP and GFT, the feedstock is dried so that moisture does not inhibit the decomposition reactions, which is accomplished by heating the biomass from ambient temperatures (15C) to 120C using excess process heat from elsewhere in the system. Finally, feedstock for all pathways is finely ground to allow for fast and even transfer of heat when it enters the reactor. **Table 12** provides the electricity demand for each process, used in the utility estimations. Besides evaporated moisture from drying, the model assumed no mass loss during pretreatment.

Table 12. Feedstock pretreatment power usage.

Process	Electricity use		Source
Cleaning and feedstock Handling (all pathways)	10.0 kWh	per tonne, wet feedstock inlet	(Tews et al. 2014)
Grinding (all pathways)	71.2 kWh	per tonne, dry feedstock inlet	(Tews et al. 2014)
Drying (FP, GFT)	4.2 kWh	per tonne, wet feedstock inlet	(da Silva 2016)

3.3.2 Hydrothermal Liquefaction (HTL)

Figure 8. Hydrothermal liquefaction, as modeled.



Hydrothermal liquefaction was modeled as in **Figure 8** and **Table 13**. The wet, milled biomass is saturated with water at a ratio of 6:1-10:1, heated and pressurized to a subcritical state where it decomposes in the reactor for 10-30 minutes. The resulting output is then separated into aqueous, oil, solids, and gaseous fraction. Char and offgasses are sent to the cogeneration plant for combustion. The energy content of the biocrude and char fractions were taken from literature, and the gas energy content was calculated based on the given or assumed gas composition, available in the accompanying spreadsheet. The energy content of the biomass in the aqueous fraction was assumed to be that of unreacted biomass. Since hydrothermal liquefaction oil has been successfully combusted in diesel and marine engines (Nabi et al. 2015), upgrading via hydrotreatment or product separation was assumed to be unnecessary.

Table 13. Hydrothermal liquefaction reactor products, their energy contents, and reactor process conditions.

	Reactor Yields, % of fresh dry feed				**Product HHV**, MJ/kg			**Process Conditions**		**Sources**
	Biocrude	Aqueous	Char	Gas	Biocrude	Char	Gas	H_2O-biomass ratio	Reactor Temperature	
Forestry Residues										
Eucalyptus	**23%**	16%	27%	19%	27	26	4	6:1	250 C	Sugano et al. 2008
Pine	**35%**	35%	6%	18%	25	29	4	6:1	355 C	Tews et al. 2014
Spruce	**36%**	9%	28%	7%	27	22	2	10:1	350 C	Mosteiro-Romero et al. 2014; Tran et al. 2017
Grain Residues										
Barley	**35%**	41%	8%	15%	28	22	4	7:1	300 C	Zhu et al. 2015a
Corn	**23%**	38%	9%	14%	30	26	2	8:1	351 C	Panisko et al. 2015; Hoekman et al. 2013; Elliott et al. 2010
Rice	**24%**	11%	31%	20%	26	18	4	6:1	300 C	da Silva 2016; Li et al. 2014; Kalderis et al. 2014
Wheat	**29%**	34%	24%	5%	27	26	4	6:1	280 C	Singh et al. 2015; Reza et al. 2014
Sugar Residues										
Sugarcane	**25%**	39%	22%	4%	25	24	4	6:1	280 C	Singh et al. 2015; Hoekman et al. 2013
Sorghum	**42%**	19%	23%	17%	30	30	4	5:1	300 C	Bi et al. 2017
Sugar beet	**23%**	13%	36%	29%	33	24	4	10:1	350 C	Brilman et al. 2017

Aqueous Recycling

The aqueous fraction is recycled into the reactor feed to reduce the process water demand. Following Zhu et al (2015a) and Zhang (2010), the organics in the aqueous recyclate convert to biocrude and char, but at a lower biocrude yield and higher char yield than fresh feedstock. Due to the lack of feedstock specific data, all recyclates were assumed to convert proportionally to the barley aqueous recyclate yields from Zhu et al (2015a), **Table 14**. For each feedstock, the aqueous yields were adjusted to linearly correlate with fresh feed biocrude yields, with feedstocks that have higher fresh feed conversion having higher aqueous conversion rates. The remainder of aqueous organics was assumed unconverted and leaves the reactor as aqueous. In each cycle, 20% of the aqueous outflow is purged and replaced with fresh water to prevent organic buildup in the reactor.

Table 14. HTL Aqueous Recyclate Yields, % of dry organics in aqueous.

Feedstock	Biocrude	Char
Forestry Residues		
Eucalyptus	5%	15%
Pine	8%	23%
Spruce	8%	24%
Grain Residues		
Barley	8%	23%
Corn	5%	15%
Rice	5%	16%
Wheat	7%	19%
Sugar Residues		
Sugarcane	6%	16%
Sorghum	10%	28%
Sugar beet	5%	15%

Based on Zhu et al. 2015a

As the aqueous recycling affects the product output, system yields were calculated by iterating the model until the aqueous recyclate quantity reached equilibrium and then dividing the total biofuel output by the total fresh biomass input. To achieve equilibrium, the recycling model was iterated 25 times until the change in the recyclate organics mass was less than 0.001%. For the biofuel yield calculation, a further 75 runs at equilibrium were also included. Only the biofuel yields were considered at equilibrium; process inputs and utility demand were from the 25th iteration. If the water content of the aqueous fraction exceeded the solvent demand of the fresh biomass, no fresh water was assumed necessary, but no adjustment to the rate of aqueous recycling was made. The system iterations and equilibrium calculations are available in the accompanying spreadsheet.

Table 15 lists the electricity demand for each HTL process. Heat demand was estimated based on the reactor feed temperatures in **Table 13**, and the reactor was also assumed to require an additional 90MJ of heat per kilogram of feed to maintain reactor temperature for the entire residence period (Tews et al. 2014).

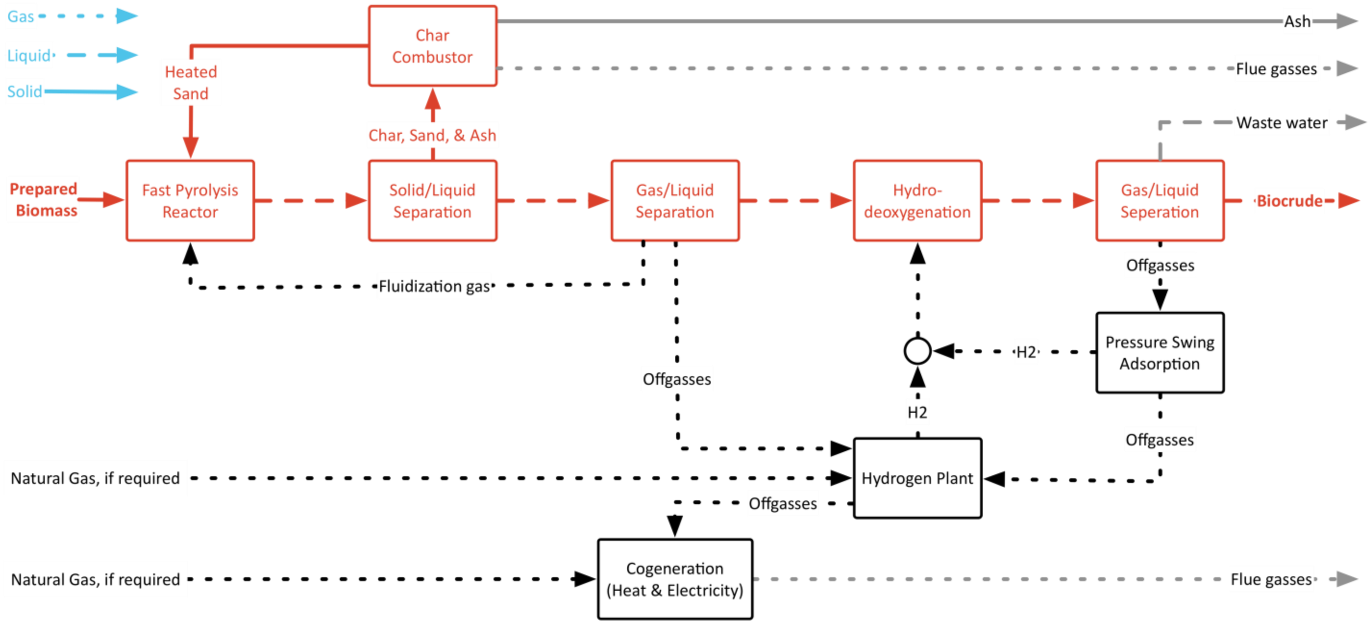
Table 15. Hydrothermal liquefaction electricity demand.

Process	Electricity demand		Source
Water injection and pressurization	12.0 kWh	per tonne, dry feedstock inlet	Tews et al. 2014
HTL Reactor	9.0 kWh	per tonne, reactor feed inlet	

Finally, it must be emphasized that the yields and process conditions for hydrothermal liquefaction are subject to high uncertainty, as all available data are from lab scale experiments. The product yields are explored in a sensitivity analysis as is the inclusion of HTL biofuel upgrading via hydrodeoxygenation.

3.3.3 Fast Pyrolysis (FP)

Figure 9. Fast pyrolysis, as modeled.



In Fast Pyrolysis, **Figure 9**, dried, finely ground feedstock is fed to the reactor in a fluidizing medium of sand and gas, in ratios of 14.5:1 and 3:1 to the feedstock mass (da Silva 2016). The feedstock is reacted at 450-750C in the absence of oxygen for 0.5-3.0 seconds, resulting in a slurry of gas, liquids, and char. The reactor temperature, product yields and their energy contents are listed in **Table 16**. The solid fraction of the pyrolysis reactor output, consisting of char, ash, and sand is diverted to a combustor. The char is combusted with an assumed 100% efficiency, heating the sand, which is returned to the reactor feed, providing the dominant heat source for the pyrolysis reactor (Tews et al. 2014). Part of the gas fraction is recycled to fluidization gas for the reactor, and the remainder is sent to a hydrogen plant, described below. The entire gas output, both the fluidization gas and that sent to the hydrogen plant, were assumed to have the same composition, available in the accompanying spreadsheet. The organic fraction of the fluidization gas was assumed to have no influence on the product yields.

Table 16. Fast pyrolysis reactor product yields, their energy content, and reactor process conditions.

	Reactor Yields, % of dry feed			**Product HHV,** MJ/kg			**Reactor Temperature**	**Source**
	Pyrolysis Oil *(% H₂O)*	Char	Gas	Pyrolysis Oil	Char	Gas		
Forestry Residues								
Eucalyptus	**59%** *(26%)*	22%	13%	17	31	10	500 C	Chang et al. 2013
Pine	**64%** *(24%)*	17%	18%	17	27	10	520 C	Tews et al. 2014
Spruce	**78%** *(26%)*	15%	22%	17	27	7	500 C	Piskorz et al. 1998
Grain Residues								
Barley	**52%** *(31%)*	32%	16%	11	26	5	500 C	Oasmaa et al. 2010; Mulligan et al. 2010
Corn	**65%** *(9%)*	17%	21%	22	22	6	500 C	Mullen et al. 2010
Rice	**75%** *(25%)*	18%	17%	19	22	9	491 C	Jung et al. 2008
Wheat	**54%** *(46%)*	32%	14%	15	28	5	500 C	Mulligan et al. 2010
Sugar Residues								
Sugarcane	**70%** *(26%)*	17%	13%	18	25	11	495 C	Hugo 2007
Sorghum	**69%** *(15%)*	13%	17%	16	23	6	510 C	Piskorz et al. 1998
Sugar beet	**46%***(13%)*	21%	33%	18	25	2	723 C	Aho et al. 2013

Hydrodeoxygenation (HDO)

The liquid reactor product, called pyrolysis oil has a high water content and a low pH, which makes it unsuitable for use as-is in marine engines. Therefore, it is sent to a hydrotreatment reactor along with hydrogen gas, where it undergoes hydrodeoxygenation at 400C. Hydrodeoxygenation was assumed to function as described in Gracà et al. (2013). During HDO, the oxygenated hydrocarbons react with hydrogen and a catalyst under high heat and pressure to convert to water and diesel-length hydrocarbons. Also, some of the nitrogen and sulfur in the pyrolysis oil reacts with the hydrogen and is removed.

During HDO, the pyrolysis oil's total organic content increases slightly from the addition of hydrogen. After the upgraded oil leaves the reactor, it is separated again, to remove unreacted hydrogen gas, gaseous light organics formed during HDO, and the now-separable aqueous fraction. Based on Meyer et al. (2016) and Howe et al. (2015), a large fraction of the oil's organics (**Table 17**) was assumed lost to imperfect separation of the aqueous fraction. Da Silva, in contrast, assumes no organic losses to the aqueous phase. The remaining HDO oil was assumed to have an oxygen content below 1% and an energy content of 35 MJ/kg (Wildschut 2009) for all feedstocks, as feedstock specific data was unavailable. HDO oil has been tested as stable and functional in diesel engines (Wildschut 2009) and was assumed to be usable in marine diesel engines without the need for further upgrading or separation.

50% of hydrogen gas fed to the HDO unit was assumed to exit unreacted (Tews et al. 2014). Unreacted hydrogen from hydrotreatment is recovered from the offgasses via pressure swing adsorption and recycled into hydrotreatment, with an 85% recovery rate (da Silva 2016). The remaining offgasses are sent to the hydrogen plant.

Table 17. Hydrotreatment yields, in % of dry pyrolysis oil.

	HDO Oil	Losses to Gas	Losses to Aqueous
Forestry Residues			
Eucalyptus	51%	10%	39%
Pine	51%	10%	39%
Spruce	45%	10%	45%
Grain Residues			
Barley	50%	10%	40%
Corn	50%	10%	40%
Rice	50%	10%	40%
Wheat	50%	10%	40%
Sugar Residues			
Sugarcane	50%	10%	40%
Sorghum	50%	10%	40%
Sugar beet	50%	10%	40%

Sources: Meyer et al. 2016; Howe et al. 2015

Hydrogen Plant

The hydrogen plant, **Figure 10**, accepts the fast pyrolysis and hydrotreatment offgasses and converts their light organic content into hydrogen via steam methane reforming and the water gas shift. Based on da Silva (2016), a 100% conversion of light hydrocarbons and a water-to-light-organics ratio of 1.52:1 was assumed. The hydrogen plant has a product yield of 0.42 kg H/kg light hydrocarbons, and also produces 0.96 kg CO and 1.13 kg CO2 per kilogram of light hydrocarbons. 85% of produced hydrogen was assumed recovered by pressure swing adsorption. Offgasses from the hydrogen plant are sent to the cogeneration plant. If the hydrogen produced by the offgasses is insufficient, a supplemental feed of natural gas is used to produce the additional necessary hydrogen.

Figure 10. Hydrogen production, as modeled.

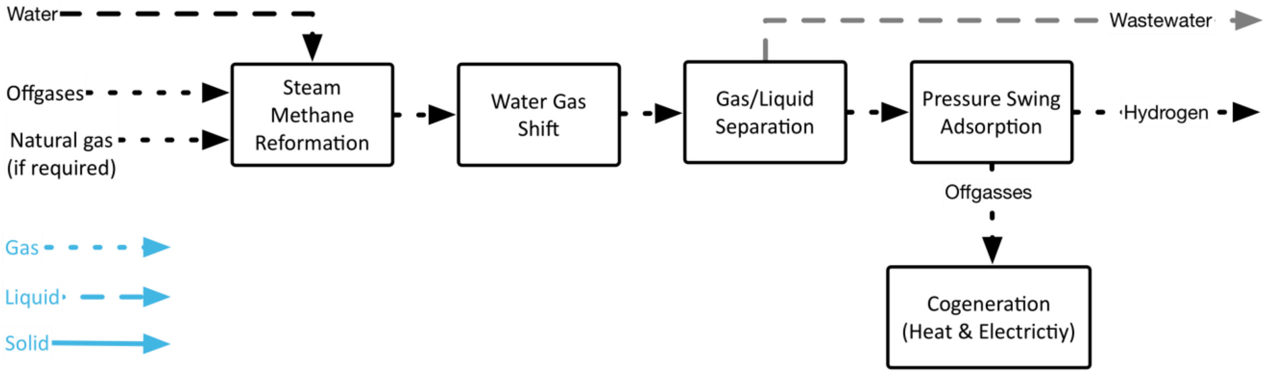


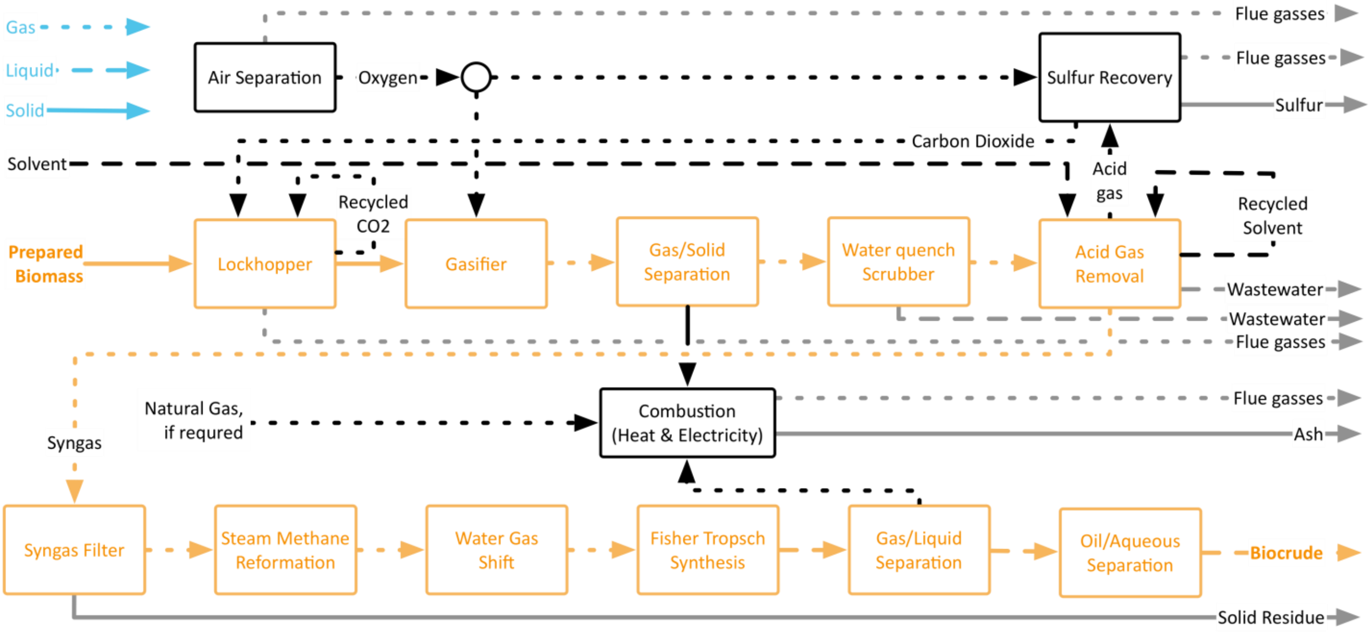
Table 18 lists the electricity demands considered in the fast pyrolysis utility model.

Table 18. Fast pyrolysis electricity demand.

Process	Electricity demand		Source
FP Reactor	2 kWh	per tonne, dry feedstock inlet	Tews et al. 2014
HDO reactor	170 kWh	per tonne, reactor feed inlet	Zhu et al. 2011
Hydrogen Plant	421 kWh	per tonne, hydrogen output	da Silva 2016

3.3.4 Gasification with Fischer-Tropsch synthesis (GFT)

Figure 11. Gasification with Fischer-Tropsch synthesis, as modeled.



Gasification with Fischer-Tropsch synthesis was modeled as in **Figure 11**. The dried, ground feedstock is pressurized with carbon dioxide and gasified with oxygen and steam with a 4:1 biomass-to-oxygen and a 1.5:1 oxygen-to-steam ratio at a temperature of 700-900C, over a catalyst, such as nickel-dolomite. Oxygen is provided via an air separation unit. The gasification produces a “synthesis gas,” char, and tar residue, **Table 19**. The syngas is comprised of hydrogen, carbon monoxide, carbon dioxide, methane, and light hydrocarbons (C_2H_n to C_4H_n, abbreviated as C_2-C_4). If the source literature for a given feedstock was for air-gasification, rather than oxygen-gasification, the nitrogen yield was excluded. Solids are separated via a cyclone, and sent to the cogeneration plant for combustion. 5% of carbon dioxide was assumed to leak into the gasifier and the rest is recycled in the lockhopper.

Table 19. Gasification yields, syngas composition, product energy content, and reactor temperature.

	Yields, % dry feed			**Syngas Composition,** % syngas					**HHV,** MJ/kg		**Reactor Temperature**	**Source**
	Syngas	Char	Liquid	%H_2	%CO	%CO_2	%CH_4	%C_2-C_4[1]	Syngas	Liquid		
Forestry Residues												
Eucalyptus	**72%**	2%	27%	9%	33%	58%	0%	0%	15.9	24.1	700 C	Garcia et al. 1999
Pine	**72%**	1%	27%	9%	33%	58%	0%	0%	17.4	24.1	700 C	Garcia et al. 1999
Spruce	**72%**	2%	27%	9%	33%	58%	0%	0%	17.4	24.1	700 C	Garcia et al. 1999
Grain Residues												
Barley	**70%**	16%	14%	2%	33%	42%	11%	11%	15.0	24.1	830 C	Carpenter et al. 2010
Corn	**79%**	7%	14%	2%	32%	57%	4%	5%	11.7	24.1	780 C	Swanson et al. 2010
Rice	**70%**	16%	14%	2%	44%	38%	15%	1%	15.7	24.1	830 C	da Silva 2016
Wheat	**54%**	20%	26%	2%	33%	42%	11%	11%	15.0	24.1	830 C	Carpenter et al. 2010
Sugar Residues												
Sugarcane	**93%**	2%	3%	1%	30%	60%	4%	5%	9.6	24.1	800 C	Figueroa et al. 2014
Sorghum	**76%**	9%	14%	1%	30%	63%	6%	0%	8.3	24.1	700 C	Panopoulos and Vamvuka 2009
Sugar beet	**70%**	16%	14%	1%	30%	63%	6%	0%	8.3	24.1	700 C	Panopoulos and Vamvuka 2009

1: C_2-C_4 refers to light hydrocarbons in the range of C_2H_n and C_4H_n

After solids separation, the syngas is cleaned via a water quench and scrubber, which removes solids, tar, CO_2, and ammonia, with the efficiencies assumed in **Table 20**. Some light hydrocarbons are also lost. Acid gas removal then removes CO_2 and sulfur using a solution of 20% monoethanolamine (MEA) in water as a solvent. The CO_2 and 98% of the solvent are recovered and recycled. The syngas is then filtered to remove any remaining solids as well as reduce sulfur and ammonia content to 50ppb and 10ppm, respectively. The clean syngas is then subject to steam methane reforming with a steam-to-methane ratio of 6:1 until the output syngas has a methane content of 1.5%, and, if necessary, a water-gas shift to improve the hydrogen-to-carbon monoxide ratio to a minimum of 2.15:1.

The upgraded syngas is sent to a Fischer-Tropsch reactor, which was assumed to operate at 200C with a cobalt-aluminium catalyst, with an assumed syngas-to-fuel conversion efficiency of 78%. In the reactor, the hydrogen and carbon monoxide in the syngas is synthesized into hydrocarbons whose size was assumed to follow the Anderson-Schulz-Flory equation and the associated chain-growth factor for cobalt catalysts (detailed in da Silva 2016). The energy content of the resultant GFT biofuel was calculated using its hydrocarbon distribution.

Table 20. Syngas upgrading process efficiencies.

Syngas Upgrading Process	Cleaning Process	Efficiency
Cyclone	Char Removal	99%
	Ash Removal	99%
Water Quench	Solids removal	99%
	NH_3 removal	90%
	Tar removal	100%
	CO_2 removal	19%
	C_2-C_4 removal	19%
Acid Gas Removal	CO_2 removal	90%
	Sulfur removal	99%
Syngas Filter	Solids removal	100%
Steam methane reforming	Methane conversion	100%
	C_2-C_4 conversion	100%

Source: da Silva 2016

The electricity demands considered in the GFT model are provided in **Table 21**.

Table 21. Gasification with Fischer-Tropsch synthesis electricity demand.

Process	Electricity Demand	
Air separation (O2 production)	280	kWh per tonne, O_2 outlet
Gasifier	139	kWh per tonne, dry biomass inlet
Fischer-Tropsch Reactor	26	kWh per tonne, dry biomass inlet

Source: da Silva 2016

3.3.5 Utilities, Heat Recovery, and Cogeneration

Electricity and Heat Demand

The biorefinery's **electricity demand** was estimated using the power consumption of major equipment for each pathway (**Table 15**, **Table 18**, **Table 21**). **Heat demand** was estimated for unit processes using the temperatures and mass of the inlet and outlet streams, per **Equation 2**, using the specific heats in **Table 22**. The ambient temperature of the biorefinery was assumed to be 15C. Changes in specific heat based on temperature or pressures are assumed to be insignificant and are not considered.

Equation 2. Unit process heat demand.

$$Heat\ Demand = \sum_{streams} (Temperature_{out} - Temperature_{in}) \times Mass_{stream} \times Specific\ heat_{stream}$$

Table 22. Specific heats of materials modeled in this thesis.

Material	Specific Heat	
Water	4.182	kJ/kg/K
Air	1.005	kJ/kg/K
Oxygen	0.918	kJ/kg/K
Hydrogen	14.304	kJ/kg/K
Steam	3.985	kJ/kg/K
Sand	0.830	kJ/kg/K
Carbon dioxide	0.814	kJ/kg/K
Methane	3.000	kJ/kg/K
Carbon monoxide	1.000	kJ/kg/K
C_2-C_4 hydrocarbons	1.500	kJ/kg/K

Source: Engineering Toolbox 2017a

Heat recovery

The biorefinery was assumed to have a **heat exchange network** to recover process heat and satisfy heating and cooling demand. Since an equipment-level heat integration was the scope of this study, an overall level of heat recovery was assumed for each technology, **Table 23**, based on literature. A value for fast pyrolysis was unavailable, and therefore the value for GFT, which is a typical value for high efficiency heat exchange systems, was used. The effect of heat integration on the economic and environmental performance is explored in a sensitivity analysis.

Table 23. Heat recovery efficiencies.

	Efficiency		Source
Hydrothermal liquefaction	80%	of process heat recovered	Johanssen et al. 2016
Fast pyrolysis	90%	of process heat recovered	Swanson et al. 2010
Gasification with Fischer-Tropsch synthesis	90%	of process heat recovered	Swanson et al. 2010

Cogeneration

Heat and electricity are produced on-site in a **cogeneration plant**. All char and offgasses unused in elsewhere in the refinery are combusted in a furnace with 20% excess of air. The heat and flue gases generated from gas combustion were determined stoichiometrically using the equations in **Table 24**. The heat is used to produce steam in a condensing boiler and electricity is generated via a steam turbine. Both the boiler and turbine are assumed to have efficiencies of 80% (da Silva 2016). If the combustion of process residues do not generate sufficient to satisfy the biorefinery demands, natural gas is purchased and combusted to supply the deficit. If the combusted residues produce excess energy, it is sold to the grid as electricity.

Table 24. Combustion reactions modeled in cogeneration processes.

Reactants				Products	Heat of Reaction[1]	
CO	+	0.5 O_2	$\rightarrow$	CO_2	-10.1	MJ/kg CO
CH_4	+	2 O_2	$\rightarrow$	CO_2 + 2 H_2O	-55.5	MJ/kg CH_4
H_2	+	0.5 O_2	$\rightarrow$	H_2O	-141.6	MJ/kg H_2
S	+	O_2	$\rightarrow$	SO_2	-9.3	MJ/kg H_2
C_2H_4	+	4 O_2	$\rightarrow$	2 CO_2 + 2 H_2O	-50.3	MJ/kg C_2H_4
C_3H_6	+	4.5 O_2	$\rightarrow$	3 CO_2 + 3 H_2O	-52.5	MJ/kg C_3H_6
C_4H_{10}	+	10 O_2	$\rightarrow$	4 CO_2 + 5 H_2O	-49.5	MJ/kg C_4H_{10}
$C_{2.5}H_6$ [2]	+	4 O_2	$\rightarrow$	2.5CO_2 + 3 H_2O	-50.8	MJ/kg $C_{2.5}H_6$
natural gas	+	2 O_2	$\rightarrow$	CO_2 + 2 H_2O	-50.0	MJ/kg gas

1: Negative values indicate that the reaction is exothermic

2:.Used for light hydrocarbons (C_2-C_4) not otherwise specified.

Source: NIST 2016

Water Demand

Water demand was estimated from explicit process water demand and from the total heat demand of the system, which is provided by steam, assuming 2.4MJ per kilogram of steam. Water within the heat exchange system was assumed to be recycled. However, the make-up water is needed to replace steam that has evaporated during condensation. The evaporation rate is dependent on the pressure differential of the hot steam and the cooled condensate. The steam was assumed to have pressure of 25 bar and condensate was assumed to be at atmospheric pressure. Therefore, make-up water of 22% of steam demand is needed (TLV 2017).

The boiler also requires blowdown water, which is water that is flushed from the system and then replaced to prevent the buildup of solids that can damage the boiler (Engineering Toolbox 2017b). A boiler blowdown of 3% of steam demand (da Silva 2016) was assumed.

Waste Treatment

Waste treatment was assumed to take place outside of the biorefinery's system boundaries and no mass balances or utility estimation was made. The quantity of solid waste, wastewater, and flue gasses were used for estimating waste treatment costs.

Solid waste was assumed to be landfilled. The wastewater from biofuel production was heavily contaminated by organics, and was assumed to require primary, secondary, and tertiary treatment to reach a quality where it could be discharged into the environment. Flue gasses were assumed to be cleaned before emissions to remove sulfur dioxide, nitrogen oxides, and particulate matter (Carlsson 2008). Therefore, it was assumed there are no process emissions of SO_2 or NO_x.

3.3.6 Energy Balances

Detailed energy or enthalpy balances are beyond the scope of this study. However, the use of assumed compositions for the conversion process's char and gas phases when values are unavailable from the source literature creates a potential source of error in the total energy yields of the systems. Therefore simple in/out energy balances were conducted for the main product reactor and the overall system using higher heating values to ensure no energy yields exceed the theoretical maximum. The balances use the biomass energy contents in **Table 9** and the reactor product energy contents in **Table 13**, **Table 16**, and **Table 19**, and the biofuel energy content is derived as discussed in each technology section, above. For HTL, the energy balance is performed on a single pass of the system using the equilibrium recyclate quantity, and assuming the biomass in the recycled aqueous has the same energy content as fresh biomass. Natural gas was assumed to have an energy content of 40MJ/kg. The energy content of chemicals and process water are excluded.

3.4 Economic Modeling

Estimations of the biorefineries' capital expenses, annual operation costs, and sales revenue provides a metric for assessing the potential commercial viability of each technology-feedstock-country combination, and allows for comparison between combinations and other fuel production and emission abatement technologies.

All monetary values were standardized to 2015 US dollars (USD) to align with prior HIP reports (da Silva 2016; Santos 2016a). For capital costs, the Chemical Engineering Plant Cost Index (CEPCI) (Chemical Engineering 2016) was used to adjust source values from other years. Source values in foreign currencies were converted to USD using origin-year exchange rates and then adjusted for inflation.

3.4.1 Sales Revenue

Annual sales revenue is a factor in capital and operating expenses estimations (**3.4.2**, **3.4.3**) and so was calculated first. Sales revenue for each combination was calculated by multiplying the annual biofuel and electricity yields for that technology and feedstock by the national product selling price and summing over both products. For the purposes of estimating the sales revenue, the biofuel was assumed to be sold at the wholesale price of marine gas oil and electricity at the wholesale market rate, **Table 25**. Using marine gas oil prices puts the cost of the marine biofuel at the low end of the International Chamber of Shipping's estimated price for sulfur cap compliant fuel (ICS 2016).

Table 25. Prices of biorefinery products, by country, in 2015 USD.

	Unit	Brazil	Denmark	Finland	Norway	Sweden	Source(s)
Biofuel (MGO price)	tonne	$680	$477*	$477*	$517	$511	(Ship & Bunker 2017) March 31 prices
Electricity	MWh	$43	$31	$36	$29	$29	(CCEE 2017; Nord Pool 2017) 2016 average price

* No country-specific price was available, so Rotterdam fuel prices were used

3.4.2 Capital Expenses (CapEx)

Capital expenses (CapEx) are the investment necessary to construct a new biorefinery. Following the methodology of biofuel technoeconomic analysis in da Silva (da Silva 2016) and others (Tews et al. 2014; Zhu et al. 2014; Swanson et al. 2010; Kempegowda et al. 2015), the capital expenses were estimated assuming “nth-plant” construction, that the construction and operation of the plant are based on well-established design and processes, and excludes the additional design, time, and learning costs inherent in a “first of a kind” construction.

Capital costs were estimated using the methodology and suggested factors in (Seider et al. 2009), summarized in **Table 26** and elaborated below, which is the same methodological source used by da Silva. However, in this study, more conservative factors for installation costs, contingency, start-up costs, and location factors were used, based on the suggestions of Seider et al. (2009) and other literature. Given their high uncertainty, capital expenses were subjected to a sensitivity analysis to determine their influence on the over biofuel selling price.

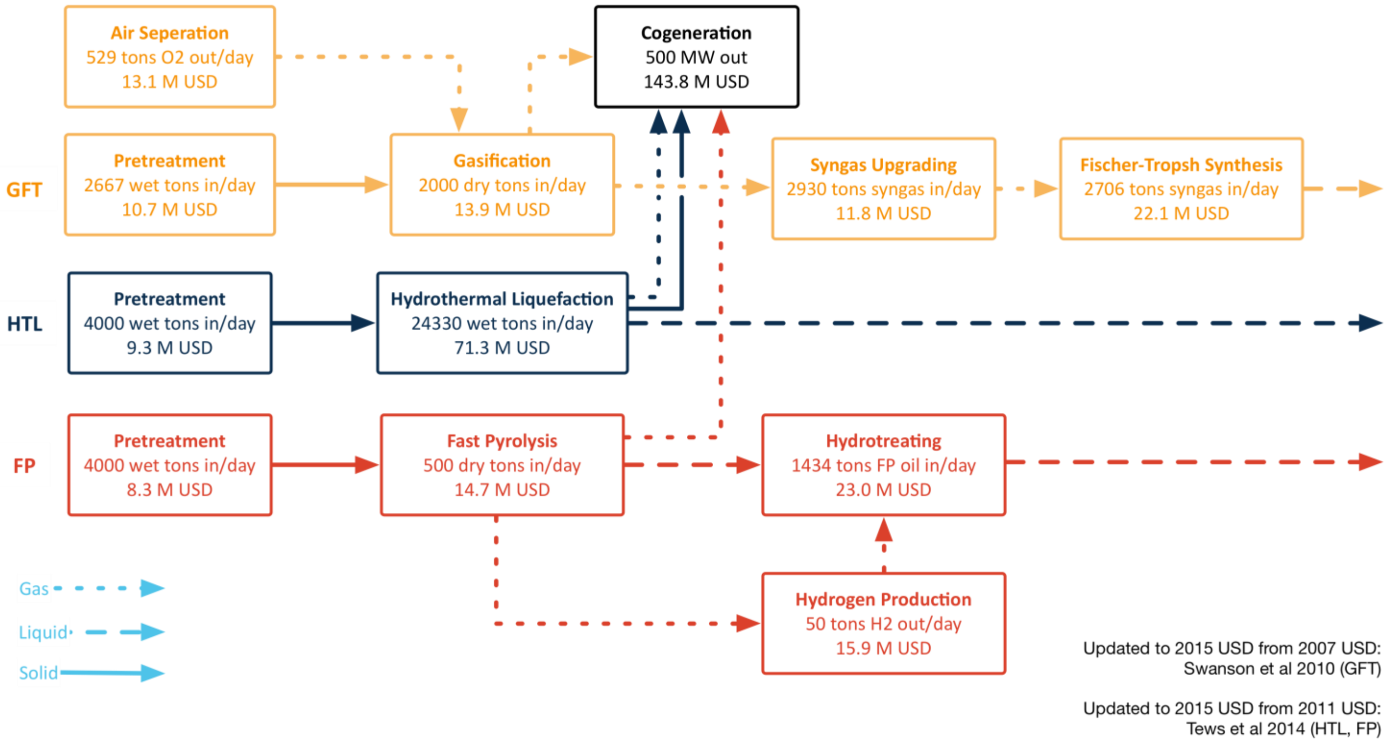
Table 26. Capital expenses model.

code		Factor or Formula	
FCI	**Fixed Capital Investments, including**	**FCI =** DC **+** IC **+** C	
DC	Direct Capital Cost, including	DCI = *TPEC + INST*	
TPEC	*Total Purchased Equipment Cost*	*TPEC = sum of scaled equipment costs*	
INST	*Installation Costs*	*250%*	*of TPEC*
IC	Indirect Costs	34%	of Direct Costs
CF	Contractor's Fee	23%	of TPEC
C	Contingency	50%	of TPEC
WC	**Working Capital**	**20%**	**of Sales Revenue**
SC	**Start-up Costs**	**7%**	**of FCI**
TCI	TOTAL CAPITAL INVESTMENT	TCI = FCI + WC + SC	
CapEx	**LOCATION-ADJUSTED CAPITAL INVESTMENT**	**CapEx = TCI x Location Factor**	

The **total purchased equipment costs** (TPEC) are the costs of bare equipment delivered to the biorefinery. TPEC were determined by scaling literature costs to the necessary capacities determined in the process model. To correspond with the level of detail in the process model, the equipment costs were considered on a section level rather than by individual pieces of equipment. **Figure 12** summarizes the reference equipment costs and source capacities for all pathways. Tews et al. (2014) was the primary source for equipment costs for the hydrothermal liquefaction and fast pyrolysis pathways and Swanson et al. (2010) was the primary source for Fischer-Tropsch gasification. The source values were adjusted from 2007 (CEPCI: 525.4) and 2011 (CEPCI: 585.7) to 2015 (CEPCI: 556.8) using **Equation 3.** The updated costs were then adjusted for the difference in capacities using **Equation 4** and the scaling factors (n) in **Table 27**. For biofuel conversion processes, the inlet mass flow was used as the capacity reference, while the product outflow was used for the utility processes.

The equipment’s **installation costs** account for the materials (e.g. piping, wires, control units) and labor of installation and are calculated by multiplying the TPEC by an installation factor. Depending on the complexity of the equipment, the factor can vary widely, e.g. from 1.4 for crushers, to 4.1 for pressurized vessels (Seider et al. 2009). In biofuel technoeconomic assessments, installation factors typically range between 2.0 and 3.0 (Elliott et al. 2009; Jones et al. 2009; Swanson et al. 2010; Zhu et al. 2011). This study used an installation factor of 2.5 for all equipment.

Figure 12. Equipment costs and scales in source literature 2015 USD.



Updated to 2015 USD from 2007 USD: Swanson et al 2010 (GFT)

Updated to 2015 USD from 2011 USD: Tews et al 2014 (HTL, FP)

Equation 3. Investment costs scaling for different investment years.

$$Investment_{year\ A} = Investment_{year\ B} \times \left(\frac{Index_{year\ A}}{Index_{year\ B}}\right)$$

Equation 4. Investment costs scaling for different investment capacities.

$$Investment_{scaled} = Investment_{base} \times \left(\frac{Capacity_{scaled}}{Capacity_{base}}\right)^{n}$$

Table 27. Capacity scaling factors (n) used in this thesis.

Process	Scaling Factor (n)
Feedstock Handling	0.7
Hydrothermal Liquefaction	0.75
Fast Pyrolysis	0.7
Gasification Fischer Tropsch	0.65
Hydrotreatment	0.75
Hydrogen Production	0.65
Cogeneration & Utilities	0.7

The equipment and installation costs make up the **direct capital costs**. **Indirect costs** are other costs associated with construction, including freight, insurance, office expenses, and worker benefits (Seider et al. 2009). Indirect costs were estimated at 34% of direct capital costs. The **contractor's fee** was estimated at 23% of equipment costs. A **contingency factor**, to account for unexpected costs or costs currently unaccounted for, was set at 50% of equipment costs. The direct and indirect costs, contractor's fee, and contingency make up the **fixed capital investment**.

Start-up costs are incurred after the construction is complete but before the plant is operational. These include testing of equipment, plant commissioning, and related labor costs (Seider et al. 2009). Start-up costs were estimated at 10% of fixed capital costs. Relatedly, **working capital** is the investment needed to cover operational costs before sales begin, including inventory, process inputs, and utilities (Seider et al. 2009), here estimated at 20% of annual sales revenue. Fixed capital, working capital, and startup costs form the **total capital investment**.

Since the sources used for equipment costs are for USA-based construction, a **location factor** (**Table 28**) was added, to account for the difference in construction costs in the USA, Brazil, and Scandinavia using **Equation 5**. Location-specific costs include labor, land, taxes, and the domestic availability materials and equipment. Location factors for Scandinavian countries were unavailable, so the factor for Germany was used as a proxy. Da Silva (2015) used a location factor of 1.1 for Brazil, but the source was unknown.

Table 28. Location factors for capital investment used in this thesis.

Country	Location Factor (May 2015)
Brazil	1.25
Scandinavia	1.07
USA	1

Source: (Intratec Solutions 2017)

Equation 5. Investment cost adjustment for investments in different locations.

$$Capital\ Costs_{location\ A} = Capital\ Costs_{location\ B} \times \left(\frac{Location\ Factor_{location\ A}}{Location\ Factor_{location\ B}}\right)$$

3.4.3 Operating Expenses (OpEx)

Operating expenses (OpEx) are the costs of the daily production of biofuel, including feedstock, utilities, labor, maintenance, taxes, and insurance. Together with the sales revenue, operating expenses were used to determine the biorefinery's potential earnings.

In this study, the operation expenses were calculated according to the methodology and suggested factors in (Seider et al. 2009) (**Table 29**), which is the methodological source of da Silva (2016), though more conservative factors were chosen for maintenance and general expenses and an additional contingency factor was added. Country-specific costs were used for feedstock, utilities, waste treatment, and labor.

Table 29. Operational costs model.

code		Factor or Formula		
DPC	**Direct Production Costs, including**	DPC = VC + L + M		
VC	Variable costs, including	VC = f + c + u + wt		
f	*feedstock*	*Location specific,* **Table 30** *and* **Table 31**		
c	*chemicals*	*Location generic*		
u	*utilities*	*Location specific,* **Table 32**		
wt	*waste treatment*	*Location specific,* **Table 34**		
L	Labor Related Costs, including	L = dw + sv		
dw	*direct wage and benefits*	*Location specific,* **Table 35**		
sv	*supervision and supplies*		*50%*	*% direct wages*
M	Maintenance		10%	% fixed capital costs
C	**Contingency**		20%	% of direct production costs
PO	**Plant Overhead**		70%	% of labor related costs
FC	**Fixed Charges, including**	**FC = lt + i + d**		
		Brazil	**Scandinavia**	
lt	Local Taxes	1.5%	3.0%	% fixed capital costs
i	Insurance	1.0%	1.0%	% sales revenue
d	Depreciation	15.0%	11.0%	% fixed capital costs
GE	**General Expenses**		10%	**% Sales Revenue**
OpEx	**TOTAL OPERATING EXPENSES**	**OpEx = DPC + C + PO + FC + GE**		

Feedstock costs were calculated using the price of feedstock at its source, **Table 30**, and adding the costs of transport to the biorefinery by truck, **Table 31**. When region-specific prices were not available, the prices from the closest neighboring country were used, and when feedstock-specific prices were not available, the price of the most similar feedstock was used. For sorghum in Brazil, corn in Denmark, and sugar beet, an "as delivered" price was used, due to the lack of available at-source prices.

The only reagent **chemical** considered was the solvent used for GFT syngas cleaning. Due to the lack of country-specific data, the same price of $1850/tonne monoethanolamine (da Silva 2016) was used for all countries.

Utilities considered include water and natural gas, **Table 32**.

Table 30. Feedstock costs, by country, in 2015 USD per wet tonne.

	Brazil	Denmark	Finland	Norway	Sweden
Forestry residues					
Eucalyptus	$18 (Alves 2015)	—	—	—	—
Pine	$24 (Alves 2015)	$44 (Olsson et al. 2010)	$32	$63	$32 (Ericsson and Werner 2016)
Spruce	—	$44 (Olsson et al. 2010)	$32	$63	$32 (Ericsson and Werner 2016)
Grain Residues					
Barley	$38 (Bain 2007)	$70 (Statistics Denmark 2017)	$44 (Kühner 2013)	$44	$44
Corn	$38 (Bain 2007)	$90* (Wormslev et al. 2016)	—	—	—
Rice	$24 (Alves 2015)	—	—	—	—
Wheat	$38 (Bain 2007)	$66 (Kühner 2013)	$44	$44	$44
Sugar Residues					
Sorghum	$85* (Alves 2015)	—	—	—	—
Sugar beet	—	$150* (Gudoshnikov 2016)	$150*	$150*	$150*
Sugarcane	$17 (Alves 2015)	—	—	—	—

* Feedstock price is as-delivered, because no at-source price was available.

Table 31. Feedstock transportation costs, by country, in 2015 USD per unit.

	Brazil	Denmark	Finland	Norway	Sweden	unit
Truck transport, fixed	$5.6	$7.5	$7.5	$7.5	$7.5	per tonne
Truck transport, variable	$0.16	$0.31	$0.49	$0.19	$0.26	per tonne-kilometer
Source	(Alves 2015)	Scandinavian average	(Hannula and Kurkela 2013)	(Kempegowda et al. 2015)	(Bergström and Di Fulvio 2014)	

Table 32. Utility costs, by country, in 2015 USD per tonne.

	Brazil	Denmark	Finland	Norway	Sweden
Process Water	$0.25 (da Silva 2016)	$0.69 (Stockmarr and Thomsen 2009)	$0.51 (Rajendran et al. 2016)	$0.49 (Kempegowda et al. 2015)	$0.51 (Rajendran et al. 2016)
Natural Gas	$104.7 (da Silva 2016)	$424 (BEIS 2017)	$539 (BEIS 2017)	$364.7 (BEIS 2017)	$584 (BEIS 2017)

Waste treatment costs include the ash disposal, wastewater treatment, and flue gas cleaning. For ash disposal to landfill, direct literature costs were used. For wastewater treatment and flue gas cleaning, consistent literature values were not available, and they were estimated using the method from Ulrich and Vasudevan (2006), **Equation 6**. The formula estimates the waste treatment costs based on utility-specific constants (*a* and *b,* **Table 33**); the CEPCI as a measure for inflation; and fuel prices, in this case natural gas, as a measure for energy-dependent costs. For wastewater treatment, the factors for tertiary treatment include filtration, activated sludge, and chemical processing. For flue gas cleaning, the cost of thermal incineration without flue gas cleaning was subtracted from the cost of thermal incineration with flue gas cleaning to estimate the flue gas cleaning costs themselves. Since the waste treatment is outside the system boundaries, the scale of the processing facilities are unknown and midrange values from Ulrich and Vasudevan (2006) were used. **Table 34** presents the waste treatment costs used in this study.

Equation 6. Utility estimation formula from Ulrich and Vasudevan (2006).

$$Cost_{utility} = a \times CEPCI_{2015} + b \times Cost_{fuel}$$

Table 33. Waste treatment constants used in **Equation 6**, from Ulrich and Vasudevan (2006).

	a	*b*	*q [assumed scale]*
Tertiary wastewater treatment	$0.0005 + 1 \times 10^{-4} \times q^{-0.6}$	0.1	0.1 m^3/s
Thermal incineration with flue gas cleaning	$1.5 \times 10^{-5} \times q^{-0.23}$	0.003	0.5 Nm^3/s
Thermal Incineration without flue gas cleaning	$1 \times 10^{-5} \times q^{-0.23}$	0.002	0.5 Nm^3/s

Table 34. Waste treatment costs, by country, in 2015 USD per tonne.

	Brazil	Denmark	Finland	Norway	Sweden
Ash Disposal	$23	$142	$77	$163	$135
	Leme et al. 2014	Crillesen et al. 2006			
Wastewater treatment*	$0.53	$0.60	$0.63	$0.59	$0.64
Flue gas cleaning*	$2.77	$7.17	$8.75	$6.35	$9.38

* Calculated using natural gas prices (**Table 32**) and the two-factor methodology from Ulrich and Vasudevan (2006)

Labor costs were calculated following Seider et al. (2009), in line with da Silva (2016). Five 8-hour shifts of hourly workers were assumed with eight workers per shift for fast pyrolysis and Fischer-Tropsch gasification, and six for the less-complex hydrothermal liquefaction pathway. The annual costs for **direct wages and benefits** can be calculated using **Equation 7** the base hourly wages, **Table 36**, and the annual operating days of the plant, **Table 10**.

Equation 7. Total annual direct wages for biorefinery workers.

$$\frac{Direct\ Wages}{Year} = \frac{Workers}{Shift} \times \frac{Hours}{Shift} \times \frac{Shifts}{Day} \times \frac{Operating\ Days}{Year} \times \frac{Base\ Wage}{Hour}$$

Table 35. Base hourly wage for biorefinery workers, per country, in 2015 USD per hour.

	Brazil	Denmark	Finland	Norway	Sweden
Base wage	$11	$48	$17	$25	$24
Source	da Silva 2016	Statistics Denmark 2017	Statistics Finland 2017	Statistics Norway 2017	Statistics Sweden 2017

Supervision and supplies accounts for the additional salary of supervisory personnel, office supplies, protective clothing, and other day-to-day supplies required by the plant workers. In this study, a single factor of 50% of direct wages was used.

Maintenance accounts for planned replacement and repairs necessary to keep the plant in working order (Seider et al. 2009), including labor and supplies, and was assumed to be 10% of fixed capital costs. This is more conservative than the 5% used by da Silva, but in line with Seider et al. (2009) recommendations. The **variable costs** of feedstock, chemicals, waste treatment, and utilities; labor; and maintenance make up the **direct production costs** of operation.

A **contingency** factor is used to account for unanticipated or excluded costs. A contingency of 15% of direct production costs was assumed, plus an additional 5% to account for catalyst use, which is not explicitly calculated.

Plant overhead accounts for expenses beyond direct production costs, such as non-production personnel (e.g. human resources, janitorial staff), warehousing, health and safety compliance, and transportation. (Seider et al. 2009). Following da Silva, plant overhead is estimated at 70% of labor related costs.

Fixed charges includes **local taxes**, such as property taxes and utility hookup fees (Seider et al. 2009), assumed at 1.5% and 3% of fixed capital investment for Brazil and Scandinavia, respectively. **Insurance** was assumed to be 1% of fixed capital for all countries. **Depreciation** which accounts for the equipment's loss of value over time, was calculated using a linear model, **Equation 8**, that includes the interest rate (*i*) of 12% for Brazil (da Silva 2016) and 7% for Scandinavia (Kempegowda et al. 2015), the biorefinery lifespan (n), which was assumed to be 15 years, and the plant's location-adjusted total capital investment.

Equation 8. Depreciation as a function of capital investment (CapEx), interest rate (i), and project lifespan (n).

$$Depreciation = CapEx \times \frac{i}{1-(1+i)^{-n}}$$

Finally, **general expenses** are those outside the immediate scope of biofuel production, e.g. sales, marketing, research and development, management, and other administrative expenses (Seider et al. 2009). They were assumed to be 10% of annual sales revenue.

3.4.4 Earnings Before Tax

Once sales revenue and operating expenses were estimated, the annual before-tax earnings of the biorefinery was estimated by subtracting the annual operating expenses from the annual sales revenue, **Equation 9**. Positive earnings are subject to income tax, which is beyond the scope of this study. The internal rate of return (IRR) was also not considered. The IRR is the profit expected by the investors that makes their investment worthwhile, usually expressed as a factor of total operating expenses, similar to depreciation. The internal rate of return varies with the interest rate and with the perceived risk of the investment.

Equation 9. Earnings before tax.

$$Earnings\ Before\ Tax = Sales\ Revenue - Operating\ Expenses$$

3.4.5 Minimum Biofuel Selling Price (MFSP)

The minimum fuel selling price is an indicator used to evaluate the cost of biofuel production and compare it to other fuel sources, such as fossil fuels. The MFSP, **Equation 10**, is the marginal price of biofuel where each unit sold exactly covers the operating costs of producing it, without accounting for any internal return or profit. If all the plants biofuel was sold at the MFSP, the before-tax, before IRR, earnings of the plant would be zero. Since the biorefinery is a two-product system, the revenue from electricity generation (**Table 25**) was subtracted from the operating costs before dividing it by the biofuel production quantity.

Equation 10. Minimum biofuel selling price (MFSP)

$$MFSP = \frac{Operating\ Costs - Electricity\ Sales\ Revenue}{Biofuel\ Production\ Output}$$

If the MFSP is on par with the price of fossil fuel, the modeled biofuel can be estimated to be potentially competitive with fossil fuels in the current market. If it is higher, it provides an indicator of how far away the technology is from being competitive. For ease of comparison with fossil fuel prices, the MFSP is expressed as a ratio with the marine gas oil price (**Table 25**).

3.5 Environmental Impact Modeling

The expectation of improved environmental performance, such as the reduction in non-biogenic greenhouse gas emissions from fuel combustion, is a driver of biofuel development. However, to holistically evaluate the biofuel's environmental performance, it is necessary to include the complete biofuel life cycle, from feedstock production, through transport, biofuel production, and biofuel use. This provides a clearer estimate of impacts that could be expected with a switch from fossil fuels to biofuels, and provides the ability to compare complete supply chains as well as identify the main impacts within the supply chain.

This study uses simplified attributional life cycle assessment (LCA). Attributional LCA is a method of cataloging the environmental impacts attributable to a particular a product or service throughout its life cycle, including not only emissions and resources that come from its direct production and use, but also from the production and use of all inputs used in the supply chain, all the way to the original resource extracted from the environment. The study follows the framework elaborated in (Guinée et al. 2002), which has four major steps:

1. **Goal and scope assessment**, which elaborates the purpose of the LCA, the product/service under consideration, the boundaries of supply chain considered, and the geographic, temporal, and technological scope of the study.
2. **Inventory analysis**, which catalogs the flows of goods and services through the supply chain, along with their resource use from and emissions to the environment.
3. **Impact assessment**, which quantifies the supply chain's environmental impacts by grouping them into impact categories and standardizing each category to a single reference unit of impact.
4. **Interpretation**, which analyzes the results of the impact assessment, and evaluates them for consistency and completeness.

In this study the life cycle inventory database ecoinvent v2.2 (Frischknecht et al. 2005) was the primary data source for emissions and resource use, and the CML 2001 characterization factors (CML 2013) were used to categorize and standardize impacts. The free LCA software CMLCA 5.2 facilitated the inventory catalog and impact categorization. Impact results for each process conditions and calculations for the total life cycle impact assessment are available in the accompanying spreadsheet.

3.5.1 Goal and scope assessment

The **goal** of the life cycle assessment portion of this study is to evaluate the environmental impacts of lignocellulosic marine biofuel supply chains for each of the country-technology-feedstock combinations considered. The impacts of each combination are compared with each other, as well as to a reference system of the production and combustion of fossil heavy fuel oil, to provide an order of magnitude reference for the biofuel impacts. Due to the simplified nature of the analysis, the results are intended as a foundation for future research and are not recommended for commercial decision-making or public comparative assertion.

This study’s **scope** covers a simplified cradle-to-grave, or “well-to-wake,” life cycle product system of the biofuel supply chain. The inventory data from ecoinvent corresponds to the time span of 2005-2010. When possible, region-specific inventory data is used, but is not always available. These limitations are discussed in the results.

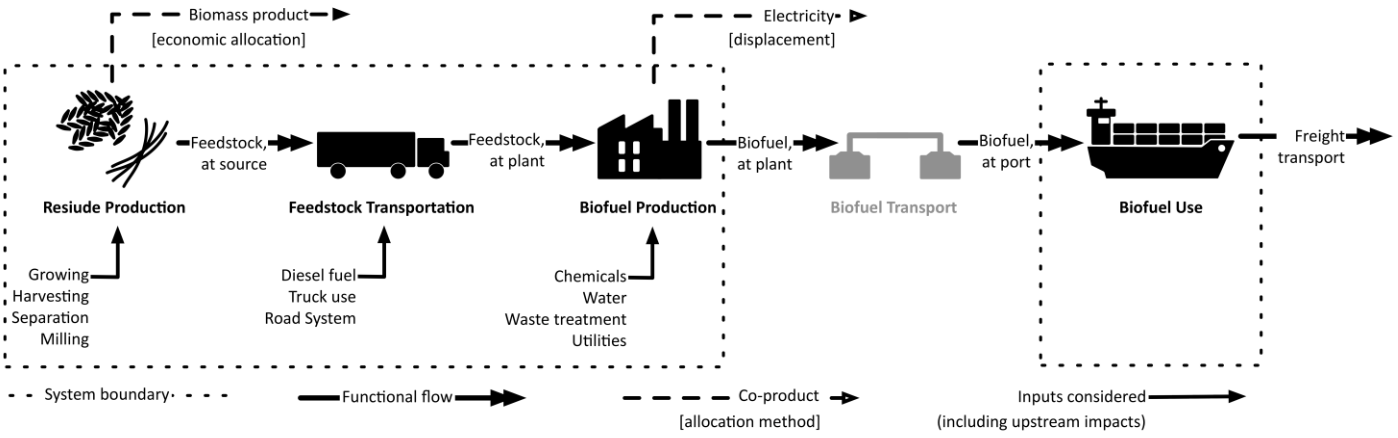
In LCA, the target of analysis is not a product or a service, but the **function** provided by that product or service. In the case of [bio-]marine fuel, that function is *the transport of freight across bodies of water*. Since the distance of transport provided by a quantity of fuel varies with the ship and engine, the **functional unit**, is expressed in terms of the energy in the fuel itself, and is defined in this study as*, the transport of freight across bodies of water provided by one gigajoule (GJ) of marine fuel*. In this study there are twenty-eight **reference flows**, corresponding to the combinations of region, technology, and feedstock, which can generalized as: *the transport of freight across bodies of water provided by one GJ of marine biofuel produced in Brazil or one of four Scandinavia countries using one of three biofuel production technologies and one of ten lignocellulosic feedstocks.*

3.5.2 Inventory analysis

Figure 13 summarizes the biofuel supply chain considered in this study. Due to the number of technologies, feedstocks, and regions considered, only the major supply chain links—production of biomass residues, transport of feedstock to the biorefinery, production of biofuel at the biorefinery, use, and combustion of the biofuel during its use phase—were considered. Feedstock storage, catalyst use, biofuel storage, biofuel-to-port transport, biofuel bunkering, non-fuel inputs related to the use of biofuel onboard the ship, and disposal of any waste fuel or use byproducts are excluded in this simplified LCA, but biofuel-to-port transport is included in a sensitivity analysis.

A list of all ecoinvent processes and other data sources used in this LCA, including the region and year of the data are available in the accompanying spreadsheet.

Figure 13. Biofuel product system considered in LCA.



Residue production incorporates the production of the biomass product via agricultural or forestry, including machinery, fuel, seed, fertilizer, water, and other inputs to the cultivation process, as well as the harvesting and separation of primary product from residue. In the case of sugar crops, milling of the sugar is included. In all cases, the impacts of the biomass production system are allocated between primary product and the residue using economic allocation. In most cases, the source data from ecoinvent was pre-allocated. Exceptions are eucalyptus, corn and rice, as only whole crop production data was available. Economic allocation is based on the relative market value of each product allocated and in all cases 15% of the total production impacts were allocated to residues.

Due to time constraints, ecoinvent was used as the data source for residue production inventory, even though the region specific production data was mostly unavailable.

Feedstock transport from the field, forest, or mill to the biorefinery was assumed to use 28-tonne diesel trucks. Transported feedstock mass was calculated using the biorefinery scale (**3.2.1**) and wet density of the residue products (**Table 9**). Transport distance was based on the refinery siting (**3.2.3**) In all regions, the trucks are assumed to comply with Euro 5 heavy truck emission standards (European Parliament 2007), which are equivalent to the Brazilian PROCONVE P-7 heavy truck emission standards (CONAMA 2008). A transport efficiency of 2.5 MJ/ton-km was assumed (EEA 2016). Scandinavian trucks were assumed to use 100% fossil diesel (45.4 MJ/kg), whereas Brazilian trucks use a 10% blend of biodiesel in fossil diesel, in line with the mandated fuel blending level for 2020 (Barros 2015). The ecoinvent process for soybean methyl ester production in Brazil was used to model upstream biodiesel production, and the transport emissions were assumed to correspond to 90% of the ecoinvent Euro 5 diesel truck emissions and 10% of soybean biodiesel emissions from Özener et al. (2014), and were adjusted to account for the lower energy content (37.1 MJ/kg) of the biodiesel.

Biofuel production includes the emissions of flue gasses and the upstream impacts of chemicals, water, wastewater, and utilities during process modeling (**3.3**). Flue gas cleaning was assumed to remove 100% of NO_x and SO_2 from the emitted gasses. Due to lack of specific equipment data and the study's time constraints, impacts of the biorefinery's buildings, maintenance, and administration were excluded.

The biorefinery produces two products, marine biofuel and electricity. Therefore **allocation** was needed to divide the impacts of the biorefinery output, including the upstream processes of feedstock production and transport. Following the recommendations of ISO, Concawe, and the EPA for biofuels (Wang et al. 2011), **displacement** was used to allocate the biorefinery impacts. In displacement allocation, a co-product of the biofuel was assumed to replace the production of that product from a standalone facility. In this study, the coproduced electricity replaces the electricity produced as a nearby power plant. Since the power plant was assumed to no longer produce the quantity of electricity produced by the biorefinery, the impacts that it would have generated were subtracted from the total impacts of the biorefinery's system. These impacts were "displaced" by the biorefinery's production of electricity. In this study, the average impacts of the 2014 national electricity mix (IEA 2016) were used. The impacts remaining after subtracting the displaced electricity are those attributable to biofuel, as in **Equation 11**.

Equation 11. Environmental impacts allocated to biofuel using displacement allocation of coproduced electricity.

$$Biofuel\ Impacts = Total\ Biorefinery\ Impacts - \left(Quantity\ of\ Coproduced\ Electricity \times \frac{National\ Electricity\ Production\ Impacts}{National\ Electricity\ Production\ Quantity}\right)$$

However, the allocation method chosen can have a substantial effect on estimate of biofuel impacts (Wang et al. 2011; Zaimes et al. 2015), and therefore was subjected to a sensitivity analysis, both for the origin of displaced electricity and the allocation method itself.

Biofuel use includes only the emissions released during the combustion of the biofuel. Data on the combustion of lignocellulosic biofuel emissions is limited, and for HTL and GFT only biofuel blend combustion data was available (Nabi et al. 2015; Nabi and Hustad 2012); only pure biofuel combustion data was found for FP (Wildschut 2009). In all sources the biofuel emissions are expressed in comparison to fossil diesel fuel, **Table 36**. Therefore, biofuel emissions were modeled by adjusting the value of 100% diesel emissions by the difference in emissions reported in the source literature. For HTL and GFT, the emissions of 100% biofuel were estimated by linearly extrapolating the blend emission profile. Emissions not catalogued in the source were assumed to be the same as fossil emissions. As the emissions were given on a mass basis, they were converted to an energy basis by multiplying them by the ratio of the energy content of the reference fuel (43 MJ/kg) to the energy content of the biofuel. **Equation 12** summarizes the calculation used to convert the literature data to emissions per MJ of pure biofuel.

Table 36. Source literature values for biofuel combustion emissions.

	10% HTL + 90% Diesel	100% FP	10% GFT + 90% MGO	100% MGO (Diesel)
	in % change from the per kg emissions of a 100% diesel reference			
CO$_2$ emissions[1]	0%	+ 3.3%	0%	74 g/MJ
CH$_4$ emissions	n.d.	n.d.	n.d.	0.0005 g/MJ
N$_2$O emissions	n.d.	n.d.	n.d.	0.004 g/MJ
NO$_x$ emissions	+ 5.7%	- 4.7%	- 1.3%	1.5 g/MJ
SO$_2$ emissions	- 9.0%	- 100%	- 10.0%	0.05 g/MJ[2]
Energy Content	- 3.3%	- 23%	+0.3%	43 MJ/kg
Source:	Nabi et al. 2015	Wildschut 2009	Nabi and Hustad 2012	Bengtsson et al. 2011

n.d. = data not available. Assumed to be the same as 100% diesel
1: Includes both biogenic and non-biogenic CO2 emissions
2: The source fuel has a 0.1% sulfur content; this value was linearly extrapolated to 5.0g/MJ for a 1% sulfur content

Equation 12. Estimation of biofuel emissions from literature data expressed in percent change from diesel emissions.

$$\frac{Biofuel\ Emissions}{MJ} = \frac{Diesel\ Emissions}{MJ} \times \frac{(1 + \%\ Change\ in\ Emissions\ using\ Biofuel\ Blend)}{Biofuel\ Blend\ \%} \times \frac{Diesel\ Energy\ Content\ in\ MJ/kg}{Biofuel\ Energy\ Content\ in\ MJ/kg}$$

Heavy Fuel Oil Reference System

To provide a context for the biofuel impacts, they are presented with a reference value of the impacts of the production and combustion of heavy fuel oil. This allows the biofuel impacts to be discussed in comparison to the current status quo of marine fuel production and combustion. The value is meant only as an order-of-magnitude reference, as both the biofuel and fossil fuel impacts are from simplified systems. The HFO production data is from ecoinvent (Frischknecht et al. 2005), and, like biofuel production, excludes the impact of the refinery's buildings and ground. The combustion emissions are from Bengtsson et al. (2011), as well as the energy content of 40.4 MJ/kg.

3.5.3 Impact assessment

In this study, four simplified **impact categories** were used:

1. **Greenhouse gases emissions (GHG)**, in kg CO_2-eq, include carbon dioxide, methane, and dinitrogen monoxide emissions to air, standardized to their 100-year global warming potential expressed in kilograms of CO_2-equivelant, using the characterization factors in **Table 37**. This three-emission category is the same used in the sources referenced in other HIP reports, including (da Silva 2016) and (Santos 2016a). Following CML-2001 characterization methodology, biogenic CO_2 is accounted for by assuming their combustion emissions are equal to the biomass's carbon uptake, with an effective net balance of zero CO_2 emissions.
2. **Sulfur dioxide emissions (SO_2)**, in kg SO_2, a single emission category, include SO_2 emissions to air.
3. **Nitrogen oxides emissions (NO_x)**, in kg NO_x, a single emission category, include NO_x emissions to air.
4. **Non-renewable energy use (NREU)**, as MJ, includes the use of fossil fuels and uranium, using the characterization factors in **Table 38**.

Table 37. Greenhouse gas characterization factors.

Emissions	Characterization Factor
Carbon dioxide, fossil	1 kg CO_2-eq/kg
Carbon dioxide, biogenic	0 kg CO_2-eq/kg
Methane, fossil	25 kg CO_2-eq/kg
Methane, biogenic	25 kg CO_2-eq/kg
Nitrous oxide	298 kg CO_2-eq/kg

Source: CML 2013

Table 38. Non-renewable energy use characterization factors.

Energy source	Characterization factor
Crude oil	43 MJ NREU/kg
Natural gas	37 MJ NREU/kg
Hard coal	24 MJ NREU/kg
Brown coal	15 MJ NREU/kg
Peat	15 MJ NREU/kg
Uranium	500 MJ NREU/kg

Source: FAO 1990

3.5.4 Interpretation

A **consistency check** was performed to ensure that the methodology has been applied consistently across all combinations.

A **contribution analysis** was used to evaluate the relative impact of the different links of the supply chain.

Sensitivity analyses were performed on the method of allocation, the characterization factors for biogenic CO_2 emissions, the method and distance of feedstock transport, and the inclusion of biofuel transport. The analysis methodology is detailed in section **3.6.6**

3.6 Scaling Analysis

The scaling analysis evaluates the supply and demand model and the economic and environmental results in the context of a potential large-scale implementation of biofuel production. Each combination was evaluated for its ability to satisfy marine fuel demand and comply with maritime environmental regulation, and how it compares to other emission reducing technologies. The possible impacts of model uncertainty were evaluated by subjecting the process model, economic model, and environmental model to a series of non-stochastic sensitivity analyses. Variations of the biorefinery setup were also explored. The results may be displayed for all combinations or for a relevant selection, but full results for all combinations are available in the accompanying spreadsheet.

3.6.1 Demand Satisfaction

Using the biofuel mass yields and the estimated energy content of the biofuel, each feedstock-technology combination was evaluated for its ability to satisfy the predicted marine fuel demand in each country. Marine fuel demand was estimated using the international marine bunker statistics for heavy fuel oil and marine gas oil for each country (IEA 2016). Based on the EU target of 10% renewable transport energy, and tested biofuel blends (Nabi et al. 2015; Nabi and Hustad 2012; Prucole et al. 2014; Ljubas et al. 2010), a biofuel production target of 10% of marine fuel demand was chosen.

2020 marine fuel demand was modeled as 6% above 2014 levels for all countries, **Table 39**. This assumption is in line with a linear regression of Brazilian marine fuel demand since 2000, a global marine fuel consumption prediction by CE Delft (CE Delft 2016), and a Concawe report on estimated European marine fuel demand (Dastillung et al. 2009).

Table 39. Marine fuel demand, PJ per year, by country.

	Brazil	Denmark	Finland	Norway	Sweden
2014	154.0	32.8	4.3	6.4	76.0
2020, predicted	**163.3**	**34.7**	**4.5**	**6.8**	**80.5**

Marine fuel demand is also considered on a port level, which was assumed proportional to the port's cargo throughput, as shown in **Table 40**. Port demand determines how far the biofuel has to travel after it is produced: if the biofuel cannot be consumed entirely at the nearest large port, it is transported to the next nearest port that can consume the entirely of the excess fuel. In Scandinavian countries, if no single port can absorb the excess fuel, the fuel was assumed to be transported to Rotterdam, which is the largest port in Europe.

The ability of the available residues and biofuel production to satisfy the marine fuel demand of the country and the delivery port was evaluated for each combination. Additionally, the biorefinery scale necessary to satisfy both port and national demands were determined, for use in the biorefinery refinery scale sensitivity analysis.

3.6.2 Environmental Regulation Compliance

For each biofuel, the minimum blend necessary to satisfy the 2020 sulfur content cap was determined, using blendstocks of heavy fuel oil with 3.5% sulfur content and marine gas oil with a 1% and 1.5% sulfur content. The economic and environmental indicators of these blends are evaluated in comparison to 100% HFO and 100% biofuel. Fossil fuel production impacts are from ecoinvent and the combustion emissions are from (Bengtsson et al. 2011) Additionally, the NO_x emissions of each biofuel and its most cost effective sulfur-cap compliant blend were evaluated for their ability to comply with IMO regulations.

Table 40. Major ports and their projected fuel demand, by country.

Port	**Cargo Throughput**, tonnes	**% of National Throughput**	**Projected 2020 fuel demand,** PJ
Brazil	**2013** (ANTAQ 2013)		
Tubarao	110 480 000	11.9%	*18.3*
Ponta Da Madeira	107 328 000	11.5%	*17.8*
Santos	99 808 000	10.7%	*16.5*
Itaguai	58 328 000	6.3%	*9.6*
Barroso	52 808 000	5.7%	*8.7*
Paranagua	41 912 000	4.5%	*6.9*
MBR	39 758 000	4.3%	*6.6*
Maximiano Fonesca	25 797 000	2.8%	*4.3*
Madre de Deus	22 698 000	2.4%	*3.8*
Pona de Ubu	22 683 000	2.4%	*3.8*
Denmark	**2014** (Statistics Denmark 2017)		
Fredericia	9 037 000	*9.8%*	*3.2*
Aarhus	7 614 000	*8.3%*	*2.7*
Statoil	6 968 000	*7.6%*	*2.5*
Rødby Færge	6 296 000	*6.8%*	*2.2*
Københavns	6 145 000	*6.7%*	*2.2*
Esbjerg	4 565 000	*4.9%*	*1.6*
Helsingør	4 422 000	*4.8%*	*1.6*
Stigsnæs	3 584 000	*3.9%*	*1.3*
Aalborg	2 558 000	*2.8%*	*0.9*
Frederikshavn	2 419 000	*2.6%*	*0.9*
Finland	2015 (Finnish Transport Agency 2015)		
Sköldvik	17 393 026	*19.5%*	*0.8*
Haminakotka	12 098 548	*13.6%*	*0.6*
Helsinkihelsingfors	11 180 961	*12.5%*	*0.5*
Rauma-Raumo	5 647 195	*6.3%*	*0.3*
Naantali-Nådendal	5 413 615	*6.1%*	*0.3*
Kokkola-Karleby	5 205 930	*5.8%*	*0.2*
Raahe-Brahestad	5 146 066	*5.8%*	*0.2*
Hanko-Hangö	4 134 514	*4.6%*	*0.2*
Pori-Björneborg	3 076 231	*3.4%*	*0.1*
Tornio-Torneå	2 898 864	*3.3%*	*0.1*
Norway	**2015** (Statistics Norway 2017)		
Bergen	43 568 620	*21.2%*	*1.4*
Narvik	17 558 820	*8.5%*	*0.5*
Kirkenes	15 224 355	*7.4%*	*0.5*
Kragerø	11 817 490	*5.7%*	*0.4*
Karmsund	11 659 177	*5.7%*	*0.4*
Tønsberg	9 560 472	*4.6%*	*0.3*
Kristiansund	7 072 499	*3.4%*	*0.2*
Olso	5 768 211	*2.8%*	*0.2*
Molde	4 839 872	*2.4%*	*0.2*
Hammerfest	4 735 284	*2.3%*	*0.1*
Sweden	**2015** (Transportföretagen 2016)		
Göteborg	37 838 000	*28.4%*	*21.6*
Trelleborg	10 947 000	*8.2%*	*6.2*
Helsingborg	8 165 000	*6.1%*	*4.7*
Luleå	7 918 000	*6.0%*	*4.5*
Stockholm	7 714 000	*5.8%*	*4.4*
Malmö	7 621 000	*5.7%*	*4.4*
Oxelösund	5 851 000	*4.4%*	*3.3*
Gävle	5 575 000	*4.2%*	*3.2*
Karlshamn	4 632 000	*3.5%*	*2.6*
Norrköping	3 563 000	*2.7%*	*2.0*
Netherlands	(fuel demand reference only)		
Rotterdam	—	—	**476.4**

3.6.3 Comparison with other emission reducing technologies

The economic and environmental indicators for each biofuel combination and its most cost effective sulfur-cap compliant blend were compared with four other options for reducing the sulfur emissions of maritime freight: liquid natural gas (LNG), heavy fuel oil with exhaust scrubbers, ultra low sulfur heavy fuel oil (ULSHFO), and soy biodiesel.

Table 41 summarizes the cost data used for the compared technologies. For HFO scrubbers and LNG, the costs of the additional equipment needed for their operation was included by adding the prorated depreciation costs of the equipment into each tonne of fuel, calculated using **Equation 8**, assuming an annual fuel use of 8 000 tonnes for heavy fuel oil and 7 500 tonnes MGO-equivalent for liquid natural gas and a 15 year technology lifespan. The price of the HFO scrubbers also includes their additional fuel consumption and maintenance costs. For ease of comparison, the costs of these technologies were also expressed as a ratio with the MGO prices.

The environmental impacts of each technology are taken from literature, using the same impact categories and characterization factors. The environmental impact data sources used for each technology are listed in **Table 42**.

Table 41. Costs of other marine emission reducing technologies, in 2015 USD

USD 2015	Fuel Cost		Fuel Energy Content	Additional Costs	Sources
	Brazil	Scandinavia			
Liquid Natural Gas[1]	$226/tMGO-e	$217/ tMGO-e	43 GJ/tMGO e	$10 M LNG retrofit capital expense	DNV GL 2016; FERC 2017
HFO with Scrubber	$303/t	$285/t	40.4 MJ/kg	$5 M scrubber installation, 1.5% fuel use increase, $36 000 maintenance per year	Boer and Hoen 2015; Jiang et al. 2014
ULS HFO	$423/t[2]		40.4 MJ/kg	—	Ship & Bunker 2017
Soy Biodiesel	$890/t[2]		37.3 MJ/kg	—	OPIS 2017

1: tMGO-e is tonne MGO equivalent, which is a quantity of LNG that has the same energy content as one tonne of MGO

2: Region specific data was unavailable.

Table 42. Data sources for comparison technology environmental impacts.

	Fuel production data source	Combustion data source
Liquid Natural Gas	ecoinvent	Brynolf et al. 2014
HFO with Scrubber	ecoinvent Bengtsson et al. 2011	Bengtsson et al. 2011
ULS HFO	ecoinvent	ecoinvent
Soy Biodiesel	ecoinvent	Petzold et al. 2011

3.6.4 Process model sensitivity analysis

Biorefinery scale

The biorefinery scale was varied between 100 and 5000 dry tonnes of feedstock per day to determine its impact on each combination's economic performance and the availability of residues to satisfy the biorefinery's feedstock demand. The biorefinery scales that satisfy national demand and port demand were also evaluated.

Biorefinery siting

The location of the biorefinery site, in terms of its distance from the feedstock source and the biofuel's destination port was varied to determine the impact of the additional feedstock transport on each combination's economic and environmental performance.

Heat recovery efficiency

There is limited data on the efficiency of biofuel heat exchange networks and this study lacks a full heat integration analysis. Therefore, different heat exchange efficiencies were evaluated to determine their impact on the economic and environmental performance of biofuel production. Heat exchange efficiencies of 50%, 60%, 70%, 80% and 90% were evaluated for each combination.

3.6.5 Economic model sensitivity analysis

Capital Expenses

A review of biorefinery capital costs estimates show that technoeconomic analyses tend to vary widely and overestimate the direct capital costs of biorefinery construction (Tsagkari et al. 2016). However, direct capital costs estimates do not account for the cost of engineering, construction, labor, and contingency that lead cost estimates for “first-of-a-kind” plants to be up to three times as expensive as nth plant estimates (Swanson et al. 2010; Wright et al. 2010). To determine the impact of CapEx uncertainty on the minimum fuel selling price, the CapEx for each combination was varied from -50% to +100% of the base CapEx.

Feedstock Price

The uncertainty in feedstock prices, which vary with harvest, region, season, and competing demands, was evaluated by varying the feedstock price from -50% to +50% of the base price to determine its impact on the economic performance of each combination.

3.6.6 Environmental model sensitivity analysis

Allocation sensitivity analysis

A sensitivity analysis was performed to determine the effect the allocation method on the impact results. Impacts calculated using allocation by the energy content of the biorefinery products and allocation by their market value (**Table 25**) were compared to the impacts using the original displacement allocation.

The origin of the displaced electricity was also evaluated. Some methods of electricity production, such as nuclear, hydropower, and wind are designed to run at full capacity all the time and cannot respond to changes in electricity demand. If the biorefinery’s electricity is a replacement, rather than a supplement, to existing electricity production, it is most likely to replace electricity from power plants designed to respond to fluctuations in demand. These “dispatchable power plants” typically produce electricity via the combustion of fossil fuel, biomass, or waste. The use of the national electricity mix for the displaced electricity, which include nuclear, wind, and hydropower will have a different impact mix than if just dispatchable sources were considered. Therefore, the displacement allocation using the national electricity mix was compared to displacement allocation using the national dispatchable electricity mix, including electricity from coal, oil, natural gas, biomass, and waste. Displacement allocation using single-source electricity production for natural gas, coal, and biomass was also evaluated. Biomass electricity production in Brazil was assumed to be via the direct combustion of sugarcane bagasse, while woodchip combustion was assumed for Scandinavia. All electricity production impacts were calculated from ecoinvent data.

Biogenic CO_2 global warming potential sensitivity analysis

The standard method of accounting for biogenic CO_2 emissions is to assume that the emissions from the combustion of biomass are equal to the carbon sequestered by the growth of that biomass, and therefore the net balance is zero

(Cherubini et al. 2011). However, recent research strongly suggests that the emissions from biomass production are not always carbon neutral, and that their effect on global warming is dependent on the growing period of the combusted biomass (Cherubini et al. 2011; Repo et al. 2015; Pingoud et al. 2016; Holtsmark 2015). The longer the biomass grows before it is harvested and combusted, the longer it takes for the amount of carbon emitted during combustion to be sequestered by the regrowth of the biomass. Cherubini et al (2011) proposed global warming potentials for biomass (GWP_{bio}) to account for the time that the biogenic CO_2 is present in the atmosphere and thus having a radiative forcing effect, and increase by approximately 5 kg CO_2eq/kg biogenic CO_2 per decade of the rotation period. Using these factors and the rotation period of each feedstock, **Table 43**, the greenhouse gas emissions of each biofuel system were recalculated and compared to the base model. Based on the literature reviewed, the residual nature of the feedstocks was assumed to have no effect on the GWP_{bio} factor.

Table 43. GWP_{bio} factors and crop rotation periods.

Feedstock	Crop Rotation Period	GWP_{bio} factor kg CO_2 -eq/kg biogenic CO_2
Forestry Residues		
Eucalyptus	16 years	0.06
Pine, Brazil	22 years	0.09
Pine, Scandinavia	80 years	0.34
Spruce	54 years	0.22
Grain Residues		
Barley	1 year	0.0
Corn	1 year	0.0
Rice	1 year	0.0
Wheat	1 year	0.0
Sugar Residues		
Sugarcane	1 year	0.0
Sorghum	1 year	0.0
Sugar beet	1 year	0.0

Sources: da Silva 2016; Rytter et al. 2016; Cherubini et al. 2011

Feedstock transportation

The assumed method and distance of feedstock transportation was subject to variation to determine its effect on the system impacts. Feedstock transport by barge and by train were compared to the base choice of transport by truck.

Biofuel Transportation

Biofuel transport is excluded from the base system to allow it to be easily compared with other technologies in the scaling analysis. However, a sensitivity analysis adds biofuel transport from the biorefinery to port by pipeline and by barge to evaluate its effect on system impacts. Biofuel transported to a second port was assumed to travel by tanker.

3.6.7 Biorefinery Variations

Combined Sugarcane-sorghum biorefinery

Sugarcane and sorghum both have six-month harvest periods and require immediate processing of their sugar and bagasse. However, their harvest seasons do not overlap (USDA 1994) and the composition of their residues is similar (**Table 9**), suggesting the possibility of a dual-feedstock plant, operating using a single feedstock in each harvest season. The dual feedstock plant was assumed to operate 330 days per year and have the capital costs and capital-dependent operating costs of the more expensive single-feedstock biorefinery. The variable operating costs were assumed to be that of the single-feedstock sorghum and sugarcane biorefineries combined.

Hydrothermal liquefaction without aqueous recycling

The aqueous recycling in the HTL model uses assumed values for aqueous biomass conversion. To determine the impact of these assumptions on the model yields, the HTL system is considered both without aqueous recycling and with aqueous recycling with zero biomass conversion assumed.

Hydrotreated hydrothermal liquefaction

Hydrotreatment of HTL biocrude can increase the energy content of the biofuel and potentially reduce the nitrogen and sulfur content, (Sudasinghe et al. 2014; Yu et al. 2017; Biller et al. 2015). Therefore, hydrodeoxygenation of HTL is modeled to determine its impact on the biofuels' economic and environmental performance. Tews et al. (2014) was the reference for the hydrotreater (734 tonnes biocrude/day), whose cost was adjusted to 13.5 M 2015 USD using **Equation 3**, for a capacity of 734 tonnes per day of biocrude and scaled using **Equation 4** and a scaling factor of 0.7. The hydrogen plant model was the same as for fast pyrolysis (**3.3.4**) The hydrotreated biofuel was assumed to have an energy content of 42 MJ/kg and a 80% reduction in sulfur content (Yu et al. 2017). Following Tews et al. (2014), 21% of the biocrude's mass was assumed lost to aqueous and 4% to offgasses.

Data on the combustion of hydrotreated HTL is not available, and nitrogen content does not necessarily decrease (Yu et al. 2017), but the potential decrease in oxygen content by 80-90% (Yu et al. 2017) and decrease in double-bonded molecules (Sudasinghe et al. 2014) strongly suggest that NO_x emissions would significantly decrease (Palash et al. 2013). Therefore, the hydrotreated HTL biofuel was assumed to have a 30% reduction in NO_x emissions.

Upgraded and distilled fuels

The base model left the biofuel as undistilled biocrude. A variation of the model, where the biofuel is separated into naphtha (C_5–C_8 hydrocarbons; used for gasoline), kerosene (C_9–C_{14}; used for jet fuel), and heavier cuts (C_{15}+; for marine fuel), was evaluated to provide a better comparison to preexisting HIP work. To implement this variation, distillation was added to all technologies. For HTL and FP, 17% of the biocrude was assumed distilled to naphtha, 31% to kerosene, 49% to heavier, and 3% lost to offgasses (da Silva 2016). For GFT, the distillation cuts were made based on the distribution of hydrocarbons that was calculated using the Anderson-Schulz-Flory equation 3.3.4 Hydrotreatment for HTL was also included, as above. No hydrocracking was included.

The cost of fuel distillation and storage were taken from PNNL reports and adjusted to 2015 USD, **Table 44,** and scaled to the appropriate capacity using a scaling factor of 0.7. The additional fuel cuts were assumed sold at their wholesale pre-tax prices, **Table 45**. The additional fuel coproducts were allocated using displacement and the default European ecoinvent impacts for kerosene and light naphtha. No Brazil-specific values were available.

Table 44. Literature costs of fuel separation.

	HTL	FP	GFT
Source cost, fuel separation (in 2015 USD)	$1.9 M	$1.9 M	$2.1 M
Source scale, fuel separation (tonnes fuel/day)	534	534	330
Source	Jones et al. 2013		Swanson et al. 2010

Table 45. Gasoline and jet fuel prices, March 2017, in 2015 USD.

	Brazil	Scandinavia
Gasoline (naphtha) price	$549 / tonne[1] EIA 2017c	$483/ tonne[2] RAC Foundation 2017
Jet fuel (kerosene) price	$503 / tonne IATA 2017	$492/ tonne IATA 2017

: US Gulf coast price; no Brazil-specific data accessible.

2: UK price; no Scandinavia-specific data accessible.

4 Results & Discussion

4.1 Feedstock Availability

The different sizes of the regions—Brazil is eight times larger than the whole of Scandinavia in both area and population—are immediately apparent when comparing the scale of crop production projected for 2020, **Table 46**. **Table 47** shows the annual quantity of feedstock required to supply a biorefinery processing 500 dry tonnes of biomass per day. The quantity of wet residues required varies with both the moisture content (**Table 9**) and the number of operating days of the biorefinery (**Table 10**), which was dependent on the growing season and storability of the feedstock.

Using these quantities and the equation for determining the proportion of available residue (**Equation 1**), **Table 48** shows the biorefinery's feedstock demand a percentage of the nationally available residues. In Brazil, only barley is excluded. For eucalyptus residues, corn stover, and sugarcane bagasse, the demand is less than 1% of available residues, with pine and rice residues also under 5%. In Finland, Norway, and Sweden forestry residues are the most abundant feedstock, whereas straw is more abundant in agricultural Denmark. Pine residues and corn stover in Denmark, sugar beet pulp in Finland and Sweden, and wheat in Norway were immediately eliminated as possible feedstocks due to lack of supply. The biorefinery demand consumes over 75% of the estimated available residues for barley straw in Norway and spruce residues and sugar beet pulp in Denmark, which makes them also unlikely feedstocks, as there is little room for uncertainty in residue available.

Table 46. Projected crop production in 2020, by country, in 1000s of tonnes.

	Brazil	Denmark	Finland	Norway	Sweden
Forestry Crops					
Eucalyptus	327 784	—	—	—	—
Pine	55 515	613	22 891	937	23 167
Spruce	—	1 037	14 767	3 126	43 366
Grain Crops					
Barley	265	3 239	1 712	195	1 581
Corn	92 030	125	—	—	—
Rice	13 063	—	—	—	—
Wheat	7 340	5 079	1 189	144	2 387
Sugar Crops					
Sugarcane	1 024 780	—	—	—	—
Sorghum	2 746	—	—	—	—
Sugar beet	—	2 820	123	—	1 888

Table 47. Feedstock demand for the 500 dry tonne/day biorefinery, in wet tonnes of feedstock per year.

	Biorefinery feedstock demand
Forestry Residues	
Eucalyptus	284 483
Pine	330 000
Spruce	330 000
Grain Residues	
Barley	179 348
Corn	194 118
Rice	194 118
Wheat	194 118
Sugar Residues	
Sugarcane	194 805
Sorghum	195 652
Sugar beet	133 333

Table 48. Biorefinery annual feedstock demand, as a percentage of available residues, by country.

	Brazil	Denmark	Finland	Norway	Sweden
Forestry Residues					
Eucalyptus	0.3%	—	—	—	—
Pine	1.8%	**131%**	3.5%	35.2%	3.5%
Spruce	—	77.1%	5.4%	10.6%	1.8%
Grain Residues					
Barley	**161%**	13.2%	24.9%	91.9%	27.0%
Corn	0.6%	**445%**	—	—	—
Rice	4.5%	—	—	—	—
Wheat	5.8%	8.4%	35.9%	**135%**	17.9%
Sugar Residues					
Sugarcane	0.1%	—	—	—	—
Sorghum	13.6%	—	—	—	—
Sugar beet	—	81.1%	**1852%**	—	**121%**

Bolded red values indicate that feedstock demand exceeds the national supply.

4.2 Biorefinery Siting

4.2.1 Regional feedstock availability

The biorefinery siting criterion (3.2.3) that the feedstock demand is satisfied by the administrative region within each country where it is sited led to the additional exclusion of the feedstocks of straw in Denmark, forestry residues in Norway, and sugar beet in Denmark, as no single region could provide sufficient residues. **Table 49** lists the feedstocks that were estimated to be available in sufficient quantity and density in each country and that were considered in the rest of the analysis.

Regional feedstock availability for Brazil and Scandinavia is mapped in **Figure 14** and **Figure 15** (pages 66 and 67). The feedstock was assumed to be equally distributed across the region, and the specific location of each icon is unimportant. The ten largest ports in each country are also shown for reference.

Table 49. Feedstocks available in **sufficient** and **insufficient** quantity and density, by country.

Feedstock	Brazil	Denmark	Finland	Norway	Sweden
Forestry Residues					
Eucalyptus	🟦				
Pine	🟦	🟥	🟦	🟦	🟦
Spruce		🟥	🟦	🟦	🟦
Grain Residues					
Barley	🟥	🟦	🟦	🟥	🟦
Corn	🟦	🟥			
Rice	🟦				
Wheat	🟦	🟦	🟦	🟥	🟦
Sugar Residues					
Sugarcane	🟦				
Sorghum	🟦				
Sugar beet		🟥	🟥		🟥

4.2.2 Biorefinery site selection

Figure 16 and **Figure 17** (pages 68 and 69) show the feedstock origin region and destination ports selected for each feedstock and country combination. The biorefinery sited halfway between the feedstock source and the port. From this selection, the feedstock-to-port distances were estimated, **Table 50**. The scale of Brazil is apparent by the distances, which are more than double those for Scandinavia for most feedstocks. Sugar residues are an exception, as they are densely cultivated in Brazil, including in coastal regions.

Table 50. Feedstock origins, biofuel destination ports, and the distances between them, by feedstock and country.

		Brazil	Denmark	Finland	Norway	Sweden
Forestry Residues						
Eucalyptus	Feedstock origin region	Sao Paulo	—	—	—	—
	Biofuel destination port	Santos	—	—	—	—
	Distance (km)	480	—	—	—	—
Pine	Feedstock origin	Minas Gerais	—	Keski-Suomi	Buskerud	Örebro
	Biofuel destination	Turbarao	—	Sköldvik	Oslo	Gothenborg
	Distance (km)	640	—	300	160	240
Spruce	Feedstock origin	—	—	Päijät-Häme	Akershus	Kronoberg
	Biofuel destination	—	—	Sköldvik	Oslo	Gothenborg
	Distance (km)	—	—	220	140	100
Grain Residues						
Barley	Feedstock origin	—	Midtjylland	Kanta-Häme	—	Västra Götaland
	Biofuel destination	—	Fredericia	Sköldvik	—	Gothenborg
	Distance (km)	—	60	140	—	110
Corn	Feedstock origin	Marahão	—	—	—	—
	Biofuel destination	Ponta da Madeira	—	—	—	—
	Distance (km)	400	—	—	—	—
Rice	Feedstock origin	Marahão	—	—	—	—
	Biofuel destination	Ponta da Madeira	—	—	—	—
	Distance (km)	400	—	—	—	—
Wheat	Feedstock origin	Parana	Syddanmark	Varsinais-Suomi	—	Västra Götaland
	Biofuel destination	Santos	Fredericia	Sköldvik	—	Gothenborg
	Distance (km)	640	60	170	—	110
Sugar Residues						
Sugarcane	Feedstock origin	Espirito Santo	—	—	—	—
	Biofuel destination	Tubarao	—	—	—	—
	Distance (km)	190	—	—	—	—
Sorghum	Feedstock origin	Sao Paulo	—	—	—	—
	Biofuel destination	Santos	—	—	—	—
	Distance (km)	240	—	—	—	—

Figure 14. Feedstocks available in Brazilian administrative regions in sufficient quantity to satisfy biorefinery demand.

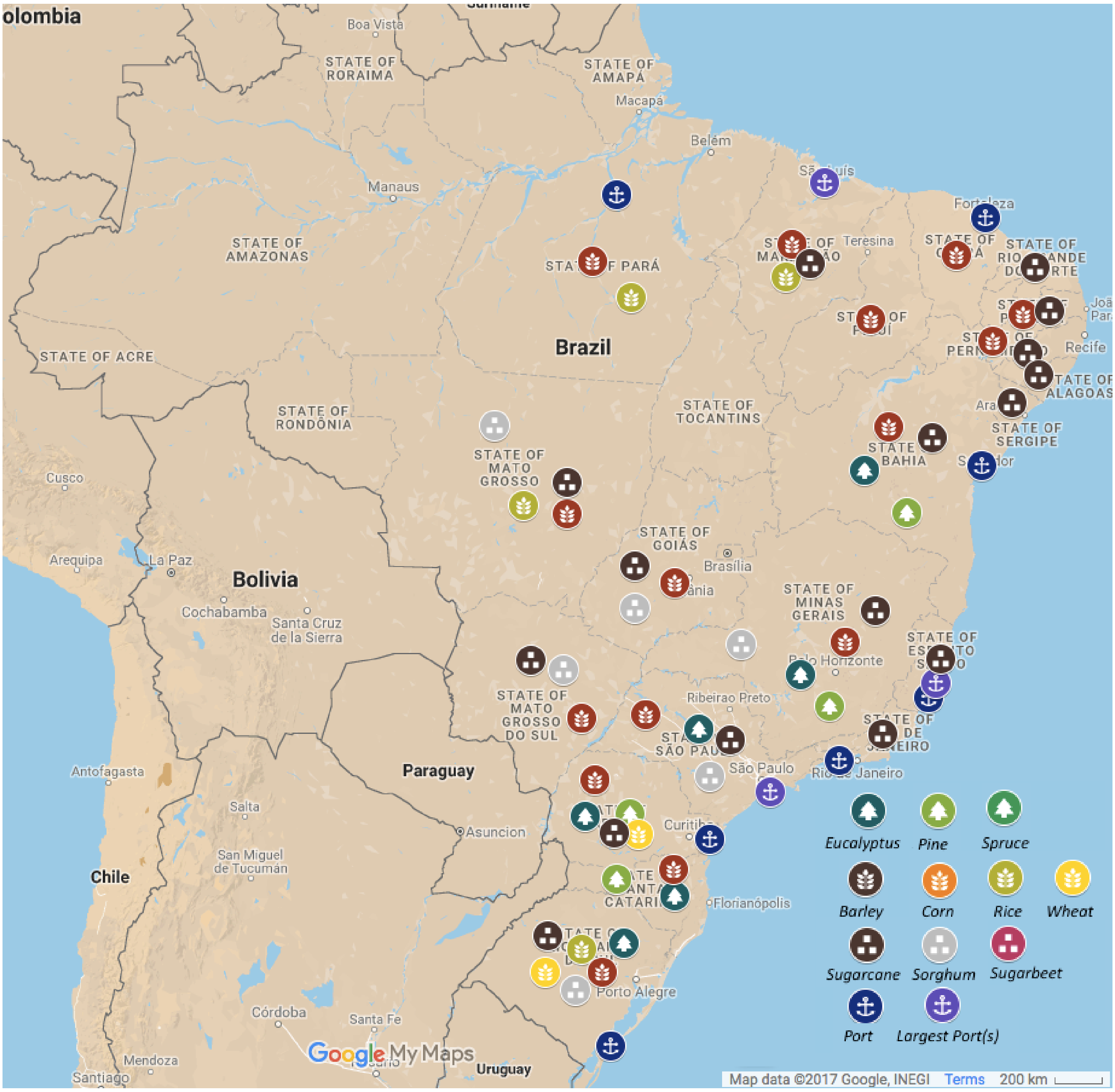


Figure 15. Feedstocks available in Scandinavian administrative regions in sufficient quantity to satisfy biorefinery demand.

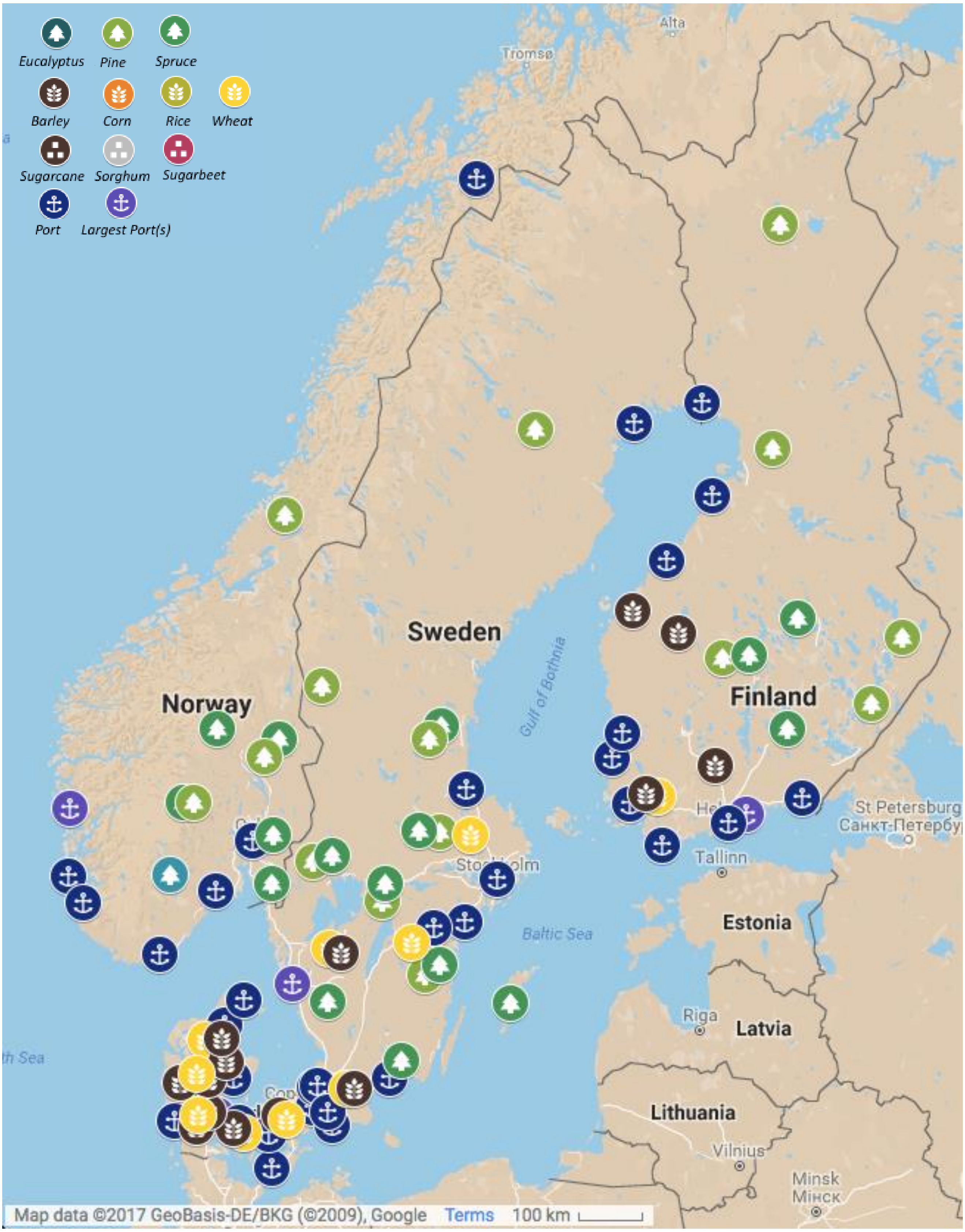


Figure 16. Selected feedstock source regions and biofuel destination ports, Brazil.

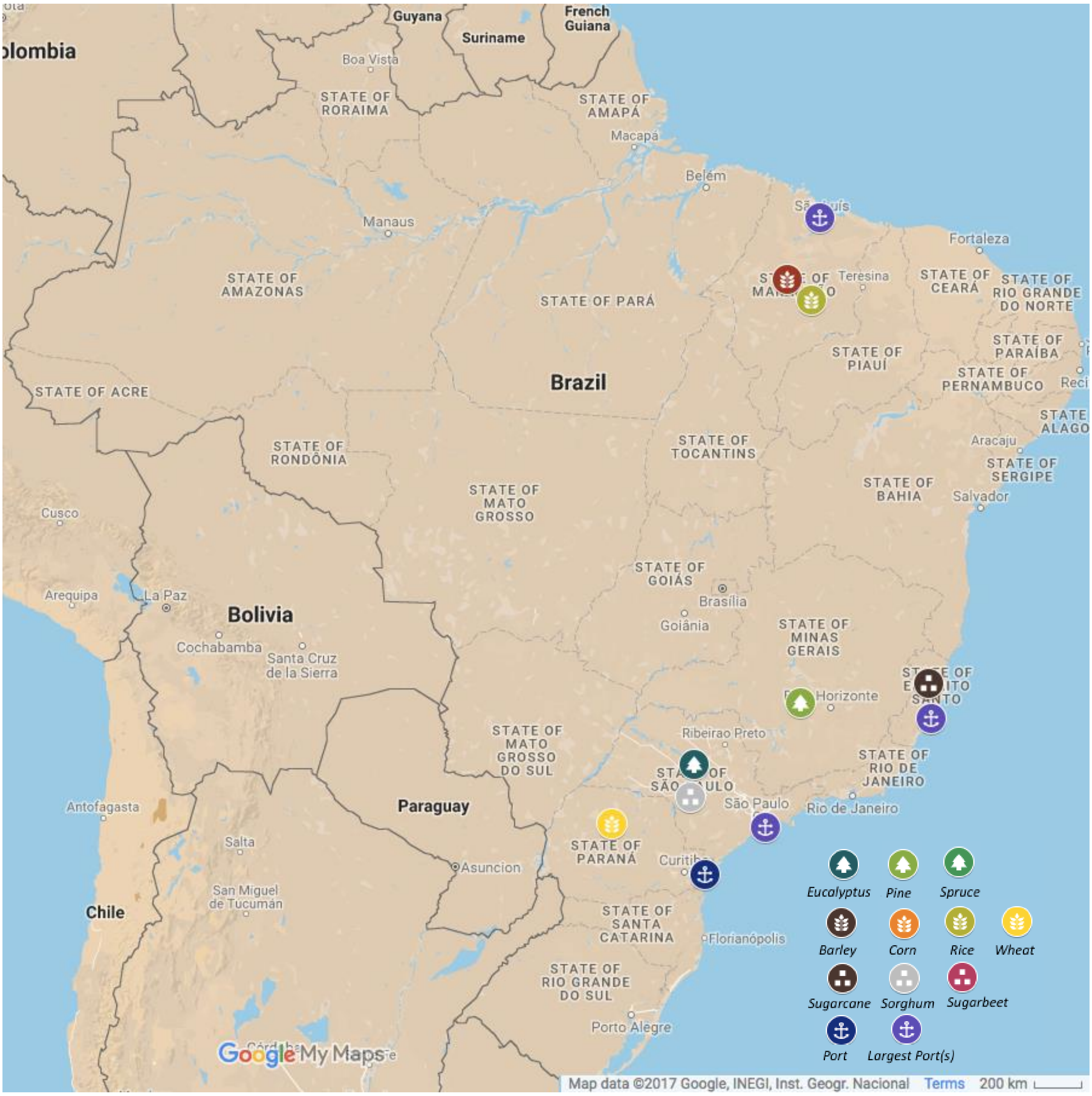
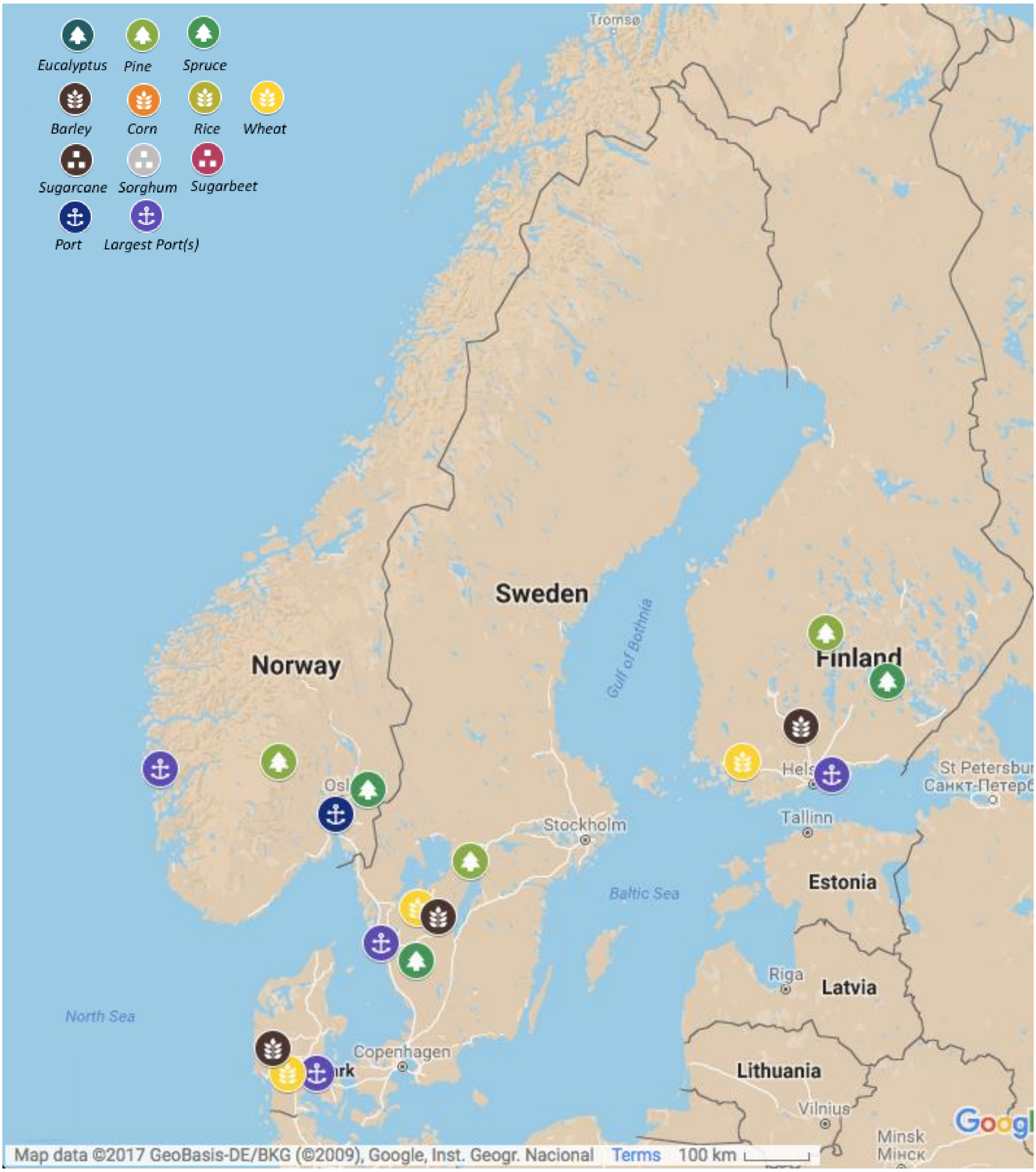


Figure 17. Selected feedstock source regions and biofuel destination ports, Scandinavia.



4.3 Process Yields

4.3.1 Product Yields

Figure 18 and **Figure 19** show the estimated biofuel yield for each feedstock and technology combination in terms of energy yield and mass yield. HTL had highest mass yields for almost all feedstocks, however, the higher energy content of hydrodeoxygenated pyrolysis oil led to a higher energy yield for FP eucalyptus, spruce, corn, rice, and sugarcane. The energy yields range from below 5 GJ to over 14 GJ per tonne of dry feedstock. Interestingly, both extremes are seen in the sorghum feedstock, which had the lowest combination yield for GFT and the highest for HTL. HTL barley, and FP spruce and sorghum also had yields over 11 GJ/tonne.

GFT performed poorly for all combinations, with an average energy yield of 6.7 GJ/tonne across feedstocks, though performed best with grain feedstocks. However, GFT biofuel has the highest energy content, of 45 MJ/kg for each feedstock. GFT energy contents were calculated from the distribution of hydrocarbons produced by FT synthesis and are available in the accompanying spreadsheet. Patterns in FP and HTL yields are less clear. Both performed best with sugar crop residues, and HTL had a higher average energy yield than FP for grain residues, though the reverse was true for forestry residues.

Figure 18. Biofuel yields (GJ/tonne dry biomass) for **HTL**, **FP**, and **GFT**.

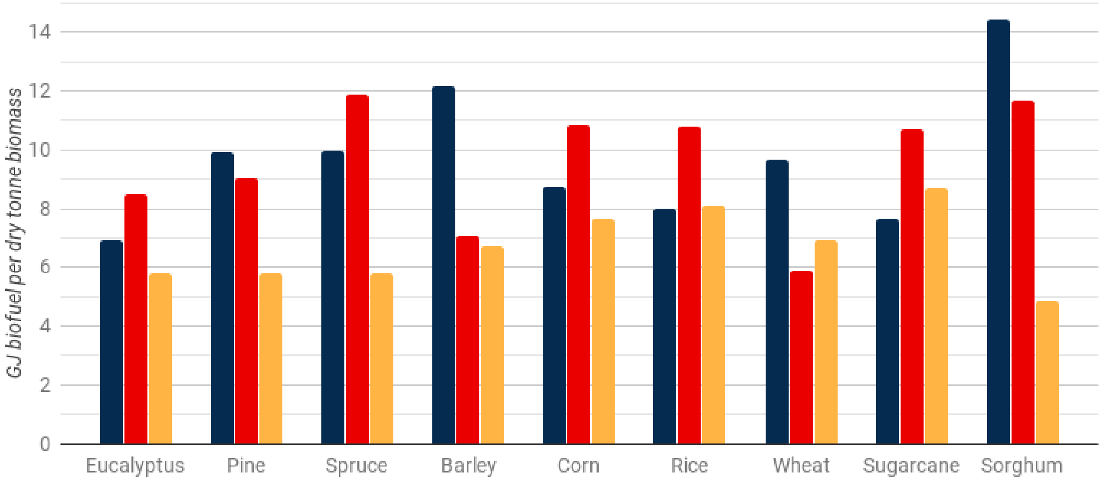
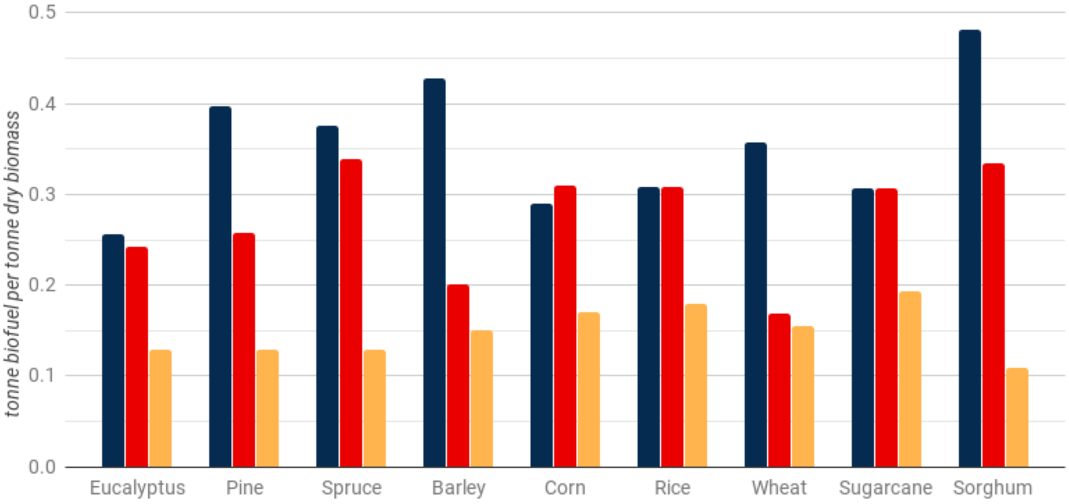


Figure 19. Biofuel yields, tonne/tonne dry biomass for **HTL**, **FP**, and **GFT**.



The production of salable electricity, **Figure 20**, was dependent on combustible product yields, the energy required by the system, and the efficiency of the heat recovery system. GFT had the highest average salable electricity production due to the low estimated system energy demand and the high energy content of the Fischer-Tropsch synthesis offgasses, which contain significant quantities of hydrogen and light hydrocarbons. FP had the highest energy yield from cogeneration, but the combined heating demand of the reactor, hydrogen production, and hydrotreater meant that there was little or no excess energy for electricity production. For HTL, the electricity production dependent on the both char yield and the solvent ratio, which determined the quantity of reactor feed that needed to be heated.

The total annual output of the biorefinery, **Figure 21**, follows the same trends as the per tonne yields except for sugar crop yields, which have a depressed annual yield due to the shorter biorefinery operating season.

Figure 20. Electricity coproduct yields (GJ/tonne dry biomass) for **HTL**, **FP**, and **GFT**.

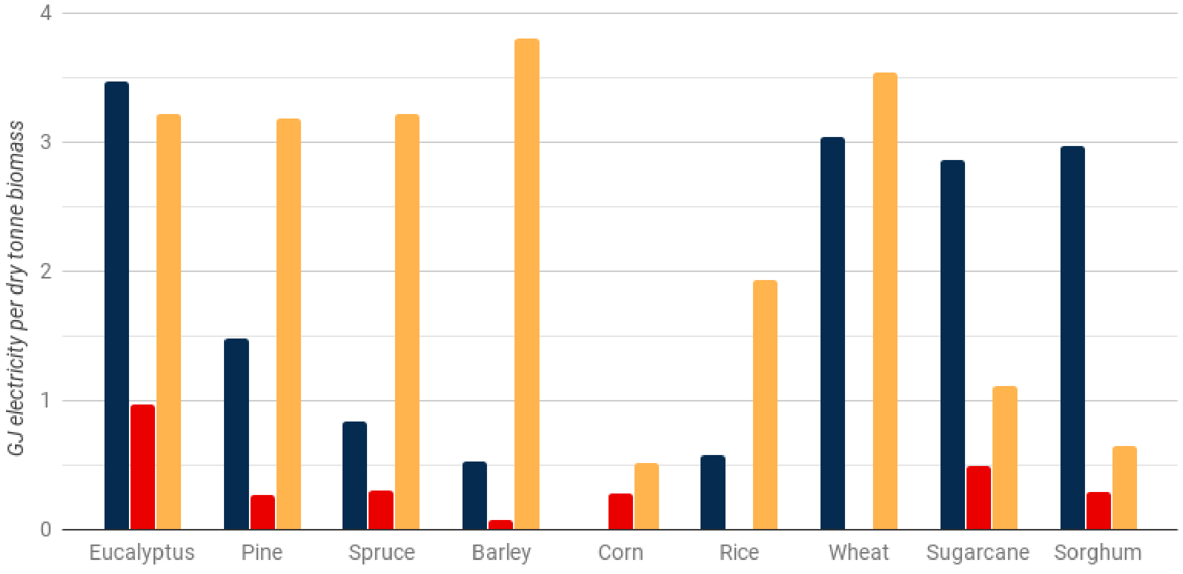
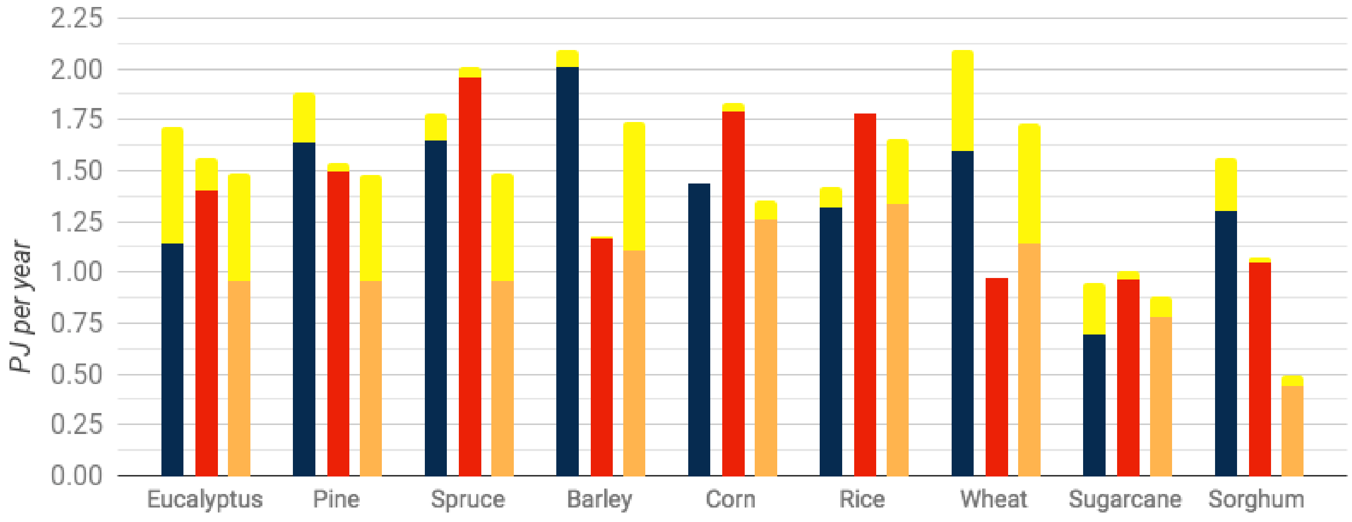


Figure 21. Annual biorefinery output for **HTL**, **FP**, and **GFT** biofuels and **electricity**.



This study's biofuel yields are mostly within the range seen in other biorefinery TEAs, **Table 51**, though lower than those in Da Silva, primarily due to higher assumed losses. However, the salable electricity yields for GFT and HTL were higher for many feedstocks, suggesting that the estimated energy use of the biorefinery may be excluding significant process energy demand. Further research is needed to determine more accurate biorefinery energy demand, as well as the impact of the exclusion of the fuel upgrading and distillation.

Table 51: Lignocellulosic biorefinery product yields from literature.

Feedstock	Biofuel technology	Biofuel Yield (MJ / dry kg of feedstock)	Electricity Yield (MJ / dry kg of feedstock)	Source
Pine	**HTL**	**9.9 MJ / kg**	**1.5 MJ/kg**	**this study**
Pine	**FP**	**9.0 MJ / kg**	**0.3 MJ/kg**	**this study**
Pine	**GFT**	**5.8 MJ / kg**	**3.2 MJ/kg**	**this study**
Wood	Acid hydrolysis and fermentation	6.3 MJ / kg	1.1 MJ/kg	Gnansounou and Dauriat 2010
Pine	FP	16.5 MJ / kg	0 MJ / kg	da Silva 2016
Eucalyptus	HTL with hydrotreatment	18 MJ / kg	0 MJ / kg	da Silva 2016
Wood	FP	11.3 MJ / kg	0.2 MJ / kg	Dutta et al. 2015
Stover	GFT	7.3 MJ / kg	0.7 MJ / kg	Swanson et al. 2010
Wood	FP	11.7 MJ / kg	0 MJ / kg	Jones et al. 2013
Sugarcane	Fermentation to ethanol	6.9 MJ / kg	2.2 MJ / kg	Colombo et al. 2014; Shapouri and Salassi 2006

4.3.2 Energy balances

Figure 22, **Figure 23**, and **Figure 24** show the overall system energy balances for HTL, FP, and GFT, displaying the distribution of energy exiting the system as a percentage of the total energy input of biomass and natural gas. In no case did energy output exceed energy input, though the output energy accounted for varied between technologies. The quantity of unidentified losses directly correlate with the complexity of the system, with HTL having the lowest proportion and GFT the highest. On average, FP has the highest proportion of energy leaving as biofuel.

Figure 22. Hydrothermal liquefaction system energy output.

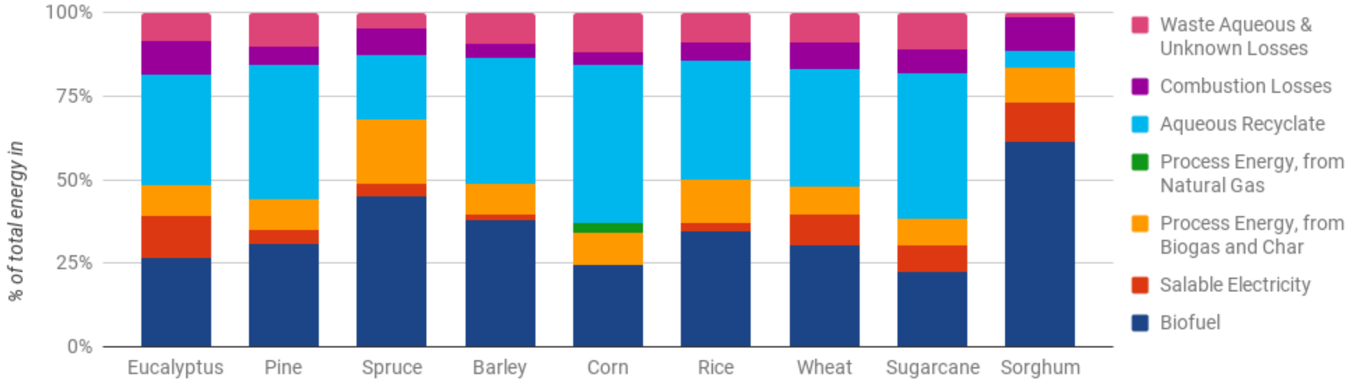


Figure 23. Fast pyrolysis system energy output.

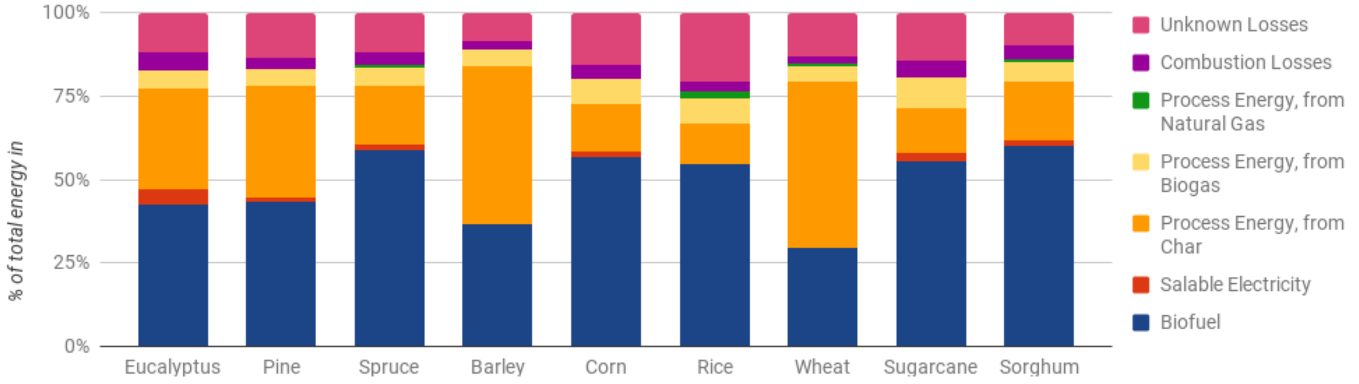
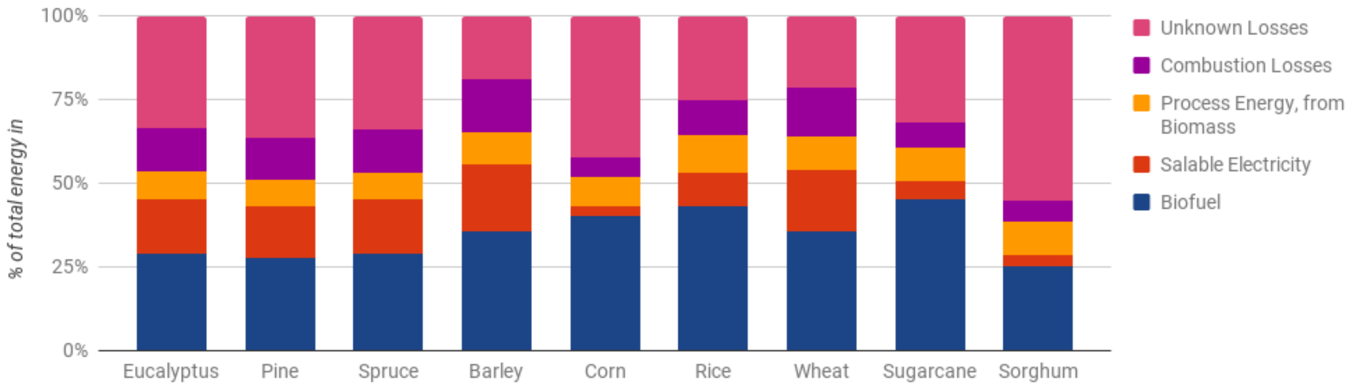


Figure 24. Gasification with Fischer Tropsch synthesis system energy output.



4.3.3 Refinery input demand

The model estimated each combination's demand of natural gas, chemicals, water, and waste processing. These estimates were used in the economic modeling, along with feedstock demand (**Table 47**) to determine the variable costs of the operating expenses. Each of these inputs was also considered in the life cycle assessment.

Natural Gas

All GFT combinations were energetically autarkic, requiring no additional purchase of natural gas. Most FP combinations required small quantities of natural gas to supplement either process energy generation or hydrogen production. Only HTL of corn required the purchase of natural gas, though in substantial amounts. In both cases, their char yield leads to a deficit of available cogeneration energy. For corn, the high aqueous yield of the fresh feed but the low aqueous conversion rate led to an equilibrium aqueous recyclate mass that was 50% higher than any other HTL combination. The additional heat required by the larger reactor feed led to an almost 50% higher system heating demand, 10% of which needed to be satisfied by natural gas.

Table 52. Biorefinery gas use in MJ per GJ of biofuel, by feedstock-technology combination.

	HTL	FP	GFT
Forestry Residues			
Eucalyptus	0	0	0
Pine	0	22	0
Spruce	0	12	0
Grain Residues			
Barley	0	47	0
Corn	152	0	0
Rice	0	82	0
Wheat	0	84	0
Sugar Crop Residues			
Sugarcane	0	0	0
Sorghum	0	18	0

Chemicals

The only chemical considered was the MEA solvent used in GFT for acid gas cleaning. Since a 98% solvent recovery rate was assumed, the demand for fresh solvent is only a few grams per MJ of biofuel produced, **Table 53**. A higher MEA demand indicates that the syngas had a high proportion of CO_2 that needed to be removed.

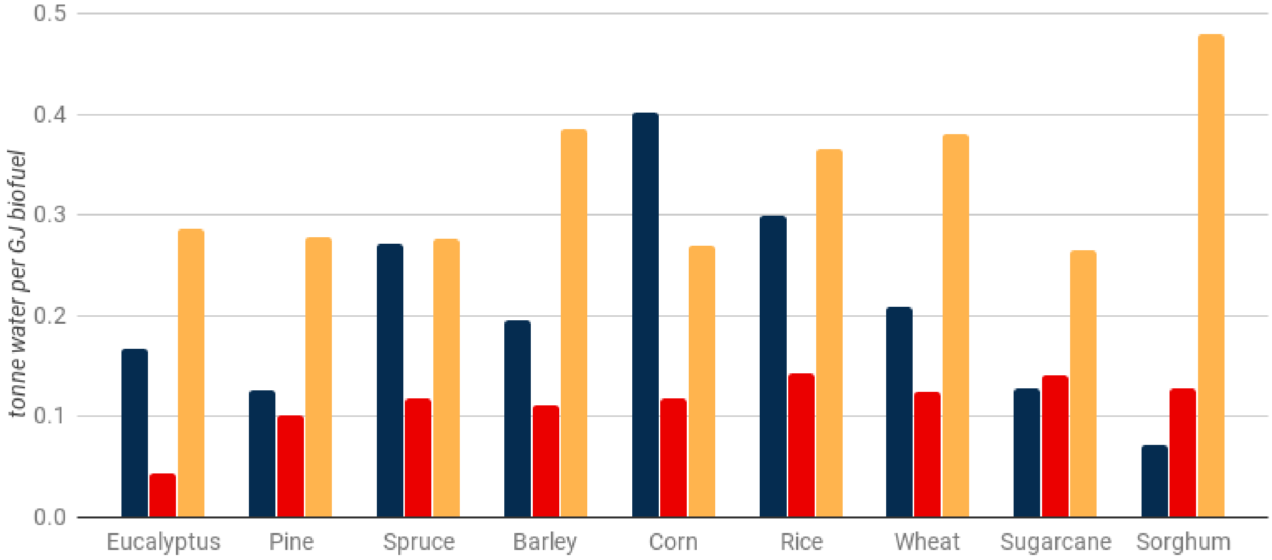
Table 53. GFT solvent demand, kg per GJ of biofuel produced.

	Forestry Residues			***Grain Residues***				***Sugar crop residues***	
	Eucalyptus	Pine	Spruce	Barley	Corn	Rice	Wheat	Sugarcane	Sorghum
MEA	7	7	7	4	6	3	4	6	10

Water

Water demand includes both process water and make-up and blowdown water for the steam boiler in the cogeneration plant. As seen in **Figure 25, i**n average, FP has the lowest water use of all combinations and GFT had the highest. The high water use of GFT is a factor of having the greatest steam needs, the use of water in syngas cleaning, and low product yields. For HTL, the aqueous recyclate satisfies 100% of the solvent demand in all cases, and the only demand for externally supplied was water was for the cogeneration plant.

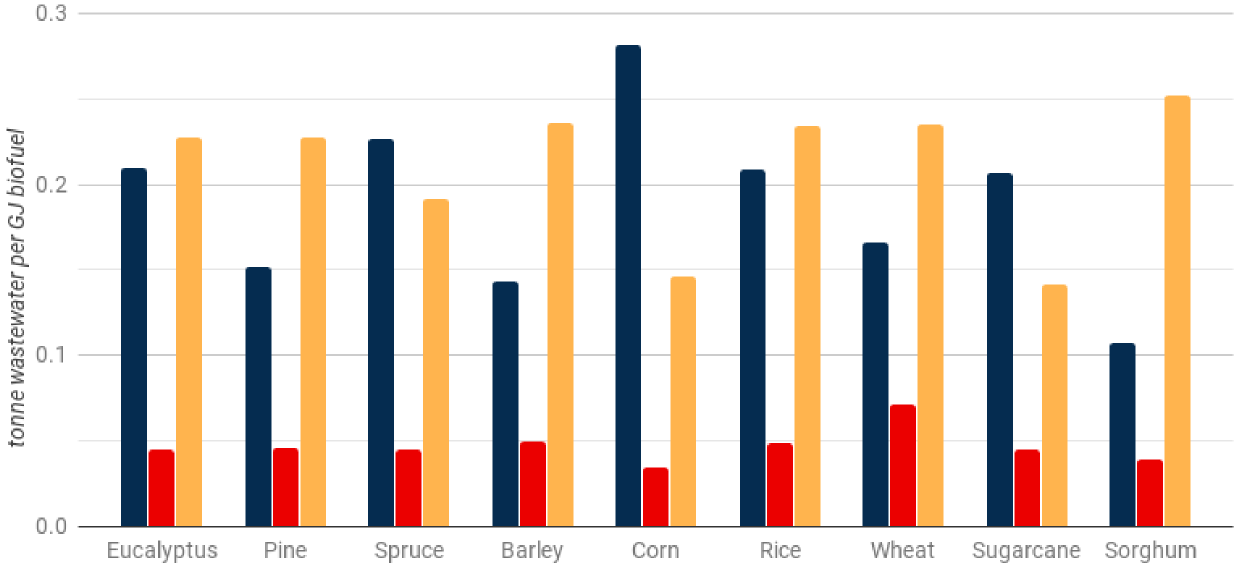
Figure 25. Biorefinery water demand, in tonnes per GJ of biofuel output for **HTL**, **FP**, and **GFT**.



Waste Treatment

The wastewater produced by the biorefinery, **Figure 26** was determined by the purged aqueous fractions of the biofuel conversion process, boiler blowdown, and water used by fuel cleaning processes. The distribution is similar to that of water demand, but HTL has significantly higher wastewater production than water demand, due to the partial purge of the reactor's aqueous output.

Figure 26. Biorefinery wastewater treatment demand, per GJ of biofuel output, for **HTL**, **FP**, and **GFT**.



Solid waste to be landfilled, **Figure 27**, varied between feedstock based on the ash content of the residue. GFT has the highest average solid waste production of the technologies as the sulfur produced from acid gas cleaning was also landfilled. The demand for gas cleaning, **Figure 28,** was based on the system flue gasses, which were from the combustion of char and gas. 10-20% of GFT flue gasses was the CO_2 released during acid gas cleaning that was not used for the pressurization of the gasifier feed.

Figure 27. Biorefinery solid waste to be landfilled, per GJ of biofuel output by technology, for **HTL**, **FP**, and **GFT**.

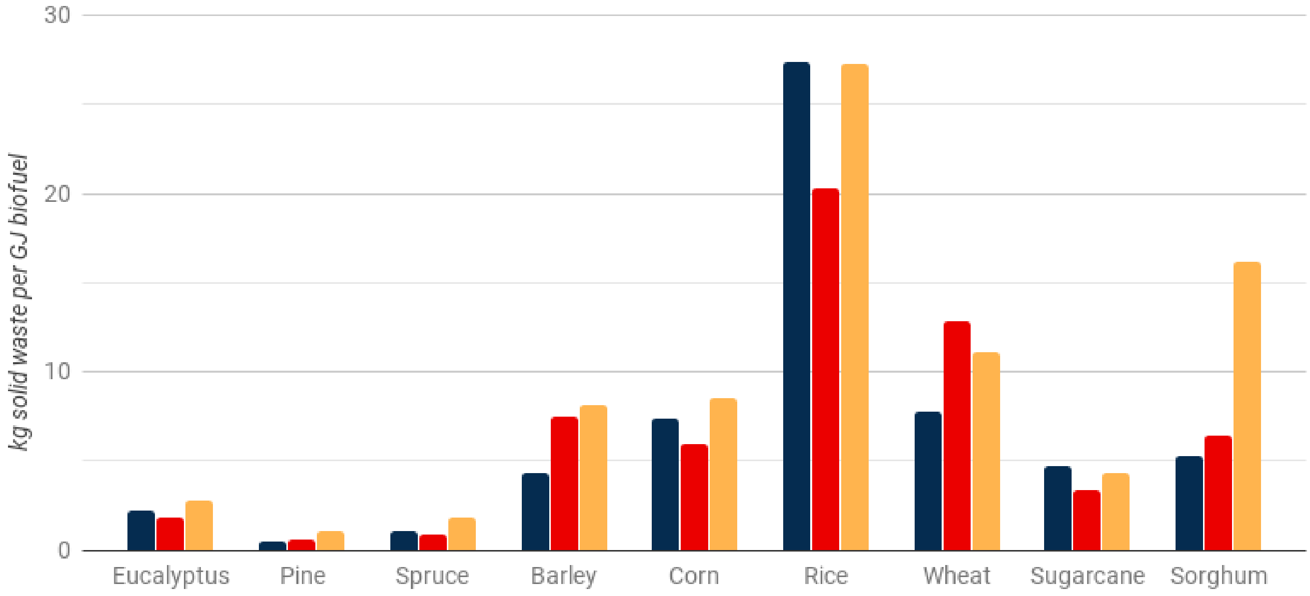
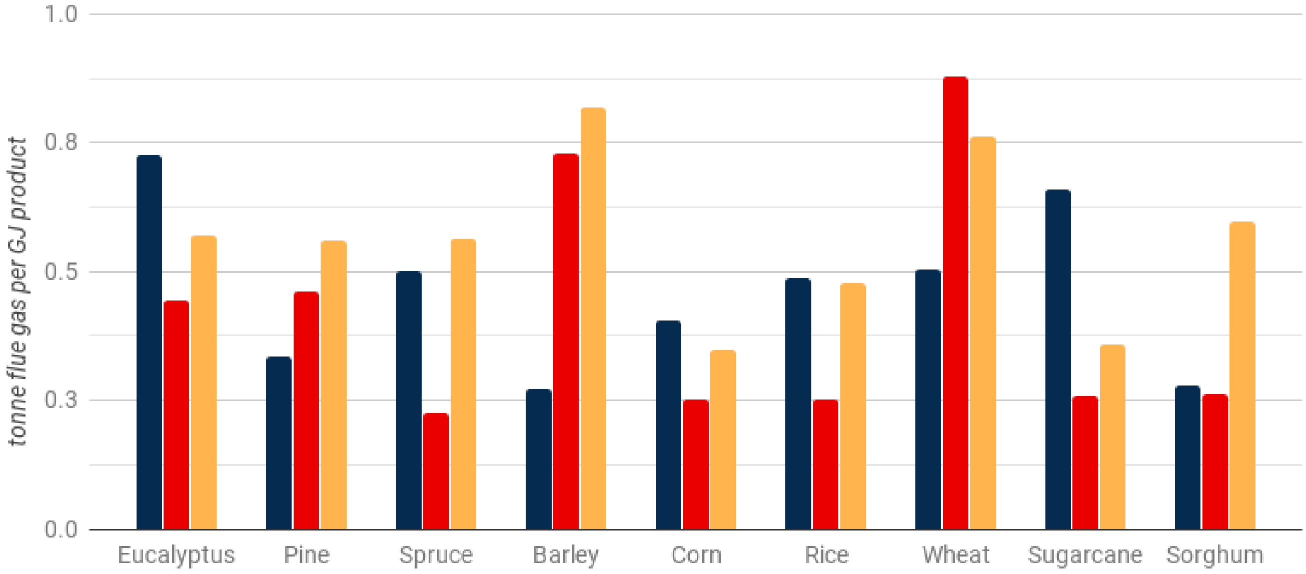


Figure 28. Biorefinery flue gas cleaning demand, per GJ of biofuel output for **HTL**, **FP**, and **GFT**.



4.4 Economic modeling results

4.4.1 Capital Expenses

Since location factors were only applied on the total capital investment, the distribution of capital expenses was nearly identical for all technologies, and identical for countries and regions. The installed equipment costs contributed to almost 60% of the total capital expenses. Indirect costs accounted for 20% of the total CapEx, the contingency for 8%, and start up costs for 9%. The contractor's fee and the working capital were the remaining 5%

Figure 29 breaks down the total purchased equipment costs for each technology, prior to location adjustment. For all three technologies, TPEC varies no more than 10% from the mean value, and for the majority of variation is in the scale of the cogeneration plant. HTL and GFT have nearly equivalent reactor costs, though GFT includes both gasification and Fischer-Tropsch reactors. The equipment costs for HTL and FP are similar, though the cogeneration costs of HTL are almost double that of FP, as the char was directly combusted the FP reactor system, thus significantly reducing the size of the boiler and steam turbine needed for the cogeneration plant. The high contribution of the cogeneration costs overall, however, warrants that additional verification of those costs estimates in future work.

Figure 29. Average total purchased equipment costs prior to location adjustment.

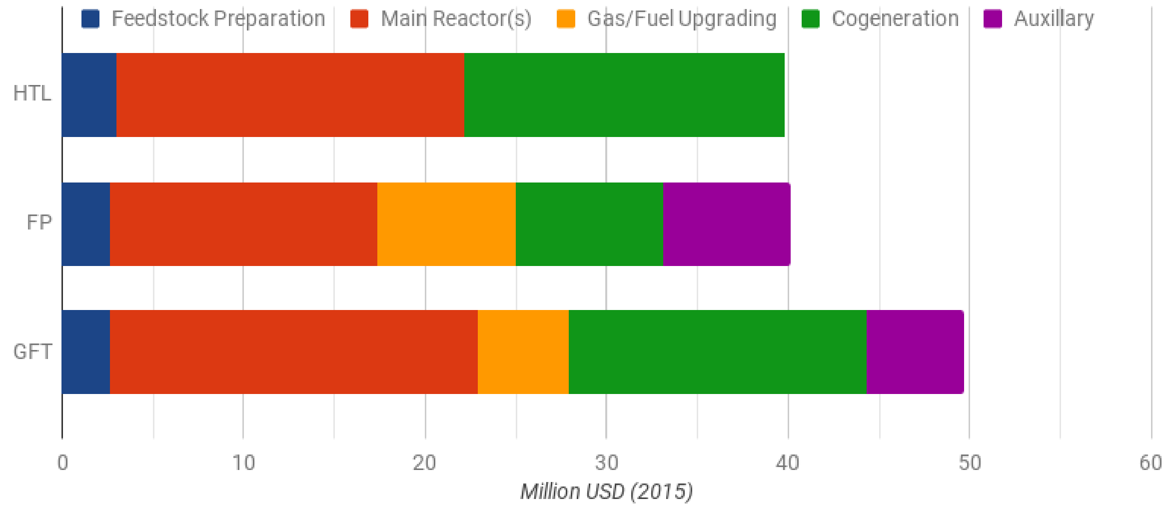


Figure 30 (page 79) compares the capital expenses of combination, and **Figure 31** (page 79) compares CapEx per gigajoule of annual biofuel output, which is known as the installed biofuel capacity. The variation between technologies is significantly more pronounced in CapEx per GJ than in total CapEx. In almost all cases, HTL has the lowest CapEx per GJ, though total capital costs are equal or slightly higher than for FP. GFT has the worst performance in terms of total CapEX, but per gigajoule, wheat GFT is less than wheat FP. Corn rice, and wheat are the most consistent performers between technologies, though HTL barley and FP spruce have the lowest overall CapEx/GJ at $91/GJ and $108/GJ in Scandinavia, and FP corn has the lowest CapEx/GJ, $132/GJ, in Brazil. Sugar crops perform poorly when considered on the basis of installed capacity, as their biorefineries have half the operating days of the remaining feedstocks, due to their limited harvest season and high perishability.

The high location factor for Brazil means that it has 20% higher CapEx for every combination than in Scandinavia. The other location-dependent factor, working capital, which is a factor of sales revenue, is too small a contributor to noticeably impact the CapEx in Brazil or between Scandinavian countries.

Table 54 compares this study's total capital investment estimates, which are the capital costs prior to location adjustment to the pre-location-adjusted TCI costs from (da Silva 2016) and three US-based NREL studies which were representative of the literature review and use uses lower contingency and indirect cost factors than this study. The CapEx of the literature studies were converted to 2015 USD and the total refinery costs were scaled to 500 dry tonnes/day using a scaling factor of 0.7 and **Equation 4**. The CapEx estimates of HTL and FP are within the same order of magnitude as both da Silva and the NREL studies, though the GFT estimates of this study are lower than da Silva, but in line with the NREL study. This study did not include HTL hydrotreatment, or hydrocracking and distillation for any technology, which were included in the reference studies. If these costs are excluded, the estimates of this study are slightly higher than the literature, excluding the FP TEA from Jones et al (2013). An additional review of CapEx estimates from TEA literature for each of the three technologies is available in the accompanying spreadsheet.

Table 54. Comparison of standardized capital costs, this study and literature.

	HTL			FP			GFT		
	This Study	da Silva 2016	Knorr et al 2013	**This Study**	da Silva 2016	Jones et al 2013	**This Study**	da Silva 2016	Swanson et al 2010
Feedstock	**Pine**	Pine	Wood	**Pine**	Pine	Wood	**Pine**	Pine	Corn Stover
Original Capacity (dry t/day)	**500**	1836	2000	**500**	1571	2000	**500**	2221	2000
Scaled Capacity (dry t/day)	**500**	500	500	**500**	500	500	**500**	500	500
Scaled Capital Costs (500 t/day) M USD (2015), USA	**180**	175	138	**186**	175	252	**194**	179	189
Installed equipment costs for hydrocracking and distillation,[1] M USD (2015)	**0**	51	4	**0**	34	32	**0**	16	12

1: For HTL, also include hydrotreatment and hydrogen projection

4.4.2 Operating Expenses

Figure 32 (page 79) compares the annual operating expenses per gigajoule of installed biofuel capacity for all combinations, which vary from \$37/GJ for HTL barley in Sweden to \$212/GH for GFT sugarcane in Brazil. On average, GFT has the highest OpEx and HTL the lowest, though there is substantial variation between technologies and FP has lower operating costs per GJ HTL for spruce, corn, rice, and sugarcane. For sugarcane, HTL has the highest OpEx of all technologies. This pattern is the same as in CapEx, the reason for which is made clear by the breakdown of total OpEx in **Figure 33**, **Figure 34**, and **Figure 35** (page 80). Depreciation and maintenance, which are dependent on CapEx, account for over half of operating expenses for each combination. Flue gas cleaning accounts for 90% of utility costs, though for GFT, MEA demand outweighs utility costs by 400-600%. Feedstock accounts for 10-20% percent of OpEx, and labor costs are under 1% of total expenses in Brazil, and average 3% in Scandinavia. The increased feedstock transport costs and higher CapEx in Brazil mostly negate Brazil's advantage of low labor costs and low at-field feedstock costs. Only Finland has higher OpEx than Brazil. Sweden has the lowest operating expenses across feedstocks and technologies, by up to 15%, as it has the lowest Scandinavian feedstock costs, partially due to the close availability of feedstock to ports.

The OpEx is more difficult to compare with literature, as there are more factors that influence their calculation. However, if da Silva's operating costs for pine in Brazil are scaled to 500 tonnes per day using a 0.7 scaling factor, the operating expenses in this study are about 30% higher, **Table 55**. This is attributable to the higher estimates of waste treatment costs, the higher capital expense estimate, and the inclusion of a contingency factor for unknown costs.

Table 55. Annual operating expenses for pine residue biorefineries in Brazil, this study and da Silva (2016), in 2015 USD.

	HTL	FP	GFT
This study, original capacity (500 dry t/day)	102 M USD	104 M USD	121 M USD
da Silva, scaled to 500 dry t/day capacity	75 M USD	72 M USD	85 M USD
da Silva, original capacity (~2000 t/day)	168 M USD	178 M USD	242 M USD

4.4.3 Earnings Before Taxes

Revenue is generated by the sale of biofuel and electricity. For FP, biofuel sales account for over 85% of sales revenue for all combinations; for HTL, over 95%. For GFT, the biofuel sales proportion ranges between 65% for barley in Finland to 91% for sugarcane in Brazil. Earnings are the difference between revenue and OpEx, and in no cases are earnings positive, **Figure 36** (page 82), when the biofuel selling price was assumed to be the same as marine gas oil.

4.4.4 Minimum Biofuel Selling Price (MFSP)

Using the estimated expenses and earnings, the minimum price at which the biofuel must be sold to have net zero marginal earnings was calculated, **Figure 37**. The MFSP was converted into a ratio with the current price of marine gas oil for each country, **Figure 38** (page 82). The ratio is presented on an energy basis, to account for the differences in energy content between fuels. The MGO prices used are from March 2017, and do not estimate changes in fuel prices due to the upcoming sulfur cap. The MFSP ratio for a biofuel produced and sold in Brazil will be lower than one with the same MFSP in Scandinavia, as the price of MGO in Brazil is 30-40% higher than in Scandinavian countries.

None of the combinations are within the ICS estimate for the cost of sulfur-cap compliant heavy fuel oil, whose upper bound is equivalent to a MFSP ratio of 0.8 in Brazil and 1.1 in Scandinavia. The lowest MFSP is 3.2 for HTL barley in Sweden and for FP corn and rice in Brazil. HTL pine, wheat and rice in Brazil and HTL barley in Denmark and Finland, and FP spruce in Sweden round out the combinations with MFSP ratio below 4.0. The lowest GFT MFSP ratio is 4.7 for rice, and the technology performs overall poorly, which was expected from the high capital and operating costs and low biofuel yields. Brazil, despite its high CapEx and OpEx, has the best MFSP ratios for the shared feedstocks of pine and wheat, due to the high price of Brazilian MGO and electricity.

As shown in **Table 56**, the minimum fuel selling prices estimated in this study are different than their counterparts in da Silva (2016), despite the reduced refining. The MFSP ratios for forestry FP and HTL are 3-5x higher in this study, though for rice they are only 10-30% higher. For GFT rice, the estimate in this study is lower than that of da Silva. These differences arise partly from the higher cost estimates that come from the more conservative factors used in this study, and for the smaller biorefinery size, which reduces the economies of scale. The assumed biofuel yields are also different in this study, often lower, due to the use of additional experimental data for each feedstock, as well as increased losses for FP and HTL. Finally, the MFSP ratios in da Silva on a mass basis rather than an energy basis and that the energy contents assumed by da Silva are the same as fossil jet fuel, while the energy contents used in this study are those from experimental literature. When the MFSP in this study are considered on a mass basis, **Table 56**, HTL and FP have lower fuel selling prices, though the very high energy content of GFT.

However, it is likely that ship owners would not purchase pure biofuel, but rather biofuel blended into fossil fuel oils. When considered as 10% blend in MGO, **Figure 39** (page 82), the MFSP ratios are less daunting. In Brazil, all HTL and FP combinations besides sugarcane have a 10% blend MFSP ratio below 1.5. HTL barley has a ratio of 1.2 in Sweden. As does FP rice and corn in Brazil. HTL barley in Denmark and Finland, and HTL pine, wheat, and rice in Brazil have ratios below 1.3. A 10% blend in marine gas oil that has a sulfur content of 1.5%, however, would not comply with the 2020 sulfur cap. Sulfur-cap compliant blends, and their MFSP ratio, are discussed in the scaling analysis.

Table 56. Comparison of minimum fuel selling ratios for biofuel combinations shared between this study and da Silva (2016).

	Biofuel Type	Price basis	Eucalyptus[1]			Pine			Rice		
			HTL	FP	GFT	HTL	FP	GFT	HTL	FP	GFT
MFSP-MGO price ratio, this study	**Marine**	**USD / GJ**	**5.0**	**4.3**	**6.9**	**3.9**	**4.5**	**7.8**	**3.9**	**3.2**	**4.7**
MFSP-MGO price ratio, this study	Marine	USD / tonne	3.1	3.5	7.2	2.3	3.6	8.0	2.4	2.6	4.9
MFSP-jet fuel price ratio, da Silva (2016)	Jet	USD / tonne	1.0, 1.3	1.2, 1.5	6.0, 6.7	1.4	1.3	4.5	2.8	2.9	6.0

1: Two eucalyptus biorefinery sites were considered in da Silva.

Figure 30. Total biorefinery capital expenses for **HTL**, **FP**, and **GFT**.

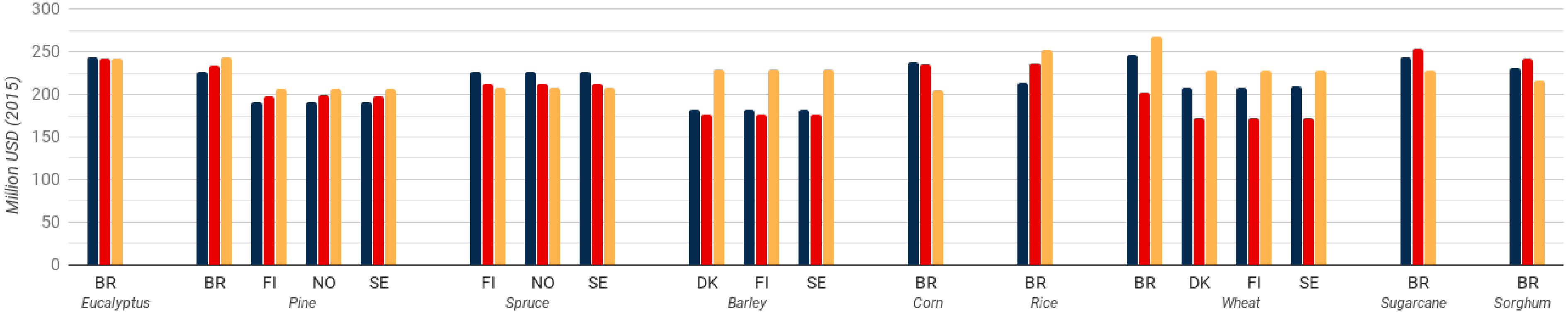


Figure 31. Biorefinery capital expenses, per GJ installed biofuel capacity for **HTL**, **FP**, and **GFT**.

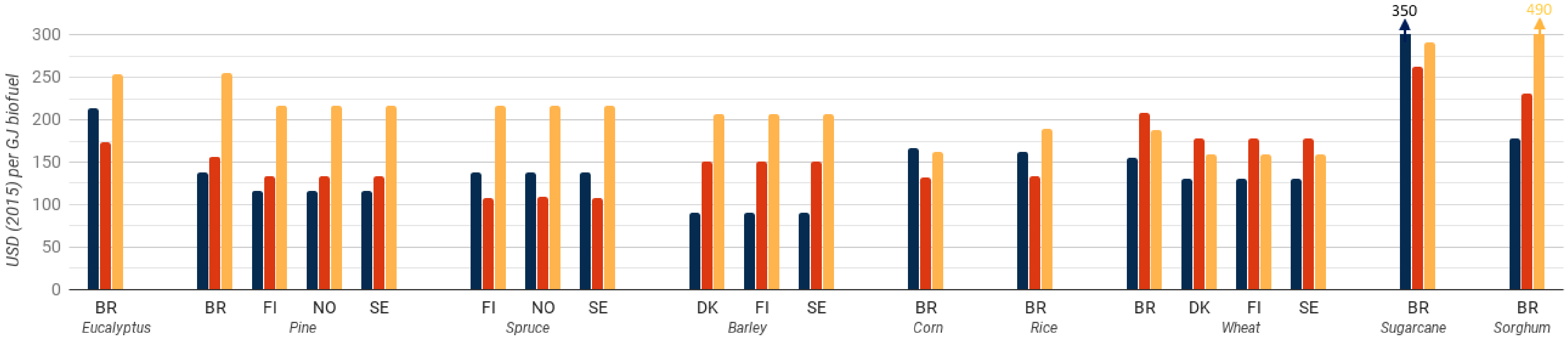


Figure 32. Biorefinery operating expenses, per GJ of installed biofuel capacity for **HTL**, **FP**, and **GFT**.

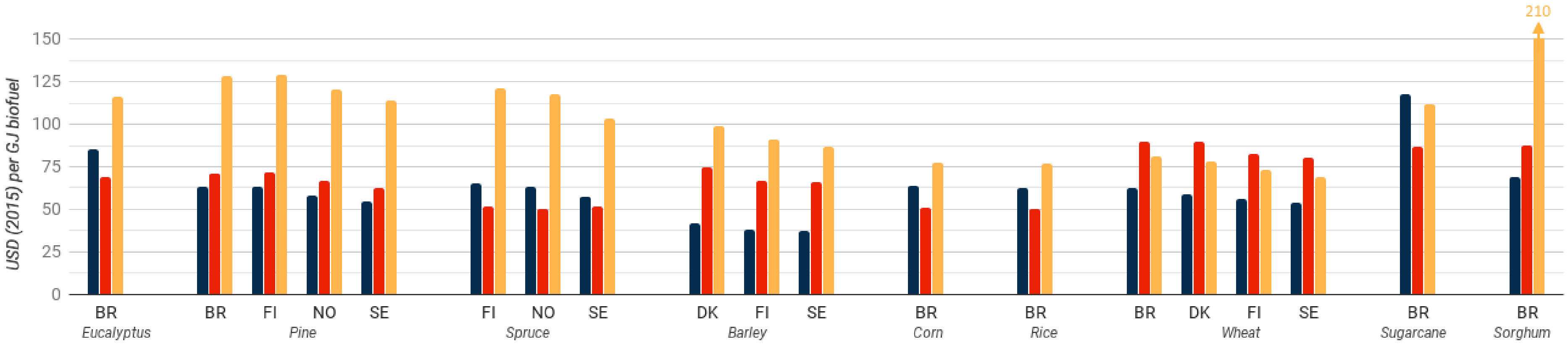


Figure 33. Biorefinery annual operating expenses, HTL.

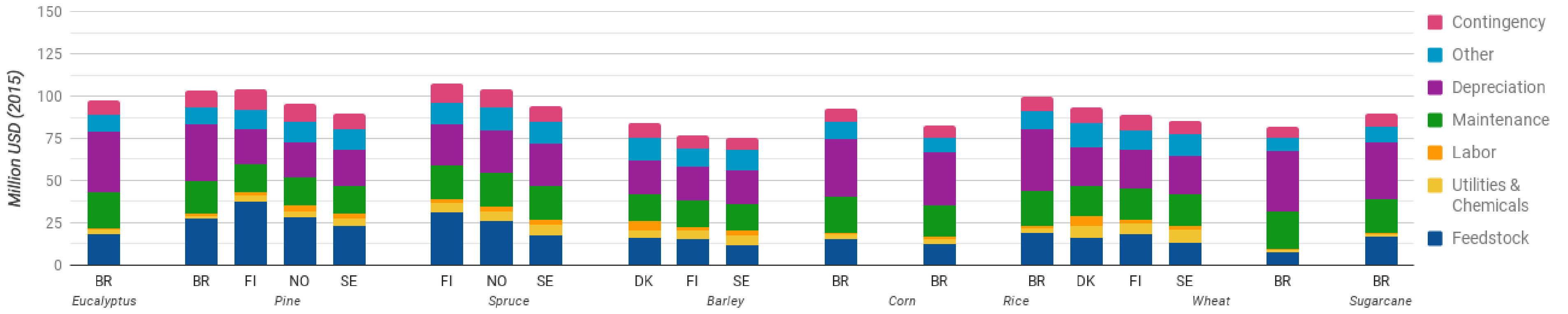


Figure 34. Biorefinery annual operating expenses, FP.

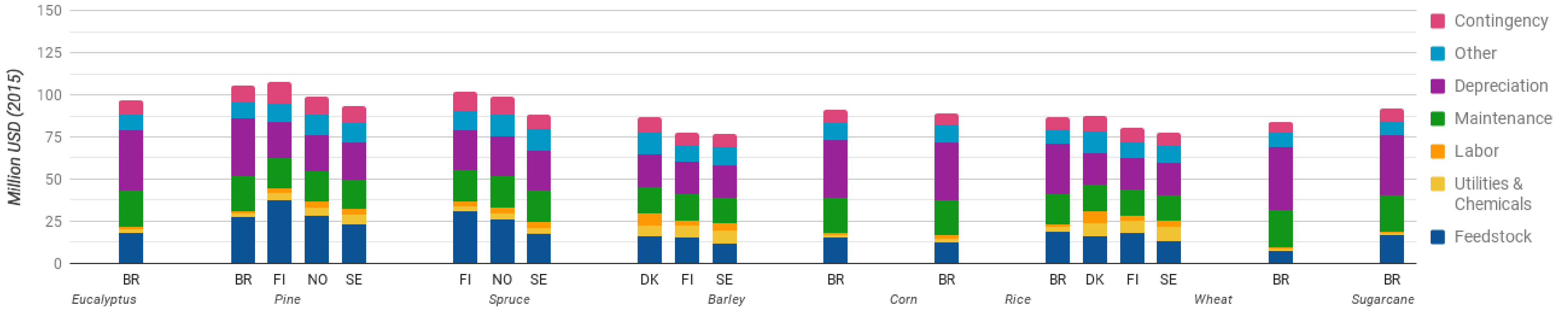


Figure 35. Biorefinery annual operating expenses, GFT.

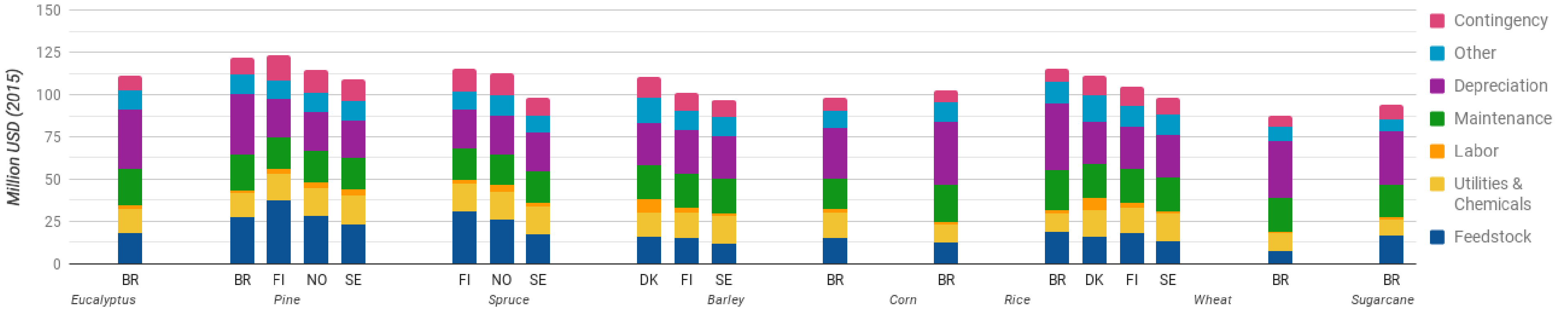


Figure 36. Biorefinery total annual earnings before tax for **HTL**, **FP**, and **GFT**.

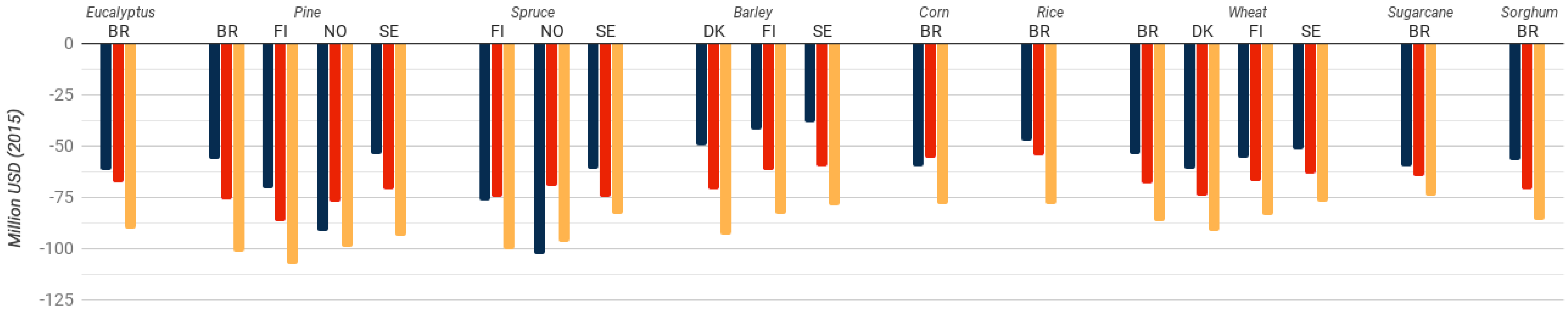


Figure 37. Minimum biofuel selling price for **HTL**, **FP**, and **GFT**.

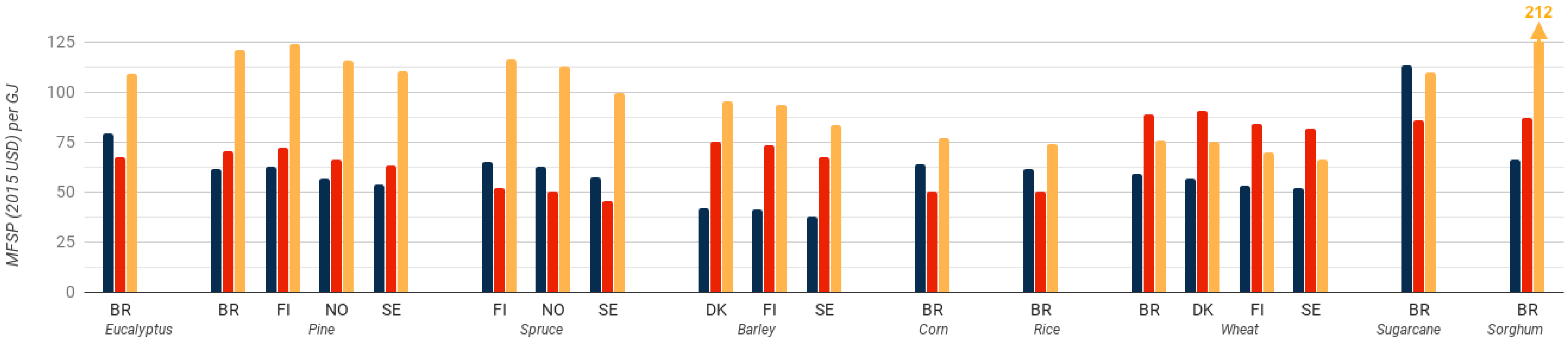


Figure 38. Minimum biofuel selling price, energy basis, ratio to MGO price for **HTL**, **FP**, and **GFT**.

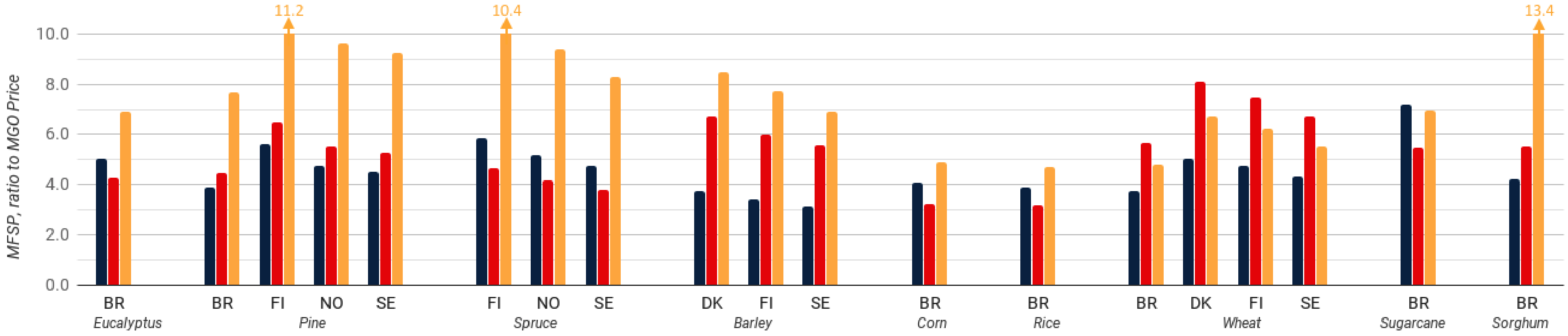
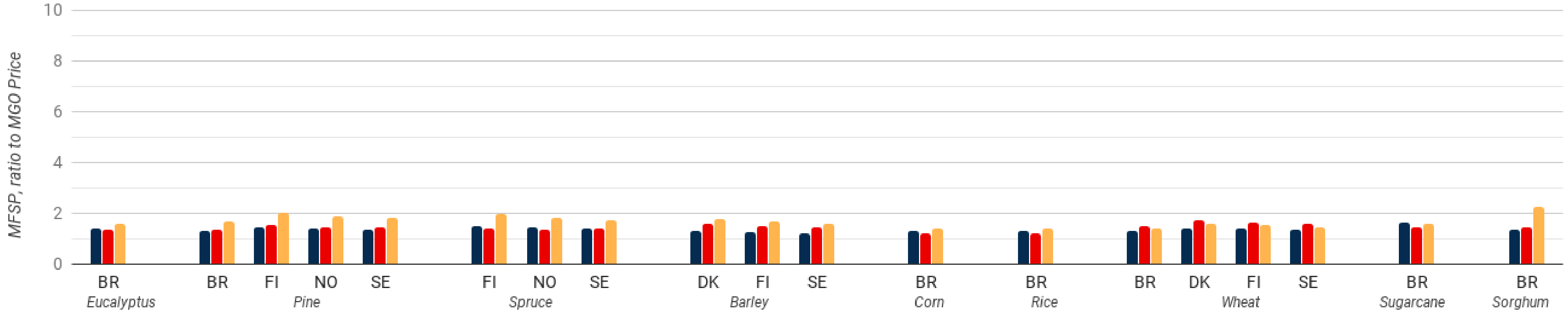


Figure 39. Minimum biofuel selling price, energy basis, 10% biofuel blend with MGO, ratio to MGO price for **HTL**, **FP**, and **GFT**.



4.5 Environmental Impact Results

Except in the case of nitrogen oxide emissions, the estimated life cycle impacts of biofuel production were substantially lower than heavy fuel oil production. The use of displacement allocation resulted in negative impacts for several combinations. This occurred when the emissions displaced by the coproduct electricity were greater than the total emissions produced by the biorefinery and upstream processes.

Additional charts that detail the contributions of different processes to the environmental impact results are available in the accompanying spreadsheet.

4.5.1 Greenhouse Gas Emissions

The low life cycle greenhouse gas emissions in **Figure 40** compared to the HFO reference (89 kg CO_2-eq/GJ HFO) are primarily a function of the exclusion of biogenic CO_2 emissions from biofuel combustion. The only combustion emissions, approximately 1kg CO_2-eq/GJ biofuel, were those from N_2O and CH_4, which were assumed to be the same as MGO, due to lack of biofuel emission data. The FP GHG emissions in this study are similar to those calculated by da Silva, **Table 57**, though lower for HTL due to the greater displaced electricity production.

Rice performs worse than any other feedstock (36-42 kg CO_2-eq/GJ biofuel), due to the high use of fossil fuels during feedstock production that contributed over 80% of the combination's emissions. HTL corn also had high emissions for the technology (25 kg CO_2-eq/GJ), due to the contribution of 8 kg CO_2-eq/GJ from the combustion of natural gas in biorefinery cogeneration. GHG emissions for GFT area also increased by solvent use, which contributes 2.3 kg CO_2-eq/kg MEA, and GFT demand an average of 6 kg MEA/GJ biofuel.

The variation between countries for the same feedstock-technology combinations is primarily attributable to the differences in national electricity mix. Denmark's electricity mix is 40% fossil fuels and the mix for Brazil and Finland are both 25% fossil. Combinations with high electricity coproduction in those countries have negative net emissions, including GFT of forestry residues, barley, and wheat and HTL of wheat, eucalyptus, and sugar residues. In Brazil, emissions from feedstock transport are 3-4x higher than in Scandinavian countries, due to the increased distances.

Table 57. Comparison of life cycle greenhouse gas emissions in this study and da Silva (2016), in kg CO_2-eq per GJ biofuel.

	HTL		FP	
	This study	da Silva (2016)	**This study**	da Silva (2016)
Eucalyptus, Brazil	**-21.5**	19	**6**	9
Pine, Brazil	**2**	15	**13**	6
HFO Reference	89			

4.5.2 Sulfur Dioxide Emissions

Biofuel life cycle sulfur dioxide emissions, **Figure 41** are less than 13% than that of HFO (2.5 kg SO_2/GJ HFO) for all combinations and less than 3% for GFT and FP, which have near zero (0.003 kg SO_2/GJ biofuel) combustion emissions. For all combinations, emissions upstream of biofuel combustion, including those of biorefinery processes and feedstock production, are below 0.08 kg SO_2/GJ. HTL has the lowest upstream emissions but has the highest combustion emissions, due to estimated biofuel sulfur content of 0.1%. However, all pure biofuels comply with the strictest SECA sulfur restrictions. Upstream emissions are tied to fossil fuel use, and follow the same distribution as for GHG and NREU; attributable to feedstock production and transport for all combinations, and MEA use for GFT.

4.5.3 Nitrogen Oxide Emissions

Biofuel life cycle emissions of nitrogen oxide are on par or higher than those of HFO (1.6 kg NO_x/GJ HFO), **Figure 42**. Over 95% of biofuel NO_x emissions for all combinations are from combustion. HTL emissions (2.9 kg NO_x/GJ HTL for all combinations) are nearly double those of HFO, likely due to the high oxygen content of the fuel, which increases combustion NO_x emissions, and exacerbated by the lower energy content (25-33 MJ/kg), which requires more fuel to be combusted for the same energy output. FP and GFT emissions were estimated within 10% of the HFO reference. GFT NO_x emissions are slightly less than HFO, likely due to the high quality of the biofuel.

As NO_x emissions are dominated by biofuel combustion, the displacement of coproduct electricity, which only allocates upstream emissions, has no visible effect on life cycle emissions between countries. Nor do differences between feedstocks. The largest non-combustion contributor to NO_x emissions is feedstock production, but largest impacts, from rice and barley, are still less than 3%.

4.5.4 Non-Renewable Energy Use

Non-renewable energy use, **Figure 43**, for FP and HTL roughly follow the same distribution and proportion to the HFO reference (1.2 GJ NREU/GJ HFO) as GHG emissions, as fossil fuel use in the supply chain is the primary contributor. GFT NREU, in contrast, is dominated by the production of MEA, which accounts for over 50% of NREU in all combinations. Like GHG emissions, the countries' electricity mixes impacts estimations of NREU, with the displaced fossil electricity contributing heavily to the negative impacts for Denmark and Finland.

The NREU estimated in this study are lower than in da Silva (2016), **Table 58**, though of the same order of magnitude. The difference is primarily attributable to the higher biorefinery electricity production, whose emissions are displaced, and the lower natural gas demand, as the lower level of biofuel upgrading in this study requires less energy and hydrogen than in da Silva's biojetfuel biorefinery model.

Table 58. Comparison of non-renewable energy use in this study and da Silva, in GJ NREU per GJ biofuel

	HTL		FP	
	This study	da Silva (2016)	**This study**	da Silva (2016)
Eucalyptus, Brazil	**-0.19**	0.43	**0.21**	0.09
Pine, Brazil	**0.01**	0.31	**0.07**	0.05
HFO Reference	1.22			

4.5.5 Consistency Check

Each combination was modeled using ecoinvent inventory data for feedstock production, feedstock transport, biorefinery utilities, chemicals, and waste treatment. Combustion data was from engine testing literature, and HTL and GFT emissions had to be extrapolated from biofuel blends. The reference system of HFO also used ecoinvent data for impacts upstream of biofuel combustion, using the process for "heavy fuel oil, at refinery," but did not estimate input demand independently. The fossil fuel refinery process has a more comprehensive inventory of chemicals used in the process and less uncertainty in yields than the biofuel combinations. In all cases, the impacts of the refinery site were excluded.

Data did not correspond to the region of origin besides Scandinavian natural gas production, electricity production for all regions, and sugarcane bagasse for Brazil. The remaining processes were assumed to have the same impacts regardless of location. Combustion data was more recent, 2009-2015, than upstream process data, 1992-2006.

Figure 40. Life cycle greenhouse gas emissions (CO_2, N_2O, CH_4) per GJ biofuel, displacement allocation for **HTL**, **FP**, and **GFT**. (**HFO** life cycle emissions for reference)

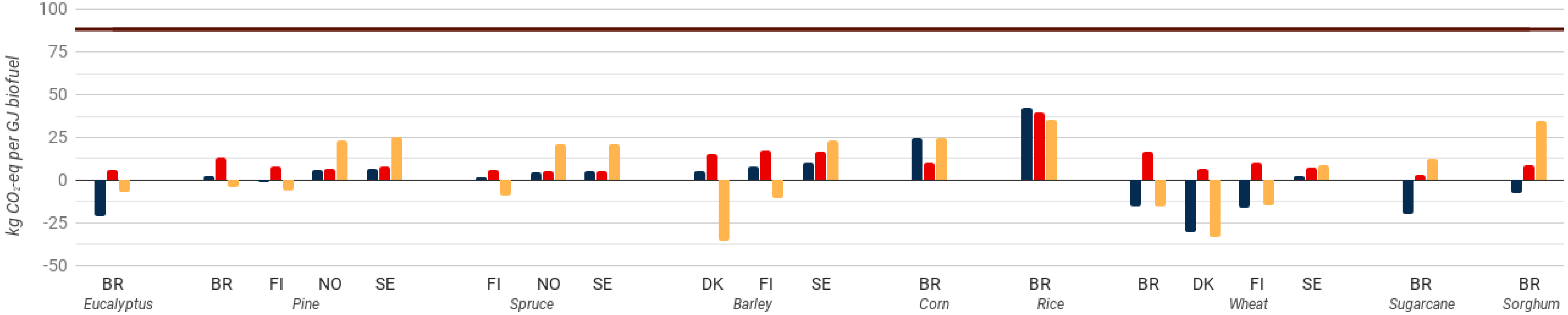


Figure 41. Life cycle sulfur dioxide emissions per GJ biofuel, displacement allocation for **HTL**, **FP**, and **GFT**. (**HFO** life cycle emissions for reference)

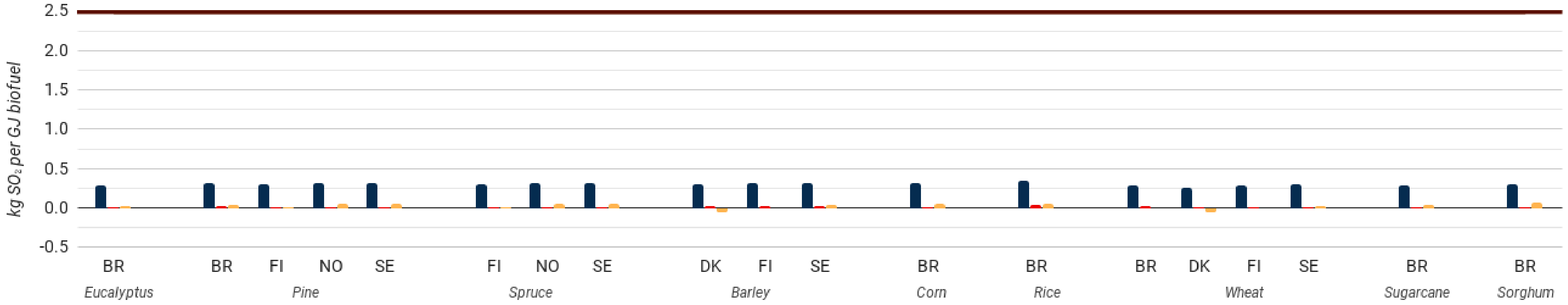


Figure 42. Life cycle nitrogen oxide emissions per GJ biofuel, displacement allocation for **HTL**, **FP**, and **GFT**. (**HFO** life cycle emissions for reference)

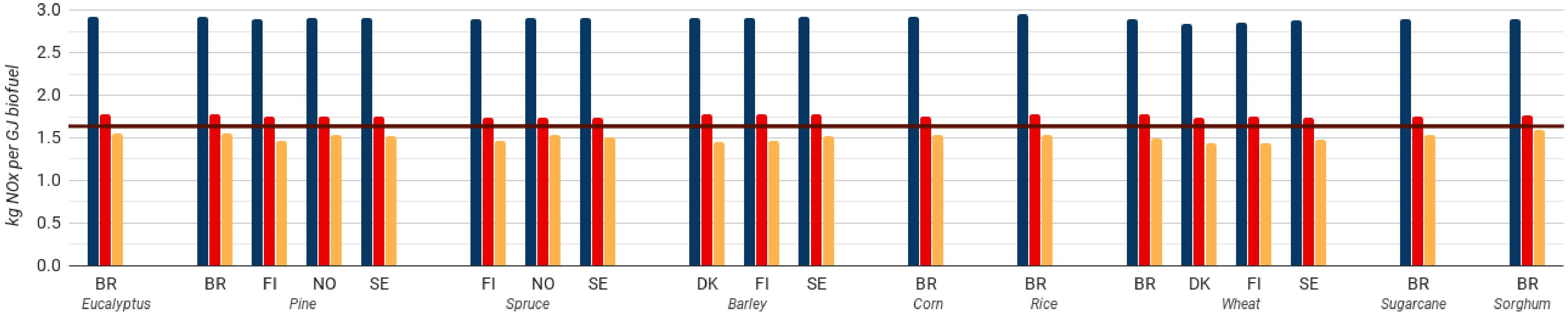
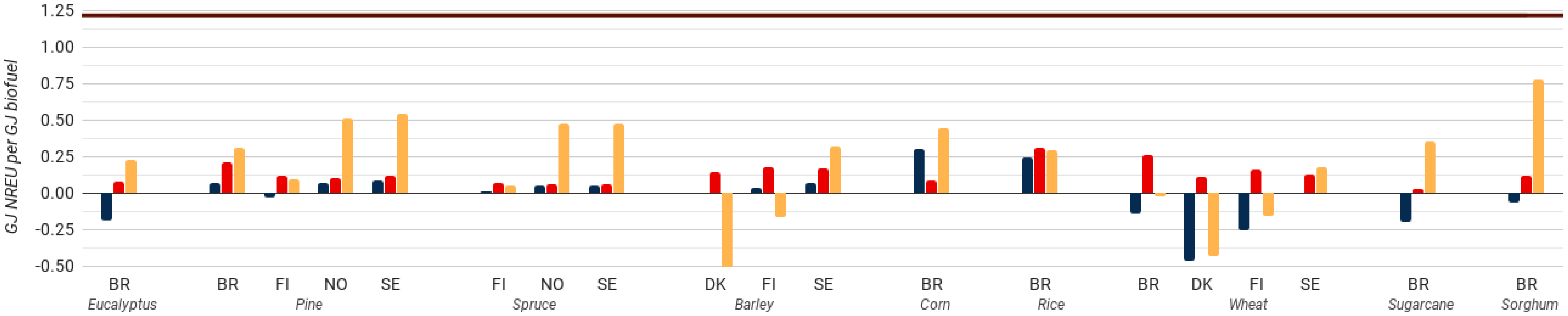


Figure 43. Life cycle non-renewable energy use per GJ biofuel, displacement allocation for **HTL**, **FP**, and **GFT**. (**HFO** life cycle NREU for reference)



4.6 Scaling Analysis

To conserve space, only a selection of results is visualized in this thesis. HTL wheat, FP pine, and GFT wheat in Brazil and Sweden were selected to demonstrate variations between technologies, grain and forestry residues, and regions. Wheat and pine, though not the best performing combinations, are available in both Brazil and Scandinavia, Sweden was selected to represent Scandinavia, as it had the best economic performance in that region, with up to 20% lower MFSPs. Complete results in table form and extensive additional charts are available in the accompanying spreadsheet.

4.6.1 Demand Satisfaction

10% of marine fuel demand

The biofuel demand of each country was assumed to be 10% of the total national marine fuel demand. The ability of a single 500 dry tonne/day biorefinery to satisfy that demand is charted in **Figure 44** for each feedstock-technology-country combination. A single biorefinery's output never exceeds 15% of Brazil's estimated demand. In Scandinavia, Finland and Norway have such low biofuel demand that there is no case where the fuel produced by a single biorefinery does not exceed national demand, and the majority of the biofuel must be exported.

When individual port biofuel demand was considered, over 90% of the biofuel in the Finnish and Norwegian combinations would need to be forwarded to a port with a higher marine fuel demand, such as Rotterdam. 70-80% of biofuel from the Danish combinations would also need to be forwarded. The port of Gothenborg in Sweden is large enough to absorb the biofuel produced by all combinations.

There are sufficient residues to satisfy the national biofuel demand for most of the combinations, **Figure 45**. Exceptions are for grains in Sweden, sorghum in Brazil, and FP wheat in Brazil. The biofuel demand in Finland and Norway is low enough that it could be satisfied by a single refinery of less than 300 tonnes/day, as seen in **Figure 46**, whereas in Brazil, the smallest possible refinery to satisfy biofuel demand would be a 4350 tonnes/day FP corn biorefinery. In Denmark, a single biorefinery of 1000-1500 tonnes/day would satisfy national demand, and would likely require the smallest increase in transport distances due to the density of agriculture in the small country. For Sweden, the biorefinery would need to be between 2000-4000 tonnes/day.

100% of marine fuel demand

Biofuel produced from eucalyptus, pine, corn, or sugarcane via any technology could satisfy 100% of marine fuel demand in Brazil, as could pine, spruce and barley in Finland and spruce in Norway. In Sweden, HTL and FP spruce could satisfy national demand, but require over 70% of available residues. No combination in Denmark could satisfy 100% of its marine fuel demand. In Finland, satisfying national demand would require less than 20% of available residues for either pine or spruce but the majority or entirely of its barley residues. Satisfying national demand via a single biorefinery is only a reasonable for Finland and Norway, whose low demand would require a scale of less than 2000 tonnes/day for most combinations, as low as 1100 tonnes/day for HTL barley and FP spruce in Finland.

In Brazil, the lowest total biorefinery throughput needed would be 43 500 tonnes/day for FP corn. Only 16% of national sugarcane residues would satisfy the entire country's marine fuel demand if converted by fast pyrolysis, but a daily biorefinery throughput of 80 000 tonnes would be needed.

Figure 44. National marine biofuel demand (10% of total marine fuel demand, by energy content) satisfied by biorefinery output, for **HTL**, **FP**, and **GFT**.

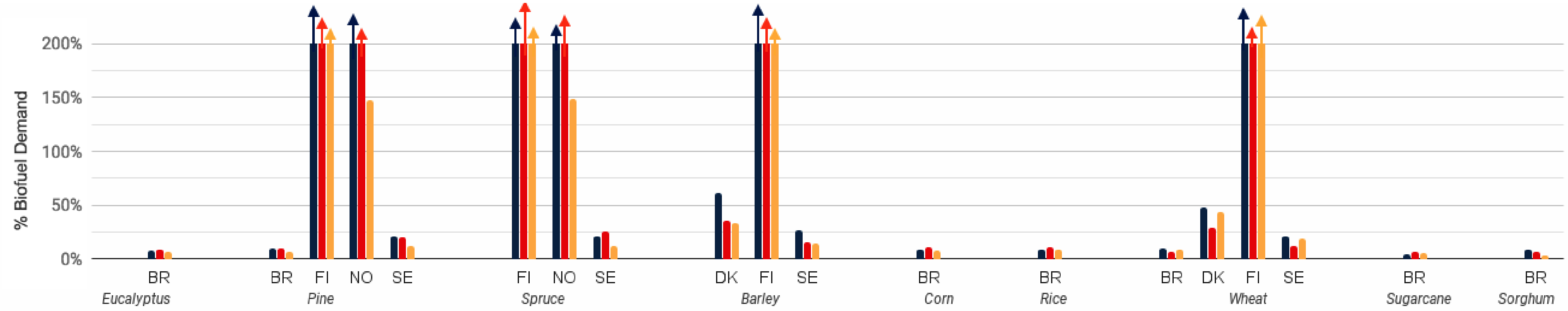


Figure 45. Proportion of available residues to national marine biofuel demand (10% of total marine fuel demand, by energy content), for **HTL**, **FP**, and **GFT**.

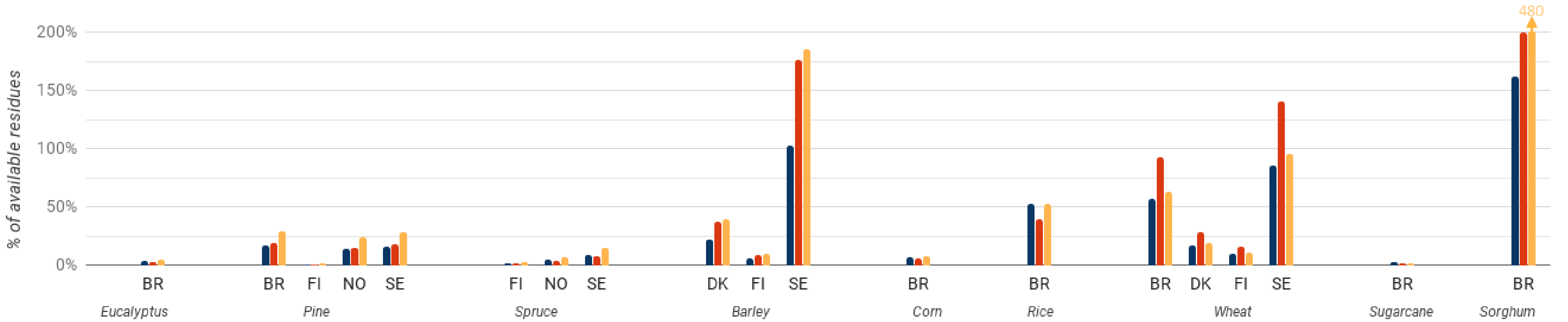
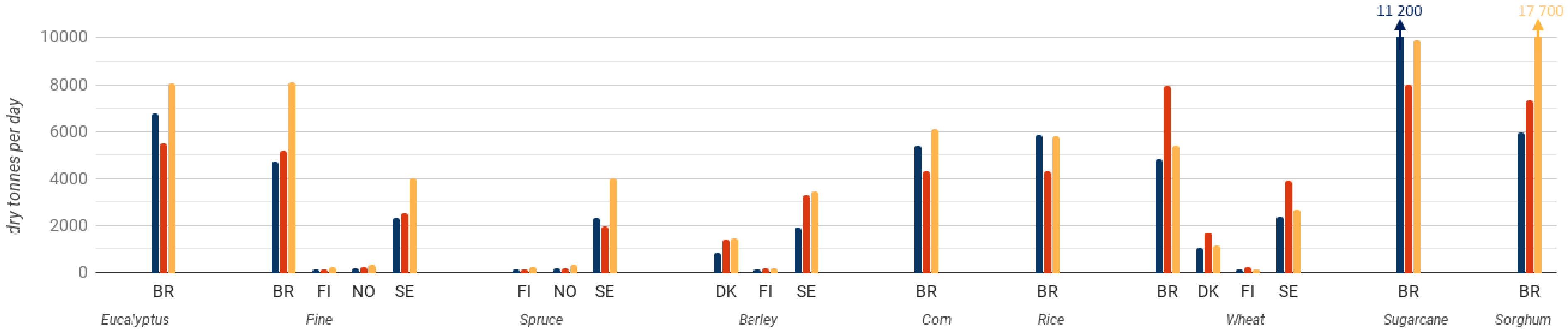


Figure 46. Biorefinery scale needed to satisfy national marine biofuel demand (10% of total marine fuel demand, by energy content),, for **HTL**, **FP**, and **GFT**.



4.6.2 Environmental regulation compliance

Sulfur cap compliant biofuel blends

All biofuels modeled in this study are compliant with both the 2020 0.5% open water sulfur content cap and the 0.1% SECA cap. To reduce cost and potentially improve performance, the biofuels could be blended into fossil fuels. With a 1% sulfur blendstock, a 50% blend would be required to sufficiently reduce the sulfur content of FP and GFT fuel, and a 57% blend of HTL, to accommodate its higher sulfur content, **Table 59**. The 3.5% sulfur content of HFO would required a blend level of 86%/89%; almost entirely biofuel, to reach a 0.5% sulfur content.

A 2020 sulfur-cap compliant blend of biofuel and 1% MGO leads to a 25-45% reduction in the MFSP ratio from the use of pure biofuel, depending on the energy content of the biofuel. The blend with HTL barley has an MFSP ratio of 2.2 in Sweden and 2.4 in Denmark. FP corn and rice in Brazil also have a MFSP ratio of 2.1. The next lowest ratio for Scandinavia is 2.6 for FP spruce in Norway and HTL barley in Denmark.

Table 59. Minimum biofuel blend to meet 2020 sulfur cap requirements.

Sulfur content of fossil blendstock	HTL	FP	GFT
1.0%	57%	50%	50%
1.5%	73%	67%	67%
3.5%	89%	86%	86%

Nitrogen oxide emission cap

All modeled biofuels comply with IMO Tier II NO_x emission standards for slow speed diesel engines (<300 RPM), assuming a 50% engine efficiency, which allow them to operate in open waters. GFT biofuels could potentially also be usable in NECAs. However, NO_x emissions are engine-dependent, and the engines used for biofuel testing were all high speed engines, so further testing is needed to verify the biofuel emissions in slow speed engines.

Table 60. Allowable NO_x emissions for slow speed (< 300 RPM) engines with 50% engine efficiency.

Tier	NO_x emissions g/kWh engine power produced	NO_x emissions kg/GJ fuel	Applicable to Ships built after	Applicable in
I	14.06	7.81	1990	Global
II	11.85	6.58	2011	Global
III	2.88	1.60	2016	only NECAs

Source: IMO 2017b

4.6.3 Comparison with other emission reducing technologies

The estimated biofuel costs are currently several times higher than the estimated costs of liquid natural gas, ULSHFO, or HFO with exhaust scrubbers, **Table 61**. The performance of a biofuel blend is better, at only 2.5-4x that of the fossil technologies, as the MGO blendstock is much cheaper than the biofuel itself. Soy biodiesel costs are roughly half that of this study's biofuel estimates. The high ratios are possibly partly due to the lower crude oil price ($51/barrel) at the time of this report, but the influence of the oil price was too complex to project its influence on the prices of the different technologies within the scope of this report. There also exists high uncertainty of how the new maritime environmental regulation will influence the oil price.

In terms of environmental impacts, **Table 62**, the fossil alternatives have high GHG emissions and non-renewable energy use. Soy biodiesel also has high GHG emissions compared to this study's biofuel due to the impacts of land use change. While LNG has significantly lower combustion CO_2 emissions than fuel oils, the increase in CH_4 emission negates most of that reduction. GFT has the lowest SO_2 emissions of any technology considered, with LNG and FP only slightly higher. HTL has the highest NO_x emissions, though only LNG has emissions that are substantially lower than fuel oil and other biofuels.

Table 61. Cost comparison of other emission-reducing technologies, ratio with current MGO prices.

	Brazil	Denmark	Finland	Norway	Sweden
ULSHFO	0.7	1.0	1.0	0.9	0.9
HFO + Scrubber	0.7	0.8	0.8	0.8	0.8
LNG	0.6	0.8	0.8	0.7	0.7
Soy Biodiesel	1.5	1.5	1.5	1.5	1.5
HTL Wheat MFSP (57% blend in 1% S MGO)	3.7 (2.5)	5.0 (3.3)	4.7 (3.1)	—	4.3 (2.9)
FP Pine MFSP (50% blend in 1% S MGO)	4.4 (2.7)	—	6.5 (3.7)	5.5 (3.3)	5.3 (3.1)
GFT Wheat MFSP (50% blend in 1% S MGO)	4.7 (2.9)	6.7 (3.9)	6.2 (3.6)	—	5.6 (3.3)

Table 62. Life cycle emissions of other marine emission-reducing technologies.

	GHG (kg/GJ fuel)	SO_2 (g/GJ fuel)	NO_x (kg/GJ fuel)	NREU (GJ/GJ fuel)
ULSHFO	86	148.1	1.54	1.17
HFO + Scrubber	90	342.1	1.67	1.22
LNG	73	11.0	0.12	1.16
Soy Biodiesel	92	66.0	1.76	0.29
HTL Wheat (Brazil/Sweden)	-15 / 3	300 / 300	2.90 / 2.90	-0.14 / 0.01
FP Pine (Brazil/Sweden)	13 / 8	19 / 13	1.78 / 1.75	0.20 / 0.12
GFT Wheat (Brazil/Sweden)	-15 / 9	2 / 9	1.49 / 1.48	-0.30 / 0.18

4.6.4 Process model sensitivity analysis

Biorefinery scale

The assumed scale of the biorefinery is 500 dry tonnes of biomass per day, which is in line with current planned biorefinery construction. If the biorefinery could be enlarged to the 2000 t/day scale used in da Silva and PNNL studies, the economy of scale would decrease the minimum biofuel price by 25%, as shown in **Figure 47**. The costs scale exponentially, and further increases have less impact on biofuel prices, with a 5000 t/day scale showing only a 10% further decrease in costs. Additionally, increasing the scale would eliminate several feedstock options, **Table 63**. While all feedstocks would still be available in Brazil, it would require over 50% of national sorghum residues, and over 20% of barley and wheat residues. Spruce would be the only feedstock available in Norway, and grain feedstocks would not be tenable in Finland. Additionally, the fuel demand for all ports would be oversatisfied and require fuel forwarding. A single biorefinery would satisfy the national demand of all Scandinavian countries and half of Brazilian national demand.

At 1000 t/day, the fuel prices are 15% lower than at 500 t/day, all feedstocks are still available, and all ports will be oversupplied. At 250 t/day, the MFSP is 30% higher than for 500 t/day, but forestry residues and sugar beet pulp become viable feedstocks in Denmark, as does grain in Norway, but the MFSP is 20% higher.

Figure 47. Impact of biorefinery scale on biofuel price, **HTL wheat**, **FP pine**, and **GFT wheat**.

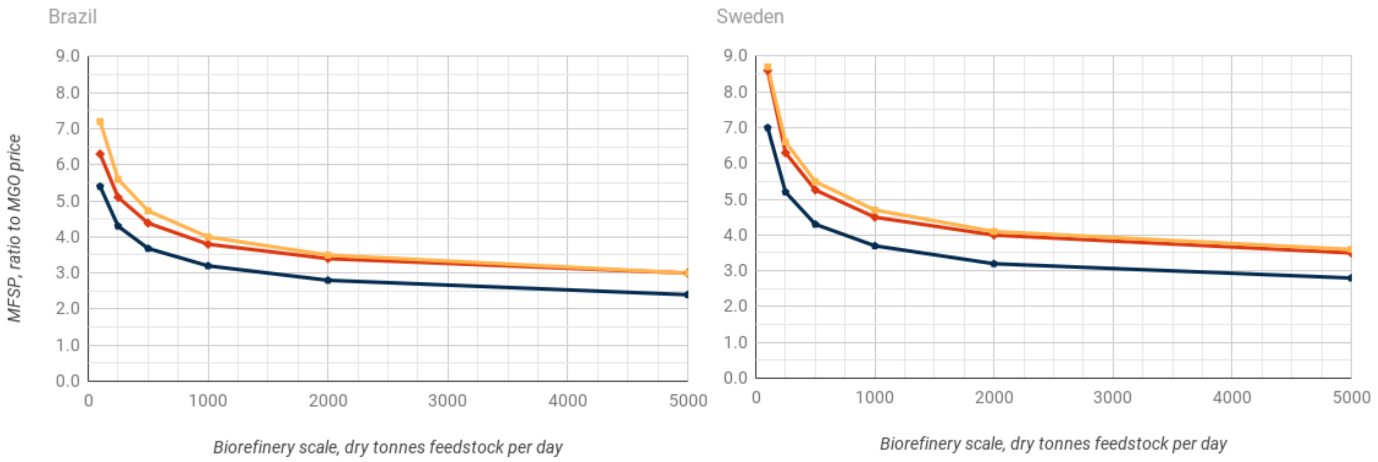


Table 63. Proportion of national residues required to satisfy a 2000 dry tonne/day biorefinery.

Feedstock	Brazil	Denmark	Finland	Norway	Sweden
Forestry Residues					
Eucalyptus	1%	—	—	—	—
Pine	7%	**522%**	14%	**141%**	14%
Spruce	—	**308%**	22%	42%	7%
Grain Residues					
Barley	23%	53%	**100%**	**368%**	**108%**
Corn	2%	**1778%**	—	—	—
Rice	18%	—	—	—	—
Wheat	23%	34%	**144%**	**538%**	71%
Sugar Residues					
Sugarcane	0%	—	—	—	—
Sorghum	54%	—	—	—	—

Red values indicate feedstocks unavailable to satisfy a 2000 t/day biorefinery
Faded values indicate feedstocks also unable to satisfy a 500 t/day biorefinery

Biorefinery siting

Biorefinery siting does not vary biofuel MFSP in Sweden by more than 5%, **Figure 48**, and not more than 5% in Scandinavia. In Brazil, where feedstock-port distances are longer, there is a 30% difference in MFSP for a biorefinery sited at feedstock source and at the port. However, the MFSP are prices for the fuel at the biorefinery gate, and changes in biofuel transportation costs are not considered. Siting the biorefinery as close as possible to the feedstock also decreases the biofuel's GHG emissions by up to 25 kg CO_2-eq/GJ in Brazil compared to siting at the port, though in Scandinavia the average difference is less than 5 kg CO_2-eq/GJ.

Figure 48. Impact of biorefinery siting on biofuel price for **HTL wheat**, **FP pine**, and **GFT wheat**.

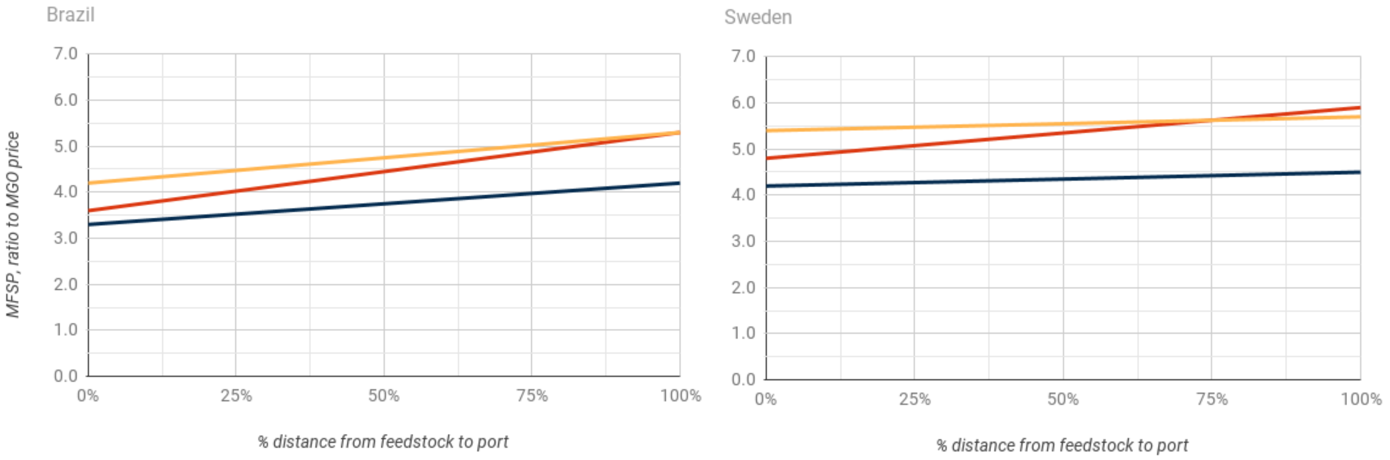
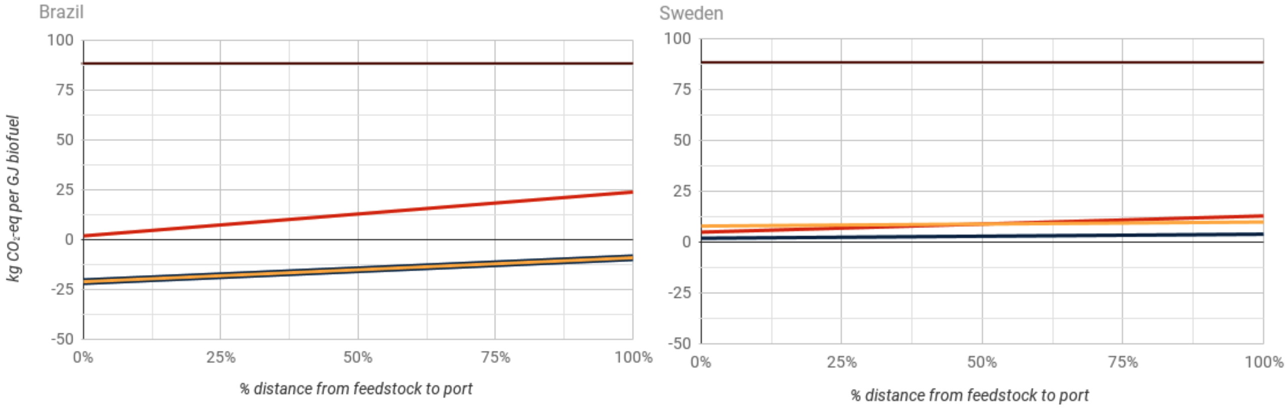


Figure 49. Impact of biorefinery siting on life cycle GHG emissions for **HTL wheat**, **FP pine**, and **GFT wheat**.



Heat recovery efficiency

The inclusion of an efficient heat recovery system has a major impact on the economic performance of HTL biofuels, **Figure 50**, particularly in Scandinavia where natural gas prices are 300-400% higher than in Brazil. At the current level of 80% recovery of process heat, the MFSP for HTL would not improve more than 5% for additional increases in efficiency, but without any heat recovery the MFSP would be 50% higher.

Heat recovery plays significant role in GHG emissions, **Figure 51**, and NREU, particularly in Brazil and Finland, where the impacts of natural gas production are higher. Increasing HTL heat recovery to 90% would decrease life cycle GHG emissions up to 10 kg CO_2-eq/GJ in Brazil and Finland, but only up to 2 kg CO_2-eq/GJ in Norway or Sweden. Without heat recovery, the life cycle GHG emissions of HTL would over 90% those of HFO for all feedstocks except wheat, eucalyptus, and sorghum. For FP and GFT, the difference is less dramatic, and the difference between 80% and 90% is less than 5 kg CO_2-eq/GJ for GFT and less than 2 kg CO_2-eq/GJ for FP.

Figure 50. Impact of biorefinery heat recovery on biofuel price for **HTL wheat**, **FP pine**, and **GFT wheat**.

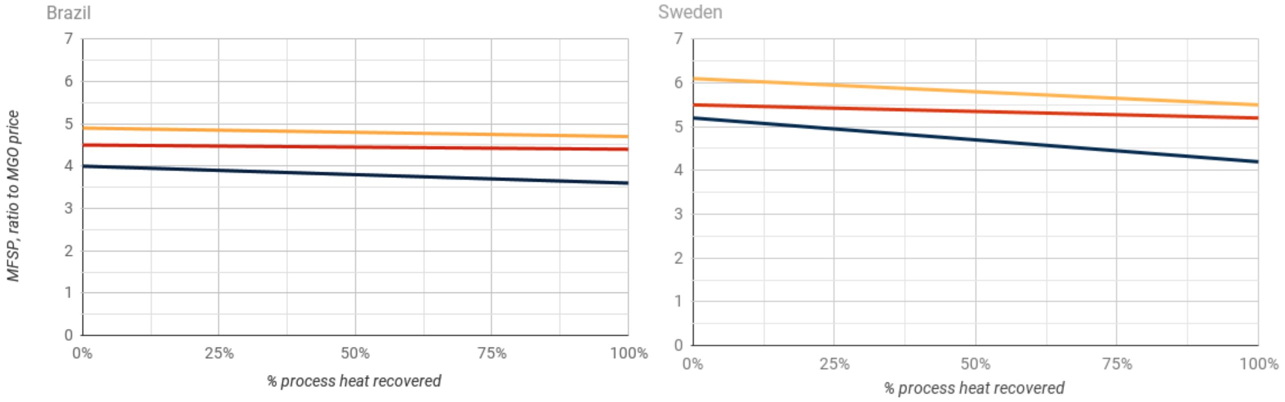
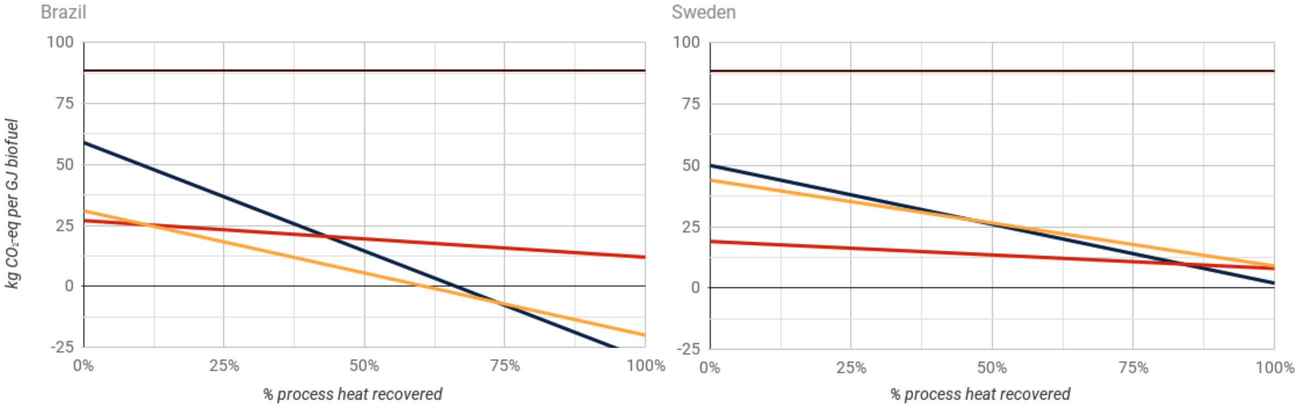


Figure 51. Impact of biorefinery heat recovery on life cycle GHG emissions for **HTL wheat**, **FP pine**, and **GFT wheat**.

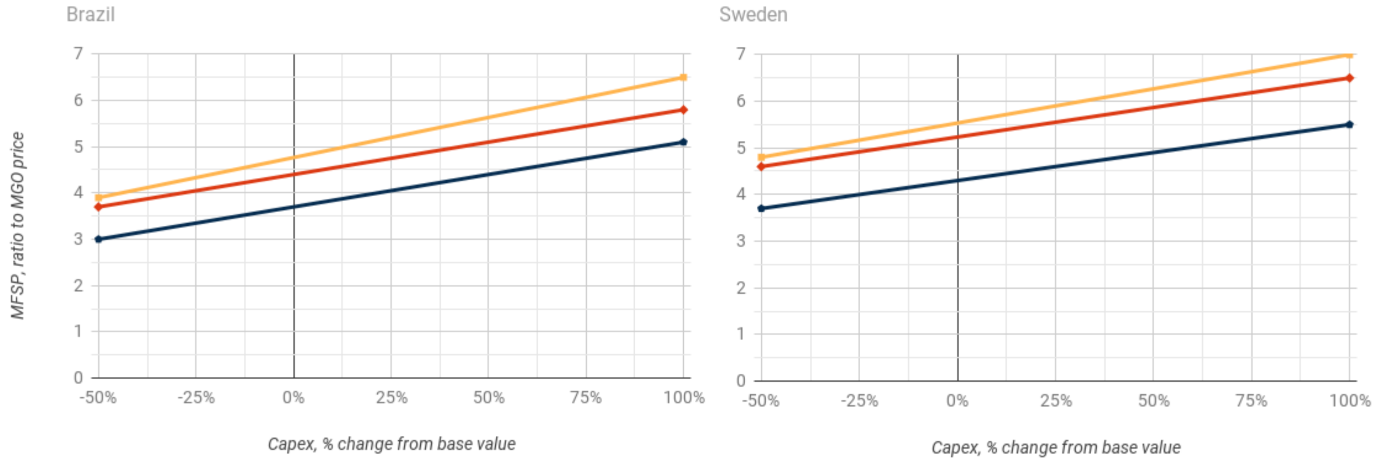


4.6.5 Economic model sensitivity analysis

Capital expenses

Capital expenses have a significant impact on the biofuel's economic performance, **Figure 52** and the rate of variation is similar across technologies and slightly higher for Brazil, which has higher average CapEx. A 50% change in CapEx results in a 15%-20% change in the minimum biofuel selling price in Brazil and 13-15% change for Scandinavia.

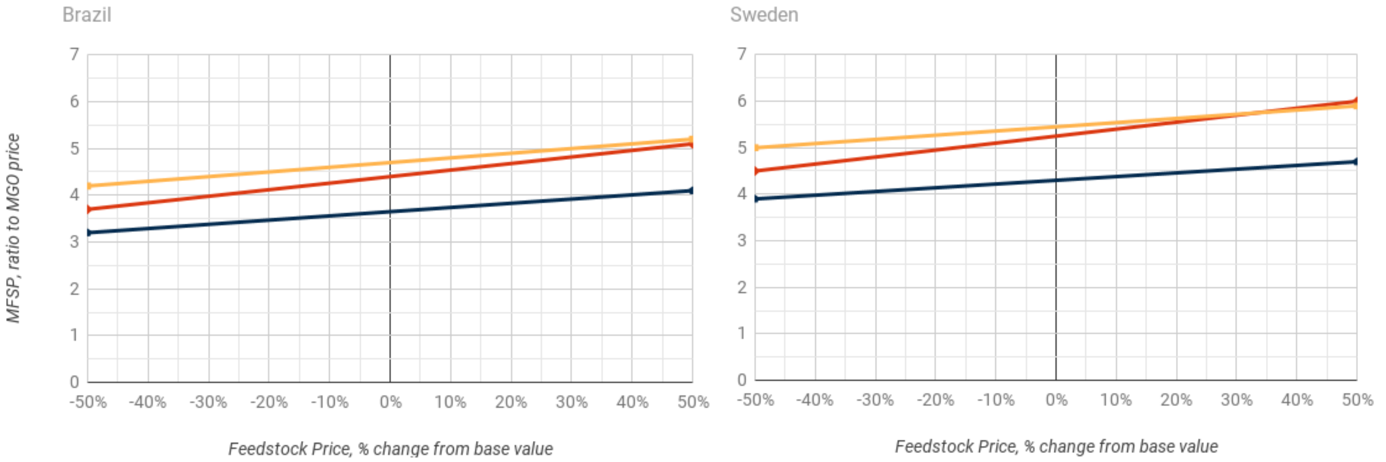
Figure 52. Impacts of differences in capital expenses on biofuel price for **HTL wheat**, **FP pine**, and **GFT wheat**.



Feedstock prices

Feedstock prices account for up to 20% of operating costs and the magnitude of its impact on the biofuel selling price, **Figure 53**, is similar to that of capital expenses. A 50% change in feedstock prices leads a10-15% change in the MFSP for all combinations.

Figure 53. Impacts of differences in feedstock price on biofuel price for **HTL wheat**, **FP pine**, and **GFT wheat**.



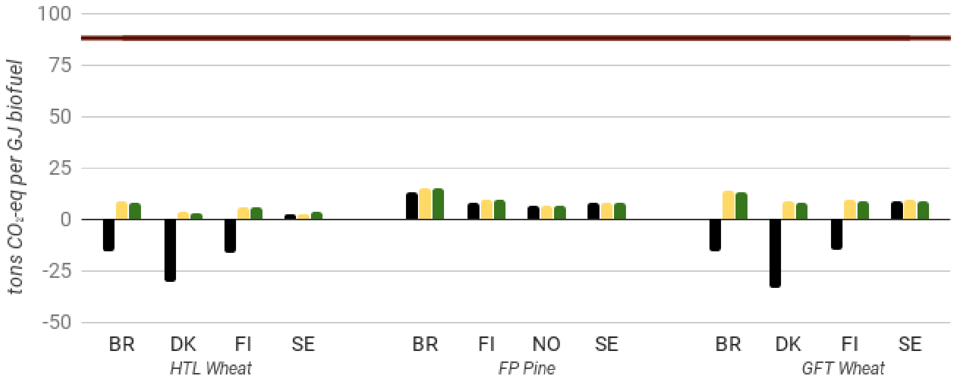
4.6.6 Environmental model sensitivity analysis

Allocation

The effect of allocation on life cycle SO_2 and NO_x emissions is negligible (<1%), as those impacts are dominated by biofuel combustion, as only impacts upstream of biofuel combustion are allocated. The effect on GHG emissions and NREU are similar, and vary with the quantity of the electricity coproduct. As shown in **Figure 54**, emissions allocated by economic value or energy content are similar, but displacement significantly decreases the estimated impacts for combinations with high electricity production in countries with fossil-heavy electricity mixes, such as GFT wheat in Brazil, Denmark and Finland. The GHG emissions show little difference between allocation methods in Norway and Sweden, which have high proportions of nuclear and hydropower. FP combinations have little or no electricity coproduct and are not affected by allocation.

Figure 54. Comparison of life cycle GHG emissions using **displacement**, **energy allocation**, and **economic allocation**.

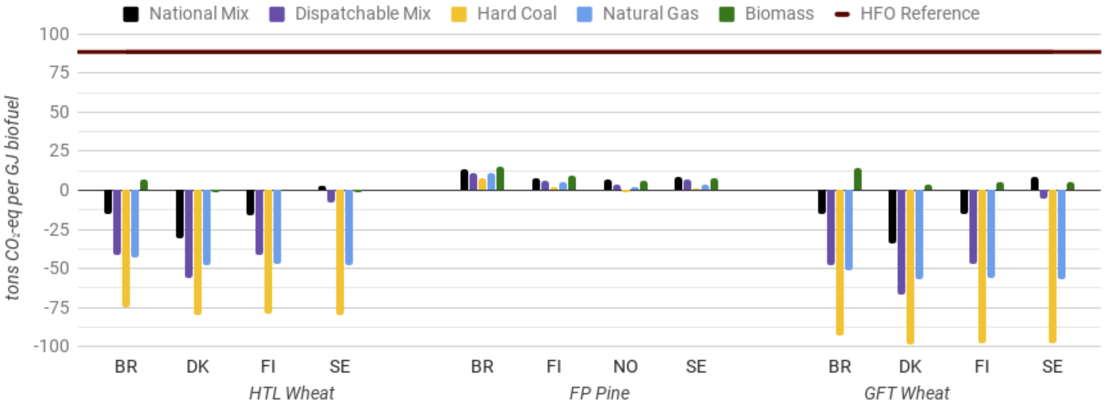
(**HFO** life cycle emissions for reference)



Displacement electricity mix

Like method of allocation, the assumed source of the displaced electricity has much greater impact on combinations with high coproduction of electricity, as seen in **Figure 55**. The use of the dispatchable-only national electricity mix (i.e. excluding always-on power sources such as hydropower, wind, and nuclear), leads to a 33 kg CO_2-eq/GJ decrease in for GFT wheat in Brazil, and 14 kg CO_2-eq/GJ decrease in Sweden. If the electricity produced by the biorefinery is displacing electricity produced by coal or natural gas, the decrease is greater. However, if the biorefinery's electricity was assumed to displace directly combusted biomass, the biofuel's life cycle impacts increase slightly, as direct combustion of biomass into electricity is likely more efficient than coproduction. The effects of the displaced electricity source follow the same trend for NREU as for GHG and have no significant impact on SO_2 or NO_x emissions.

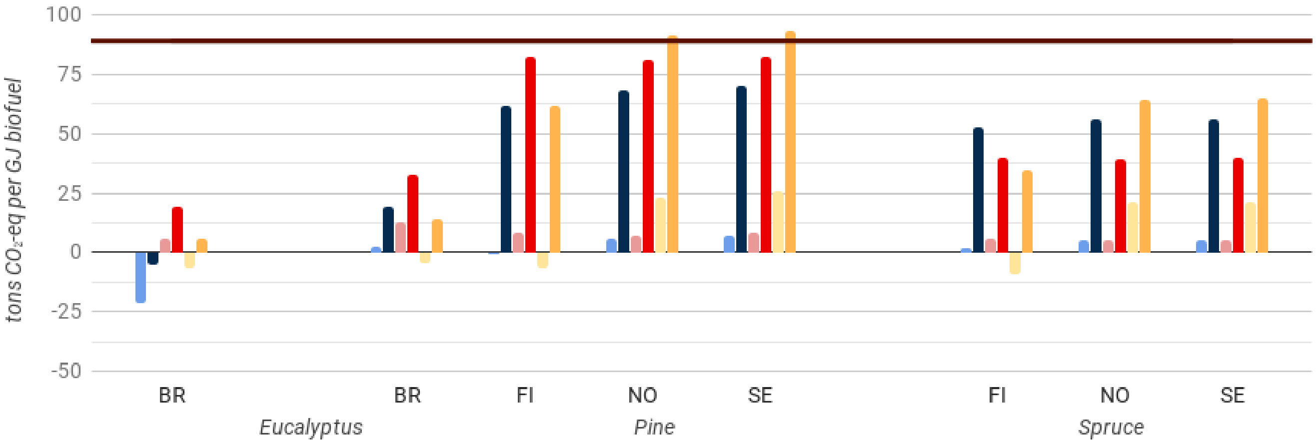
Figure 55. GHG emissions, comparison of displaced electricity source. (**HFO** life cycle emissions for reference)



Biogenic CO_2

The use of biogenic CO_2 global warming potential factors (GWP_{bio}) only affects forestry residues, as both grain and sugar crops are planted on a single year rotation, and have a GWP_{bio} factor of zero. The effect is particularly significant for Scandinavian pine where the 80-year rotation period results in life cycle GHG emissions that approach those of HFO. The short rotation periods in Brazilian plantation forestry allow all Brazilian forestry combinations to maintain GHG emissions of less than 40% of HFO, but only HTL Eucalyptus remains carbon neutral.

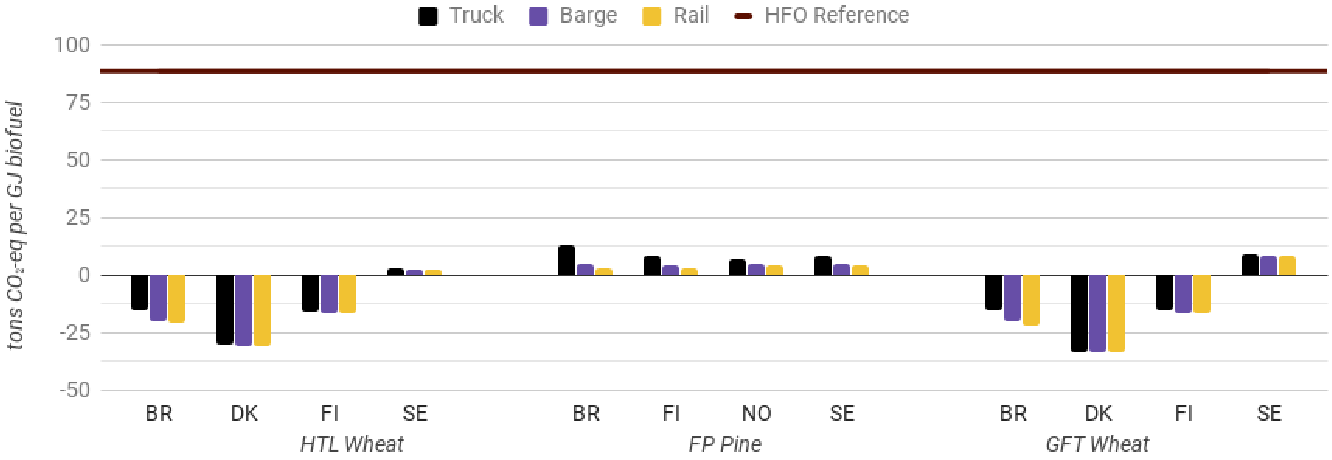
Figure 56. Life cycle GHG emissions with GWP_{bio} factors for **HTL**, **FP**, and **GFT**. (lifeccycle **HFO** emissions for reference)



Feedstock transportation

As seen in **Figure 57**, the method of feedstock transport has only a minor impact on life cycle GHG emissions for grain crops, which have a low water content and therefore low transport weight. The impact is greater for forestry and sugar crops, which have higher transport weights, and with rail being the most efficient means of transport. The effect increases with transport distances, and the largest effect is seen for Pine in Brazil, which has an average transport distance of 320 km, and whose life cycle emissions decrease up to 10kg CO_2-eq/GJ if the feedstock is transported by barge or rail.

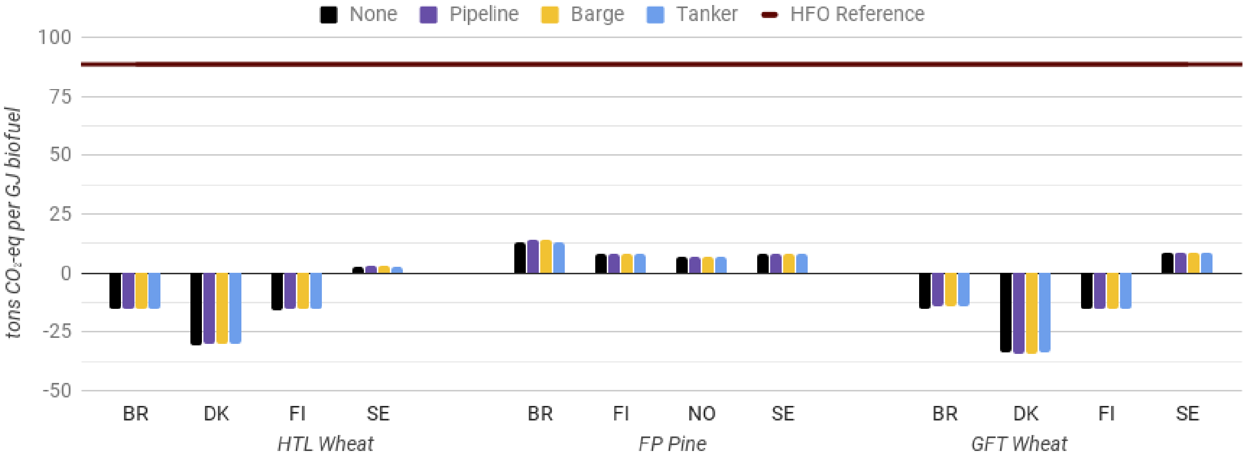
Figure 57. Life cycle GHG emissions, comparison of feedstock transport methods. (**HFO** life cycle emissions for reference)



Biofuel transportation

The inclusion of biofuel transport, as in **Figure 58**, has a negligible impact (<1kg CO_2-eq/GJ) on the life cycle GHG emissions for all combinations. The effect on all other impact categories is similarly insignificant.

Figure 58. Life cycle GHG emissions, addition of biofuel transport to port. (**HFO** life cycle emissions for reference)



4.6.7 Biorefinery variations

Dual feedstock sugarcane and sorghum plant

As shown in **Table 64**, a combined sugarcane-sorghum biorefinery has much better economic profile than a single-feedstock plant. If it is able to operate all year round, the HTL dual-feedstock pant would have the lowest minimum fuel selling price of any biofuel in Brazil.

Table 64. Combined sugarcane-sorghum biorefinery

	Sorghum & Sugarcane	Sugarcane	Sorghum
Seasonality days/year	**360**	180	180
HTL MFSP ratio with MGO price	**3.1**	7.2	4.2
FP MFSP ratio with MGO price	**3.4**	5.5	5.5
GFT MFSP ratio with MGO price	**6.2**	7.0	13.4

HTL aqueous recycling

The impact of aqueous recycling on the economic performance of the HTL combinations is a function of the conversion rate of the aqueous biomass to oil and char, as well as the total reactor throughput. Higher aqueous biomass to oil conversion rates increase the overall biorefinery yields and decrease the minimum fuel selling price, **Table 65**, as expected. However, the exclusion of recycling improves the MFSP from the base scenario, due to the decreased necessary size of the HTL reactor and cogeneration plant.

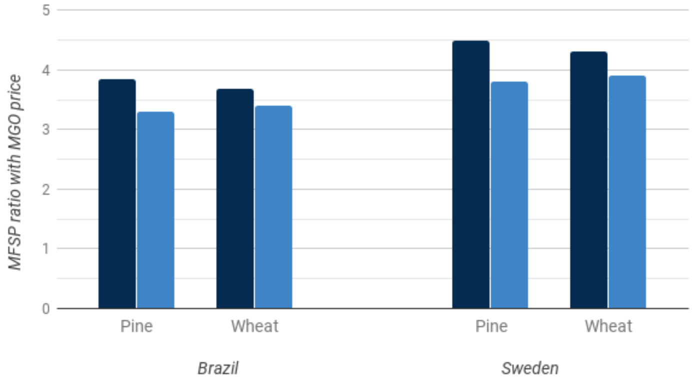
Table 65. Sensitivity analysis of the effect of HTL aqueous recycling on the MFSP, ratio to MGO prices.

Aqueous recyclate fate	Pine		Wheat	
	Brazil	Sweden	Brazil	Sweden
80% recycled with 0% biomass conversion	4.0	4.80	4.0	4.50
80% recycled with conversion-to-oil equal to fresh feed conversion	3.0	3.50	2.9	3.30
No recycling	3.6	4.4	2.6	4.2
80% recycled with 5-10% conversion (base system)	3.9	4.5	3.7	4.3

Hydrotreatment for Hydrothermal Liquefaction

The hydrotreatment of HTL biocrude increases the capital expenses by approximately 15% across combinations and decreases the biofuel mass yield by 20%. However, the total biofuel energy yield increases by 15%-25%, which is a product of the conversion of the offgasses into hydrogen, whose energy increases the energy content during hydrotreatment. The net effect is a slight improvement in the biofuel selling price, **Figure 59**. Life cycle SO_2 emissions also decrease to 0.1 kg SO_2/GJ, on par with those of FP and GFT biofuels. NO_x emissions also decrease to 2.1 kg NOx/GJ, which is still higher than the HFO reference and Tier III emission restrictions. GHG emissions change slightly (<3 kg CO_2-eq/GJ, due to decreased electricity production, and thus decreased displaced emissions.

Figure 59. Minimum fuel selling price, ratio with MGO price, for **HTL** and **HTL with hydrotreatment**.



Inclusion of full fuel upgrading and distillation

A biorefinery that also produces light naphtha (for gasoline) and kerosene (for jet fuel), requires the additional equipment and operating costs of distillation towers and additional storage capacity. For hydrothermal liquefaction, the addition of hydrotreatment and hydrogen plant, as above is also required. While the additional distillation costs increase total CapEx increases less than 5% and OpEx less than 3%, the addition of the slight (3%) yield losses from distillation and the low wholesale prices of gasoline and jet fuel lead to minimum selling price of the marine biofuel that is double that of the base scenario of HTL, 30% higher for FP, and 50% higher for GFT. The effect of the additional displacement leads to substantially lower environmental impacts attributed to marine biofuel for most combinations, though the total emissions of biorefinery production are unchanged.

Figure 60. MFSP ratio, distilled fuels variant, for **HTL**, **FP**, and **GFT**.

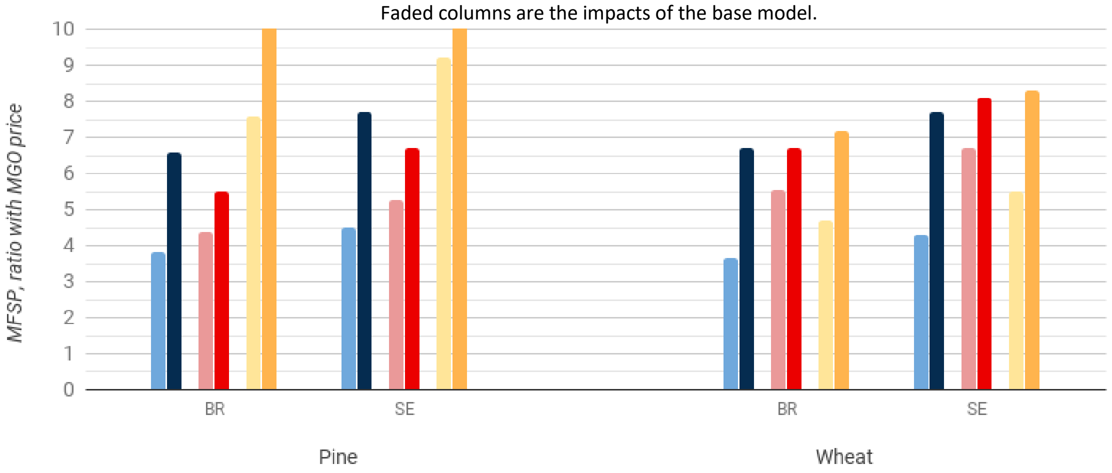
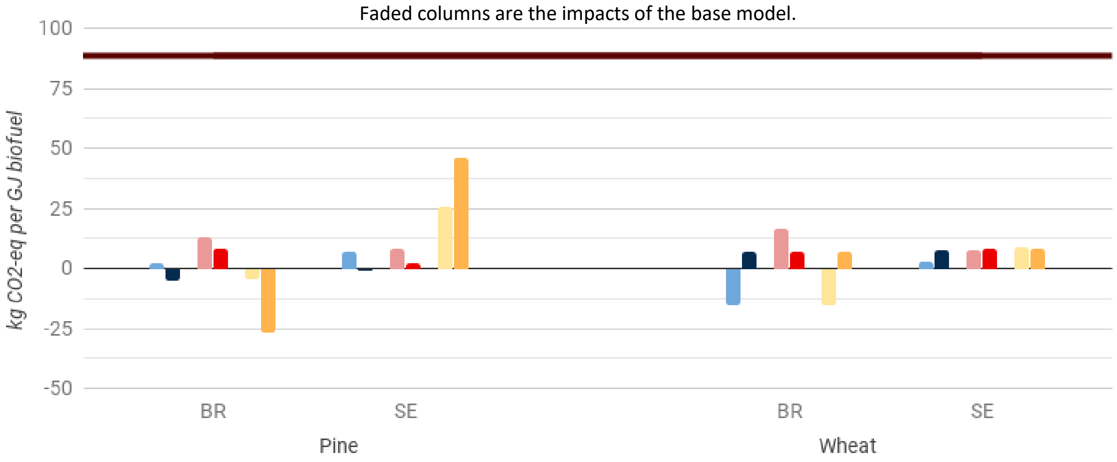


Figure 61. Life cycle GHG emissions, distilled fuels variant, for **HTL**, **FP**, and **GFT**. (**HFO** life cycle emissions for reference)



5 Conclusions

In this thesis, the conversion of ten lignocellulosic residues to a biocrude for use in marine engines was modeled via three thermochemical biofuel production pathways. The capital expenses, operating expenses, and earnings of a biorefinery using each feedstock-technology combination was estimated using local cost factors for Brazil, Denmark, Finland, Norway, and Sweden, when the feedstock was available in that country. The economic analysis was condensed to the indicator score of the minimum biofuel selling price, in a ratio to current marine gas oil prices. The life cycle emissions of CO_2, SO_2, NO_x, and life cycle non-renewable energy use of biofuel production and use were also estimated for each feedstock-technology-country combination. Their economic and environmental performance of the combinations evaluated in comparison to each other, as well as to other emission reducing technologies. Several sensitivity analyses showed the impact of uncertainty in the demand scenario, biorefinery costs, biorefinery design, transportation methods, allocation of coproducts, and the fate of biogenic CO_2.

5.1 Feedstocks

Lignocellulosic residues are abundant in both Brazil and Scandinavia. It would be possible to satisfy the entirety of national marine fuel demand via lignocellulosic biofuel in all countries except Denmark. The environmental impacts of feedstock are driven by the quantity of fossil fuel used in their production, which is high for wheat and rice. Rice also releases emissions during paddying, and its combinations have the highest impacts of any feedstock. The high moisture weight of forestry and sugar crop residues leads to higher impacts during feedstock transportation, the effect of which is significant for Brazil, where average transport distances are longer.

Economic performance trends between feedstock categories are weak, though grain residues had the slightly better performance across technologies, **Table 66**, with the best economic performance being from HTL barley in Sweden and FP of corn and rice in Brazil, all of which have a MFSP-to-MGO ratio of 3.2. FP spruce has the second best MFSP ratio (3.8 in Sweden) of feedstocks in Scandinavia and is also the most abundant feedstock in Norway and Sweden. Sugar crops in Brazil perform better if a single biorefinery can accommodate both sugarcane and sorghum in their disjoint harvest season, with a dual-feedstock HTL biorefinery having a MFSP of 3.1. However, while sugarcane is the most abundant feedstock in Brazil, sorghum is the least, with 14% of national residues required to supply a single 500 dry tonnes of feedstock/day biorefinery.

Table 66. Feedstocks with the best performance in each indicator category, by technology.

Feedstock with the lowest biofuel…	HTL	FP	GFT
MFSP ratio	Barley	Corn, Rice	Rice
GHG emissions, life cycle	Wheat[1]	Spruce	Wheat[1]
SO_2 emissions, life cycle	n.d.	n.d.	n.d.
NO_x emissions, life cycle	n.d.	n.d.	n.d.
NREU[1], life cycle	Wheat	Sugarcane	Wheat[1]

n.d.: negligible (<1%) difference across feedstocks
1: when considered across countries and allocation methods

The greenhouse gas emissions of forestry feedstocks increase significantly when biogenic CO_2 global warming potential factors are included. When included, pine in Scandinavia, which has an 80-year rotation period and thus a GWP_{bio} factor of 0.34 kg CO_2-eq/kg biogenic CO_2, has life cycle GHG impacts greater than those of the HFO reference system. Grain and sugar crops have a one-year rotation period and therefore a GWP_{bio} factor of zero.

A 50% variation in feedstock costs causes a 15% change in overall economic performance. In Brazil, where distances between feedstock origin and port are up to 320km, siting as close as possible to the feedstock source can decrease the MFSP by 30% and GHG emissions 25 kg CO_2-eq/GJ compared to siting at the port. However, the costs of biofuel transport are not considered. The method of transport also can decrease GHG emissions up to 10 kg CO_2-eq/GJ for wet forestry and sugar crop residues in Brazil.

5.2 Technologies

As shown in **Table 67**, there is no technology that performs the best for all indicators for any given feedstock. Hydrothermal liquefaction has the lowest average MFSP, but only on a slight margin from fast pyrolysis, and HTL barley has the best economic performance, though insufficient residues are available in Brazil. However, several fast pyrolysis combinations are competitive with HTL, and produce a higher quality fuel. Gasification with Fischer-Tropsch synthesis has the worst economic performance, due to high system losses, despite producing the highest quality fuel.

Life cycle SO_2 emissions were estimated at 0.1 kg SO_2/GJ biofuel, <5% that of heavy fuel oil for FP and GFT, and 0.3 kg SO_2/ GJ, or 12% of HFO, for HTL. All biofuels were estimated to be compliant with the 0.5% 2020 sulfur cap, the 0.1% SECA sulfur cap, and Tier II NO_x regulations. However, only GFT biofuels were estimated to have lower life cycle NO_x emissions than HFO (1.6 kg NO_x/GJ HFO), and HTL's NO_x emissions were almost double that of HFO. Hydrotreatment of HTL can potentially improve fuel quality and decrease its sulfur content and NO_x emissions, with having a comparable or slightly improved economic performance.

The estimates of life cycle greenhouse gas emissions and non-renewable energy use depend largely on the displacement of coproduced electricity. When considered prior to allocation, HTL has the lowest average impacts, due to the higher yields leading to less feedstock production and transport per GJ of biofuel. GFT has the highest impacts, due to the combination of low years and the high impacts of solvent use, whose production can account for over 50% of the biofuel's GHG emissions and NREU use.

Distillation of the biofuel into additional cuts of light naphtha and kerosene cause the MFSP to double, due to the increase capital and operating costs and the lower selling prices of the additional fuel cuts.

Table 67. Technologies with best performance in each indicator category, by feedstock.

Technology with lowest biofuel….	*Forestry Residues*			*Grain Residues*				*Sugar crop residues*	
	Eucalyptus	Pine	Spruce	Barley	Corn	Rice	Wheat	Sugarcane	Sorghum
MFSP ratio	FP	HTL	FP	HTL	FP	FP	HTL	FP	HTL
GHG emissions, life cycle	HTL	HTL^1	HTL^1	HTL^1	FP	GFT	HTL^1	HTL	HTL
SO_2 emissions, life cycle	FP	FP	FP	FP	FP	FP	HTL^1	FP	FP
NO_x emissions, life cycle	GFT	GFT	GFT	GFT	GFT	GFT	GFT	GFT	GFT
NREU^1, life cycle	HTL	HTL	HTL	HTL^1	FP	HTL	HTL	HTL	HTL

1: For these feedstocks, GFT performs better in this impact category in Brazil, Denmark and/or Finland, due to the effect of the displaced electricity production, but total HTL biorefinery impacts are lower when unallocated or allocated on an economic or energy basis.

5.3 Regions

Biofuels produced in Brazil have lower estimated biofuel selling price than in Scandinavian countries, **Table 68**. The higher costs of construction and feedstock transport in Brazil are offset by the lower costs of feedstock, labor and utilities and the higher product selling prices. Within Scandinavia, differences in MFSP are minor, biofuel produced in Sweden has the best economic performance overall, due to the slightly lower feedstock costs estimates. Denmark has the highest Scandinavian MFSPs due higher water and labor costs.

Brazil and Sweden are the only countries with ports large enough to absorb the output of a biorefinery at a scale of 500 dry tonnes of feedstock per day, assuming a biofuel demand scenario of 10% of national fuel demand. The entire marine fuel demand of Finland and Norway could each be satisfied with a single 2000 t/day biorefinery. In contrast, Brazil would require at least 40 000 t/day of biorefinery capacity and Sweden at least 20 000 t/day.

The national electricity mix has a significant impact on the allocation of GHG emissions and non-renewable energy use. Norway's and Sweden's electricity mixes are <2% fossil, and thus have much lower displaced impacts for the same combinations than the other countries. As noted in **Table 68**, biofuels produced in Denmark for combinations with electricity coproduction have the lowest estimated impacts due to an electricity mix that is 40% fossil fuels, which has the highest impacts that are displaced by the biorefinery's electricity.

Table 68. Countries with the best average performance in each indicator, across combinations.

Country with the lowest average biofuel…	Overall
MFSP ratio	Brazil
GHG emissions, life cycle	Denmark
SO_2 emissions, life cycle	n.d.
NO_x emissions, life cycle	n.d.
NREU[1], life cycle	Denmark

n.d.: negligible (<1%) difference across countries

5.4 Scaling

Blending the biofuel with fossil marine oil to achieve a sulfur content of 0.5% would require a 50% (mass) blend with a 1% sulfur fossil fuel, and almost 90% biofuel if with a 3.5% sulfur HFO. A 50% blend with MGO would have a MFSP 25%-45% lower than that of pure biofuel, depending on the energy content of the fuel.

Substantial progress in cost reduction is necessary to make the biofuels modeled in this study economically competitive with other emission reducing technologies, particularly for liquid natural gas, ultra low sulfur HFO and exhaust scrubbers, who each have a per-GJ cost lower than MGO. Increasing the scale of the biorefinery to 2000 dry tonnes per day would reduce the MFSP ratio by 25%, but would exclude half of Scandinavian feedstock options and also increase the transport distances for Brazilian feedstocks, further increasing their environmental impacts.

The GHG emissions and NREU of all biofuels in this study were estimated to be substantially lower than those of fossil fuel sources or soy biodiesel, except when considering GWP_{bio} factors for forestry feedstocks. FP and GHG biofuels were estimated to have lower life cycle SO_2 and similar life cycle NO_x emissions as fossil fuel oils, exhaust scrubbing and biodiesel, but higher than those of liquid natural gas. HTL has higher SO2 and NOx emissions than any other technology considered. However, the combustion emissions for the biofuels are subject to high uncertainty due to the paucity of available literature sources.

6 Limitations & Future Work

6.1 Limitations

This study considered 81 combinations of feedstock, technology, and country, and five indicators of economic and environmental performance. To comply with the time limit of this project, the choice was to focus on breadth rather than depth. Biorefinery modeling was conducted at the black-box unit process level, and there are an uneven number of assumptions between feedstocks, as literature data was not available for every feedstock-technology combination under similar process conditions. Spruce GFT was based on pine yields from da Silva (2016), and barley GFT gas composition and yields were proxied from wheat straw (Carpenter et al. 2010). When process conditions were unavailable from feedstock specific literature, values from da Silva (2016) were used as a default assumption.

Expense estimation is limited both by the level of detail of process modeling and by the lack of available data on commercial scale biorefinery costs, which is an concern that leads to high variance in biorefinery cost estimates (Tsagkari et al. 2016). The issue is summed up by Brown (2015): “This underinvestment has resulted in a chicken-and-egg dilemma: investors are unwilling to finance widespread capacity construction due to production cost uncertainty but the lack of actual cellulosic biofuel production prevents additional knowledge of production costs from being gained” Additionally, a location factor for Scandinavia was unavailable and one from Germany was used instead.

The environmental impact results are limited by the exclusion of country specific data on feedstock production, which was beyond the scope of this project, and limited availability of lignocellulosic biofuel combustion data. The assumption of biofuel transport to port via pipeline also deserves further investigation, since more impactful forms of transport, such as by truck, could have a major impact on the overall system impacts.

6.2 Recommendations for Future Work

In-depth modeling of HTL of grain residues and pine, with and without hydrotreatment, and FP of corn and rice is recommended. In particular, further investigation into the effect of solvent ratios and aqueous recycling in HTL pathways are warranted by their high effect on the overall economic performance. Likewise, the size and cost of the cogeneration plant should be scrutinized, as it has a high impact on overall costs and is highly sensitive to process assumptions of electricity and heating demand and yields of offgasses and char. Similarly, focusing on fully autarkic biorefinery design, without the use of supplemental natural gas or other fossil inputs, such as by the additional combustion of biomass or the use of solar or wind power for heat and electricity, would provide a perspective that estimates the biorefinery performance given a more complete shift to the bioeconomy. Additionally, a broader survey of the biofuel combustion emissions is needed, along with further research on reducing the NO_x emissions of the biofuels, particularly for HTL.

An update of this report using country-specific feedstock production environmental impacts, as well as comparison of different feedstock pretreatment options, would provide greater accuracy into the regional variations in impacts, as well as possibly provide insight into agricultural techniques and feedstock preparation methods that will further decrease the biofuels impacts.

Several commercial-scale demonstration plants are under construction for the different thermochemical conversion pathways. If those companies are willing to cooperate, a survey of the capital expenses, both the original estimates and actual costs, as well as unforeseen issues encountered during plant construction would be highly beneficial to future technoeconomic assessments of lignocellulosic biofuels.

More in-depth comparisons of the biofuel with other emission reducing technologies, including an analysis of the impact of fossil fuel prices, is recommended once the refining and maritime shipping industries' response to the 2020 sulfur cap become clear and after the IMO publishes its GHG reduction plan in 2018. Additionally, liquid biogas from residual sources could be an alternate marine biofuel pathway if LNG engines become commonplace and warrants investigation in comparison with the biofuels in this study.

Final Thoughts

The tradeoff of feedstock availability, economic performance, and environmental impacts, as estimated in this study, makes it difficult to conclude that any of the proposed combinations is “the best option.” In all cases, the estimated biofuel price, at the assumed yields and costs, is at least 3.2 times higher than marine gas oil. Producing biofuel in Brazil is more economically attractive than Scandinavia due to lower costs and higher fuel prices, but the longer distances for feedstock and fuel transport, as well as potentially more impactful methods of feedstock cultivation and natural gas production, lead to higher life cycle GHG emissions prior to displacement of cogenerated electricity. Grain residues and sorghum bagasse provide superior conversion performance, but are less available than forestry residues. Hydrothermal liquefaction has the lowest estimated costs for almost all feedstocks, and the single best performing combination, but only has the lowest biofuel price for four of the ten feedstocks. For the other six, fast pyrolysis has the better performance. HTL is the most experimental technology considered, and also has the highest estimated combustion impacts, though hydrotreatment of HTL may decrease impacts without decreasing economic performance. GFT produces the highest quality fuel with the lowest combustion emissions, but is the most expensive option due to the low system yields, and also has the highest life cycle GHG emissions and non-renewable energy use to its chemical demand.

For all combinations the estimated life cycle impacts of GHG and SO_2 emissions and NREU are substantially lower than that heavy fuel oil. However, the estimated GHG emissions of long-rotation forestry are very sensitive to the assumed fate of the biogenic CO_2 that deserves critical attention. Reducing NO_x emissions of biofuel presents a challenge inherent to the higher nitrogen and oxygen levels present in biofuels.

Lignocellulosic biofuels can potentially reduce several environmental impacts of marine freight if the technology can be made competitive with fossil fuels. However, biofuels, while promising, are not inherently sustainable for large-scale production. There must be critical evaluation of impacts through the entire supply chain, including many of those outside the scope of this study, such as soil quality and indirect land use change, as well as the fate of biogenic CO_2, particularly as demand for feedstock increases. The effect of decisions made for economic reasons, such as refinery siting and scale, must also be evaluated for their upstream and impacts such as from increased feedstock transportation demand. Mutual support from industry, academia, and government is necessary to provide the funding and insight needed to reduce the uncertainties in the lignocellulosic biofuel supply chains, as well as the economic and regulatory incentives to pursue large scale biofuel production in a manner that minimizes its impacts.

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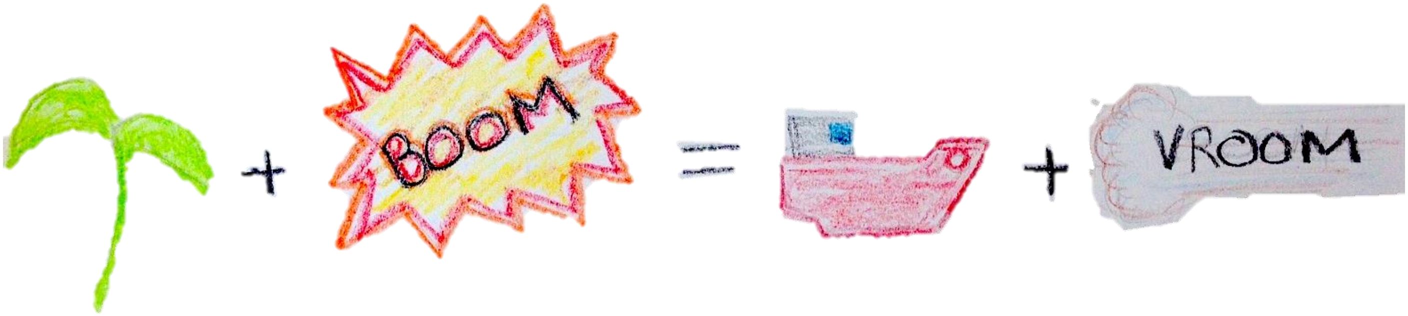
Afterword

In the recommendation for future work, I relate some small questions that were elicited by my thesis, but I did not have time to answer. But this project has also given rise to questions that I don't yet know how to answer but I am glad that I learned to ask, and I wanted to end this thesis with a few of them:

What limits must be placed on our economy to allow it to operate without causing further irreversible damage to the ecosystems we depend on? In the natural world, growth without limits is given unpleasant names such as tumor, overpopulation, and epidemic, but in the economic world it is lauded as healthy and desirable. The transition to the biobased economy means the acceptance of limits on what we ask of the soil, air, and sea: limits on environmental impacts of product systems, limits on allowable non-renewable resource extraction and use; limits on the potential output of biobased system; and even limits on economic growth itself.

How can experimental data on biofuel production be best disseminated to allow for reproduction of results and future work? In my literature review, published results of biofuel experiments only incompletely described the products, even if the information was obviously possible to easily acquire (e.g. solid residues were separated, but their yield was not given). Methodologies were also often incomplete, and there was no standardization to the presentation of experimental parameters or yields.

What is the best tool for working with large, multi-dimensional datasets that allow them to remain intuitively accessible to future researchers, while allowing easy manipulation and visualization of the day and decreasing the probability of human error? The answer is not spreadsheets. They allow for very nice data presentation but do not easily handle more than two dimensions of data and one dimension of metadata. The error rate was too high, and generating the large quantity of sensitivity analyses and charts was tedious. However, using a language like R or Python limits the accessibility of the raw data, as well as makes entering metadata more cumbersome.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