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Faculteit Bedrijfseconomische Wetenschappen

master in de toegepaste economische wetenschappen: handelsingenieur

Masterthesis

A probabilistic approach for accounting for externalities from air pollution and GHG emissions in a TEA for biofuels for aviation

Sebastiaan Lagaeysse

Scriptie ingediend tot het behalen van de graad van master in de toegepaste economische wetenschappen: handelsingenieur, afstudeerrichting technologie-, innovatie- en milieumanagement

PROMOTOR :
Prof. dr. Robert MALINA

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Summary

This master's thesis expands the work of Bann et al. (2017) by the addition of externalities. Two biofuel pathways, (1) HEFA yellow grease (YG), and (2) F-T municipal solid waste (MSW), and two externalities, (1) climate change due to the emission of greenhouse gases, and (2) air quality regarding the emission of fine particulate matter, were selected. Subsequently, the effect of the two externalities on the two pathways regarding net present value (NPV) and middle distillate selling price (MSP) was evaluated.

Both externalities were added to the model by comparing HEFA alternative jet fuel and F-T alternative jet fuel with conventional jet fuel regarding GHG and $PM_{2.5}$ emissions during their life cycle. Because of lower emissions during the life cycle of HEFA and F-T biofuel, a carbon and $PM_{2.5}$ delta or benefit originated compared to conventional jet fuel emissions. With the two calculated benefits and two damage cost estimates, (1) the social cost of carbon from the US EPA and (2) the social cost of $PM_{2.5}$ from the EU Clean Air for Europe program, a minimum, maximum, and most likely carbon and $PM_{2.5}$ benefit estimate was calculated in 2015 USD per kg alternative jet fuel. The two externality benefits were added to the HEFA YG and F-T MSW MATLAB model by modeling them as a beta-PERT distribution. Next, the model randomly selected social carbon and social $PM_{2.5}$ benefit values from the beta-PERT distribution to calculate the NPV and MSP.

The addition of the two externalities resulted in a positive effect on NPV and MSP of both pathways. Mean NPV of the HEFA YG pathway rose with 56 $M, from -0.111 $B to -0.055 $B, an increase of 50%, and the probability of a positive NPV rose with 41%, from 26.88% to 38.01%. Mean MSP decreased with $0.08/liter, from $0.91/liter to $0.83/liter, a decrease of 9%.

The addition of the two externalities to the F-T MSW model resulted in a mean NPV increase of 43 $M, from -0.206 $B to -0.163 $B, an increase of 21%. The probability of a positive NPV increased with 77%, from 7.13% to 12.62%. Mean MSP decreased with $0.068/liter, from $1.124/liter to $1.056, a decrease of 6%.

The addition of the externalities had a distinct positive effect for both pathways. The effect of the externalities was larger for the HEFA YG pathway than for the F-T MSW pathway, due to the fact that jet fuel output is larger for the HEFA pathway. However, mean NPV remained negative and mean MSP still remained well above the average conventional jet fuel price.

Table of contents

List of figures 7

List of tables.. 9

List of frequently used abbreviations 11

1. Problem situation 13

1.1 Transport...13

1.2 Aviation industry 14

1.3 Interest in alternative fuels 15

1.4 Biofuel pathways 16

2. Central research question.. 19

3. Methodology and approach.. 21

3.1 Private and social costs 21

3.2 Public goods..21

3.3 Externalities..22

3.3.1 Market inefficiency 23

3.3.2 Internalization of externalities 25

3.4 Externality selection..27

3.4.1 Climate change externality...27

3.4.2 Air quality externality 28

3.4.3 Effect of biofuels on climate change and air quality externality 28

3.5 Pathway selection 29

3.6 HEFA pathway 30

3.6.1 HEFA process 30

3.6.2 HEFA biofuel production...31

3.6.3 Emissions...31

3.7 F-T pathway..32

3.7.1 F-T process 32

3.7.2 F-T biofuel production..33

3.7.3 Emissions...33

3.8 Biofuels externality benefit...34

3.8.1 GHG emissions 34

3.8.2 Particulate matter 35

3.8.3 Conclusion emission benefit values 37
3.9 Economic valuation of GHG and PM2.5 emissions benefit 38
3.9.1 Social cost of carbon 38
3.9.2 Comparison with the shadow price of carbon 38
3.9.3 Use of USG SCC estimates 39
3.9.4 Social cost of (fine) particulate matter 40
3.9.5 $PM_{2.5}$ damage cost estimates 40
3.9.6 Use of CAFE PM2.5 damage cost estimates 40
3.10 Indexing of estimates to 2015 dollars 42
4. Empirical application 45
4.1 Modeling 45
4.1.1 Model description 45
4.1.2 Externality modelling 46
4.2 Hypothesis 47
4.3 Results 48
4.3.1 HEFA model 48
4.3.2 F-T model 57
4.4 Sensitivity analysis 64
4.5 Validation 67
4.6 Conclusion and limitations 69
4.7 Future work 70
Bibliography 71
Appendix A – Used commands 77

List of figures

Figure 1: Impact of four pillars set out by IATA on CO2 emissions 15
Figure 4: Negative externality 23
Figure 5: Positive externality 24
Figure 2: General simplified HERA/HRO process system overview 30
Figure 3: Simplified Fischer-Tropsch process with MSW feedstock 32
Figure 6: Histogram of 10,000 generated 'social carbon benefit' values (HEFA YG) 49
Figure 7: Histogram of 10,000 generated 'social PM2.5 benefit' values (HEFA YG) 50
Figure 8: Histogram of 10,000 generated 'total social benefit' values (HEFA YG) 50
Figure 9: Histogram, fitted normal density curve, and mean of total NPV without externalities (NPV) and total NPV including externalities (NPVExt.) of the HEFA YG pathway 51
Figure 10: Graphical breakdown of the mean NPV by cost and revenue streams in $M (HEFA YG) 53
Figure 11: Cumulative density function (CDF) for NPV and NPV + externalities results for HEFA YG pathway 54
Figure 12: Histogram, fitted normal density curve, and mean of total MSP without externalities and total MSP including externalities (MSPExt) of the HEFA YG pathway 56
Figure 13: Histogram of 10 000 random generated 'social carbon benefit' values (F-T MSW) 58
Figure 14: Histogram of 10 000 random generated 'social PM2.5 benefit' values (F-T MSW) 59
Figure 15: Histogram of 10 000 generated 'total social benefit' values (F-T MSW) 59
Figure 16: Histogram, fitted normal distribution, and mean of total NPV without externalities (NPVT) and total NPV including externalities (NPVExt) of the F-T MSW pathway 60
Figure 17: CDF for NPV and NPV + externalities results for F-T MSW pathway 61
Figure 18: Histogram, fitted normal density curve, and mean of total MSP without externalities and total MSP including externalities (MSPExt) of the F-T MSW pathway... 63
Figure 19: NPV sensitivity results for HEFA YG and F-T MSW pathway, mean values denoted in $/liter. Test inputs for both externalities are between parentheses (low, baseline, high). 64
Figure 20: MSP sensitivity results for HEFA YG and F-T MSW pathway, mean values denoted in $/liter. Test inputs for both externalities are between parentheses (low, baseline, high). 65

List of tables

Table 1: Overview of delta/benefit per kg biofuel, compared with conventional jet fuel 35
Table 2: Summary of externality benefits for HEFA and F-T alt. fuel 37
Table 3: USG SCC estimates for 2020..39
Table 4: Estimates of GHG benefit per kg HEFA jet fuel in 2007 dollars 39
Table 5: Estimates of GHG benefit per kg F-T jet fuel in 2007 dollars......................................39
Table 6: Estimates of $PM_{2.5}$ damage costs avoided per kg alt. fuel 41
Table 7: Estimates of GHG benefit per kg HEFA and F-T jet fuel in 2015 dollars 42
Table 8: Estimates of $PM_{2.5}$ benefit per kg alt. fuel in 2015 USD 43
Table 9: Statistical values carbon, PM2.5, and total social benefit (HEFA YG) 48
Table 10: Breakdown of mean NPV in cost and revenue streams (in $M) (HEFA YG) 52
Table 11: Breakdown of mean MSP in $/liter (HEFA YG)..55
Table 12: Statistical values Carbon, PM2.5, and total social benefit (F-T MSW) 57
Table 13: Breakdown of mean MSP in $/liter (F-T MSW) 62
Table 14: Comparison between model results and results reported in the study by Bann et al. (2017) 67
Table 15: Comparison of carbon, PM2.5, and total benefit model results with their calculated range 68

List of frequently used abbreviations

ASTM: American Society for Testing and Materials
EPA: Environmental Protection Agency (USA)
F-T: Fischer-Tröpsch
GHG: Greenhouse Gases
HEFA: Hydroprocessed Esters and Fatty Acids
IATA: International AirTransport Association
IPCC: International Panel on Climate Change
MSP: Minimum middle distillate Selling Price
NPV: Net Present Value
RFS: Renewable Fuel Standard
SCC: Social Cost of Carbon
TEA: Techno-Economic Analysis
USD: United States Dollar

1. Problem situation

Climate change is globally regarded as one of the biggest global threats of the 21st century. Climate change, as defined by IPCC Working Group I, refers to any change in climate over time whether due to natural variability or as a result of human activity. (WGI, 1996) There is scientific consensus on the manmade acceleration of the greenhouse effect. In the report by the National Academy of Sciences, it is stated that "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise". (Council, 2001) (p. 1) This statement is also shared by the IPCC in their fifth and previous assessment reports: "Previous assessments have already shown through multiple lines of evidence that the climate is changing across our planet, largely as a result of human activities". (Cubasch et al., 2013) (p. 121)

The accelerated climate change by human activity due to anthropogenic emission sources has detrimental effects for ecosystems, human health, weather, etc. all over the globe, because these anthropogenic emission sources can emit some chemicals that affect climate change, some that affect air pollution, but often affect both. (WGII, 2001) This leads to economic changes. Whereas climate change brought net benefits for the most rich and most poor countries in the past concerning agriculture and reduced demand in heating, in the 21st century the impacts of climate change turn negative in most countries. (R. S. J. Tol, 2013)

1.1 Transport

Transport is the second biggest source of GHG emissions in both the European Union (EU-28) and the United States, with a contribution of 23% and 27%, respectively, of total 2015 GHG emissions. (EPA, 2015b; Eurostat, 2017) Forecasts by the US Energy Information Administration (EIA), International Energy Agency (IEA), and World Business Council for Sustainable Development (WBCSD) estimate a 2% growth of energy use in the transport sector over the next few decades, with petroleum still as the main transport fuel with a share between 93% and 95%. As a result, CO_2 and pollutant emissions will grow with growing energy consumption. Sectors estimated to grow the most are primarily light-duty vehicles, freight trucks and air travel. (Kahn Ribeiro et al., 2007)

1.2 Aviation industry

The anthropogenic GHG emission contribution of aviation is currently 2% of total GHG emissions. Such a contribution seems to be minor, but the aviation industry is expected to grow with a doubling of the number of passengers in the next 20 years with a 3.7% annual compound average growth rate[1] (IATA, 2016b), resulting in rising emission levels of CO_2 and other pollutants.

IATA, the International AirTransport Association comprising 83% of global air traffic (in 2016 numbers), has laid out a set of separate targets to mitigate the GHG emissions (IATA, 2009):

- A cap on aviation CO_2 emissions from 2020: carbon neutral growth
- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020
- A reduction in CO_2 emissions of 50% by 2050, relative to 2005 levels

To achieve these targets, four pillars are set out by the IATA to maintain emissions at 2020 levels: (1) technology, for example new plane designs, new lightweight composite materials, radically new engines, use of biofuels, etc.; (2) operations, achieve reduction in emissions by increasing efficiency in operational practices; (3) infrastructure, for example more efficient Air Traffic Management and use of Continuous Decent Arrival (CDA) to save CO_2 at arrival; and (4) economic measures, such as airline capital expenditures. (ATAG, 2011; IATA, 2009) An indication of the projected impact of these four pillars on CO_2 emissions is visually displayed in figure 1. Note that ‘technology’ and ‘additional technologies and biofuels’ both fall under pillar one, technology.

Alternative fuels for aircraft are a promising and necessary solution. Only by using biofuels the proposed reductions can be achieved, as biofuels are the only fuels having the potential to significantly reduce GHG emissions in the short term, because increase in efficiency through aircraft improvement, and operational and/or infrastructure changes are not enough. (Starck et al., 2014) Figure 1 indicates that especially the first pillar, technology, more specifically biofuels and additional new-generation technologies, will have the biggest impact on reducing CO_2 emissions in order to achieve the targets set.

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[1] The annual compound average growth rate is a representational figure that describes the rate at which the number of passengers would have grown if it had grown at a steady rate.

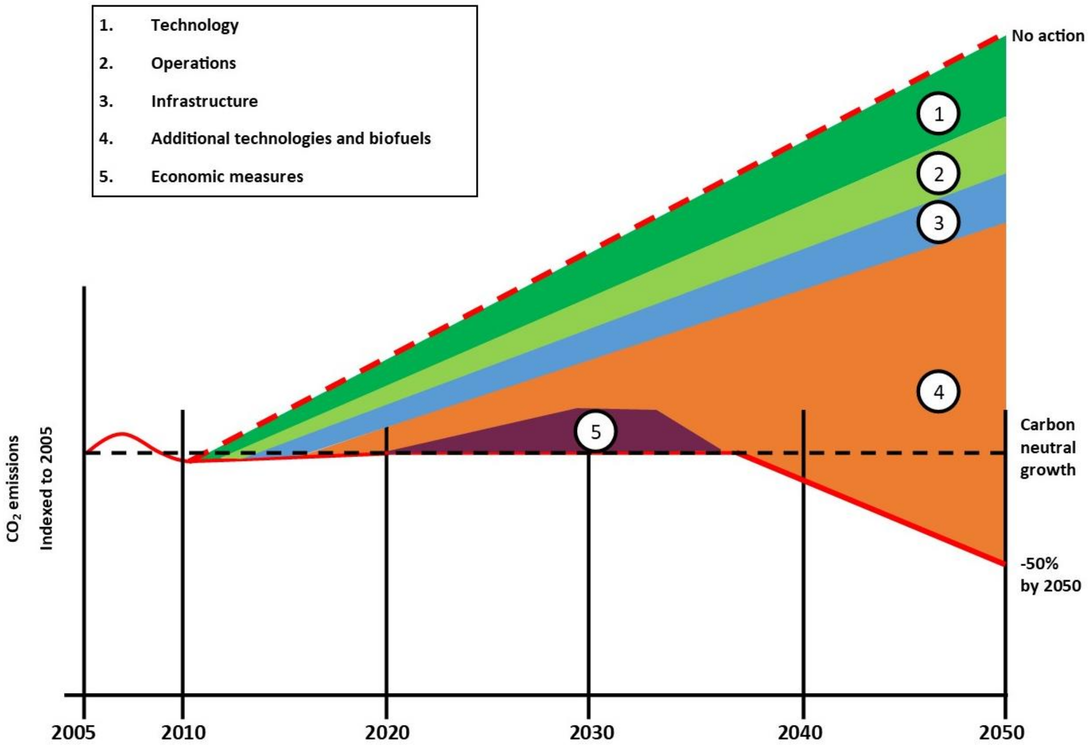

Figure 1: Impact of four pillars set out by IATA on CO_2 emissions

1.3 Interest in alternative fuels

Global warming together with uncertainty over the future crude oil price and political unrest in the Middle East, which is the largest exporter of crude oil in the world, result in rising interest from academia, industry and government agencies to produce fuels from sources other than petroleum. (Niziolek, Onel, Hasan, & Floudas, 2015) These alternative (bio)fuels offer the potential to diversify energy supplies while mitigating the net environmental impacts of aviation and other sectors. (Pearlson, Wollersheim, & Hileman, 2013)

Governments put mandates and goals in place to promote the use of alternative fuels. In 2005 the Renewable Fuel Standard (RFS) program was created and expanded in 2007 (RFS2). The RFS program is a national policy, overseen by the US Environmental Protection Agency (EPA) that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel, starting at a total of 9 billion gallons per year (BGY) in 2008 and rising to 36 BGY in 2022. (EPA, 2015a)

In October 2016 the council of the International Civil Aviation Organization (ICAO) endorsed the development of a global market-based measure scheme, the Carbon Offsetting and Reduction Scheme for International Aviation, to address any annual increase in total CO_2 emissions from international aviation[2] above 2020 levels. (ICAO, 2016b) Under this scheme, aircraft operators have to purchase carbon-offsets for the growth in CO_2 emissions covered by CORSIA. The scheme is rolled out in phases: From 2021 until 2026, for volunteering countries; From 2027, mandatory participation for countries meeting certain criteria concerning their level of aviation activities. (IATA, 2016a) On 11 January 2018, 73 countries, representing 87.7% of international aviation activity, are voluntarily participating in the CORSIA scheme. (ICAO, 2016a)

1.4 Biofuel pathways

Due to the increased interest of a lot of different parties, a lot of pathways to produce biofuels have emerged. Under the RFS program, up until march 2018, 117 pathways are approved by EPA, and are eligible for generating Renewable Identification Numbers (RINs). (US EPA, 2015a) A RIN is a unique serial number, issued by the biofuel producer at production or importer at the port of importation, where each gallon renewable biofuel has a unique RIN. These RINs are used to track production, use, and trading. Because the RFS and RFS2 program contain quotas demand a certain percentage of total motor fuels consumed in the US to be biofuels (blended into fossil fuels), obligated parties – non-renewable fuel producers/importers – need to submit a certain amount of RINs to the EPA to fulfill their RVO, Renewable Volume Obligation in order to reach the RFS quotas. (US EPA, 2015b; Yacobucci, 2013)

For a fuel to qualify as a renewable fuel under the RFS program, EPA must determine that the fuel qualifies under the statute and regulations. Among other requirements, fuels must achieve a reduction in greenhouse gas (GHG) emissions as compared to a 2005 petroleum baseline. (EPA, 2015a) Fuels, biofuels included, also need to comply with ASTM (American Society for Testing and Materials) standards, which ensure safety and quality. These standards are used in the evaluation and assessment of physical, mechanical, rheological, thermal, and chemical properties of energy resources. (ASTM, 2018)

In the article of Bann et al. (2017) six ASTM-approved drop-in alternative jet fuel pathways are quantified and compared by means of a harmonized stochastic assessment. The study suggested that no pathway is viable without any policy support based on net present value (NPV) and middle distillate selling price (MSP), as the mean NPV values were negative for each simulated pathway. However, concerning NPV, the pathway with the highest likelihood on a positive NPV is HEFA yellow grease (27.7%). Regarding the MSP, the HEFA and F-T showed the lowest MSP ($/L). The stochastic assessment considered three types of uncertainty: (1) technical uncertainty concerning capital investment and fixed operating costs, and fuel yield; (2) fuel and energy price uncertainty; (3) policy uncertainty.

The stochastic assessment did not include environmental externalities. As traditional fossil jet fuels produce additional emissions - CO_2, (fine) particulate matter, water vapor, NO_x, sulfur particulates,

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[2] This means departing in one country and landing in another country.

etc. - when burned, these emissions or pollutants have a global damaging effect by accelerating global warming, producing acidic rain, induce health risks on humans, etc. Biofuels however, do not have an additional emission of CO_2. (EPA, 2014; Hill, Nelson, Tilman, Polasky, & Tiffany, 2006) In the case of HEFA yellow grease, used vegetable or cooking oil is used as a feedstock to produce jet fuel. As the cooking oil is derived from biomass, when burning the jet fuel produced by the HEFA pathway only the CO_2 that was stored within the biomass is released, no additional CO_2 is released. Incorporating this externality, could have a positive effect on the NPV and reduce the MSP of the biofuel. Biofuels have also lower particulate matter emissions. (Beyersdorf et al., 2014) Biofuels typically have lower sulfur and aromatic contents than conventional fossil fuels, which is to be expected to change volatile and non-volatile PM emissions quantities and characteristics. (Timko et al., 2010) The use of biofuels reduces air pollution and increase air quality. Internalizing this externality, could improve the NPV and reduce the MSP of biofuels.

2. Central research question

The topic of this master's thesis can be summarized as followed:

A probabilistic approach for accounting for externalities from air pollution and GHG emissions in a TEA for biofuels for aviation.

In the literature study, the externalities and social benefits regarding the use of biofuels are studied and discussed. The empirical application of this literature study, is an addition of these externalities, air quality and climate change, to the MIT model, used in the base article of Bann et al. (2017).

The central problem statement of this master's thesis can be formulated as:

What are the private and societal benefits of using biofuels for aviation for the HEFA and Fischer-Tropsch pathway regarding the air quality and climate change difference when comparing with traditional jet fuels, and what is the impact of these benefits on NPV and MSP?

In order to answer the central research question, the first step is a literature study on the economic theory of externalities, the two selected externalities, the two selected pathways, and their social benefits. This raises a first subquestion:

1. What are the values of the benefits regarding the two externalities of using biofuels when compared with conventional jet fuel?

The second step is a literature study on the discrepancy between private and social costs regarding externalities, social benefits of using biofuels, and the monetization of these benefits. A second subquestion is raised:

2. How are the net social benefits by using biofuels produced by HEFA and FT valued? And by how much?

After the literature study, focus will shift from the economic and technical assessment to the addition of the externalities to the model of the two pathways and to the analysis of the results. The externalities are implemented into the code, and the output is submitted to a sensitivity analysis and validation. Thereafter, the output can be correctly interpreted to provide an answer to the central problem statement: What are the private and societal benefits of using biofuels for aviation for the HEFA and Fischer-Tropsch pathway regarding the air quality and climate change difference when comparing with traditional jet fuels, and what is the impact of these benefits on NPV and MSP?

3. Methodology and approach

3.1 Private and social costs

The private costs of an action (buying a product or service) are the costs experienced by the party making the decisions leading to that action. The social costs of an action are all of the costs of the action, no matter who experiences them. (Field, 2006) The private cost of a good or service may differ from the social cost if there are externalities. Externalities occur when the production or consumption decisions of one agent have an impact on the utility or profit of another agent in an unintended way, and when no compensation or payment is made by the generator of the impact to the affected party. (Perman, 2003)

In the case for air quality, the global climate and many other environmental resources, no clear enforceable property rights exist. Victims of the changing climate because of emissions like CO_2 and other GHG, or of the diminished air quality due to the emission of particulate matter, cannot obtain a compensation because they do not hold individual property rights to an appropriate climate and clean air. This is a direct result from the fact that most environmental resources, including air quality, are public goods.

3.2 Public goods

A public good has two distinct aspects: non-excludability and non-rivalrous consumption. Non-excludability means that the cost of keeping non-payers from enjoying the benefits of the good or service is prohibitive. Non-rivalrous consumption on the other hand, means that the use of the good or service by a consumer does not reduce the availability to other consumers. (Lipsey & Chrystal, 2011)

A lot of environmental resources are public goods. For example, air quality is a global public good as defined by aforementioned two aspects (and the worldwide availability, hence 'global' public good). People cannot be excluded from using air to breathe for example, and the use of air by one person does not reduce the availability of air to other people. Therefore, everyone is free to use the atmosphere. (Haab & Whitehead, 2014) A stable climate is also a public good, in similar way as air quality.

However, public goods are a source of market failure. They present the 'free-rider' problem: As public goods benefit everyone, even the ones that do not contribute to provide them, public goods are often under-provided or not provided at all by the market as there is little incentive to provide them. (Barrett, 2007) This explains the problem concerning GHG emissions, air quality, and climate change: As every country, every person benefits from less GHG emissions and better air quality, global identification and agreement on policies for the internalization of the social cost of GHG emissions are extremely difficult. (Tirole, 2008)

As an externality involves a good or bad whose level of consumption enters directly into the utility or production functions of other parties, this implies a level of non-rivalry and non-excludability. For example, each unit of GHG mitigation in order to preserve a stable climate, a public good, produces a positive externality for all parties. Whereas the use or consumption of the air as an emission sink for GHGs and other pollutants, a public bad, imposes a pollution externality on all parties, all parties are affected by the pollution. Every party can use the air and pollute, because no compensation has to be made to the other affected parties due to lack of property rights. Therefore, public goods or bads can be framed as negative or positive externalities.

3.3 Externalities

Externalities are costs or benefits of a transaction, incurred or received by other society members, that are not taken into account by the parties of the transaction. (Lipsey & Chrystal, 2011) Externalities can be positive (benefits) or negative (costs) to other members of society. In the case of a positive externality, the production or consumption decision of one party has a positive impact on the other party's utility or profit (in an unintended way). A negative externality has a negative effect on the other party's utility or profit. Because there is no recompense or penalty for the parties of the transaction, effects of the transaction are not taken into account by the parties, and these effects are thus external to their decision making. (Perman, 2003) Externalities are a source of market failure: they create a divergence between the private benefits and costs of economic activity and social benefits and costs. (Lipsey & Chrystal, 2011)

In the case of conventional fossil fuels, the burning and combustion of these fuels impose an externality on a global scale. As fuel is being burned, CO_2, particulate matter, NO_X, etc. are being emitted into the air with negative effects on the climate, the air quality and indirect on ecosystems and human quality of life. Everyone is affected by the emission or pollution of one party and no compensation is made to those who are affected by the polluter. The incremental benefit of burning fossil fuels occurs exclusively for the individual. However, environmental degradation and its costs are spread among all. (DeNyse, 2000)

3.3.1 Market inefficiency

The social cost equals the private cost plus the cost of externalities. Externalities are thus not reflected in market prices (the private cost).

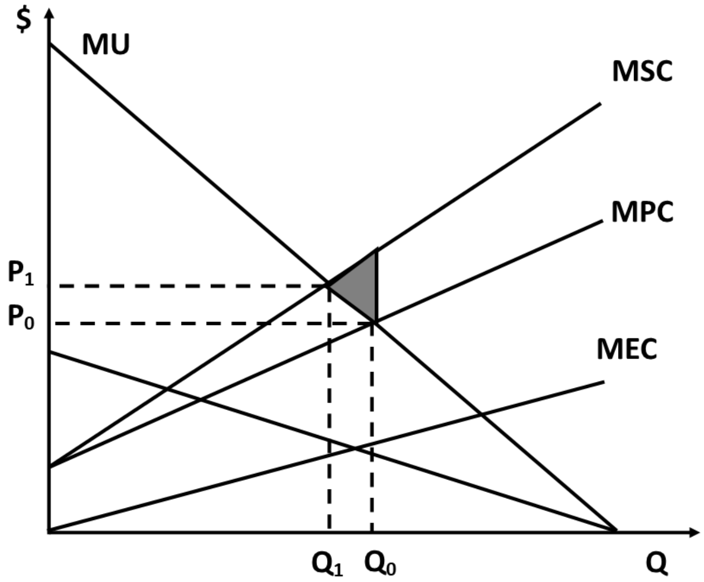

Figure 2: Negative externality

In figure 4, the impact of a negative externality on the marginal cost is depicted in a simplified competitive market graph. In this case, the private cost at P_0 does not reflect the true cost to society. Because of a negative externality, the social cost of consumption of the good or service will be higher than the private cost, at P_1. The reason behind the discrepancy between marginal private cost and marginal private benefit is that private firms do not take account of costs imposed on others.

The market price consumers have to pay, will remain at P_0 without the internalization of the externality by means of a policy or tax. Because the market price is too low in regard to the social cost, consumption of the good or service which produces the negative externality, will be inefficiently high and the externality will be overproduced. As shown by the graph, this results in welfare loss (dark area) compared to the efficient market outcome.

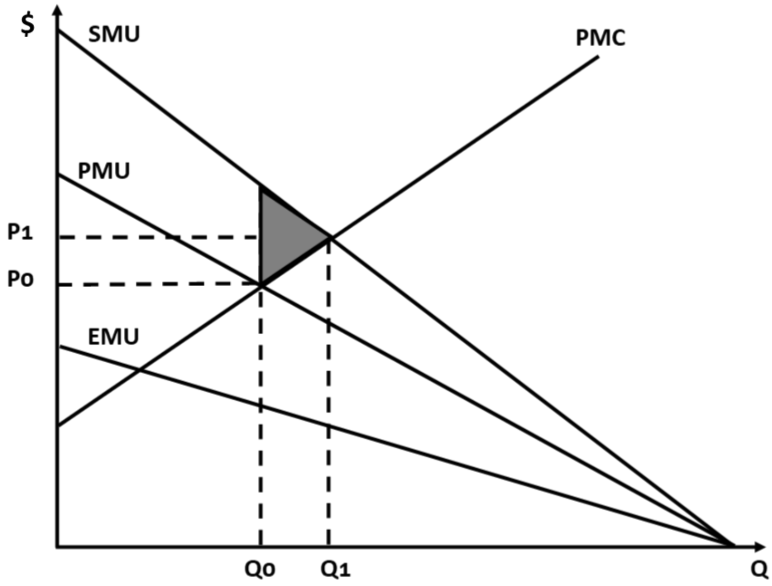

Figure 3: Positive externality

In figure 5, the impact of the consumption of a good or service with a positive externality is shown. Without the externality, the optimal market equilibrium would be at P_0, Q_0. Because there is a positive externality who benefits the utility of consumers, the externality marginal utility (EMU), the social marginal utility (SMU) is higher than the private marginal utility (PMU).

The market price will remain at P_0 and production will remain at Q_0 if no measures are taken to internalize the externality. Too little will be produced when compared to the market optimum, the intersection of P_1 and Q_1, and this results in welfare loss (dark area).

In conclusion, externalities, positive and negative, are sources of market failure, who prevent the market to reach allocative efficiency – the optimal combination of outputs by means of the most efficient combination of inputs (Brumby, 2007) – if not internalized.

3.3.2 Internalization of externalities

Individuals and firms consider only their private costs, whereas external costs, borne by society, are not considered in their decision making and activities. Governments have the task to intervene, so markets accurately represent the cost on the environment associated with the activities of individuals and firms. Governments have a couple of instruments to regulate these external effects: Bargaining, taxes, pollution abatement subsidies, cap and trade system, command and control (ban or standards). (DeNyse, 2000; Perman, 2003)

Bargaining

The government can define property rights with regard to the externality if it offers efficiency gains wherever it is cost-effective. By defining these property rights, irrespective to which economic agent (polluter or polluted party), the optimal level of externality can be achieved. In the case of "the right of pollution", parties negatively impacted by the externality can pay the polluter to produce less, up to where the marginal externality cost equals the marginal private benefit of consumption. In the case of "the right of absence of pollution", the polluter can compensate the parties negatively impacted by the externality up to the point where the marginal private benefit of consumption equals the marginal externality cost. However, there are a lot of limitations to efficient bargaining outcomes, for example: (1) Without clear, enforceable property rights, bargaining will not take place. (2) Environmental problems affect a lot of different parties which are not always easy to identify, and bargaining with all parties can lead to enormous transaction costs. (3) Environmental problems also impact future generations, however bargaining is not possible between current and future affected parties.

Emission taxes

By imposing a tax on emissions, the government eliminates the discrepancy between private efficient price and social efficient price. The externality is internalized, because the tax introduces the pollution costs into the private cost of the pollution generator, which results in lower output and higher price and the social optimum is achieved. When there are taxes, both consumer and producer split the cost of the tax.

Pollution abatement subsidies

A subsidy can be interpret as a negative tax. The price of the seller of a good or service (for example solar panels) is higher than the price for the buyer, by an amount equal to the subsidy from the government. Due to the subsidy, quantity produced and consumed increases. A positive externality is internalized – solar panels provide clean energy and mitigate GHG emissions – because the subsidy reduces the price in order to capture the positive externality who benefits the utility of consumers.

Cap and trade system

The government can put a cap and trade system in place to reduce pollution for a given sector or industry. A limit is set on the total quantity of emissions allowed, the cap, up to which companies are allowed to pollute. Companies who do not pollute up to the limit, can sell their pollution permits to other companies for an agreed price, a trade system. A trade market is created, where the right to pollute has a value (value of a permit). Because firms will abate until their marginal cost of abatement equals the cost of a permit, at the equilibrium the marginal cost of abatement will be the same for all firms. The desired emissions level is achieved at the lowest possible cost, but this emission level might not be the optimal one due to lack of information. One big drawback to a cap and trade system is a diminished effectiveness if not all emission sources are included in the system, because they are still allowed to increase.

Standard

By using emission standards, the government imposes a limit on the amount of pollutants a firm can emission. When firms emit more than permitted by the limit, they face a monetary penalty. By imposing a standard, firms are obligated to invest in abatement equipment. This will increase the average cost for a firm, and this will reflect in the price of the good or service they offer. The standard imposed by the government results in the internalization of the externality by the firms, and the market price for the good or service will now reflect the total social cost (private plus externality cost). However, there are some drawbacks to imposing a standard: Imposing one uniform standard for all firms in a sector or industry, produces inequalities in marginal abatement costs for the different polluters. Also, because of a fixed limit, polluters will only abate up until they achieve the emission limit, they will not innovate in continuous reduction of emissions. A government can also set a standard that permits zero pollutant emission, a complete ban of pollution.

3.4 Externality selection

Concerning externalities, two externalities will be evaluated with regard to two selected pathways:

(1) Climate change: temperature increase due to increased CO_2 concentration in the atmosphere.
(2) Air quality: premature deaths due to particulate pollution (fine particles).

3.4.1 Climate change externality

Climate change is regarded as the biggest threat and challenge of our times, as stated by scientists and influential people all over the world. For example, former President, Barack Obama, stated that climate change is the biggest challenge the world faces today, threatening future generations. (Park, 2015) As stated during the introduction, there is global consensus on the manmade acceleration of the greenhouse effect.

Climate change can be linked to carbon dioxide and other GHG concentrations in the atmosphere, because these gases, when emitted, accumulate in the atmosphere and increase radiative forcing. Radiative forcing is increased by carbon dioxide, because there is a positive change between the incoming solar radiation energy and the outgoing thermal infrared emission energy when the concentration of carbon dioxide increases, holding all other factors constant. (ACS, 2013) If the climate system is in equilibrium, the amount of absorbed solar energy equals the radiation emitted to space by Earth. However, due to anthropogenic emissions, this equilibrium is perturbed, and more solar energy is absorbed than radiation is emitted to space, which leads to a 'greenhouse effect' or global warming and climate change. (WGI, 1990)

A rising trend can be derived for both the carbon dioxide concentration in the air as the change in surface temperature. Due to anthropogenic emissions rising to 408 ppm (for march 2018), the global surface temperature increased with 0.9°C (for 2018) relative to 1951-1980 average temperatures. (NASA, 2014a, 2014b) If this trend is continued, the global surface temperature is likely to exceed a 1.5°C change at the end of the 21st century relative to the 1850-1900 period, with some Representative Concentration Pathway (RCP) scenarios even predicting a change of more than 3°C. This will have effects on weather patterns, with more frequent and longer heat waves, and more frequent hot temperature extremes and less cold temperature extremes. Less precipitation is very likely expected in dry regions (e.g. Middle-East), whereas more precipitation is very likely expected in wet regions (e.g. increase in monsoon precipitation). (Collins et al., 2013)

3.4.2 Air quality externality

Emissions from combustion engines do not only affect the climate, they emit a mixture of different gases. Therefore, the air people breathe also contains lots of pollutants. When these pollutants are above a certain threshold, they can have detrimental effects on human health. Air pollution has many sources: industry, power plants, cars, planes, dry cleaners, and also natural sources such as volcanic eruptions and windblown dust. Air pollution is a major environmental health problem. It affects everyone, in developed and developing countries. A World Health Organization (WHO) assessment estimated that more than two million premature deaths can be attributed to air pollution (indoor and outdoor). (WHO, 2005) Major air pollutants are particulate matter (PM), ozone, NO_2 and SO_2.

Particulate matter or particle pollution is a mixture of solid particles and liquid droplets, found in the air. These particles can come from different sources: forest fire, power plants, combustion engines, etc. and can have a wide variety of sizes. In the case of aviation and aircraft emissions, the diameter of PM is extremely small in size - size distribution usually has bimodal peaks near 30 nm an 100 nm. Therefore, PM emissions from aircraft can all be considered as $PM_{2.5}$. (Wayson, Fleming, & Iovinelli, 2009) Particulate matter can be split up in primary $PM_{2.5}$ and secondary $PM_{2.5}$. Primary $PM_{2.5}$, black carbon and organic carbon for example, are emitted directly into the atmosphere, whereas secondary $PM_{2.5}$ is formed in the air through chemical reactions of exhaust gases like NO_X, SO_2 and ammonia.

3.4.3 Effect of biofuels on climate change and air quality externality

Biofuels produce a benefit regarding GHG and $PM_{2.5}$ emissions when being burned instead of conventional jet fuel. The use of these alternative fuel pathways is less impactful with regard to climate change – less GHGs emitted to the atmosphere, resulting in lower global GHG concentrations in the air and a lower global temperature increase than when conventional jet fuel is used – and with regard to air quality – less $PM_{2.5}$ emitted, resulting in better air quality and less associated impacts and costs,(premature deaths and health costs) when compared with the use of conventional jet fuel.

As mentioned in the introduction, in the paper of Bann et al. (2017), this externality benefit when compared with conventional jet fuel, is not considered in the stochastic model. In general, externality benefits (or costs) are not considered because they are not borne by the party that produces the fuel, because fuel producers only consider their private costs. Externality benefits (or costs) are borne by society as a whole. Therefore, there is a discrepancy between the private and the true or social cost, which includes the externalities.

3.5 Pathway selection

This master thesis will focus on the following two pathways:

(1) Hydroprocessed Esters and Fatty Acids using yellow grease (YG): In the paper of Bann et al. (2017), the HEFA pathway with yellow grease as feedstock showed the lowest mean jet fuel price at $0.91/liter. Without any policy supports or financial incentives, HEFA yellow grease showed the highest net present value with a mean value of -0.112 in $B.

(2) Fischer-Tropsch using municipal solid waste (MSW): F-T is the pathway with the second lowest MSP in $/L reported by Bann et al. (2017). In absence of policy supports or financial incentives, the mean value of the NPV is -0.210 $B, second highest of all discussed pathways.

Both HEFA and F-T biofuels are drop-in fuels. They meet ASTM D7566 (renewable jet fuel), ASTM D4814 (renewable gasoline), and ASTM D975 (renewable diesel) standards and are approved by the Environmental Protection Agency, EPA. Drop-in biofuels are compatible with existing infrastructure, as they can be used in vehicles without engine modifications and can use existing petroleum distribution systems. Concerning renewable jet fuel, HEFA and F-T jet fuel can be blended up to 50% with conventional jet fuel. (DOE, 2015)

Biofuels produced by HEFA and F-T using yellow grease and MSW as feedstock, respectively, are second-generation biofuels or advanced biofuels, because the feedstock is not suitable for human consumption, and it does not threaten food supply. Yellow grease and MSW have the advantage of not using land, they are readily available, have a low or even negative cost, and they improve the environmental impact of the fuel because waste is being reused. HEFA and F-T biofuels have similar properties to conventional fuels, but have a higher cetane number[3], have lower aromatic content[4], lower sulfur content, and when burned, lower emissions.

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[3] Cetane number is a standard measure of the performance of compression ignition fuels. It has a base rating of 100. (Ghosh & B. Jaffe, 2006)

[4] Best performance and maximum lifetime of an engine is achieved when the amount of aromatics is as low as possible.

3.6 HEFA pathway

The HEFA or Hydroprocessed Esters and Fatty Acids pathway has the highest probability on a positive NPV and the lowest MSP (in \$/L) of all pathways discussed in the study by Bann et al. 2017. Hydroprocessed renewable oils, e.g. HEFA fuels, are 'drop-in' quality fuels. The fuels are chemically equivalent with conventional fuels and compatible with existing production, storage, distribution, and combustion infrastructure. (Pearlson, 2011)

3.6.1 HEFA process

The purpose of the HEFA process is to convert waste vegetable oils and animal fats into liquid transportation fuels that are chemically equivalent to transportation fuels from fossil resources. (Pearlson et al., 2013)

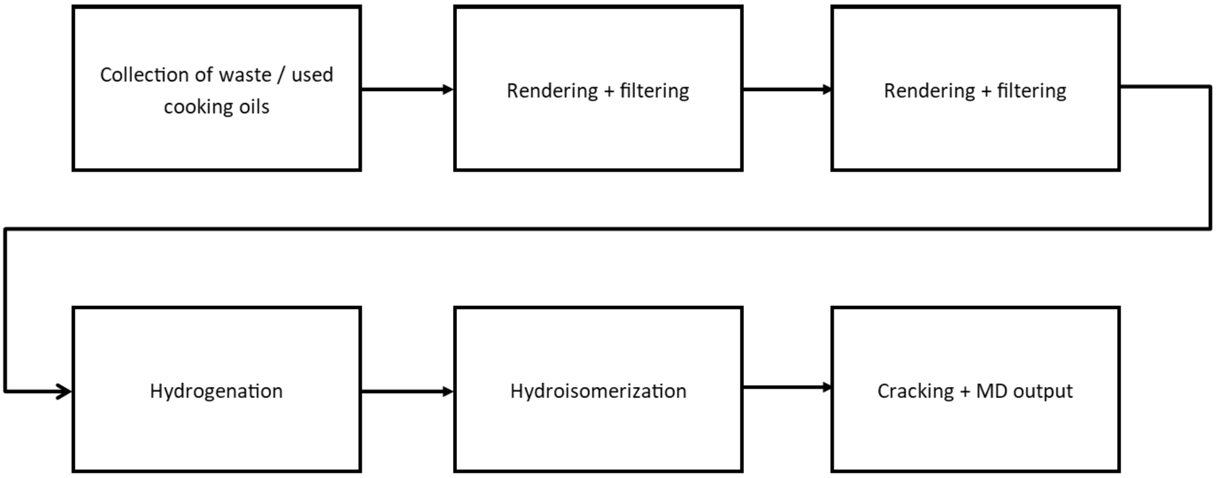

Figure 4: General simplified HERA/HRO process system overview

<u>Hydrotreatment</u>

First, the waste oils and fats are hydrogenated. The fats and oils are treated with hydrogen (H_2) in a hydrogen-rich environment (4wt% hydrogen), pressure of 7-10 MPa, and temperatures between 300°C and 400°C in the presence of a catalyst (e.g. cobalt-molybdenum) in order to remove impurities like sulfur and nitrogen, and oxygen. (Brown, Thilakaratne, Brown, & Hu, 2013) The outputs of the hydrotreatment process, are water, carbon dioxide, propane as side products, and a range of straight chain alkanes or liquid hydrocarbons as the main product. (Pearlson, 2011) Water and carbon dioxide are produced when the hydrogen reacts with the oxygen. Propane is produced when the glycerin backbone of the triglyceride (fats) is removed.

These straight chain alkanes are a 100% paraffinic diesel product covering the diesel and jet fuel carbon lengths from C_9 through C_{20}, but with very poor cold flow properties. They are not optimal for use in kerosene applications. To improve these cold flow properties a second step is carried out in the HEFA process.

Isomerization and cracking

The effluent is cooled by steam generation and sent to an isomerization unit for a hydro-isomerization treatment. This is done by means of a catalyst in order to convert linear paraffins into iso-paraffins, which leads to lower boiling and melting points. The isomerized product is being cooled with cooling water and goes into a separator where gasses, carbon dioxide, and excess hydrogen are separated from the liquid products. Next, the liquid products are separated into LNG (liquefied natural gases), naphtha, jet, and diesel.

3.6.2 HEFA biofuel production

Feedstock input

Focus will be put on the HEFA pathway with yellow grease as feedstock. This is an interesting feedstock, as in the USA alone in 2010 around 0.60 Tg (Teragram) or 600 million kilogram yellow grease was produced, accounting for almost 15% of total production of waste oils and animal fats in the USA in 2010. (Seber et al., 2014)

In order to obtain yellow grease, used cooking oil containing excess water is collected from different sources. The excess water is removed at a rendering plant. The collected used cooking oil is filtered to remove solid particles and heated to reduce the water content, and yellow grease is obtained. (Seber et al., 2014)

Outputs

The outputs of the HEFA pathway using yellow grease as feedstock are HEFA jet fuel, HEFA diesel fuel, naphtha and propane gas-mix (e.g. LPG). The biofuel producer can vary between two product slate decisions: maximize diesel/distillate production or maximize jet fuel production. Under the maximum jet fuel production case, diesel range molecules will be hydrocracked with hydrogen to produce more jet fuel. However, this implies additional energy inputs and an increase in overall GHG emissions.

3.6.3 Emissions

Following the paper from Seber et al. (2014), lifecycle GHG emissions for HEFA jet fuel derived from yellow grease in terms of g MJ^{-1} in CO_2 equivalents, ranged from 19.4 g MJ^{-1} to 21.4 g MJ^{-1}, with the system boundary set from the rendering of used cooking oil to fuel production. It is important to note that the GHG emissions values are from fuel production only, as CO_2 released during combustion of the fuel has no extra environmental impact as this is the CO_2 that is stored during plant growth. There is no additional CO_2 released.

3.7 F-T pathway

The second selected pathway is Fischer-Tropsch. In the article of Bann et al. (2017), F-T pathway showed the second lowest MSP (in $/L), after the HEFA YG pathway.

3.7.1 F-T process

The Fischer-Tropsch process uses municipal solid waste (MSW) as feedstock for the production of liquid transportation fuels that are chemically equivalent to conventional fuels.

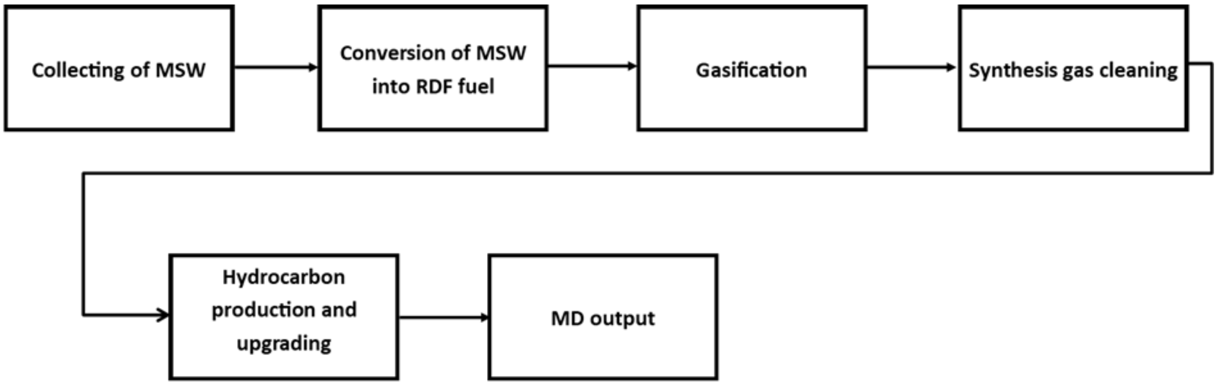

Figure 5: Simplified Fischer-Tropsch process with MSW feedstock

Discarded MSW, by US EPA's 2014 estimates, consists primarily of food (21.6%), plastics (18.5%), paper and paperboard (14.3%), rubber, leather and textiles (10.8%), metals (9.4%), wood (8.1%), yard trimmings (7.9%), and glass (5.2%). (EPA, 2016a)

As MSW consists of many different components, the removal of the non-combustibles and recyclables (e.g. glass, metals, etc.) and other inorganics must be sorted out via a Refuse Derived Fuel (RDF) facility. There, the MSW is converted into a higher-calorific fuel and the resulting RDF fuel has a more consistent quality, composition, and moisture. (Niziolek et al., 2015)

After conversion to RDF fuel, the RDF is directed to the gasification section. It goes through a drier to reduce moisture content and dry. Next, the RDF is lock hopped[5] into the gasifier with compressed CO_2. Output of the gasifier consists of a mixture of syngas, hydrocarbons, ash, tar, char, and acid gases. The char is recycled in the gasifier and converted to a vapor product.

The raw syngas from gasification still contains impurities from the feedstock. Residual tar, particulates, and NH_3 are removed during the syngas cleaning process step. Next, the effluent is directed to a another system that removes 100% of the H_2S and 90% of the CO_2 from the syngas.

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[5] A method and apparatus for transferring solid materials between zones at substantially different pressures. (Huebler, Weil, & Tarman, 1971)

The syngas is cooled and conditioned, and then synthesized to fuels and wax using a F-T-catalyst. The products are then refined to naphtha, kerosene, and diesel. The naphtha is fed into a naphtha reformer and converted into gasoline. (Niziolek et al., 2015; Suresh, 2016)

3.7.2 F-T biofuel production

Feedstock

Municipal solid waste is an interesting feedstock to use as an input for the F-T process. MSW is abundant: In the United States, MSW generated in 2014 was over 258 million tons of which over 89 million tons (34.6%) was composted and/or recycled. In comparison, 136 million tons of MSW (52.6%) were discarded in landfills. (EPA, 2016) Total MSW generated is likely to keep rising as population rises. (Pressley et al., 2014)

The use of MSW does not require additional land, and next to the advantage of conversion of MSW to fuels in regard to avoiding CO_2 emissions from fossil fuel combustion, it limits the methane emissions from landfills. Also, waste producers typically pay tipping fees for the disposal of their waste. As a result, using MSW as feedstock for biofuel production can yield negative feedstock costs. (Suresh, 2016)

Output

The main output products of the Fischer-Tropsch process are naphtha, jet fuel and diesel. The naphtha is further reformed to gasoline.

3.7.3 Emissions

Based on Suresh (2016), mean lifecycle GHG emissions for Fischer-Tropsch biofuel using municipal solid waste as feedstock, are 32.89 g MJ^{-1} CO_2eq. with a variance of 7.22 g MJ^{-1} CO_2eq., with system boundaries starting from where the MSW exits the sorting facility until combustion of the F-T fuel. This is for the total product slate. The energy product slate that was used for the allocation of emissions by share of energy, is as follows: jet fuel 12%, diesel 73%, gasoline 10.7%, excess electricity 4.0%.

3.8 Biofuels externality benefit

Jet A-1 will be used to compare with alternative fuels. Jet A-1 is among the most common used fuels in the aviation industry for gas-turbine engines, together with Jet A.

3.8.1 GHG emissions

Conventional jet fuel

Conventional jet fuel has a net heat of combustion of 43.14 MJ kg^{-1} (Moore et al., 2017) and lifecycle GHG emissions of 87.5 g MJ^{-1} CO_2eq. (Stratton, Wong, & Hilleman, 2010)

Calculation of the total GHG emissions per kg jet fuel burned (g kg^{-1} conv. jet fuel in CO_2eq.):

*(1) lifecycle GHG emissions * net heat of combustion*
= total GHG emissions per kg fuel burned

This indicates an emission of for conventional jet fuel 3774.75 g kg^{-1} conv. jet fuel burned in CO_2eq.

Comparison with HEFA yellow grease jet fuel

Lifecycle GHG emissions of HEFA yellow grease jet fuel are 21.4 g MJ^{-1} CO_2eq., and HEFA jet fuel has a net heat of combustion of 44.1 MJ kg^{-1}. (Gaspar & Sousa, 2016) The calculation of total GHG emissions per kg HEFA jet fuel burned is similar to equation (1) for conventional jet fuel. This indicates an emission of 943.74 g kg^{-1} HEFA jet fuel in CO_2eq. for HEFA yellow grease.

The comparison with conventional jet fuel:

(2) benefit = LC GHG emissions per kg conv. jet fuel - LC GHG emissions per kg alt. jet fuel

When compared with conventional jet fuel (3774.75 g kg^{-1} conv. jet fuel in CO_2eq.), the use of HEFA yellow grease jet fuel results in an emissions benefit of 2831.01 g kg^{-1} HEFA jet fuel in CO_2eq.

Comparison with F-T MSW jet fuel

Lifecycle GHG emissions of F-T MSW MD fuel are 32.9 g MJ^{-1} CO_2eq., and F-T fuel has a net heat of combustion of 44.2 MJ kg^{-1}. (Klettlinger, Surgenor, & Yen, 2010) By means of equation (1), total GHG emissions per kg of F-T fuel burned are 1454.18 g kg^{-1} F-T jet fuel in CO_2eq. for F-T MSW.

When comparing this with conventional jet fuel (3774.75 g kg^{-1} conv. jet fuel in CO_2eq.) by using equation (2), the use of F-T MSW jet fuel results in an emission benefit of 2320.57 g kg^{-1} F-T jet fuel burned in CO_2eq.

Table 1 summarizes all values for both the HEFA jet fuel with yellow grease as feedstock and F-T jet fuel with MSW as feedstock, and the benefit or delta when compared with conventional jet fuel.

Table 1: Overview of delta/benefit per kg biofuel, compared with conventional jet fuel

	Lifecycle GHG emissions ($g\ MJ^{-1}\ CO_2eq.$)	**GHG emissions per kg of fuel** ($g\ CO_2eq.\ kg^{-1}$)	**Biofuel GHG benefit, delta** ($g\ CO_2eq.\ kg^{-1}$ fuel)
Conventional jet fuel	87.5	3774.75	/
HEFA jet fuel (YG)	21.4	943.74	2831.01
F-T jet fuel (MSW)	32.9	1454.18	2320.57

3.8.2 Particulate matter

Aircraft Engine – Conventional jet fuel

For conventional jet fuel (Jet-A1), the PM mass emission index (EI_m) varied from 10 to 550 mg kg^{-1} fuel burned, measured by a nano-SMPS 30 meter behind the engine during APEX 1-3[6] (for CMF56-type, AE3007A1-type, and RB211-535E4-B engines), and was found to be correlated to the rated engine thrust as a function of fuel flow rate: emissions are the highest at idle (7% power), decline to the lowest point at medium power, and increase with higher engine power for turbofan engines. For turbojet engines (CJ610-8ATJ), PM emissions increase linear with engine trust. Other factors that influence PM emission are engine type, engine operating temperature, and fuel composition. (Kinsey, Dong, Williams, & Logan, 2010) Herndon et al. (2008) had similar results for CFM56-type engines, with black carbon (BC) mass emissions ranging from 207 to 501 mg kg^{-1} fuel burned after conducting a landing/takeoff (LTO) cycle. (Herndon et al., 2008) Klapmeyer & Marr (2012) found similar EI_m for BC for a twin engine turboprop. They measured a LTO cycle with a mast 15 m above ground level (with a Magee scientific micro Aeth AE51). For conventional Jet-A1 fuel, BC emissions were 200 to 500 mg kg^{-1} fuel burned. (Klapmeyer & Marr, 2012) Mazaheri et al. (2009) measured engine exhaust emissions for 283 individual aircrafts for the different stages of a LTO cycle. Measurements were made at 80 m from engine exhaust with a SMPS. For a Boeing 737 with a CFM56-7 engine burning conventional jet fuel, the PM mass emission ranged from 160 to 270 mg kg^{-1} fuel burned. For an Airbus-A320 with a CFM56-S engine burning conventional fuel, PM mass emission ranged from 140 to 230 mg kg^{-1} fuel burned. (Mazaheri, Johnson, & Morawska, 2009) These EI_m for PM are lower than in the articles from Kinsey et al. (2010), Herndon et al. (2008) and Klapmeyer et al. (2012). However, this can be a explained due to the measurement point being further away from the engine exhaust, at 80 m instead of 30 m.

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[6] APEX 1-3: Aircraft Particle Emissions eXperiment, 3 campaigns carried out to address the need for improved aircraft PM emissions data, with following participants: NASA, EPA, FAA, DoD, aviation industry, and the research community.

Aircraft Engine F-T alternative jet fuel

Lobo et al. (2011) compared PM emissions from a commercial jet engine (CFM56-7B) burning conventional (Jet-A1), biomass, and Fischer-Tropsch fuels. Emissions were measured 30 m from the engine exhaust for a LTO cycle (at 7%-30%-85%-100% thrust settings) with a PM probe. From the experiment, they derived that the PM mass emission index increases with increasing engine power, with minimum EI_m at idle setting (7% thrust) and maximum at full power (100% thrust). When comparing conventional Jet-A1 fuel with a 100% F-T fuel, on average 62%±4% less $PM_{2.5}$ mass per kg of fuel burned is emitted when burning a 100% F-T fuel. (Lobo, Hagen, & Whitefield, 2011) Beyersdorf et al. (2014) reported a reduction in soot emissions of 86% on average when comparing conventional military jet fuel (JP-8) to a 100% F-T fuel (Gas-to-Liquids) in CFM-56 engines, measured 30 m downwind of the exhaust plume. The EI_m of $PM_{2.5}$ for the JP-8 fuel ranged from 7.6 mg kg^{-1} at idle setting to 103 mg kg^{-1} at full power. For the 100% F-T fuel, the $PM_{2.5}$ EI_m ranged from 1.2 mg kg^{-1} to 24 mg kg^{-1}.

Comparison conventional jet fuel - alternative fuel

The EI_m of $PM_{2.5}$ for conventional jet fuel ranges from 10 to 550 mg kg^{-1} fuel burned, and was taken from the study of Kinsey et al. (2010), because this range covers also the range of $PM_{2.5}$ mass emission indices found in the other mentioned studies. One important note: this range was determined during a LTO cycle ground test. If measurements were made for aircraft engines at cruise conditions (altitude of 10 – 11 km), the range could differ substantially, because exhaust gas temperatures at cruise conditions are much higher for a given fuel flow rate in comparison with a ground test (LTO cycle) as is determined during the NASA Alternative-Fuel Effects on Contrails and Cruise Emissions (ACCESS) Flight Experiments. (Moore et al., 2013) However, values from the ACCESS flight experiments could not be evaluated as no 100% alternative jet fuel case was presented to compare with.

The EI_m of $PM_{2.5}$ for 100% F-T jet fuel is derived by using an average reduction in $PM_{2.5}$ mass emission indices from the study of Lobo et al. (2011). On average, 62%(±4%) less $PM_{2.5}$ per kg of F-T fuel burned is emitted during a LTO cycle. The F-T fuel used, is a Gas-to-Liquids (GtL) fuel[7]. It has comparable parameters as F-T fuel from MSW, concerning aromatic content (< 0.2) and sulfur content (approximately 0). Beyersdorf et al. (2014) found an average reduction of 86%. Nevertheless, a more conservative approach is taken and an average reduction of 62% will be used. Reductions in $PM_{2.5}$ mass emissions indices reduce as power increases, with highest reductions at idle setting (7% thrust) and lowest reductions at full power (100% thrust). (Beyersdorf et al., 2014; Lobo et al., 2011) However, an average reduction at all power settings will be used when determining $PM_{2.5}$ mass emissions indices for a 100% F-T fuel being burned.

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[7] Gas-to-Liquid technology converts natural gas into higher quality liquid products, otherwise made from crude oil. (Wood, Nwaoha, & Towler, 2012)

The calculation of the EI_m of $PM_{2.5}$ for a 100% F-T fuel:

*Range conv. jet fuel * (1 - 0.62) = range F-T fuel*

The range for the F-T fuel is 3.8 – 209 mg $PM_{2.5}$ kg^{-1} fuel burned.

The calculation of the benefit of using F-T fuel:

*Range conv. jet fuel * 0.62 = benefit of using F-T fuel*

The emission benefit of using F-T fuel instead of conventional jet fuel ranges from 6.2 to 341 mg $PM_{2.5}$ kg^{-1} fuel burned.

As an average value of the $PM_{2.5}$ mass emission index of conventional fuel, 350 mg $PM_{2.5}$ kg^{-1} fuel burned is selected. This value is an average derived from the studies of Herndon et al. (2008) and Klapymeyer & Marr. (2012), and lies within the range specified by Kinsey et al. (2010). Benefit of using F-T fuel when comparing with conventional fuel for the average $PM_{2.5}$ mass emission index, was calculated as follows:

*Average conv. jet fuel * 0.62 = average benefit of using F-T fuel*

The average emission benefit or delta of using F-T fuel instead of conventional jet fuel is 217 $PM_{2.5}$ kg^{-1} fuel burned. This value lies within the specified $PM_{2.5}$ emission benefit range of F-T fuel.

3.8.3 Conclusion emission benefit values

Table 2 summarizes all different emission benefit values when burning 1 kg HEFA jet fuel (yellow grease), F-T jet fuel (MSW) when compared with conventional jet fuel.

Table 2: Summary of externality benefits for HEFA and F-T alt. fuel

	Climate change externality benefit (g CO_2eq. kg^{-1} fuel burned)	**Air quality externality benefit** (mg $PM_{2.5}$ kg^{-1} fuel burned)
HEFA (yellow grease)	2831.01	217
F-T (MSW)	2320.57	217

HEFA (yellow grease) jet fuel has the same air quality externality benefit value as F-T (MSW) jet fuel because of the same fuel characteristics (e.g. high cetane number, very few to zero aromatics, and sulfur content of approximately 0).

3.9 Economic valuation of GHG and $PM_{2.5}$ emissions benefit

3.9.1 Social cost of carbon

The social cost of carbon (SCC) is the marginal damage caused by an additional metric ton of carbon dioxide emissions (or equivalent amount of other greenhouse gases). (Ackerman & Stanton, 2012) It is a monetary estimate of global climate change damages to society from an additional unit (ton) of carbon dioxide (CO_2) emissions. The SCC sums the full global cost of the damage it imposes over its atmospheric lifetime. (Price, Thornton, & Nelson, 2007) The SCC estimates are used to estimate the benefits of policies that reduce CO_2 emissions. (Rose, Diaz, & Blanford, 2017) Most estimates for the SCC are derived by using one or a combination of three integrated assessment models (IAM's)[8]: DICE (Nordhaus, 1993), FUND (R. Tol, 2018), and PAGE (Hope, Anderson, & Wenman, 1993). For example, the United States Government (USG) estimates were derived by using all three IAM's. Four USG estimates of the SCC were selected by the interagency group for the 2020 Social Cost of Carbon Values at different discount rates: average SCC at a discount rate of 2.5% (1), 3.0% (2), 5.0% (3), and for the 95th percentile at a 3% discount rate (4). The discount rate is used to calculate the present value of the stream of damages in the year when the additional unit of emissions was released. (Greenstone, Kopits, & Wolverton, 2013)

3.9.2 Comparison with the shadow price of carbon

Shadow prices are constructed prices for goods or production factors that are not traded in the market. It permits the inclusion of environmental goods into economic analysis, because these shadow prices indicate the value of the particular environmental good to society. (de Bruyn, 2010)

In the paper of Price et al., 2007, they advise to use the shadow price of carbon (SPC) for policy making. The SCC estimated to attain a given stabilization goal and the corresponding marginal abatement costs (MAC), may not be equal, and the selected SCC may under- or over-deliver carbon abatement. The SPC is based on the SCC, but can also reflect required MAC estimates to attain the stabilization goal, and other factors that may influence marginal willingness to pay for reduction in carbon emissions. However, in this master thesis, the SCC is selected.

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[8] Integrated assessment models consider both the economic and biophysical systems, and interactions between them for the purpose of assessing policy options for climate control. (Kelly & Kolstad, 1998)

3.9.3 Use of USG SCC estimates

The four USG SCC estimates (in 2007 dollars per metric ton CO_2) are shown below (EPA, 2016b):

Table 3: USG SCC estimates for 2020

Discount rate	**5%**	**3%**	**2.5%**	**High impact (95th percentile at 3%)**
Year 2020	$12	$42	$62	$123

With the CO_2 delta, the benefit of using biofuels, calculated under *2.4.1 GHG Comparison*, the economic GHG benefit was calculated by using the USG SCC estimates:

$$Delta * \left(\frac{SCC}{1{,}000{,}000}\right) = GHG\ benefit\ of\ consuming\ 1\ kg\ biofuel\ in\ 2007\ dollars$$

The GHG benefit for HEFA yellow grease jet fuel was 2831.01 g CO_2eq. per kg biofuel used.

Table 4: Estimates of GHG benefit per kg HEFA jet fuel in 2007 dollars

Discount rate	**5%**	**3%**	**2,5%**	**High impact (95th percentile at 3%)**
Year 2020 (in 2007 dollars per kg jet fuel)	$0.034	$0.119	$0.176	$0.348

The GHG benefit for F-T MSW jet fuel was 2320.57 g CO_2eq. per kg jet fuel used.

Table 5: Estimates of GHG benefit per kg F-T jet fuel in 2007 dollars

Discount rate	**5%**	**3%**	**2,5%**	**High impact (95th percentile at 3%)**
Year 2020 (in 2007 dollars per kg jet fuel)	$0.028	$0.097	$0.144	$0.285

3.9.4 Social cost of (fine) particulate matter

Considering the negative impact of the emission of (fine) particulate matter, the emission of $PM_{2.5}$ implies a social cost comparable with the social cost of carbon: The social cost of particulate matter can be interpret as the marginal damage caused by an additional ton of $PM_{2.5}$ emissions. This is a monetary estimate of the damages to society from an additional metric ton of $PM_{2.5}$ emissions.

3.9.5 $PM_{2.5}$ damage cost estimates

AEA Technology carried out a CAFE cost-benefit analysis (CBA) on behalf of the European Commission, concerning damage costs per ton emissions of air pollutants for the EU25 Member State[9] (excl. Cyprus). CAFE or the Clean Air for Europe program was set up by the European Union, in order to develop long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment. (EC, 2005)

Estimates were made for NH_3, NO_X, $PM_{2.5}$, SO_2 and VOC's, for the EU25 (excl. Cyprus) and nearby seas under 4 different sets of assumptions. For $PM_{2.5}$, average marginal damages per metric ton of $PM_{2.5}$ ranged from 26,000 to 75,000 EUR for the EU25. Difference between the low and upper end estimate can be addressed to different sensitivity combinations. For more details concerning the assumptions made, see AEAT (2005).

3.9.6 Use of CAFE $PM_{2.5}$ damage cost estimates

The average $PM_{2.5}$ emission benefit of burning one kg of HEFA or F-T fuel instead of conventional jet fuel, is 217 mg kg^{-1} fuel burned. The $PM_{2.5}$ damage cost estimates from the CAFE CBA ranged from 26,000 to 75,000 EUR per metric ton of $PM_{2.5}$, with 51,000 EUR as average value. The $PM_{2.5}$ benefit in economic values was calculated as follows:

$$\frac{\textit{CAFE Estimate}}{\textit{1,000,000,000}} * \textit{Average } PM_{2.5} \textit{ emission benefit}$$

$$= \textit{Estimate of } PM_{2.5} \textit{ benefit when burning 1 kg alt. jet fuel (in 2005 EUR)}$$

The resulting $PM_{2.5}$ benefit values per kg alternative jet fuel are shown in table 6.

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[9] EU25 consists of: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom.

Table 6: Estimates of $PM_{2.5}$ damage costs avoided per kg alt. fuel

	CAFE estimate (in 2005 EUR / metric ton $PM_{2.5}$)	**Estimate of $PM_{2.5}$ benefit** (in 2005 EUR / kg alt. jet fuel)
Low	€ 26,000	€ 0.005642
Average/most likely	€ 51,000	€ 0.011067
High	€ 75,000	€ 0.016275

3.10 Indexing of estimates to 2015 dollars

The GHG benefit values calculated with the SCC estimates, were denoted in 2007 dollars, and the $PM_{2.5}$ benefit values calculated with the CAFE estimates, are denoted in 2005 euros. However, in the model of Bann et al. (2017), all inputs were indexed for the year 2015 in USD. Therefore, in order to add the externalities in a correct way to the two pathway models, the benefit values needed to be indexed to 2015 dollars.

For the GHG benefit values, the 2007 USD values needed to be inflated to 2015 USD. This was done by using the consumer price indices (CPI) of 2007 and 2015. The CPI measures the average change over a certain period relative to a base period with base 100, in the prices consumers pay for a market basket of goods. The US annual average CPI for 2007 was 207.342, for 2015 this was 237.017. These estimates were retrieved from the Bureau of Labor Statistics and have 1982-1984 as base period. (USDOL, 2018) To calculate the inflation rate from 2007 to 2015, the following calculation is used:

$$\frac{CPI\ 2015}{CPI\ 2007} * \textit{Estimate of GHG benefit per kg alt. fuel in 2007 USD}$$

$$= \textit{Estimate of GHG benefit per kg alt. fuel in 2015 USD}$$

If the estimate of the GHG benefit in 2007 USD was 1 USD, it would be equivalent to 1.1431 USD in 2015 in purchasing power.

This calculation was applied to all estimates for the year 2020 for both HEFA and F-T, results are shown in table 7.

Table 7: Estimates of GHG benefit per kg HEFA and F-T jet fuel in 2015 dollars

Discount rate	**5%**	**3%**	**2,5%**	**High impact (95th percentile at 3%)**
HEFA (in 2015 dollars per kg jet fuel)	\$0.039	\$0.136	\$0.201	\$0.398
F-T (in 2015 dollars per kg jet fuel)	\$0.032	\$0.111	\$0.165	\$0.326

In the case of the air quality externality estimates for the $PM_{2.5}$ benefit, the values first needed to be converted from 2005 EUR to 2005 USD. Next, the 2005 USD values needed to be indexed to 2015 USD. The conversion from 2005 EUR to 2005 USD was done by using the purchasing power parity (PPP). An average PPP was used from the PPP's of the EU28 countries[10] from the OECD. This average PPP of the European Union (28 countries) differs from the countries considered in the CAFE estimates, because it includes Bulgaria, Croatia, Cyprus, and Romania.

The average PPP of the European Union was 0.849860 EUR per USD in 2005. (OECD, 2018) The conversion of 2005 EUR to 2005 USD is then:

$$\frac{1}{PPP\ EU28} * \text{Estimate of } PM_{2.5} \text{ benefit per kg alt. fuel in 2005 EUR}$$
$$= \text{Estimate of } PM_{2.5} \text{ benefit per kg alt. fuel in 2005 USD}$$

Next, the estimates needed to be denoted in 2015 USD. This was done by using the same calculation as for the indexing to 2015 USD of the GHG benefit values. The CPI of 2005 is 195.3, for 2015 this was 237.017. The calculation for 2015 USD was as follows:

$$\frac{CPI\ 2015}{CPI\ 2005} * \text{Estimate of } PM_{2.5} \text{ benefit avoided in 2005 USD}$$

$$= \text{Estimate of } PM_{2.5} \text{ benefit avoided in 2015 USD}$$

The resulting estimates are for both HEFA and F-T fuels, and are shown in table 9.

Table 8: Estimates of $PM_{2.5}$ benefit per kg alt. fuel in 2015 USD

	Low	**Average**	**High**
Estimate of $PM_{2.5}$ benefit (in 2015 USD / kg alt. fuel)	\$0.008057	\$0.015804	\$0.023241

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[10] The EU28 countries are the countries who are part of the European Union from 1st July 2013. These include all EU25, Bulgaria, Croatia, and Romania.

4. Empirical application

In the study by Bann et al. (2017), the researchers evaluated six alternative jet fuel pathways by means of a stochastic assessment and accounted for three different types of uncertainty (see 1.3) by using Monte Carlo simulations. This master thesis expands the model by incorporating climate change and air quality externality.

4.1 Modeling

In 3.10, the values of the CO_2 and $PM_{2.5}$ benefit for 1 kg alternative jet fuel in 2015 USD in comparison to conventional jet fuel, were determined. These values were added to the model used in Bann et al. (2017) to account for climate change and air quality externality in the determination of the NPV and MSP of the HEFA pathway using yellow grease and the F-T pathway using MSW.

The addition of the two externalities to the model was done with MATLAB, which was also used for the original model. MATLAB is a matrix-based language for scientific and engineering computing, integrating computation, visualization and programming, and is used for math, modeling, simulation, prototyping, etc. (MathWorks, 2018) MATLAB version R2018a was used.

4.1.1 Model description

The model used by Bann et al. (2017) calculated the net present value (NPV) and minimum middle distillate selling price (MSP) for the six different alternative jet fuel pathways over a time span of 23 years, with construction of the plants assumed to start in 2015 and plant operation in 2018. The calculation was done by means of a stochastic assessment. This is a probabilistic assessment method where selected critical inputs are treated as random variables. Monte Carlo simulation was used to asses uncertainty throughout the analysis of the pathways. By using Monte Carlo simulation, all possible outcomes and their probabilities regarding the three different types of uncertainty could be observed. The three different types of uncertainty were technical uncertainty (capital investment and fixed operating cost (FOC)), fuel and energy price uncertainty, and policy uncertainty.

To incorporate technical uncertainty, for the capital investment and FOC uncertainty, the assumed error with deterministic cost estimates (from the literature) was assumed to be ±20%, and a beta-PERT distribution was used for fixed capital investments (FCI) varying between 80%-150% of deterministic value. Working capital was modeled as 5% of FCI, fixed operating costs as a percentage of FCI. In order to incorporate fuel yield uncertainty, a beta-PERT distribution was used.

Concerning fuel and energy price uncertainty, Geometric Brownian Motion (GBM) was applied to project gas, electricity and gasoline prices, and uncertainty was included by using a beta-PERT distribution for the gasoline growth rate and 2018 start price. The yearly price variation was determined by a normal distribution of the year-to-year variations in prices from 2001 – 2015.

For the policy uncertainty, price behavior of fuel credits, Renewable Identification Numbers (RINs), were modelled by using probability distributions and the incorporation of various tax credit scenarios as sensitivity analyses.

4.1.2 Externality modelling

The externalities, climate change and air quality, were added to the HEFA YG and F-T MSW model used by Bann et al. (2017). For the climate change externality, the carbon benefit estimates for HEFA yellow grease and F-T MSW, calculated for different discount rates and for a 'high impact' scenario, were modeled in the same manner as the other uncertainties. The carbon benefit estimates were modeled according to a beta-PERT parameter distribution, with the estimate at 5% discount rate as minimum, the estimate at 95th percentile for a 3% discount rate as maximum, and the estimate at 3% as the most likely value. The estimate at 3% discount rate was picked as the most likely value, because this is the central value defined by EPA.(EPA, 2010) The high impact estimate was selected as the maximum value instead of the 2.5% average estimate, because of "extensive evidence in scientific and economic literature of the potential for low-probability, but higher-impact outcomes from climate change", as stated in the technical support document from the US EPA (2016) (p. 3). For the air quality externality, the modeling into the model was done similar to the climate change externality. A beta-PERT parameter distribution was used, with the CAFE estimate of 26,000 EUR / metric ton $PM_{2.5}$ as the minimum value, the CAFE estimate of 75,000 EUR / metric ton $PM_{2.5}$ as the maximum value, and the CAFE estimate of 51,000 EUR / metric ton $PM_{2.5}$ as the most likely value.

Regarding the social benefit estimates, the model randomly selected carbon benefits value and $PM_{2.5}$ benefit value, with the probability of selecting a given benefit value determined by the beta-PERT distribution.

Both externalities were treated as additional revenue streams, because producing and burning alternative fuels produces a social benefit when compared with conventional fuels, which was internalized by adding it to the model. Both externality benefits are dependent on the amount of jet fuel produced, because the social benefit was only calculated for jet fuel, not for other products like propane, LPG, naphtha, and diesel for the HEFA pathway, or gasoline and diesel for the F-T pathway. Therefore, the social benefits per kg of alternative fuel for both externalities were multiplied by the jet fuel output of the pathway calculated by the model, jet fuel density factor to convert kg to liter, a conversion factor to convert gallon to liter, the production capacity (0.75 in year 1, 1.0 in year 2 to 20), and a discount factor to bring all values to 2015 values.

4.2 Hypothesis

Adding the climate change and air quality externality will have an effect on the net present value of the two discussed pathways, HEFA yellow grease and F-T MSW. Because there is a benefit when using alternative fuels, the assumption to be examined is that the NPV will rise, the probability for a positive NPV will rise, and the MSP of the alternative fuels will decrease when comparing with the results from Bann et al. (2017) before the internalization of the two externalities.

Three hypotheses can be identified for both pathways:

H_1: Due to internalization of the two externalities the NPV will increase

H_2: Due to internalization of the two externalities the probability of a positive NPV will increase

H_3: Due to internalization of the externalities the MSP of the discussed pathway fuels will decrease

when compared with the values before internalization of the two selected externalities.

4.3 Results

The used commands for the figures and the values found in the tables, can be found in appendix A.

4.3.1 HEFA model

Total social carbon, $PM_{2.5}$ benefit, and total social benefit

After running the model for the HEFA yellow grease pathway, with the added externalities, 10,000 values were generated for the following three variables:

1. **Social carbon benefit** = total benefits of avoided damage costs regarding the emission of GHGs during the complete life cycle (production and combustion) of alternative jet fuels in comparison with conventional jet fuel (jet A-1) in 2015 USD, covering the complete life span of the plant as determined in the model (20-year plant lifetime)
2. **Social $PM_{2.5}$ benefit** = total benefits of avoided damage costs regarding the emission of $PM_{2.5}$ during the combustion of alternative jet fuels in comparison with conventional jet fuel (jet A-1) in 2015 USD, covering the complete life span of the plant as determined in the model (20-year plant lifetime)
3. **Total social benefit** = sum of social carbon benefit and social $PM_{2.5}$ benefit.

Table 9: Statistical values carbon, PM2.5, and total social benefit (HEFA YG)

	Carbon benefit (in 2015 USD)	**$PM_{2.5}$ benefit (in 2015 USD)**	**Total social benefit (in 2015 USD)**
Mean	$5.0770 * 10^7$	$4.8733 * 10^6$	$5.5644 * 10^7$
Median	$4.8588 * 10^7$	$4.8734 * 10^6$	$5.3439 * 10^7$
Minimum value	$1.1799 * 10^7$	$2.4171 * 10^6$	$1.6120 * 10^7$
Maximum value	$1.1934 * 10^8$	$7.2554 * 10^6$	$1.2378 * 10^8$

Table 9 shows some statistical values for the three variables. For both externality benefits, all values were bigger than zero and in the range of 2.4 $M to 120 $M, with mean and median close to each other. The distributions can be observed from figures 6,7, and 8.

For the variable 'social carbon benefit', the distribution of the data points has a moderately long right tail with the mass of the distribution, most of the values, on the left of the histogram. The skewness factor is 0.4307, which indicates a moderate positive skewness. This is a result of the beta-PERT distribution, where the mode lies closer to the minimum value than to the maximum value (see *3.9.3 Use of USG SCC estimates*).

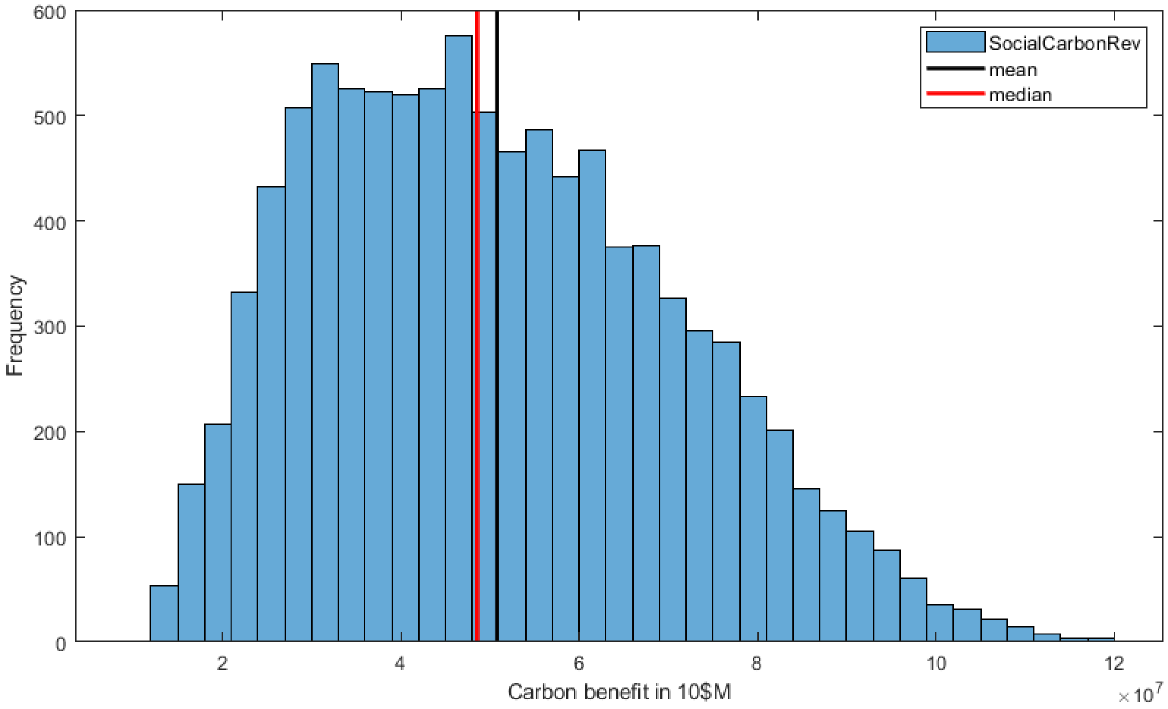

Figure 6: Histogram of 10,000 generated 'social carbon benefit' values (HEFA YG)

The variable 'social $PM_{2.5}$ benefit' has a different distribution than 'social carbon benefit', as can be observed from figure 7. The histogram of the social benefit from the air quality externality when using HEFA jet fuel, is rather symmetrical. Mean and median, depicted by the black and red line, are almost equal. The skewness factor is -0.0058, which indicates that there is some small, negligible asymmetry to the left. This is a lot smaller than the skewness of 'social carbon benefit', because the mode for the 'social $PM_{2.5}$ benefit' distribution is close to the mean of its minimum and maximum value.

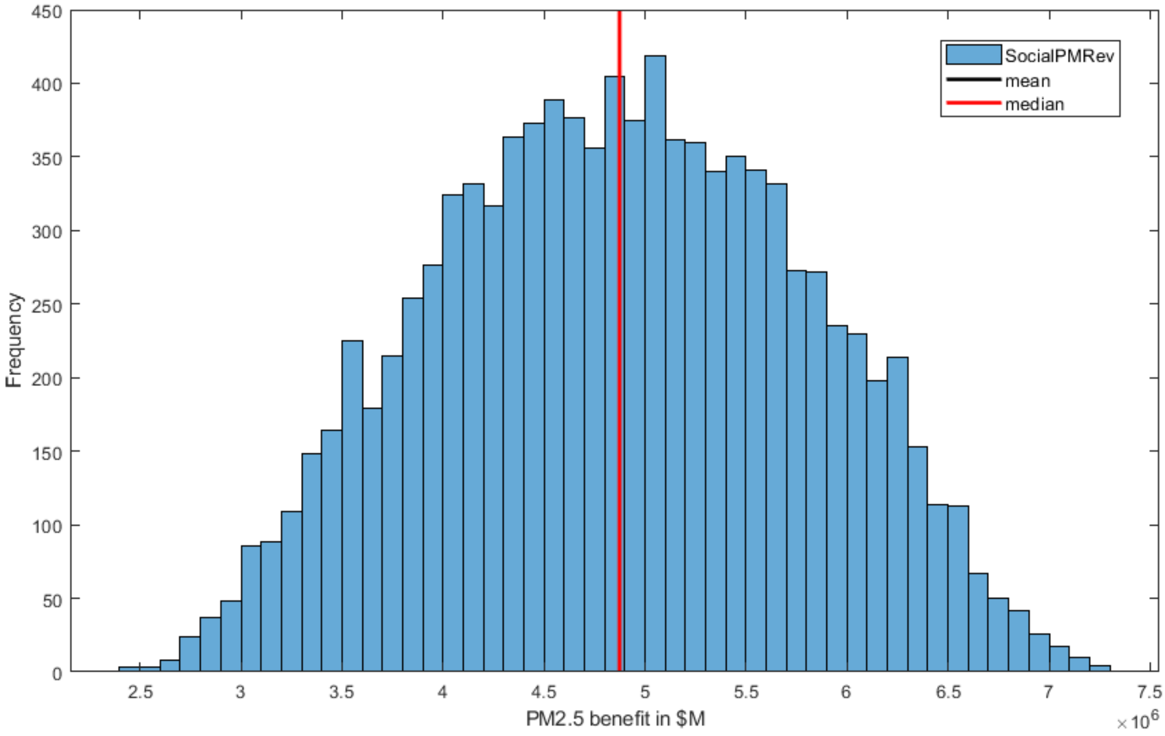

Figure 7: Histogram of 10,000 generated 'social $PM_{2.5}$ benefit' values (HEFA YG)

The variable 'total social benefit', has a distribution shape similar to the distribution shape of the 'social carbon benefit' variable, as can be observed from figure 8. The mean and median value of 'total social benefit', 56 \$M and 53 \$M respectively, are close to one another, and the distribution has a moderately long right tail. The skewness factor is 0.4320, which indicates a small asymmetry to the right side.

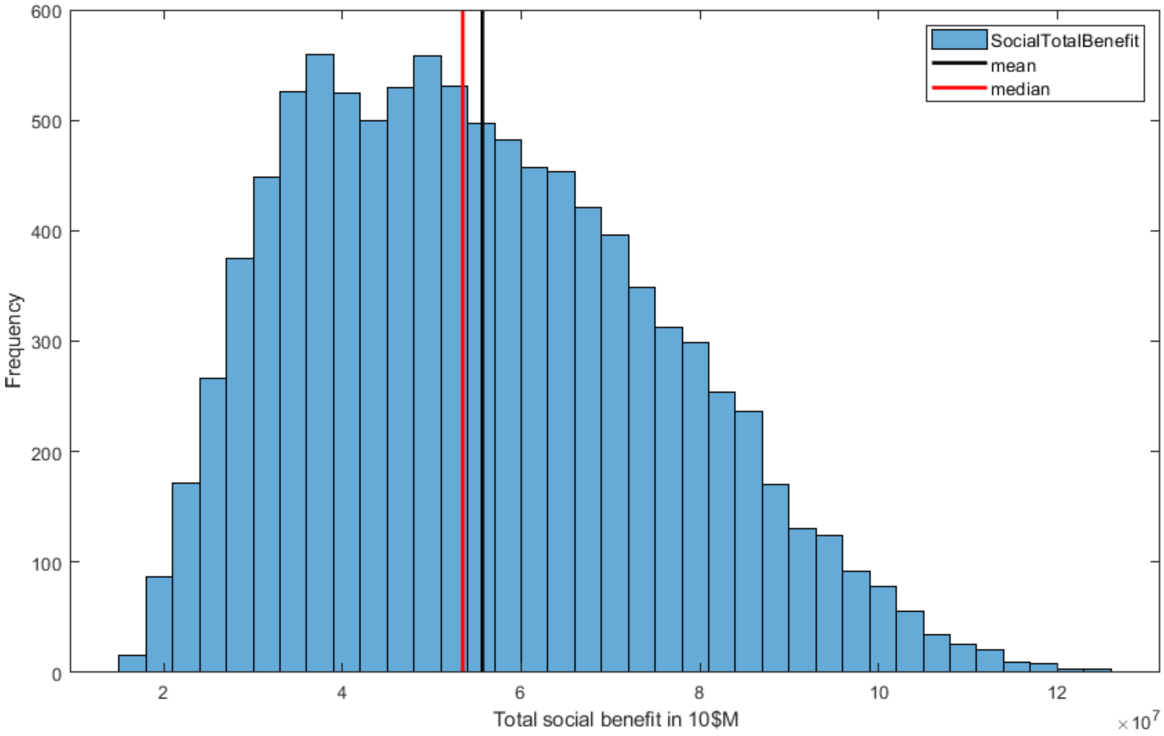

Figure 8: Histogram of 10,000 generated 'total social benefit' values (HEFA YG)

Effect on total NPV

Without the internalization of both externalities, the mean and median NPV values for HEFA yellow grease (in $B) were -0.111 and -0.109 respectively, under the 'no policy' scenario, after running the MATLAB model. The mean NPV value was almost equal to the mean value found in the paper by Bann et al. (2017), confirming their findings.

With the addition of both externalities, modeled as revenue streams, to the net present value of the pathway, the NPV was expected to increase. The carbon benefit and $PM_{2.5}$ benefit were added to the total NPV. Mean value of the new NPV (in $B) was -0.055 (in the 95% range of -0.353 – 0.239), and the median value was -0.054. Both mean and median increased, but remained negative.

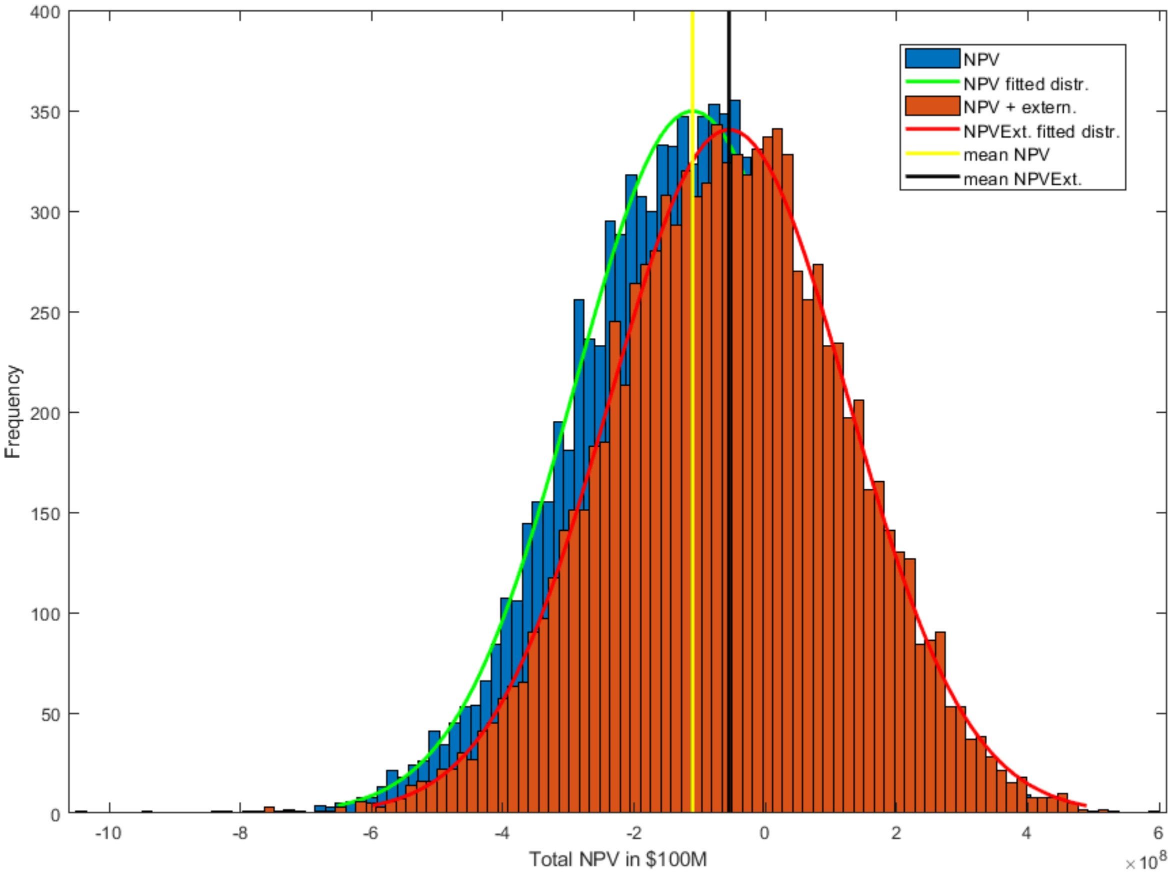

Figure 9: Histogram, fitted normal density curve, and mean of total NPV without externalities (NPV) and total NPV including externalities (NPVExt.) of the HEFA YG pathway

As can be seen from figure 9, the addition of the externality benefits regarding the HEFA biofuel, shifted the mean (and also the median) to the right. On average, the NPV increased with 0.056 $B, an increase of 51%.

The NPV was broken down to its different cost and revenue streams, similar to the paper of Bann et al. (2017). After running the model, similar values were found for the different cost and revenue streams. However, with the inclusion of the externalities, an additional revenue stream was present which increased total mean NPV.

Table 10: Breakdown of mean NPV in cost and revenue streams (in $M) (HEFA YG)

	HEFA Yellow grease
Capital costs	-129
Fixed OPEX	-48
Non-feedstock variable OPEX	-80
Feedstock	-375
Income tax	-13
Revenue from middle distillate fuels	501
Revenue from gasoline/naphtha	12
Revenue from other co-products	21
Total mean NPV excl. externalities	**-111**
Revenue from carbon benefit	51
Revenue from $PM_{2.5}$ benefit	5
Revenue from social benefit of HEFA jet fuel	**56**
Total mean NPV incl. externalities	**-55**

The mean NPV value increased with 56 $M on average with the inclusion of the externality benefits, to a total mean NPV value of -55 $M. As can be seen from figure 10, the externality benefits were the second biggest revenue stream for the HEFA pathway, accounting for 9% of total revenue, after the revenue from the middle distillate fuels.

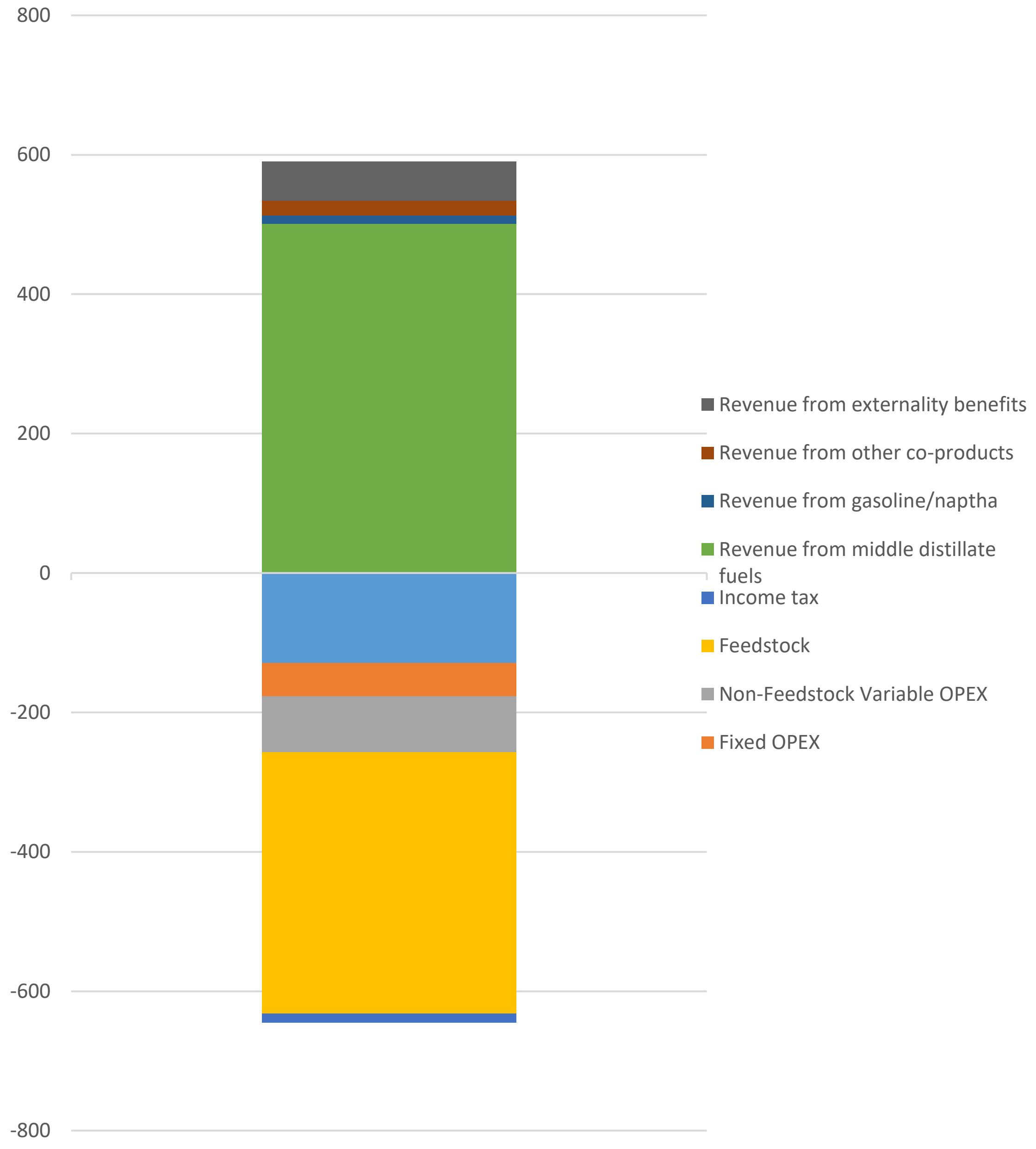

Figure 10: Graphical breakdown of the mean NPV by cost and revenue streams in $M (HEFA YG)

The internalization of the two externalities had a distinct positive effect on total NPV. Due to internalization of both externalities, mean NPV increased with 51% under the 'no policy support' scenario. Therefore, the first hypothesis 'Due to internalization of the two externalities the NPV will increase when compared with the values before internalization of the two selected externalities.' can be assumed to be true.

Effect on the probability of a positive NPV

In the paper of Bann et al. (2017), the HEFA yellow grease pathway had a probability of a positive NPV of 27.7% when no policy support was present. As discussed in the previous part 'Effect on total NPV', the addition of the externalities increased the total NPV with 56 $M on average. Therefore, the addition could have a positive effect on the probability of a positive NPV.

A comparison between the probability of a positive NPV found in the study of Bann et al. (2017) and the probability of a positive NPV including the two externalities for the HEFA YG model, was made by comparing both cumulative density functions.

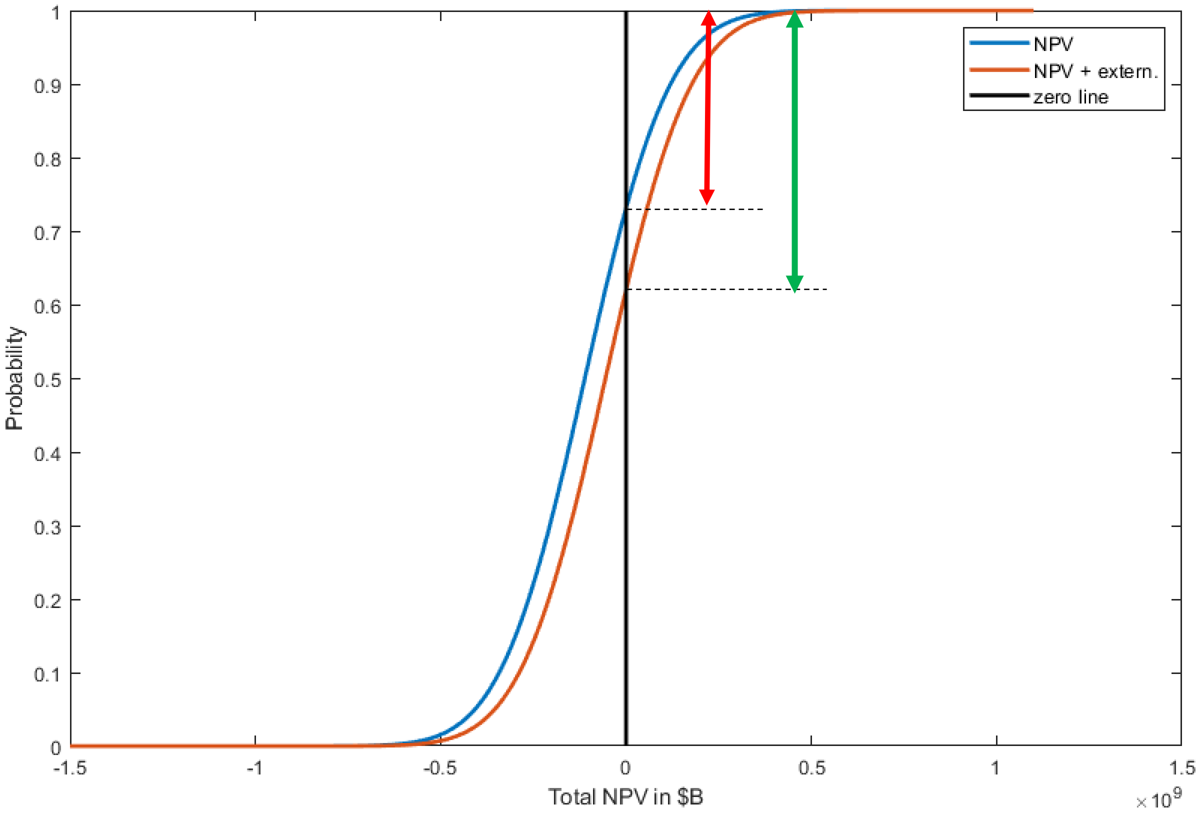

Figure 11: Cumulative density function (CDF) for NPV and NPV + externalities results for HEFA YG pathway

Figure 11 shows the cumulative density function of the total NPV and the total NPV with externalities included, for the HEFA YG pathway when no policy is present. For the NPV without externalities, the probability of a positive NPV (NPV > 0) was 26.88% after running the MATLAB model, which is close to the value found in the study by Bann et al. (2017), 27.7%. The probability value is shown in figure 3, as the part of the NPV cumulative density function (blue line) to the right of the black zero line. The probability of NPV > 0 is equal to the magnitude of the red double arrow. The probability of a positive total NPV including externalities was 0.3801 or 38.01%, equal to the magnitude of the green double arrow on figure 11. The probability of a positive net present value increased from 26.88% to 38.01%, an increase of 41% or 11.13 percentage points.

The addition of the two externalities significantly increased the probability of a positive NPV for the HEFA yellow grease pathway with 41%. Therefore, hypothesis 2 'Due to internalization of the two externalities the probability of a positive NPV will increase.' can be assumed to be true.

Effect on MSP

MSP or the minimum middle distillate selling price is defined as the market fuel price such that the NPV is positive. It was discussed under the previous two sections that the NPV and the probability of a positive NPV increase due to the addition of externalities. Therefore, with the internalization of the externalities, the MSP was expected to decline in order to attain a positive NPV, as stated in hypothesis 3.

After running the HEFA model to compute the MSP, 10,000 values were generated for the total MSP with and without the externalities included, consisting of the different cost and revenue streams divided by the total amount of middle distillate fuel produced over the total plant lifetime (in gallons). For the conversion from $/gal to $/liter, the mean MSP was multiplied by conversion factor 0.2641729 gal/liter.

Table 11: Breakdown of mean MSP in $/liter (HEFA YG)

	MSP breakdown
Capital costs	0.1943
Fixed OPEX	0.0731
Non-feedstock variable OPEX	0.1189
Feedstock	0.5623
Income tax	0.0232
Revenue from gasoline/naptha	-0.0232
Revenue from other co-products	-0.0407
Total mean MSP without externalities	**0.9077**
Total revenue from externality benefits	-0.0744
Total mean MSP with externalities	**0.8333**

Without externalities added to the HEFA model, the mean MSP was $3.44/gal or $0.91/liter in the 95% range of $0.65/liter - $1.24/liter, confirming the value found by Bann et al. (2017). With the externalities added to the model, the mean MSP decreased to $3.15/gal or $0.83/liter, in the 95% range of $0.56/liter – $1.17/liter.

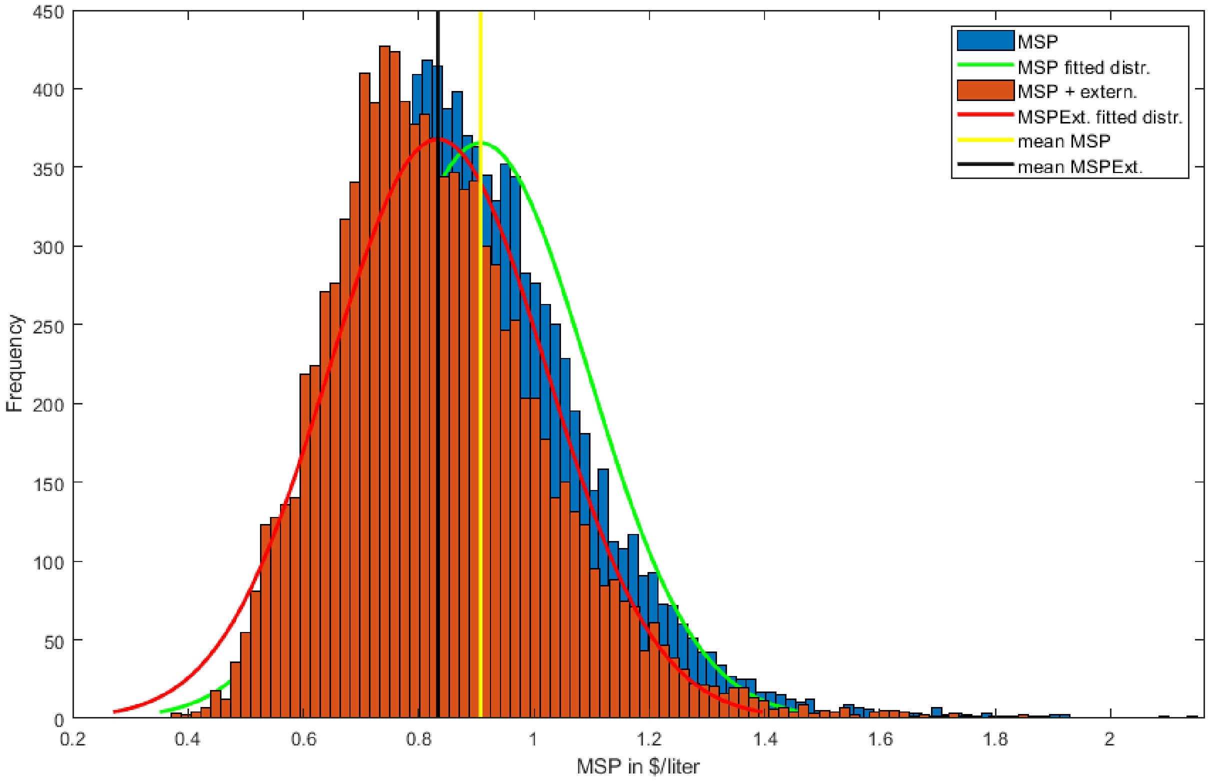

Figure 12: Histogram, fitted normal density curve, and mean of total MSP without externalities and total MSP including externalities (MSPExt) of the HEFA YG pathway

Figure 12 shows the histogram for the MSP with externalities (orange) and without (blue), their fitted normal density curves, and their respective mean. It can be observed that the histogram, fitted normal density curve, and mean shifted to the left after addition of the externalities to the HEFA YG model. The mean MSP decreased with $0.08/liter on average, a decrease of 9%.

After calculation and comparison of both MSP's, and a graphical observation of the shift in the distribution, density curve and mean of the MSP including externalities, hypothesis 3 'Due to internalization of the externalities the MSP of the discussed pathway fuels will decrease', can be assumed to be true.

4.3.2 F-T model

Without the internalization of externalities, Bann et al. (2017) reported a mean total NPV of -0.210 \$B and a mean MSP of \$1.15/liter. The probability for a positive NPV was not reported for the F-T MSW pathway, however this was calculated by running the MATLAB model without the addition of the externality benefits.

With the internalization of the externalities, the approach for the F-T model was similar as the one used for the HEFA model.

Total social carbon and $PM_{2.5}$ benefit

After running the model for the F-T MSW pathway, with the added externalities, 10 000 values are generated for three variables:

1. **Social carbon benefit**
2. **Social $PM_{2.5}$ benefit**
3. **Social benefit**

The three variables have the same description and meaning as under the HEFA model. For the three variables, following statistical values were generated by the model:

Table 12: Statistical values Carbon, PM2.5, and total social benefit (F-T MSW)

	Carbon benefit (in 2015 USD)	**$PM_{2.5}$ benefit (in 2015 USD)**	**Total social benefit (in 2015 USD)**
Mean	$3.9401 * 10^7$	$3.8146 * 10^6$	$4.3216 * 10^7$
Median	$3.7749 * 10^7$	$3.7980 * 10^6$	$4.1653 * 10^7$
Minimum value	$8.4132 * 10^6$	$1.7466 * 10^6$	$1.1624 * 10^7$
Maximum value	$1.0019 * 10^8$	$6.6770 * 10^6$	$1.0491 * 10^8$

The statistical values were in the same order of magnitude as the statistical values of the HEFA model. For both externality benefits, all values were bigger than zero (see minimum values), and in the range of 1.7 to 100 \$M. Likewise to the HEFA model, mean and median were close to each other for both externality benefits. The distribution of the three generated variables can be observed from figure 13, 14, and 15.

For the variable 'social carbon benefit', generated for the F-T MSW pathway, the distribution of the data points has a rather long right tail with most of the values on the left of the histogram (figure 13). The skewness factor is 0.4843, indicating a small positive skewness or asymmetry to the right.

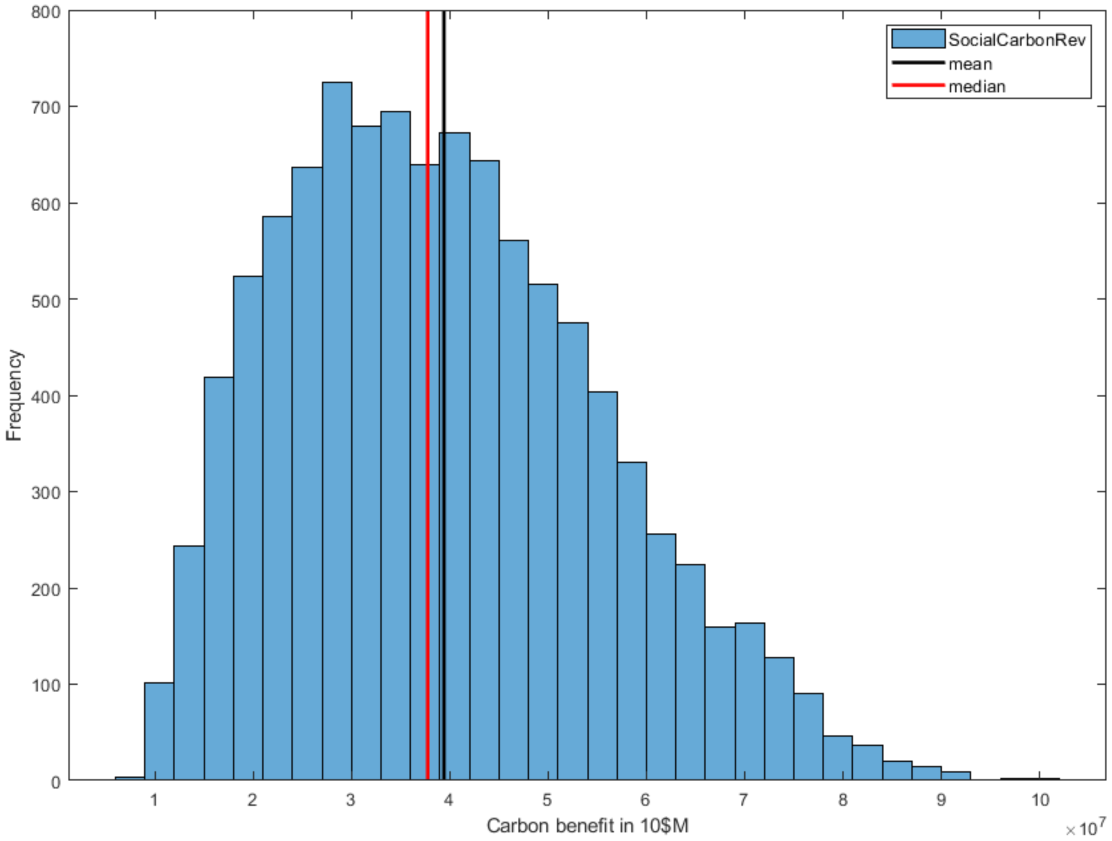

Figure 13: Histogram of 10 000 random generated 'social carbon benefit' values (F-T MSW)

The variable 'social $PM_{2.5}$ benefit' has a different distribution than 'social carbon benefit', as can be seen from figure 14. The histogram is close to being symmetrical. Mean and median, depicted by the black and red line, are almost equal. However, the skewness factor is 0.2154, which indicates that there is some small asymmetry to the right side.

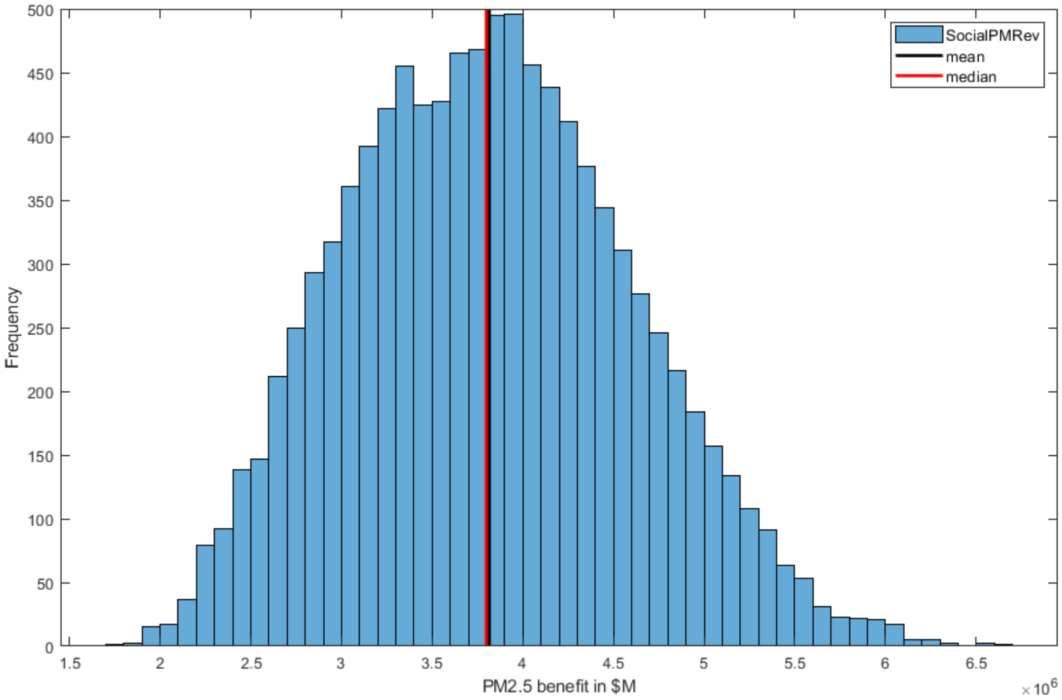

Figure 14: Histogram of 10 000 random generated 'social PM2.5 benefit' values (F-T MSW)

Similar to the HEFA model, the variable 'total social benefit', has a distribution shape similar to the distribution shape of 'social carbon benefit', as can be seen on figure 15. The mean and median value are close to one another, and the distribution of the values has a moderate right tail. The skewness factor is 0.4889, indicating a small asymmetry to the right side. A possible reason for the asymmetry, is the fact that 'total social benefit' is the sum of the two variables discussed, and both have an asymmetry to the right side.

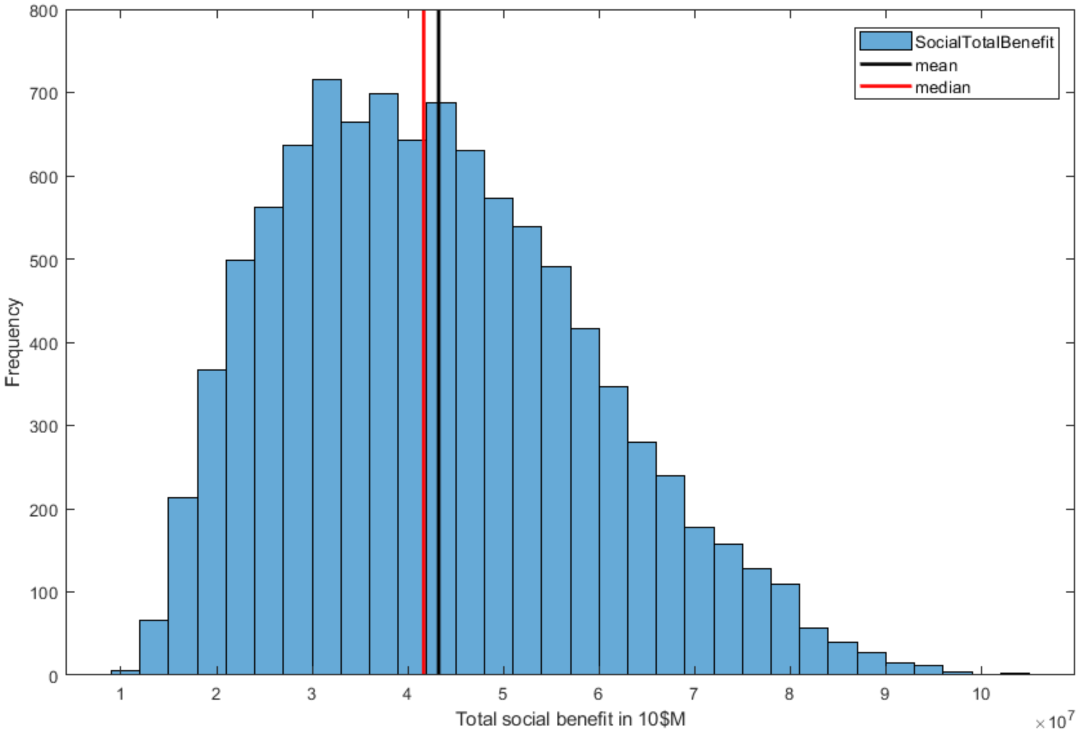

Figure 15: Histogram of 10 000 generated 'total social benefit' values (F-T MSW)

Effect on total NPV

In the study of Bann et al. (2017) a mean NPV value of -0.210 $B was reported for the F-T MSW pathway. The reported mean NPV value was calculated under the 'no policy' scenario and without the addition of externality benefits. When the F-T model was ran under the same conditions, the mean NPV is -0.206 $B in the 95% range of -0.438 – 0.025 $B, similar to Bann et al. (2017).

With the addition of the climate change and air quality externality, the NPV of the F-T pathway was expected to rise (cfr. hypothesis 1). The mean of the new NPV, with externalities, was -0.163 $B in the 95% range of -0.397 – 0.071 $B. The median value was -0.164 $B. Both the mean and median increased, but remained negative.

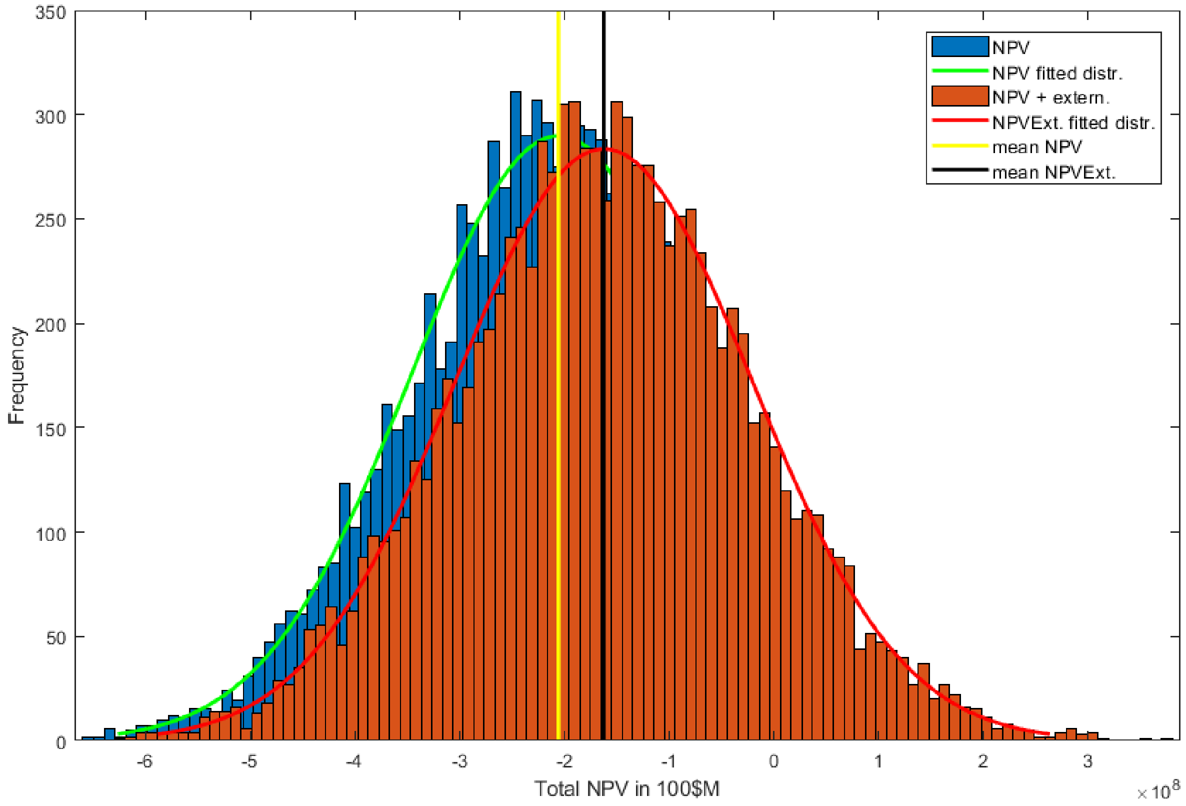

Figure 16: Histogram, fitted normal distribution, and mean of total NPV without externalities (NPVT) and total NPV including externalities (NPVExt) of the F-T MSW pathway

The shift of the NPV due to the addition of the two externalities, is depicted by figure 15. There was a clear shift in mean total NPV value with the addition of the two externalities to the model. The distribution of the values of the new NPV also shifted to the right, which can be observed from the figure. On average, the NPV increased with 0.043 $B, an increase of 21%.

It is clear that, after calculation and comparison of the NPV without and the NPV with the externalities added, and a graphical observation from figure 16, the internalization of the two externalities had a positive effect on the total NPV, with the mean total NPV increasing with 21%. Therefore, the first hypothesis 'Due to internalization of the two externalities the NPV will increase when compared with the values before internalization of the two selected externalities.' can be assumed to be true for the F-T MSW pathway.

Effect on the probability of a positive NPV

The addition of the externalities increased the total NPV with 43 $M on average, and could have a positive effect on the probability of a positive NPV, cfr. hypothesis 2.

In the paper of Bann et al. (2017), no probability of a positive NPV for the F-T MSW pathway was reported. The probability of a positive NPV without externalities, was calculated in MATLAB. This value was then compared with the probability of a positive NPV when externalities are added, in order to determine the effect of the added externality benefit.

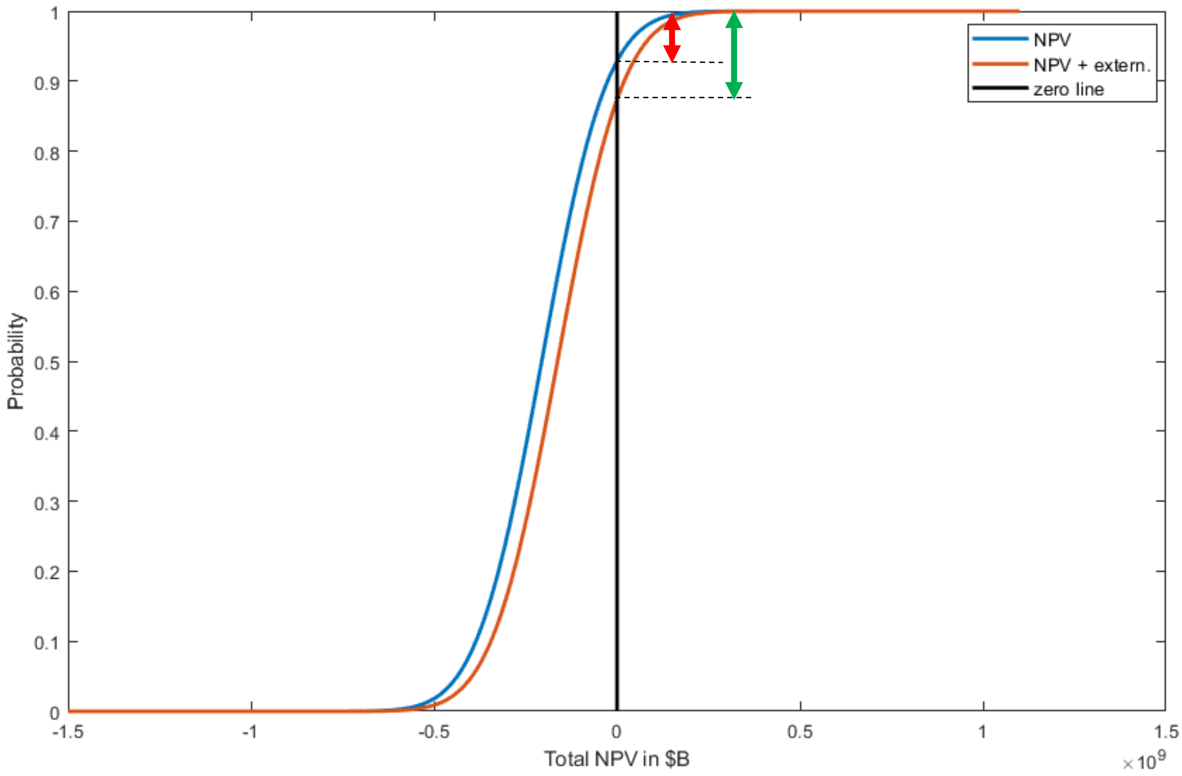

Figure 17: CDF for NPV and NPV + externalities results for F-T MSW pathway

The probability of a positive NPV (without externalities), NPVT > 0, was calculated by means of a cumulative density function, graphically displayed in figure 14. The probability was 0.0713 or 7.13%. With the addition of the carbon and $PM_{2.5}$ benefit, the probability of a positive NPV was 0.1262 or 12.62%. The probability increased with 77% or 5.5 percentage points. Graphically, the probability increased in magnitude from the red double arrow to the green double arrow.

The second hypothesis, 'Due to internalization of the two externalities the probability of a positive NPV will increase', can be assumed to be true, after comparison of the probability of the two NPV's, mathematical and graphical.

Effect on MSP

Due to the internalization of the two externalities, both the mean NPV and the probability of a positive NPV increased. This could have a positive effect on the MSP of F-T biofuel, cfr. hypothesis 3.

Bann et al. (2017) reported a mean MSP of \$1.15/liter. The F-T MSW model generated 10,000 MSP values (without externalities), with a mean MSP of \$4.25/gal or \$1.12/liter, in the 95% range of \$0.85/liter - \$1.45/liter. There was a moderate difference between the value by Bann et al. (2017) and the value generated by the model. The mean MSP of \$1.12/liter was broken down in the different cost and revenue streams of the pathway, divided by the total amount of middle distillate fuel produced during the plant lifetime. For the conversion from \$/gal to \$/liter, the mean MSP was multiplied by conversion factor 0.2641729 gal/liter.

Table 13: Breakdown of mean MSP in \$/liter (F-T MSW)

	MSP breakdown
Capital costs	0.9593
Fixed OPEX	0.2600
Non-feedstock variable OPEX	0.0196
Income tax	0.1103
Revenue from gasoline/naphtha	-0.1240
Revenue from other co-products	-0.0055
Revenue from scrap	-0.0957
Total mean MSP without externalities	**1.1239**
Revenue from carbon benefit	-0.0615
Revenue from $PM_{2.5}$ benefit	-0.0060
Total revenue from externality benefits	**-0.0675**
Total mean MSP with externalities	**1.0564**

With externalities added to the F-T MSW model, the total mean MSP decreased to \$4/gal or \$1.06/liter MD fuel, in the 95% range of \$0.78/liter – \$1.38/liter. The mean decreased 6% on average or \$0.07/liter when compared with the MSP without externalities added, and could be addressed to the internalization of the two externalities: \$0.0615/liter decrease due to the carbon benefit and \$0.0059/liter decrease due to the $PM_{2.5}$ benefit.

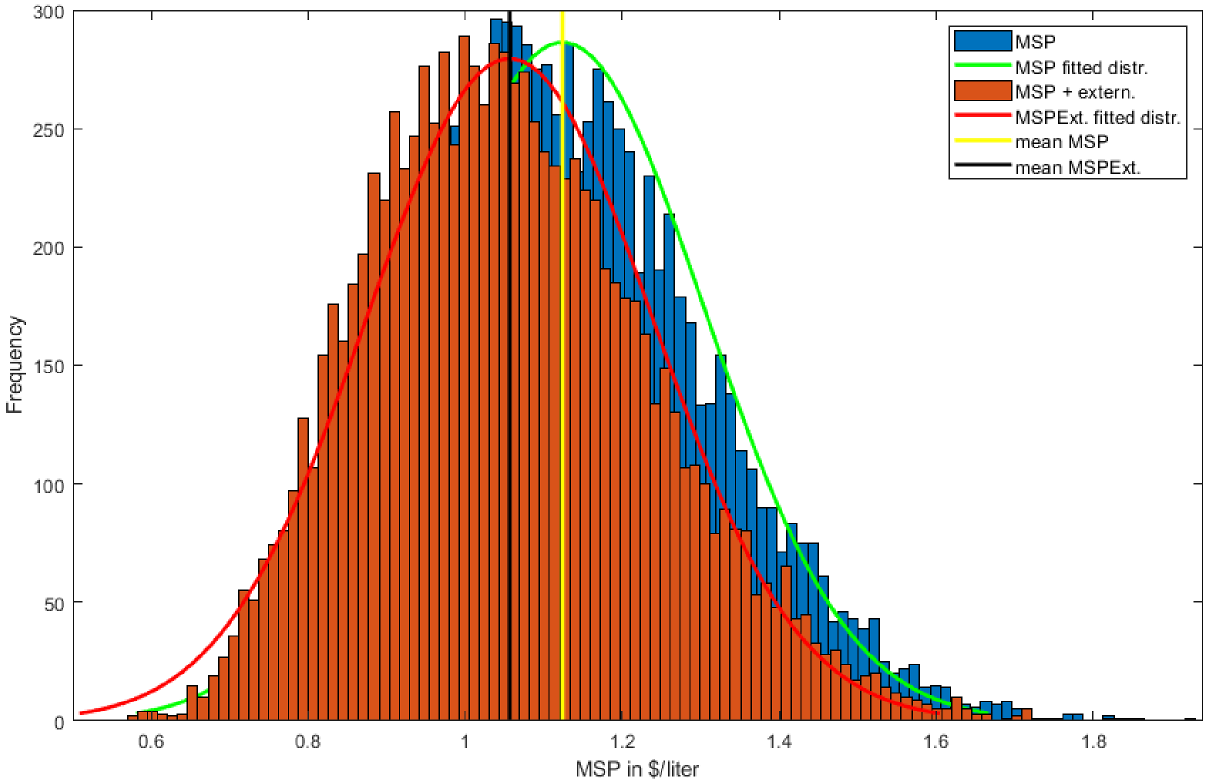

Figure 18: Histogram, fitted normal density curve, and mean of total MSP without externalities and total MSP including externalities (MSPExt) of the F-T MSW pathway

The decrease of the MSP is graphically represented in figure 18. Mean MSP, MSP distribution and fitted normal density curve shifted to the left due to the internalization of the two externalities. The average decrease of \$0.07/liter is the distance between the MSP mean value (black line) and the MSP + externalities mean value (yellow line).

After calculation and comparison of both MSP's, and a graphical observation of the shift in the distribution, density curve and mean of the MSP including externalities, it can be assumed that hypothesis 3 'Due to internalization of the externalities the MSP of the discussed pathway fuels will decrease', is true.

4.4 Sensitivity analysis

The impact of the climate change and air quality externality on the NPV and MSP (including externalities) for the HEFA YG and F-T MSW pathway was examined with a sensitivity analysis.

Considering the climate change externality, the critical variable is the social cost of carbon. For the addition of the externality to the models of the two pathways, SCC estimates for 2020 were used. The 3% average was selected as the modus for the beta PERT distribution, with the 5% average, and the high impact (95th percentile at 3%) average, as minimum and maximum estimate value respectively. The climate change externality sensitivity analysis tested the beta-PERT distribution minimum and maximum values used for both pathways. The modus of the beta-PERT distribution was decreased to the 5% average estimate, and increased to the high impact estimate, in order to test the sensitivity of the mean NPV and MSP when altering the climate change externality. For the air quality externality, the critical variable is the social cost of fine particulate matter. Analogous to the climate change externality, the air quality externality sensitivity analysis also tested the beta PERT outer bound values: € 26,000 per metric ton $PM_{2.5}$ as the minimum value, and € 75,000 per metric ton $PM_{2.5}$ as the maximum value.

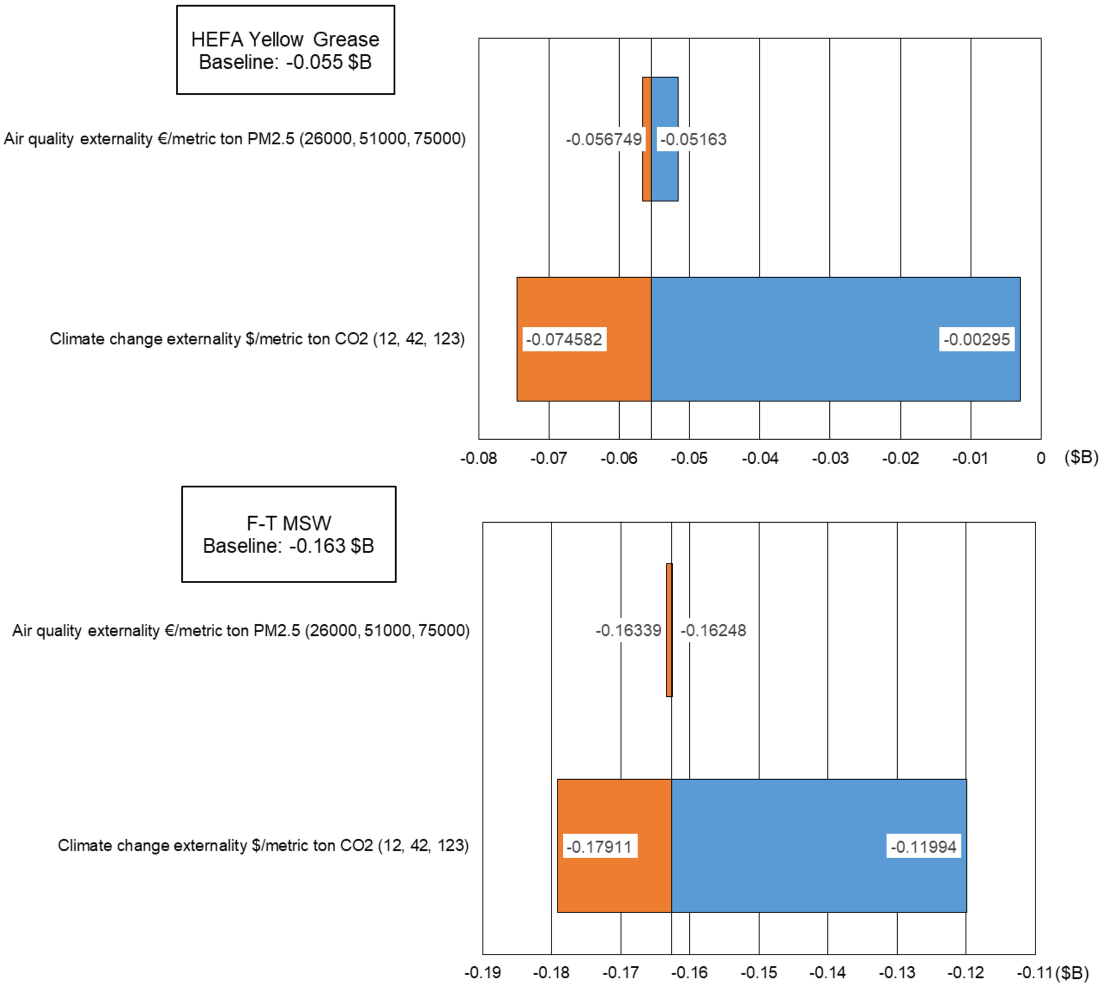

Figure 19: NPV sensitivity results for HEFA YG and F-T MSW pathway, mean values denoted in $/liter. Test inputs for both externalities are between parentheses (low, baseline, high).

In figure 19 and 20, orange represents the low value, blue the high value, with both values centered around the baseline value.

Regarding the HEFA YG pathway, a change in social cost of (fine) particulate matter (air quality externality) to its high and low value only produces a change up to 7%. The biggest change in mean NPV occured when the social cost of carbon (climate change externality) approached its high value of \$123/metric ton CO_2. Mean NPV increased to -0.003 \$B, an increase of 95%. When the SCC reached its low value of \$12, mean NPV decreased to -0.075 \$B, a decrease of 35%. It should be noted however, that the baseline SCC value is much closer to the low value than to the high value. Therefore, an increase in SCC value from \$42 to \$123 will have a larger effect on mean NPV than a decrease in SCC value from \$42 to \$12. The mean NPV value of the F-T MSW pathway remained negative, even if the social cost of carbon or the social cost of $PM_{2.5}$ reached their high value. A change in the social cost of $PM_{2.5}$ produced a change in mean NPV up to 0.5%, and a change in the social cost of carbon produced a change in mean NPV up to 26%.

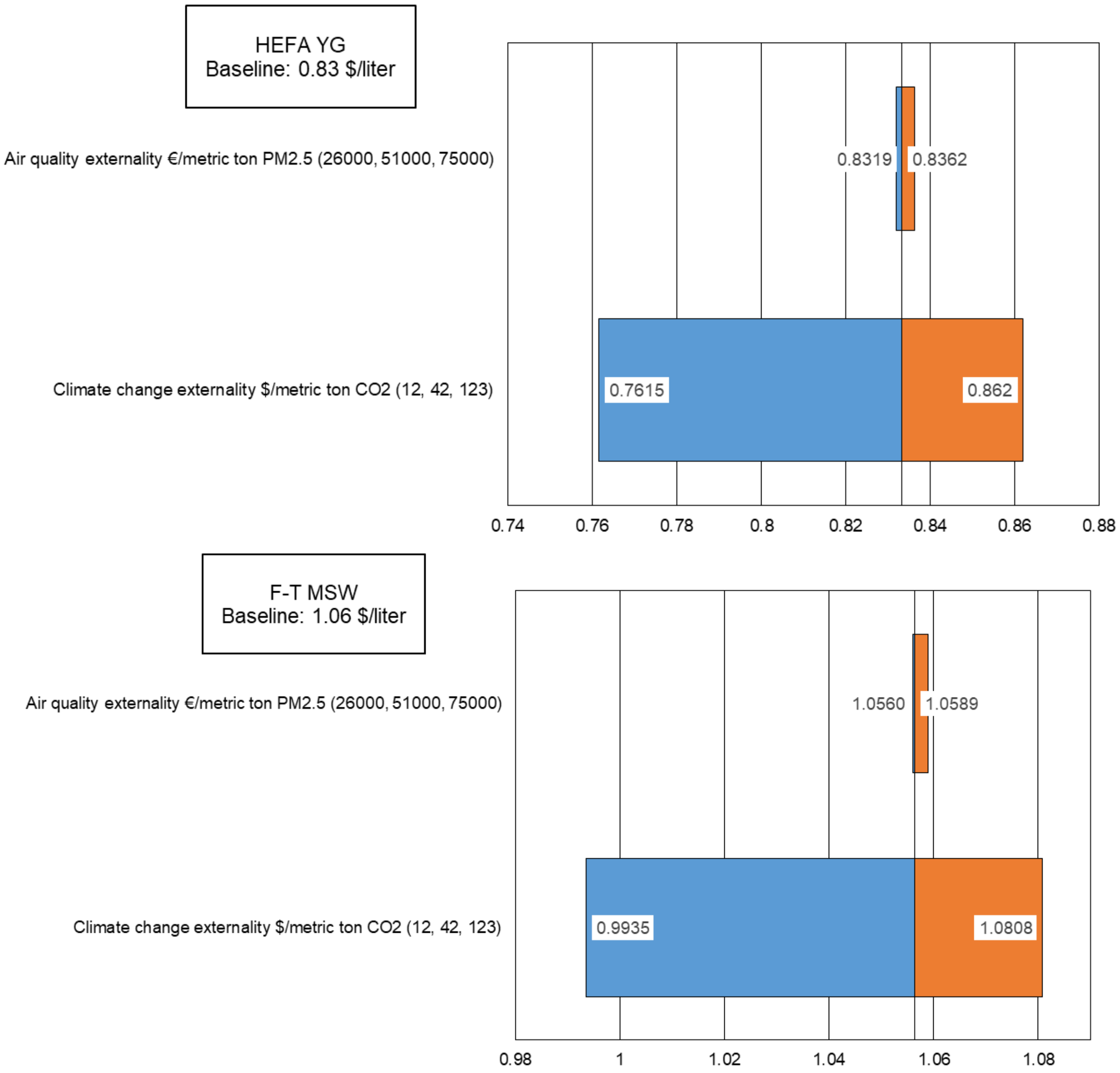

Figure 20: MSP sensitivity results for HEFA YG and F-T MSW pathway, mean values denoted in \$/liter. Test inputs for both externalities are between parentheses (low, baseline, high).

Regarding the air quality externality, varying the social cost of fine particulate matter to extreme values, produced a change in mean MSP up to 7% for the HEFA YG pathway and a change up to 5% for the F-T MSW pathway. For the climate change externality, varying the social cost of carbon to extreme values ($12 and $123 per metric ton CO_2), produced a change in mean MSP up to 9% and up to 6% for the HEFA YG and F-T MSW pathway respectively. The impact of both externalities on mean MSP is higher for the HEFA YG pathway than for the F-T MSW pathway.

4.5 Validation

In order to validate the results, the model of both pathways was first run without addition of externalities. In table 14, the results from the model are compared with the results reported by Bann et al. (2017). The probability of a NPV > 0 for the F-T MSW pathway was not compared, because no value was reported in the study.

Table 14: Comparison between model results and results reported in the study by Bann et al. (2017)

	Model run without externalities	**Bann et al. (2017)**
HEFA YG mean NPV ($B)	-0.111	-0.112
HEFA YG probability NPV > 0	26.88%	27.7%
HEFA YG mean MSP ($/liter)	0.91	0.91
F-T MSW mean NPV ($B)	-0.206	-0.210
F-T MSW mean MSP ($/liter)	1.12	1.15

The model results and reported results were similar or really close to each other, differences could be attributed to randomization of different input values. This confirms that no mistakes were present prior to adding the two externalities.

In order to validate the results with the externalities included, the minimum and maximum GHG and $PM_{2.5}$ benefit was calculated (without discounting to 2015 USD), by multiplying the total jet fuel output with the GHG benefit and the $PM_{2.5}$ benefit per liter. Next, the HEFA YG and F-T MSW model was run, and total GHG and $PM_{2.5}$ benefit (without discounting) from the model was compared with the calculated minimum and maximum. All values produced by the model should fall within the calculated minimum and maximum range.

Table 15: Comparison of carbon, $PM_{2.5}$, and total benefit model results with their calculated range

	Calculated range		**Model results**
HEFA YG	**Minimum value**	**Maximum value**	
Total carbon benefit	$3.369 * 10^7$	$3.438 * 10^8$	$1.446 * 10^8$
Total $PM_{2.5}$ benefit	$6.960 * 10^6$	$2.008 * 10^7$	$1.399 * 10^7$
Total externality benefit	$4.065 * 10^7$	$3.639 * 10^8$	$1.586 * 10^8$
F-T MSW			
Total carbon benefit	$2.764 * 10^7$	$2.816 * 10^8$	$1.127 * 10^8$
Total $PM_{2.5}$ benefit	$6.960 * 10^6$	$2.008 * 10^7$	$1.098 * 10^7$
Total externality benefit	$3.460 * 10^7$	$3.017 * 10^8$	$1.236 * 10^8$

As can be observed from table 15, all externality benefits fall within their calculated range.

4.6 Conclusion and limitations

In this master thesis, two externalities, climate change and air quality, were added to two pathways, HEFA yellow grease and F-T MSW. A comparison was made between the NPV and MSP of the two pathways before and after the addition of the two externalities. After the comparison, mathematical and graphical, it can be concluded that the addition of the two externalities had a positive effect on both net present value and minimum middle distillate selling price for both pathways. For the HEFA YG pathway, mean NPV and probability for a positive NPV increased with 51% and 41% respectively, and mean MSP decreased with 9%. For the F-T MSW pathway, mean NPV increased with 21%, probability for a positive NPV increased with 77%, and mean MSP decreased with 6%.

All values were calculated under a 'no policy support' scenario. It does not include other scenarios, as been done by Bann et al. (2017) section 3.2 Policy scenario analysis (p. 8). Blender's credit and RVO assumptions were not introduced in the model during the empirical application in this master thesis.

Mean NPV remained negative for both pathways, and mean MSP remained well above the 5-year average conventional jet fuel price of $0.64/liter. (Bann et al., 2017) However, externality benefits were only calculated and valuated for jet fuel, not for other products of the HEFA YG and F-T pathway. Therefore, the results are an underestimation. Incorporating externality benefits for all pathway products, like diesel, naphtha, LPG, could potentially increase mean NPV to a value well above zero and could potentially lower mean MSP to conventional fuel price levels.

4.7 Future work

The comparison between biofuels and conventional jet fuel regarding the climate change externality could be more refined. In the paper by Seber et al. (2014), CH_4 and N_2O emissions are converted to CO_2 equivalents when calculating life cycle GHG emissions for HEFA biofuel. However, there are different social cost estimates for CH_4 and N_2O emissions (Marten & Newbold, 2011), due to their life spans being different than the life span of CO_2. Incorporating the estimates for methane and nitrous oxide could ameliorate the pathway results.

The analysis regarding NPV and MSP for both pathways could benefit from adding more externalities to the model. Especially regarding the air quality externality, more pollutants could be taken into consideration: Sulfur dioxide, nitrogen oxides, and ozone are major pollutants, emitted by combusting fossil fuels. For example, HEFA biofuels have very low sulfur contents (<15 ppm) (Pearlson, 2011), which could produce a delta or benefit regarding damage costs, when comparing with conventional jet fuels. Subsequently, this could further increase NPV and MSP results for biofuel pathways.

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Appendix A – Used commands

The type font of the code is set to ‘Courier New’ on purpose, in order to have the correct apostrophes for the MATLAB program. The green code or text are comments to explain the code beneath them.

```
%Statistical values
mean(SocialCarbonRev)
median(SocialCarbonRev)
min(SocialCarbonRev)
max(SocialCarbonRev)

mean(SocialPMRev)
median(SocialPMRev)
min(SocialPMRev)
max(SocialPMRev)

mean(SocialTotalBenefit)
median(SocialTotalBenefit)
min(SocialTotalBenefit)
max(SocialTotalBenefit)

%Visual representation of distribution carbon benefit, PM2.5 benefit, and their summation
histogram(SocialCarbonRev);
hold on;
%Plot mean and median of Carbon benefit
x1 = mean(SocialCarbonRev);
x2 = median(SocialCarbonRev);
y1=get(gca,'ylim');
plot([x1 x1],y1,'k','LineWidth'2);
plot([x2 x2],y1,'r','LineWidth',2);
hold off;
y = skewness(SocialCarbonRev);

histogram(SocialPMRev);
hold on;
%Plot mean and median of PM2.5 benefit
x1 = mean(SocialPMRev);
x2 = median(SocialPMRev);
y1=get(gca,'ylim');
plot([x1 x1],y1,'k','LineWidth',2);
plot([x2 x2],y1,'r','LineWidth',2);
hold off;
y = skewness(SocialPMRev);
```

```
histogram(SocialTotalBenefit);
hold on;
%Plot mean and median of PM2.5 benefit
x1 = mean(SocialTotalBenefit);
x2 = median(SocialTotalBenefit);
y1=get(gca,'ylim');
plot([x1 x1],y1,'k','LineWidth',2);
plot([x2 x2],y1,'r','LineWidth',2);
hold off;
y = skewness(SocialTotalBenefit);

%NPVT and NPVTExt comparison
mean(NPVT)
median(NPVT)
mean(NPVTExt)
median(NPVTExt)

%Determine 95% range of mean NPVTExt
leftQuantNPVTExt = quantile(NPVTExt,0.05);
rightQuantNPVTExt = quantile(NPVTExt,0.95);

%Plot histogram and fitted normal distribution of NPVT and NPVTExt
histfit(NPVT);
hold on;
histfit(NPVTExt);
%Add plot of NPVT and NPVTExt mean
x1 = mean(NPVT);
x2 = mean(NPVTExt);
y1=get(gca,'ylim');
plot([x1 x1],y1,'y','LineWidth',2);
plot([x2 x2],y1,'k','LineWidth',2);
hold off;

%NPV breakdown
mean(NPVCapital)
mean(NPVFOC)
mean(NPVVOC)
mean(NPVFEED)
mean(NPVTax)
mean(NPVMD)
mean(NPVGAS)
mean(NPVCOPRO)
mean(SocialCarbonRev)
mean(SocialPMRev)
mean(SocialTotalBenefit)
mean(NPVTExt)
```

```
%Cumulative distribution function total NPV (without externalities)
NPVTpdf = fitdist(NPVT, 'Normal');
NPVTx = -1500000000:1000:1100000000;
cdf_NPVT= cdf(NPVTpdf, NPVTx);
plot(NPVTx, cdf_NPVT, 'LineWidth',2);
hold on;
%Cumulative distribution function total NPV (with externalities)
NPVTExtpdf = fitdist(NPVTExt, 'Normal');
NPVTx2 = -1500000000:1000:1100000000;
cdf_NPVTExt= cdf(NPVTExtpdf, NPVTx2);
plot(NPVTx2, cdf_NPVTExt, 'LineWidth',2);
%Draw vertical line at x = 0
x1 = 5;
y1=get(gca,'ylim');
plot([x1 x1],y1,'k','LineWidth',2);
hold off;

%Probability of NPVT > 0
probNPVT = 1 - cdf(NPVTpdf,0);
%Probability of NPVTExt > 0
probNPVTExt = 1 - cdf(NPVTExtpdf,0);

%MSP breakdown
mean(MSPCapital) * 0.2641729
mean(MSPFOC) * 0.2641729
mean(MSPVOC) * 0.2641729
mean(MSPFEED) * 0.2641729
mean(MSPTax) * 0.2641729
mean(MSPGAS) * 0.2641729
mean(MSPCOPRO) * 0.2641729
mean(MSPSUM) * 0.2641729
mean(MSPExt) * 0.2641729
%Total mean MSP, externalities included
mean(TMSP) * 0.2641729

%Convert $/gallon to $/liter
meanMSPSUML = mean(MSPSUM) * 0.2641729;
meanTMSPL = mean(TMSP) * 0.2641729;

%Determine 95% range of mean TMSP
leftQuantTMSP = quantile(TMSP,0.05) * -0.2641729;
rightQuantTMSP = quantile(TMSP,0.95) * -0.2641729;
```

```
%histogram in $/liter HEFA pathway MSP
hMSPSUM = histfit(MSPSUM * -1 * 0.2641729);
%Change color density curve
hMSPSUM(2).Color = 'g';
hold on;
hTMSP = histfit(TMSP * -1 * 0.2641729);
hTMSP(2).Color = 'r';
%Add plot of MSPSUM and TMSP mean
x1 = mean(MSPSUM) * -1 * 0.2641729;
x2 = mean(TMSP) * -1 * 0.2641729;
y1=get(gca,'ylim');
plot([x1 x1],y1,'k','LineWidth',2);
plot([x2 x2],y1,'y','LineWidth',2);
hold off;
```

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Ik/wij verlenen het wereldwijde auteursrecht voor de ingediende eindverhandeling:
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Jaar: **2018**

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