Techno-Economic Analysis of Jet Fuel Production from Waste Vegetable Oil in Mexico.

by

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Abstract

This thesis quantifies the economic feasibility of building and operating a biorefinery that converts waste vegetable oils into transportation fuels in Mexico. The hydroprocessing technology selected produces predominately diesel and jet fuel that can be used and blended with the existing fossil fuel infrastructure. The analysis shows that a 4,000 BPD plant located in Mexico can reach a positive NPV of approximately $80 million over a 20-year operating period at an internal rate of return of 15% percent. The minimum selling price for reaching this internal rate of return is $2.21 per gallon for diesel and $2.36 per gallon for jet fuel. If sufficient and reliable feedstock supply exist for a scale-up of the biorefinery to 6500 bpd, NPV increases to approximately $180 million. Sensitivity analyses shows that the NPV for the 4000 bpd facility reaches zero at an internal rate of return of 24%, and that the maximum buying price of the waste vegetable oil at the baseline internal rate of return of 15% percent the plant can afford to procure is $0.73 per gallon, which is 36% higher than the average price for the feedstock in 2013.

Finally, the thesis quantifies the commercial opportunity of exporting the produced transportation fuels to the United States where they might qualify for monetary incentives. After accounting for transportation costs the NPV of fuel production in the biorefinery increases to $294 million, 368% higher than if transportation fuels are sold in Mexico.

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I want to thank all of the people that made this a success. First I want to give thanks to my family for their unconditional love and support; to my parents Miguel and Georgina, to my sister Yoryi, to my grandfather Miguel Camacho and my uncle Hugo who with endless efforts have supported me during this path.

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"Now unto the King eternal, immortal, invisible, the only wise God, be honor and glory for ever and ever. Amen." 1 Timothy 1:17

In memoriam of my teacher, pastor and friend Gerald Nyenhuis H.

Soli Deo Gloria

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1 Introduction

Current energy consumption levels have become a global issue because of the pollution that fuel-based energies create. Trends show that energy consumption will continue to increase over the next decades.[2] This scenario requires the development of new technologies to switch from fossil fuels to cleaner fuels. The main concern regarding fuel-based energy pollution are the Greenhouse Gases (GHG) emissions, which have the potential to affect human health and contribute to climate change.[3] Biofuels have the potential of reducing up to 80% of CO_2 emissions compared to fossil fuels.[18]

The transportation sector is one of the main GHG emitters, contributing with about 25% of global emissions.[66] Aware of this, the air industry set goals for the mitigation of GHG emissions though the improvement of technology, operations, and infrastructure among others.

Developed countries have historically emitted the most GHG and have led the efforts to reduce them. However, trends show that during the next decades developing countries will become the main GHG emitters.[20] Aware of this challenge, its own pollution, and their high reliance on fossil fuels, Mexico has joined international efforts for the development and use of new energy technologies.

The purpose of this thesis is to provide a technical and economic evaluation of the profitability of building a biofuel plant in Mexico based on Hydroprocessed Esters and Fatty Acids (HEFA) technology and using waste vegetable oils. Having a biofuels plant locally would make it possible for Mexico to have fuel alternatives that would help in reducing GHG emissions, in diversifying energy sources, and in mitigating public health concerns of existing waste vegetable usage.

This thesis provides the first techno-economic evaluation for the construction and operation of a biofuels plant using HEFA technology in Mexico. The analysis aims to provide insights for investors and government officials to promote the production of biofuels in Mexico. It is divided in six chapters, including this introduction. Chapter 2 describes the relationship and trends between energy consumption, transportation and the environment with a special focus on Mexico. Chapter 3 describes the plant design required within a Mexican framework. Chapter 4 describes the economic model of the proposed plant in Mexico. Chapter 5 reports the results of the economic model, describing the economic feasibility in terms of net present value, sensitivity cost analysis and minimum selling price. Finally, Chapter 6 presents the results and conclusions, and points to future work required for the development of the biofuels industry in Mexico.

2 Fuels, Transportation and the Environment

2.1 Global Energy Consumption and the Environment

Energy consumption is highly correlated with the economic development of countries and the ability of their population to access services and goods.[77] In the period between 2014 and 2020 the projected annual world economic growth is 3 to 4 percent [1], which might lead to an increase in energy demand by 20% in 2020, compared to 2014. In the long-term, up to 2050, world energy demand is projected to increase by 50% in 2050, compared to 2009. [2] Total world energy consumption was 546.8 quadrillion Btu in 2013 with a predicted rise to 630 quadrillion in 2020 and to 820 quadrillion Btu in 2040.[4] As Figure 2.1 shows, growth in energy demand is highest for developing countries (Non-OECD).

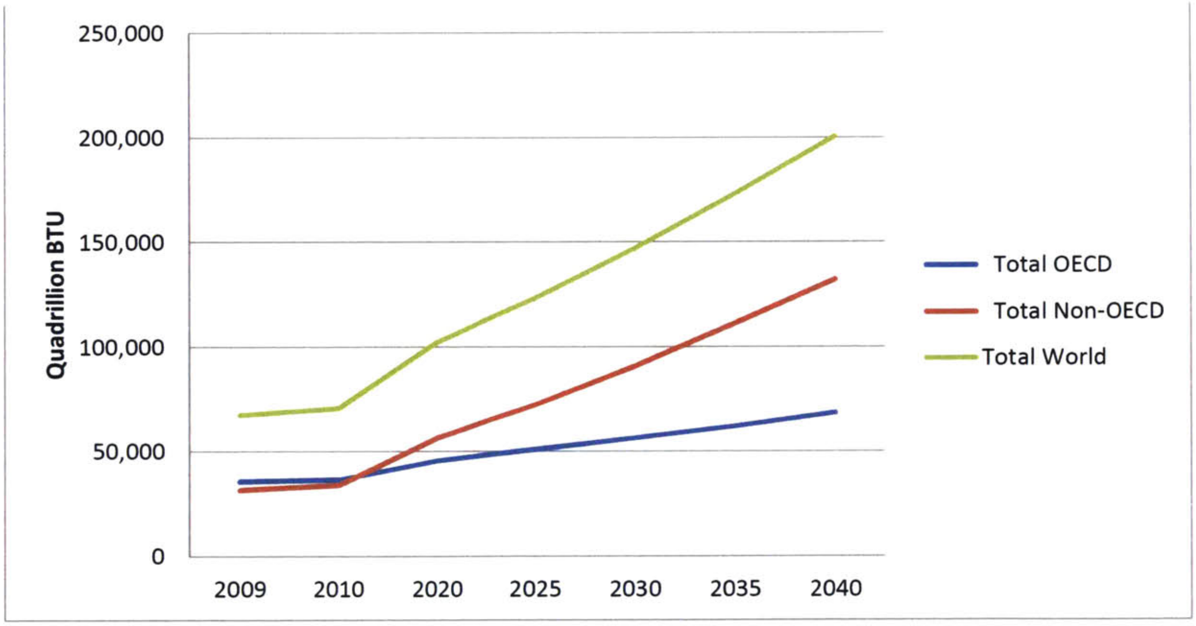


Figure 2.1: Projected world primary energy consumption.
Source: [48]

Currently, world primary energy supply is dominated by fossil fuels as shown in Figure 2.2; Petroleum has the highest share in primary energy supply, with an annual supply of 166.6 quadrillion Btu (31.4% of total energy consumed), followed by coal with 153.9 quadrillion Btu (29%) and natural gas with 113 quadrillion Btu, (21.3%). Renewable energies have a total share of 14% in energy consumption [5]

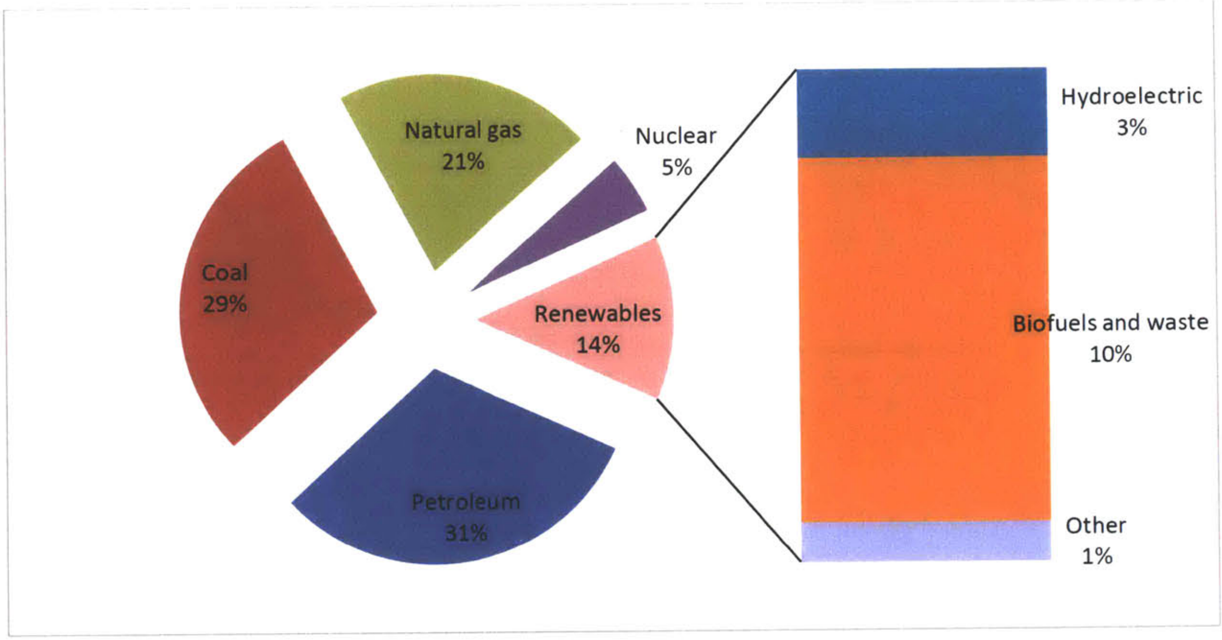


Figure 2.2: World total primary energy supply by fuel in 2012.

Source: [49]

Generation of secondary-energy products can have detrimental impacts on the environment, including, but not limited to GHG emissions, acid rain, water and soil contamination. [3]

Climate change is one of the most challenging environmental concerns globally today. According to studies performed by the Godard Institute for Space Studies, 350 parts per million of atmospheric CO_2 is the threshold needed to avoid permanent climate changes. However, global mean CO_2 in 2008 was already 385 ppm with an annual growth of around 2 ppm.[3]

In terms of CO_2 emissions related to energy production, global emissions rose from 21.5 billion metric tons in 1990 to 33.2 in 2014, a 54% increase in 24 years.[7] Furthermore, it is projected to reach 36.4 billion metric tons in 2020 and 45.5 billion metric tons in 2040, a 46% increase in global energy-related CO_2 emissions.[7]

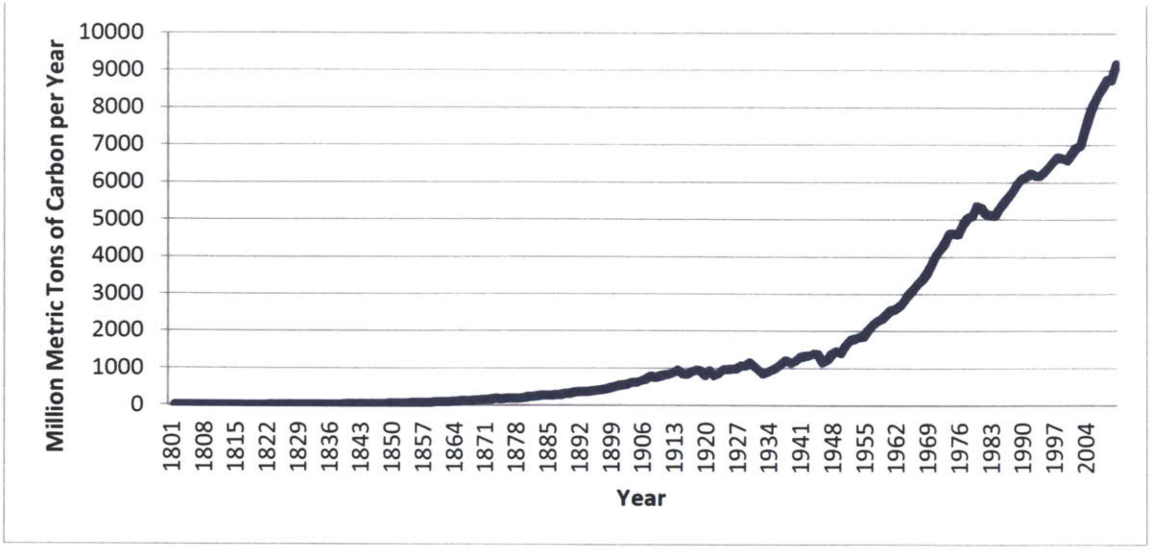


Figure 2.3: Annual global fossil fuel carbon emissions.

Source: [50]

2.2 Transportation Sector and GHG Emissions

Energy consumption is driven by four major energy end-use sectors: commercial, industrial, residential and transportation.

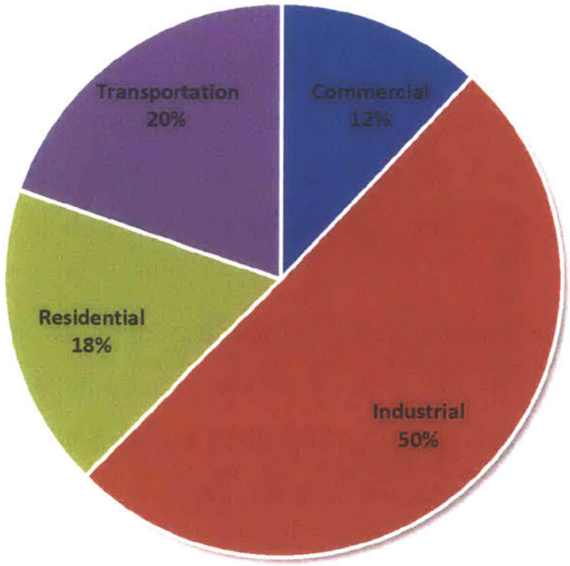


Figure 2.4: World energy consumption by end-use sector in 2011.

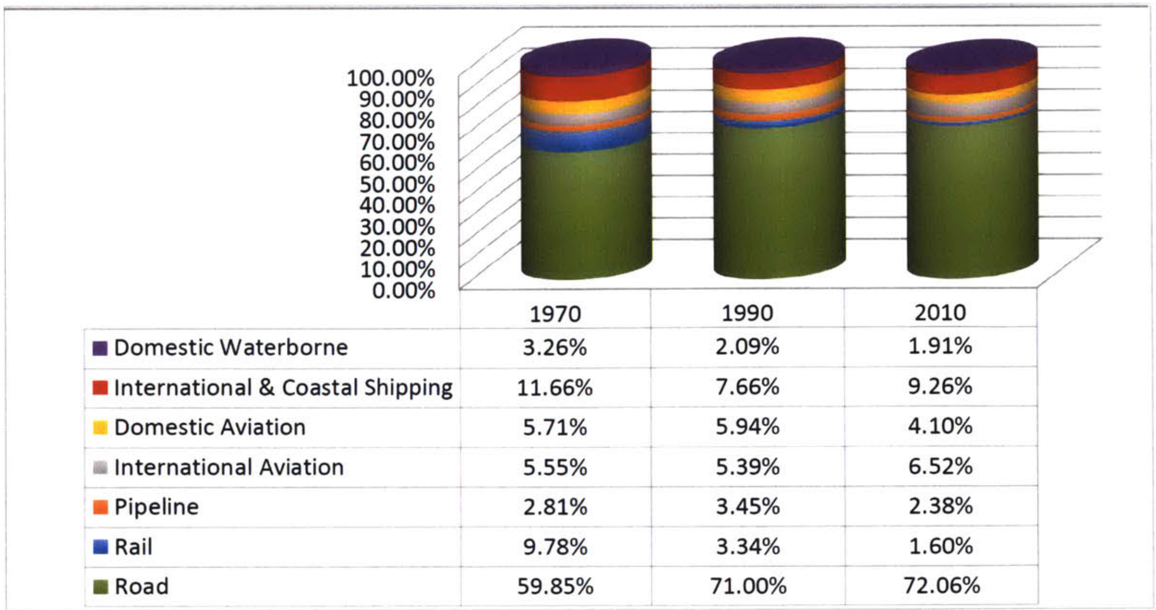
Source: [62]

After electricity, the transportation sector is the highest consumer of energy, using 20% of the world's primary energy. 97.5% (7.1 million barrels per day) of this energy is based on fossil fuels.[63] In 2012, 25% of petroleum fuel was used for the production of motor gasoline, 29% as distillate fuel oil (which includes diesel) and 6% refined as jet fuel.[64] The following table shows the consumption of these petroleum products among OECD and Non OECD countries.

	Motor Gasoline	**Jet Fuel**	**Kerosene**	**Distillate Fuel Oil**	**Residual Fuel Oil**	**Liquefied Petroleum Gases**	**Other Products**	**Total**
OECD	14.5	3.1	0.7	13.2	3.2	1.5	7.1	43.2
Non-OECD	7.9	2.3	0.9	13.5	6.2	2.2	9.0	42.0

Table 2.1: Refined petroleum consumption by type (million barrels per day).
Source: [65]

The transportation sector is one of the largest contributors to global GHG emissions, with approximately 25% of global emissions being attributable to this sector.[66] Emissions are a result of the combustion of finished fuel products in internal combustion engines of passenger cars, freight trucks, aircrafts, ships and trains, among others. 75% of these emissions are related to the use of cars and trucks. [66] Based on the current trends CO_2 emissions are projected to increase by 50% by 2030 and by more than 80% by 2050.[66] To stay below the threshold of 350 ppm of atmospheric CO_2, the transportation sector needs to play a major role in GHG emissions reduction efforts.



	1970	1990	2010
🟪 Domestic Waterborne	3.26%	2.09%	1.91%
🟥 International & Coastal Shipping	11.66%	7.66%	9.26%
🟨 Domestic Aviation	5.71%	5.94%	4.10%
⬜ International Aviation	5.55%	5.39%	6.52%
🟧 Pipeline	2.81%	3.45%	2.38%
🟦 Rail	9.78%	3.34%	1.60%
🟩 Road	59.85%	71.00%	72.06%

Figure 2.5: Direct GHG emissions of the transport sector by transport mode worldwide. Source: [67]

2.3 Air Transportation Industry and the Environment

Air traffic has doubled every fifteen years since the early 1980s and is forecast to continue to grow at a similar rate during the next fifteen years.[92] Growth is due to increasing global trade and international tourism and will be led by developing countries.[14] Currently, the air transportation industry generates approximately 12% of transportation CO_2 emissions, which is 2% of the CO_2 emissions produced globally. Motivated by growing emissions, airlines began work in 2009 to develop a common plan to reduce air transportation GHG emissions. They focused their efforts on three main goals:[15]

1. To improve fuel efficiency by an average of 1.5% annually by 2020
2. To reach net carbon-neutral growth emissions by 2020
3. Cutting net emissions in half by 2050, compared with 2005

To achieve these goals, the air transportation sector developed a strategy based on four pillars: technology, operations, infrastructure and market-based measures. Today, the 1.5% annual fuel efficiency goal has been achieved by the industry. However, the challenges are more complex for the second and third goals; if they will be achieved, further action is required from aviation stakeholders, including the use of aviation biofuels.

2.4 Potential of biofuels for mitigating aviation's contribution to anthropogenic climate change

Biofuel is a term used to refer to solid, liquid or gaseous fuels that are produced from renewable feedstock. Liquid biofuels have the potential to substitute fossil fuels, reduce GHG emissions, generate new jobs, and are sustainable.[16] Between 1991 and 2001, world biodiesel production grew continuously to 1 billion liters; growth was led by countries in Europe. Between 2001 and 2007, North America, Southeast Asia and Brazil increased their participation, reaching a global production of 9 billion liters. [17]

A constant development and use of suitable biofuels is a key factor in achieving GHG emission goals. The use of biofuels can reduce CO_2 emissions up to 80% over their life cycle.[18] The air industry has a distribution system for jet fuels with advantages for the use of biofuels; if biofuels were supplied to just 190 specific global airports, 80% of all flights would operate with biofuels.[19] In 2008, the first renewable jet fuel flight test was performed. Since then the industry has promoted the development of these technologies achieving around 1,500 commercial renewable jet fuel flights. However, there are obstacles to its adoption. Generally the obstacles are not technical but primarily economic and political. In the economic aspect, renewable jet fuels need to be produced constantly, sufficiently, and in high volumes in order to reach competitive costs. Politically, an implementation of favorable fiscal and legislative structure is required to encourage the deployment of an aviation biofuels industry;[18] this will support the investments required for the expansion of renewable jet fuel production plants and the development of a reliable supply chain.

2.5 Aviation biofuel production pathways

The main transportation fuels are: gasoline, jet and diesel. These fuels are used in different chemical variations, blends and concentrations which affect their properties and performance. One of the main chemical characteristics is the length of carbon chains which affects the boiling point of the fuels. Gasoline has a carbon length in the range of C_9 to C_{24}; jet fuel carbon length is in the range of C_9 to C_{16}; and diesel carbon length is in the range of C_9 to C_{24}. Turbine engines can operate with any of these fuels, but aircrafts require specific characteristics which are critical for performance and safety.

Renewable fuels are defined as motor vehicle fuels produced from plant or animal products or waste.[36] The term biodiesel has been used broadly without technical accuracy. Biodiesel is chemically referred to as the Fatty Acid Methyl Esther (FAME) product resulted from the transesterification process based on raw or waste vegetable oil and animal fats. Biodiesel is commonly used in blends with fossil fuels (i.e. B20, a blend composed of 20% biodiesel and 80% fossil diesel). However, biodiesel has different chemical characteristics than fossil diesel, so is not possible to share storage and transportation infrastructure.

On the other hand, renewable diesel is also produced based on raw or waste vegetable oil and animal fats. It is made through a hydrotreating chemical process. The hydroprocessing substitutes sulfur, nitrogen and oxygen atoms with hydrogen atoms and converts the oils triglyceride molecules into paraffinic hydrocarbons.

The advantage of the HEFA fuels over FAME products are that HEFA fuels are chemically similar enough to conventional diesel and jet fuels so they are compatible with existing production, storage, distribution and combustion infrastructure.[35] HEFA fuels meet ASTM specifications and HEFA jet fuel is certified to blended up to a 50% ratio with petroleum-derived jet fuel.[36]

HEFA technology is already on the market in the US and in the EU. Several companies have been producing HEFA fuels since 2008. In the EU, companies such as Neste Oil are producing renewable fuels based on HEFA technology.[97] Several airlines have conducted test flights using HEFA and conventional jet fuel blends.[37] Currently, HEFA is the leading process for renewable jet fuel production.[96] Several airlines (Including, Aeroméxico, Interjet, Air China, Air France, Finnair, Iberia, KLM, Lufthansa and United) have used HEFA renewable jet fuel in commercial flights.[96] In terms of environmental performance, lifecycle CO_2 emissions from HEFA fuel based on soybean feedstock are up to 68% less than conventional jet fuel, if there are no additional emissions from land use change induced by biomass cultivation as feedstock for fuel production.[96]

2.6 Mexican GHG Emissions reduction efforts

International efforts, technologies and research to reduce GHG emissions have been focused primarily on developed countries, currently and historically the largest emitters. GHG per capita emissions from developing countries will continue to be less than those from developed countries. However, total GHG emissions from developing countries will increase in the next decades.[20] Emission scenarios suggest that without reductions in GHG emissions in developing efforts to mitigate global climate change will be insufficient.

Mexico has vast natural resources that include metals, fossil fuels, water and ecosystems. In 2013, Mexico was the fifteenth largest economy based on its GDP, with an expected growth of 3% p.a. for the following years. [21] Also in 2013, Mexico was rated the tenth largest producer of oil in the world and one of the top tourism destinations.[78] According to PricewaterhouseCoopers, by 2050 Mexico is expected to become the seventh largest economy in the world.[22]

In 2012, 88.5% of Mexico's primary energy production was from fossil fuels and just 6.8% from renewable sources.[25] That same year, Mexico consumed 4,902 PJ. 47% of it was consumed by the transportation sector, 31% by the industrial sector and 19% by the residential and commercial sector.[26] Petroleos Mexicanos (PEMEX) is a government-owned company and the only oil producer in the country. It is ranked as the 5th oil producer in the world. However, since Mexico's crude oil production has been declining, with reserves almost depleted, the country has been importing growing amounts of fuels.[27]

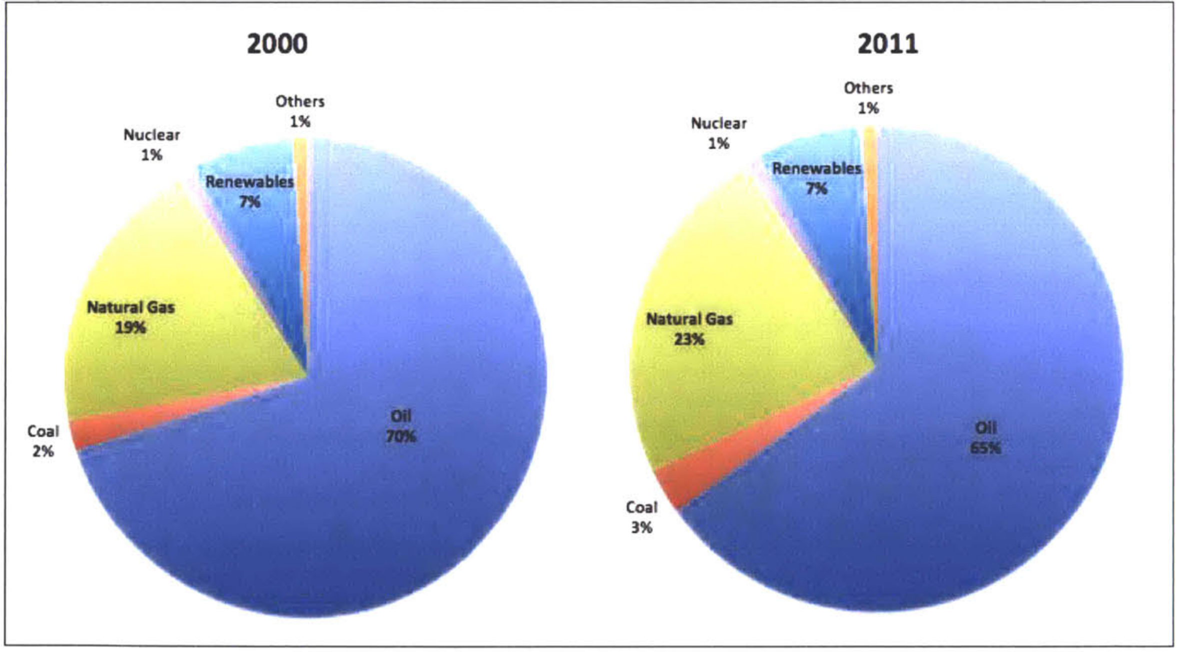


Figure 2.7: Mexico primary energy production by fuel.

Source: [52]

In 2010 Mexico generated 443.7 Mt of CO_2' representing 1.3% of global emissions[71], positioning it as the thirteenth highest emitter of CO_2. Mexico has actively participated in climate change international forums, committing its support to achieve global GHG emissions mitigation efforts. In 2009, at The Copenhagen Accord organized by the United Nations, Mexico pledged to develop programs to achieve the following targets:[68]

- 30% GHG emissions reductions (288 $MtCO_2$) compared to business as usual projection by 2020.[95] Business as usual is defined as: the scenario of emission projections based on economic growth in the absence of climate change policies.[94]
- 50% GHG emissions reductions (320 $MtCO_2$) of 2000 levels by 2050. [95]

In 2012 the Mexican government published the National Energy Strategy 2013-2026, which sets the goals for the national energy sector and gives guidelines for energy security, efficiency and environmental sustainability.[72] This strategy sets the goal for the Department of Energy to reduce the use of fossil fuels in electricity generation to 65% in 2024 and to 50% in 2050.

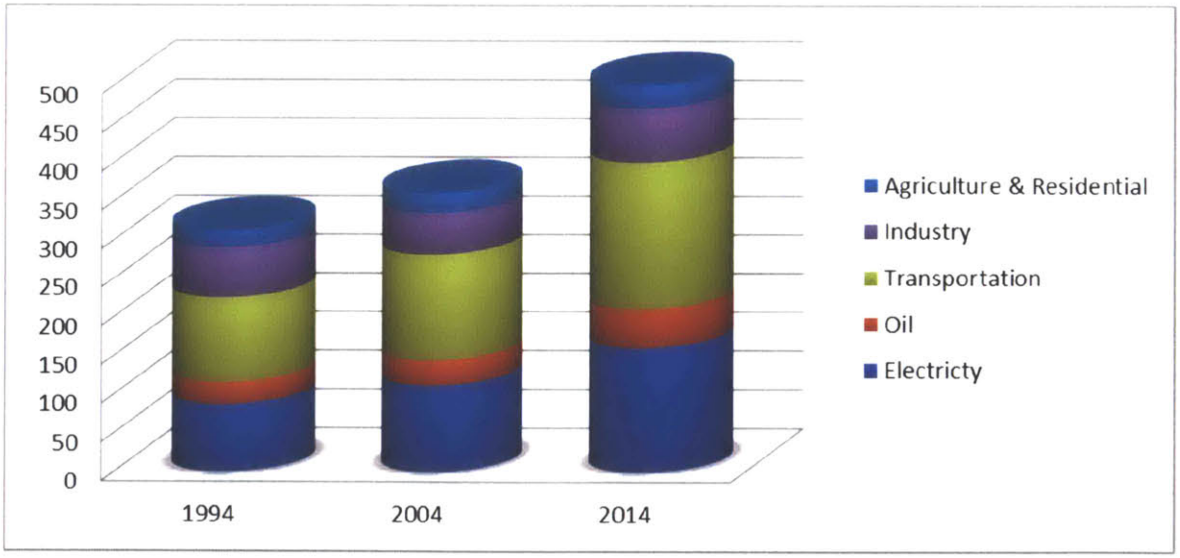


Figure 2.8: CO_2 emissions by sector in Mexico.
Source: [53]

Although biofuels could potentially significantly contribute to emissions reduction targets being met, Mexico is the only major country in Latin America lacking a biofuel industry.[74] Recently, the Mexican government has called upon governmental offices, research groups and industrial partners to join their efforts to boost national production and incentivize renewable jet fuel markets.[53] In 2008 Mexican congress approved the Bioenergy Promotion and Development Act, with the purpose to develop the production, commercialization and use of biofuels in the country.[75]

2.7 Mexican Air Transportation Industry

Aeropuertos y Servicios Auxiliares (ASA) is the governmental office in charge of administration, operations and supply of jet fuel to the airports within Mexico. In 2014, ASA operated 23 airports, providing services to 1.8 million passengers, consuming 10.5 million liters of fuel daily.[29]

Beginning in 2009, ASA initiated efforts to develop cleaner alternative fuels and promote policies to grow a national renewable jet fuel market. These efforts are outlined in the national plan called "Plan de Vuelo hacia los Biocumbustibles Sustentables de Aviación en México" (PdV). [30] The main objective of the plan is to analyze and incorporate aspects such as legal framework, raw material availability, supply chain, existing technologies and economic analyses in a single development plan. The first flight was in 2011, using 7,500 liters of renewable diesel produced by HEFA technology in blend with conventional jet fuel.[31] For these flights the production of renewable jet fuel was based mainly by vegetable oils and waste vegetable oil produced in Mexico. However, the hydroprocessing was performed in the US due the lack of refining infrastructure in Mexico.[31]

In addition, the PdV includes regional development initiatives, which are focused on two Mexican states: Hidalgo and Morelos. The state of Hidalgo was identified as a potential biofuels producer because of its existing infrastructure that includes refineries and access to national highways, in addition to its proximity to Mexico City (96 km away), the largest airport in Mexico. The state of Morelos was also identified as a potential producer based on its land availability for Jatrhopha Curcas L. production, and because of its existing biofuels research centers. [31]

2.8 Potential Use of Waste Vegetable Oil in Mexico

For several years waste vegetable oil has been used as a low cost raw material for biofuels production in developed countries.[79, 81] However, in developing countries, such as Mexico, waste vegetable oil is often discharged into houses and public sewers. Waste vegetable oil is one of the main sources of water contamination because most of it is discharged in public sewers without previous treatment, causing city sewer blockages, bad odors and noxious wildlife.[32,33] These issues generate malfunctions in water treatment plants, increase floods risks and plant treatment operation costs.

Waste vegetable oil is also used as an animal feed in some areas. This practice has been banned in the EU because it is a health hazard.[32] Waste vegetable oil is collected and sold as fresh vegetable oil in the black market. The black market collects waste vegetable oil, filters it with basic procedures and packages it as fresh cooking oil to be sold to flea markets or to food street vendors. This practice is a hazard for public health, since the reheating of cooking oil increases the trans-unsaturated fatty acids content and generates dioxins, which are a highly toxic compound. [32,33]

A study conducted by the National Autonomous University of Mexico (UNAM) estimates that in 2010 Mexico produced between 0.37 and 0.94 million tons of waste vegetable oil. With 56% of the Mexican population living in metropolitan areas, it is estimated that between 210 thousand tons and 473 thousand tons of waste vegetable oil would be available for collection to use as raw material for biofuels production. [34]

	2008	**2009**	**2010**
Production	1.091	1.138	1.192
Exports	0.051	0.05	0.046
Imports	0.692	0.685	0.729
Consumption	1.732	1.733	1.875
Potential waste vegetable oil produced			0.375 - 0.844
Potential recovery waste vegetable oil			0.210 – 0.473

Table 2.2: Vegetable oil consumption in Mexico (Mt).

Source: [54]

This amount of vegetable oil has a potential to produce between 7.84 PJ and 17.75 PJ of energy per year, which represents between 1.5% and 3.3% of diesel consumed in road transportation in Mexico. The use of this waste vegetable oil as renewable fuel feedstock has the potential to reduce CO_2 emissions between 0.45 Tg and 1.02 Tg, representing between 1% and 2.7% of CO_2 emissions associated with diesel consumption for road transportation.[34] While disposal of waste vegetable oil is currently an issue for the environment, public health, and municipal operations, it has the potential to become a beneficial factor for environmental relief when used as a feedstock for transportation biofuels. Furthermore, it has the potential to help initiating a Mexican green economy.

3 Technical overview on HEFA biorefinery

In the biorefinery, the waste vegetable oil is hydrotreated to remove the oxygen and is split into separate hydrocarbons. These hydrocarbons are then cracked to yield the carbon chain lengths required of the fuels desired. The following hydroprocessing plant design relies on previous development of the technical specifications described in detail by Pearlson (2011). [38] The section briefly describes the main aspects of the plant design and underlines the assumptions made for the economic analysis under the Mexican framework.

The plant design is based on hydrotreating and isomerization technology and operates under petrochemical standard processes. The production process starts with transporting vegetable oil from the storage unit to the hydrotreator for its reaction with hydrogen gas. The subsequent product is cooled and transported to the isomerization unit. The isomerized fluid is cooled with cooling water and sent to a separation tower where coproducts (paraffin gases, carbon dioxide and excess hydrogen) are separated and recycled. Lastly, final liquid products are separated into diesel, jet, naphtha and LNG, and then stored individually. The following chart describes this production process and the units required. Below the different processes are described in more detail, moving from left to right.

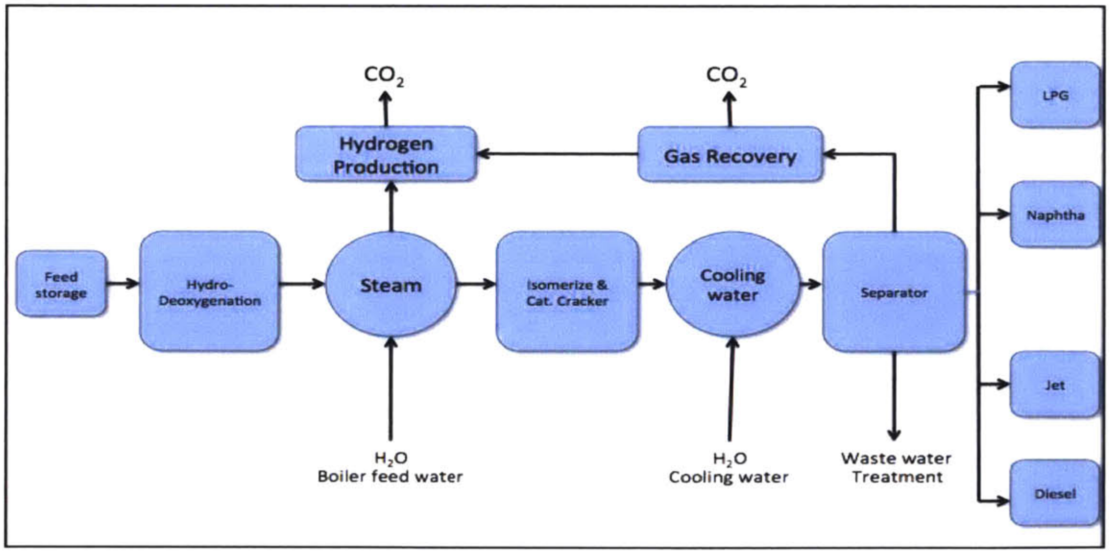


Figure: 3.1: Simplifed hydroprocessed renewable oil plant design.

Source: [56]

The plant design requires the use of waste vegetable oil as feedstock. It allows up to 13 days of storage in order to guarantee the feedstock continuity supply for production and assumes that the waste vegetable oil is delivered by the suppliers and pretreated with the chemical and physical requirements set by the plant.[39] Field research in Mexico found that due to a lack of legislation and experience of picking up and transporting waste products, vegetable oil is delivered highly contaminated with water, other oils, fat, and other chemical and physical particles. A strict quality control would need to be put in place for waste oil supplied.

In the hydro-deoxygenation unit oxygen is removed from the feed, saturates double bonds and splits the propane backbone. The main products from this process are water, carbon dioxide, propane and straight chain alkanes within the diesel and jet fuel lengths from C_9 to C_{20}.[40] During this process the distillate profile can be determined by varying the hydrogen to vegetable oil ratio. For maximizing diesel production, the ratio is 2.7%; for maximizing jet production the ratio is 4%. [41] After this, the deoxygenated product is sent to the isomerization process; which is critical for meeting ASTM specifications, including the cloud point which is the fuel characteristic that determines the cold operating temperatures. Hydrotreating and selective isomerization are exothermic processes which need to be controlled. This is why a temperature control system is required in the plant. Temperature regulation is based on water flow through circulation pumps and fans. After the hydrotreating and isomerization processes, gas products are separated from liquid products and purified. Then the hydrogen and carbon dioxide that remain are separated and recycled. Finally, through an atmospheric distillation process, column liquid products are separated using their boiling point. After this process, diesel, jet, naphtha and LNG are obtained and sent to storage.

The plant design has twenty-five days of storage capacity for each product. A continuous supply of hydrogen is critical for the plant operation. To guarantee this, two options are available: The first option is to build and operate an on-site hydrogen facility. The second option is to buy hydrogen from an industrial supplier. According to interviews conducted with field experts, Mexico currently has a deficit in hydrogen production, and because of that, PEMEX is reluctant to sign new industrial supply contracts. Therefore, it can be expected that the hydrogen will have to be bought from an international supplier.

Due to the design of this plant and the feedstock selected, the producer will have the option to produce more diesel or more jet fuel by cracking diesel down to jet characteristics. The economic analysis considers two scenarios. The first scenario (maximum distillate) explores outcomes of when the producer chooses to maximize diesel production. The second scenario (maximum jet) explores outcomes when the producer chooses to maximize jet fuel production, which required additional hydrogen. The following table summarizes the product profiles for these scenarios.

Product Profiles	**Maximum Distillate [wt%]**	**Maximum Jet [wt%]**
Waste Vegetable Oil	100.0	100.0
Hydrogen	2.7	4
Total In	102.7	104.0
Water	8.7	8.7
Carbon Dioxide	5.5	5.4
Propane	4.2	4.2
LPG	1.6	6.0
Naphtha	1.8	7.0
Jet	12.8	49.4
Diesel	68.1	23.3
Total Out	102.7	104.0

Table 3.1: Mass-based product yields by product profile sources.
Source: [57]

4 Economic Modeling

This chapter describes the development of the economic model under different scenarios and specific economic factors based on historical data within the Mexican context. The main purpose of this model is to estimate the economic performance of a HEFA plant construction and operation in Mexico. A Discounted Cash Flow Rate of Return (DCFROR) model is used in order to evaluate the economic feasibility. Economic feasibility is shown in terms of the Net Present Value (NPV) of the project. This economic model is a continuance of the work started by Pearlson.[38]

4.1 Discount Cash Flow Rate of Return Model

Discounted Cash Flow Rate of Return is a valuation method that can be used to quantify the economic feasibility of a project. The DCFROR determines the rate of return by taking into account the Time Value of Money (TVM, is the idea that money accessible in the present is worth more than the same amount in the future).[98] DCFROR uses the future cash flow projections of the project and discount them to obtain the net present value. The discount rate used reflects the TVM and a compensation for the capital investment risk. The sum of all discounted cash flows determine the NPV of the project. If the NPV value is positive, the project yields more than the desired return. If NPV is zero, the desired return is achieved. The DCFROR model used is based on Pearlson and its main parameters are shown in Table 4.1.[100]

Facility size	(2000-6500) BPD
Working capital (% TPI)	5%
Equity	20%
Loan Interest	5.5%
Depreciation period	10 years
Construction period	3 years
Internal rate of return	15%
Operating hours per year	8,400

Table 4.1: DCFROR Model Parameters Values and Units. Source: [99]

Besides the calculation of the NPV, the DCFROR model is also used to calculate the Minimum selling price (MSP) of the fuels produced. The MSP is the lowest selling price of outputs that the producer is willing to the price that the producer is willing to sell the products in order to obtain the profits expected. The DCFROR model is used to calculate the minimum selling price of the selling products. The minimum selling price is the selling price of the biofuels at which the NPV reaches zero.

4.2 Capital and Operating Expenses

Capital and operating expenses are analyzed using a traditional petrochemical plant design costs. It is assumed that Nth plants have been constructed previously, which resulted in design and operating processes experience. Given this acquired knowledge, no economic penalties for the learning of doing effects are considered in the model. Capital expenses include the costs of the purchase, installation and maintenance of the equipment required. Equipment required can be categorized as: inside of the battery and outside of the battery. The inside of the battery equipment includes the units required for the core development of the process; outside battery equipment refers to the equipment required for the cooling system and to store feedstock and liquid products. Additional costs for supplementary infrastructure such as roads and fences, project management costs, office and lab furniture, contingency plans, location and escalation factors are considered as well.

Capital Expenses	
Inside Battery	Hydrotreator
	Isomerizer
	Hydrogen Island
	Saturated gas plant
	Feedstock Storage
Outside Battery	Liquid Products Storage
	Gas Products Storage
	Cooling System
	Offsite Costs
	Special Costs
	Colling System
	Escalation
	Location

Table 4.2: Capital expenses distribution: Inside and outside of the battery.

Capital expenses for the facility in Mexico are assumed to be the same as the US since the equipment is sold on international base prices. The model does not consider extra costs for import-export overheads due the free trade agreement between the US and Mexico. Likewise no extra charges for shipping are considered due the proximity of the countries.

Operating expenses are calculated annually and are classified as fixed and variable expenses. Fixed operating expenses are constant and not proportional to the production levels. Variable expenses are proportional to the production levels and they are not constant.

Fixed operating expenses are recurrent and are reported monthly or yearly depending upon the amount of fuel production. These expenses include facilities maintenance, taxes, insurance and salaries, among others. Fixed operating expenses used in this analysis are based on heuristics found in literature. [101]

Fixed Operating Expenses US-MEX	
Catalyst	$/lb feed
Insurance	0.5% Total Plant Investment
Maintenance	1% Total Plant Investment
Miscellaneous Supplies	0.2% Total Plant Investment
Contingency	10% of above subtotal

Table 4.3: Fixed operating expenses in the US and in Mexico.

Based on the difference of labor cost among the US and Mexico, the plant staff and operators' fixed expenses have been adjusted as well as the local tax expenses. In Mexico, the plant could be exempted of local taxes if the local government is willing to support this investment since it will improve the economy and provide local jobs.

Plant staff and operators' salaries are calculated based on the data obtained from PEMEX; an oil sector specialist operator would earn $9,000 USD in comparison to the same worker in the US that would earn a salary of $72,000 USD per year.[43] This adjustment is included in the economic analysis in terms of a 1:0.18 salary ratio.

Fixed Operating Expenses Mexico	
Plant staff and operators	12 staff @ $9,000/Yr
Local Taxes	1% Total plan Investment

Table 4.4: Fixed operating expenses in Mexico.

Variable operating expenses are proportional to the production level. This means that if the plant increases its production by 50% the operating expenses will increase in the same proportion. These costs are mainly attributable to raw materials and energy consumption. The plant's variable operating expenses include natural gas to feed the reactors, water for the steam generations, waste vegetable oil as primary feedstock, hydrogen for the hydro-deoxygenation process and finally electrical energy to power all the equipment.

The Mexican government controls fuel retail prices. Therefore they do not reflect properly international market prices, variations and trends. During the last decade, Mexico has been going through several reforms that have started to liberalize fuel and electrical power prices.

In 2014 and in 2015, reforms were approved by the Mexican Congress to deregulate the electricity and oil industries. Due to the above, the prices selected for this economic analysis are the average cost for each good over the period from 2009 to 2013. The following table shows the variable operating expenses and its cost in Mexico.

Variable Expenses Mexico	
Electric power	0.09 ($/kWh)
Natural gas	230.66 ($/$10^3$lb)
Makeup water	2.60 ($/Mgal)
Hydrogen	0.66 ($/lb)

Table 4.5: Variable expenses in Mexico.

Sources: [58, 59, 82, 83]

In order to determine the price of waste vegetable oil, field research and interviews were conducted in Mexico City with local collectors. The price reported in 2013 varies from $0.31 to $0.76 per liter depending on the quality of the oil and its availability on the market. In order to have a better understanding of the effect of the price of waste vegetable oil in the economic feasibility of production, the economic analysis conducted a cost sensibility analysis based on waste vegetable oil price. This analysis and its results are reported in Chapter 5.

As discussed in the previous chapter, according to interviews with Mexican oil industry experts there is a limited availability of hydrogen in the country. This situation requires that the hydrogen needed for the plant operation should be produced within the plant or purchased abroad. As such, the hydrogen price used in the economic analysis is based on US gulf coast prices.

As in the US, in Mexico the main oil infrastructure is located on the coast of the Gulf of Mexico. [85] Locating the plant in this area would provide the advantage of the existing infrastructure such as pipelines, fuel storage and distribution routes. Furthermore, this strengthens the case of building a plant in Mexico that sells to Mexico or the US. Location will set water prices, since it is the Mexican Federal Government who sets the water prices according to predetermined zones. This analysis will assume that the plant will be in zone 4, where several oil facilities are already located.[84] The price reported for this zone is $2.61 per Mgal for industrial activities[82], which is more expensive than in the US where the price is $1.69 per Mgal. [83]

4.3 Plant size

Plant size determines feedstock needs and determines the capacity of the process. This means that higher levels of production will reduce production cost; more production requires more feedstock, which is limited and relies on consumption and collection of waste vegetable oil. In order to have a fair comparison with previous research, three plant sizes were selected for the analysis: 2,000, 4,000 and 6,000 BPD.

4.4 Gross Income: Estimation of Plant Sales

Plant gross income depends on the amount, type and price of the products made. It is assumed that the products are sold at the plant gate, referred to as "gate price." This price includes production costs and plant profits. However, it does not include transportation, distribution and final retail costs. Gate price does not include governmental incentives for renewable fuel production, such as $1 per gallon Blender's credit or Renewable Identification Numbers (RINs). However, in section 5.2 one case study will integrate these incentives in order to have an overview of its influence on the economic feasibility of the plant.

As described, hydroprocessed renewable oil provides the flexibility to vary the amount of product profiles of the plant, which includes different products such as: propane, LNG, naphtha, jet and diesel fuels, as well as non-value products like water and carbon dioxide. The plant has the option to maximize jet fuel or diesel fuel. The product profile maximization decision depends on the economic performance of the plant. Diesel and jet fuel products are considered to be commodities and their prices vary according to different variables such as: oil price, demand, economic growth, political stability, etc. Due to this fluctuation the economic analysis uses the average price from the period from 2009 to 2013 which is $2.54 per gallon of diesel and $2.69 per gallon of jet fuel. The prices are based on PEMEX reports and on reports from the Mexican Department of Energy (SENER);[44] however, these reports include the federal sales tax (Impuesto al Valor Agregado, IVA) of 16%, which for these calculations has been subtracted.

4.5 Revenues from US Biofuel Incentives

For the case analysis that considers production in Mexico and selling in the US, two types of incentives were considered, the Renewable Fuels Standard and the blender's credit. They contribute to the revenues of the biorefinery. In addition, transportation costs have to be taken into account.

The US government has developed policies to support the development and use of renewable energies. The federal Renewable Fuel Standard (RFS) was established in 2005 as part of the Energy Policy Act of 2005. For 2013, the RFS required the use of 16.55 billion gallons of renewable fuel for transportation. The RFS will require the use of 36 billion gallons of renewable fuels, including 21 billion gallons of advanced biofuels by 2020.[45] The RFS is a system where refiners and operators submit credits to cover their obligations. These credits are called Renewable Identification Numbers (RINs). For each gallon of renewable fuel in the RFS program a RIN is generated. RINs are managed as commodities; they can be sold or bought. In 2011, biodiesel RIN prices averaged $0.75 per gallon, however in 2013 the lowest price was $0.31. Additionally, each gallon of biodiesel account for 1.5 RINs, meaning that diesel blenders received an average $1.13-per-gallon incentive for each gallon in 2011.[46] Renewable jet fuel receives the same incentive. For the case developed in section 5.2, two scenarios are developed: the high RIN price scenario will add $1.13 per gallon incentive and the low RIN price scenario will add $0.465 for per gallon of biodiesel and renewable jet fuel produced.

Blender's credit allows blenders of biodiesel to claim a credit of $1 per gallon against their US federal tax liability. The US Department of Energy states: "Qualified biodiesel producers or blenders are eligible for an income tax credit of $1.00 per gallon of pure biodiesel (B100) or renewable diesel produced or used in the blending process".[90] Being an income-tax credit, this incentive cannot be treated as a direct discount or subsidy on the biofuel price, since it would only apply to a certain volume, depending on the profit to be made by the blender, and not to all the biofuel purchased. Therefore every purchaser needs to make his economic analysis according to its particular tax situation. Although the tax credit has been suspended four times since 2009, it has been reinstated retroactively three times and is expected to remain intact for the foreseeable future.[47]

As mentioned above, in the scenario that the production will be done in Mexico and sold in the US gulf coast, a transportation cost should be incorporated in the model. A rail tank transport is chosen with a cost of $10 per barrel of fuel transported[91], and transportation of each gallon of fuel from Mexico to the US gulf coast is calculated at cost of $0.24.

5 Results

This chapter reports the results of the economic analysis based on the assumptions and the data described in chapters 3 and 4. This chapter describes the results for two main cases: The first case analyzes production and sale of biofuels in Mexico. The second case analyzes production of biofuels in Mexico and its sale in the US. Sensitivities of results are explored in relation to the facility size, the internal rate of return and the price of waste vegetable oil, respectively.

5.1 Analysis of Production and sale in Mexico

The following case analyzes the economic feasibility of producing and selling the biofuels through the HEFA process in Mexico. Capital expenses, operating expenses and gross income have been calculated based on Mexican parameters as described in sections 4.1 and 4.2.

Mexican Parameters	
Power ($/kWh)	0.09
Natural Gas ($/$10^3$*lb)	230.66
Vegetable Oil ($/$10^3$*lb)	254.74
Water ($/$10^3$*gal)	2.6
Diesel [$/gal]	2.54
Jet Fuel [$/gal]	2.69
Propane [$/gal]	3.23
Naphtha [$/gal]	3.03
Inflation	3.6%
Labor Cost Ratio US vs MX	0.18
Exchange Rate	1 USD = 13.08 MXP

Table 5.1: Mexican parameters for HEFA economic analysis production.

Sources: [35, 82, 86, 87, 88, 89]

5.1.1 Baseline Case

The baseline case considers the Mexican parameters described before and a plant with a nameplate capacity of 4,000 BPD and a discount rate (internal rate of return) of 15% and a lifetime of 20 years. In case of maximizing diesel production, around 45,800 gallons of diesel, and 8,700 gallons of jet fuel will be produced per year; and in case of maximizing jet fuel production, around 33,000 gallons of jet fuel and 15,700 gallons of diesel will be produced per year. If production is set to maximize diesel production, the NPV is $83.78 million; and if set to maximize jet fuel the NPV is $73.79 million. According to these results, the producer will be more willing to maximize diesel than jet fuel production since the NPV that can be obtained is $10 million higher. NPV values are higher as maximizing jet fuel production leads to additional costs due to additional hydrogen needs that are not offset by higher revenues from the change in product slate.

	NPV
Max Diesel	$83.78
Max Jet Fuel	$73.79

Table 5.2: NPV results for maximizing diesel and jet fuel production based on baseline case parameters. Values reported are in millions of dollars.

The minimum selling price is calculated as the price of jet and diesel products at which the NPV reaches zero for the assumed internal rate of return. The following table shows the minimum selling price for maximizing both diesel and jet fuel options.

		Minimum selling price [$/gal]
Max Diesel	Diesel	$2.21
	Jet Fuel	$2.36
Max Jet Fuel	Diesel	$2.22
	Jet Fuel	$2.37

Table 5.3: Minimum selling price for maximizing diesel and jet fuel production based on baseline case parameters.

As shown, if the producer chooses to maximize diesel production instead of maximizing jet fuel, minimum selling prices are $0.01 per gallon higher for both diesel and jet than if jet fuel production is maximized.

5.1.2 Sensitivity of results to facility size.

The following analysis explores the economic impact of economies of scale in the HEFA refinery. As reported by Pearlson, an increase of production capacity leads to a less than proportionate increase in capital expenses as economies of scale are present for e for the engineered equipment such as the hydrotreator, isomerizer, and the saturated gas plant. [56] In the following sensitivity analysis, the impact of facility size on NPV was quantified for capacities of 2,000 BPD, and 6500 BPD, compared to the case of our 4000 BPD facility assumed in the analysis above. All other assumptions remain constant.

Nameplate Capacity [BPD]		**2,000**	**4,000**	**6,500**
Max Diesel	NPV	$10.03	$83.78	$183.03
Max Jet Fuel	NPV	$5.04	$73.79	$166.80

Table 5.4: NPV results of the economies of scale analysis based on baseline case. Values reported are in millions of dollars.

As show in table 5.4, economies of scale affect the NPV for different plant sizes. The NPV for a maximum diesel production for the 6,500 BPD plant is 18.2 times higher than the NPV of the 2,000 BDP plant, although the 6,500 plant nameplate capacity is just 3.25 times bigger. For the 4,000 BPD plant, the NPV is 8.4 times higher than the 2,000 BPD plant. For the maximum production of jet fuel option, the results are similar; the NPVs of the 6,500 and 4,000 BPD are 33.4 and 14.8 times higher compared with the NPV of the 2,000 BPD plant.

Nameplate Capacity [BPD]/ Minimum Selling Price [$/gal]		**2,000**	**4,000**	**6,500**
Max Diesel	Diesel	$2.47	$2.21	$2.10
	Jet Fuel	$2.62	$2.36	$2.25
Max Jet Fuel	Diesel	$2.50	$2.22	$2.09
	Jet Fuel	$2.65	$2.37	$2.24

Table 5.5: Minimum selling price for 2,000, 4,000 and 6,500 nameplate capacities for the baseline case.

As shown in table 5.5, economies of scale influence the minimum selling price of the fuels produced as well. A plant maximizing diesel production with a nameplate capacity of 2,000 BPD requires a minimum selling price of $2.47 per gallon of diesel, however a plant with capacity of 6,500 BPD only requires a minimum selling price of $2.10 per gallon of diesel.

5.1.3 Sensitivity to choice of discount rate

Discount rate is used at the DCFROR analysis to determine the present value of future cash flows. This term takes into consideration the time value of money and the risk associated with the project. Table 5.6 shows the results of the NPV and the minimum selling prices of the baseline case evaluated with 10%, 15% and 20% discount rates.

Discount Rate		**10%**	**15%**	**20%**
Max Diesel	NPV	$172.93	$83.78	$30.33
Max Jet Fuel	NPV	$158.75	$73.79	$22.83

Table 5.6: Evaluation of the effect of the discount rate in the NPV for the baseline case. Values reported are in millions of dollars.

As expected, the 10% discount rate provides the highest NPV. However, it is important to recognize that the 20% discount rate still offers a positive NPV of $30.33 million. The break-even discount rate is 24%.

5.1.4 Waste Vegetable Oil Sensitivity Analysis

In a third sensitivity analysis, the impact of waste vegetable oil prices on the economic performance of the biorefinery is quantified. Figure 5.1 shows the NPV generated by the plant under the baseline case for different waste vegetable oil prices.

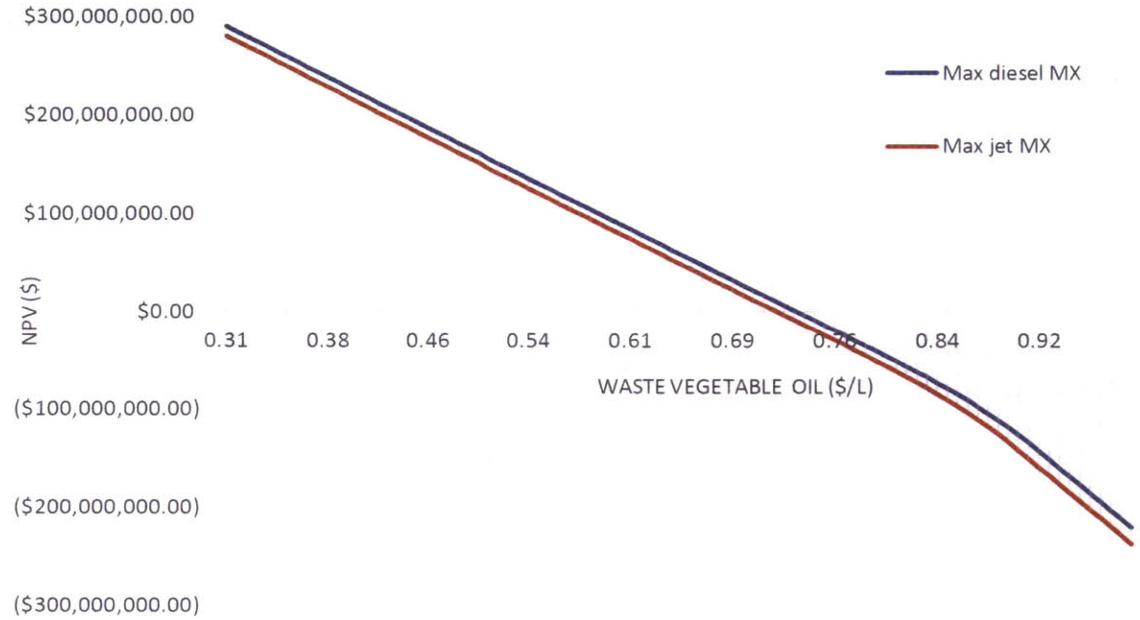


Figure 5.1 Waste vegetable oil cost sensitivity analysis for the baseline case.

As the sensitivity cost analysis shows, the maximum price the plant can afford to pay for waste vegetable oil is $0.73 per liter to produce maximum diesel and $0.72 per liter for maximum jet fuel. This is 36% percent above the average selling price reported in the local markets in 2013, but 4% percent lower than the highest reported prices.

5.2 Analysis of production and sale in US and Mexico

The following section quantifies different cases for location of HEFA fuel production and geographical markets that the fuel is sold in. First, production costs in Mexico as calculated above are compared to production costs in the United States. Second, the sensitivity of results to prices of waste vegetable oils is assessed. Third, the economic viability of producing fuels in Mexico and exporting them to the United States is quantified.

5.2.1 Base case

The following case compares production cost in Mexico with production cost in the US. This analysis is done based on the baseline case, which considers a 4,000 BDP plant and 15% discount rate. Table 5.7 shows the average price from the period from 2009 to 2013 of the parameters considered for the calculations for the US and Mexico. Cost data was obtained from SENER, PEMEX and Banco de Mexico for Mexico and from IEA and US Energy Information Administration for the US, as explained in section 4.2.

	Mexico	**US**
Power ($/kWh)	$ 0.09	$ 0.07
Natural Gas ($/10^3*lb)	$ 230.66	$ 131.89
Diesel [$/gal]	$ 2.54	$ 2.55
Jet Fuel [$/gal]	$ 2.69	$ 2.54
Propane [$/gal]	$ 3.23	$ 1.07
Naphtha [$/gal]	$ 3.03	$ 2.53
Water ($/10^3*gal)	$ 2.60	$ 1.90
Vegetable Oil ($/10^3*lb)	$ 254.74	$ 332.23
Inflation	3.60%	2%
Labor Cost Ratio US vs MX	0.18	1
Transportation Cost MX to US [$/gal]	0.24	
Exchange Rate	1 USD = 13.08 MXP	

Table 5.7: Production parameters for Mexico and the US.

Sources: [35, 82, 86, 87, 88, 89, 8, 64]

As shown, the price of fossil fuels, electricity and water are higher in Mexico than in the US. For Mexico this represents a disadvantage in terms of production costs since the energy required is more expensive. However, at the same time, revenues are also higher as finished products of the biorefinery sell at a higher price than in the US. Labor cost in Mexico are significantly less than in the US (-82%). The cost of the main raw material of the plant, waste vegetable oil, is 23% less expensive in Mexico than in the US. The following table shows minimum selling prices. The minimum selling price for Mexico for maximum diesel is $0.77 less for diesel and $0.61 less for jet fuel than in the US. This means it is 35.6% less expensive to produce and sell in Mexico than produce and sell in the US. For the case of maximum jet fuel the minimum selling prices are $1.08 per gallon of diesel and $0.92 per gallon jet fuel less than in the US.

Minimum Selling Price [$/gal]		**Mexico**	**US**
Max Diesel	Diesel	$ 2.21	$ 2.93
	Jet Fuel	$ 2.36	$ 2.92
Max Jet Fuel	Diesel	$ 2.22	$ 3.17
	Jet Fuel	$ 2.37	$ 3.16

Table 5.8: Minimum selling prices in Mexico and in the US based on the baseline case.

NPV results provide an overview of the profitability of the plant depending on its location. Over the lifetime of the facility the NPV is $173 million higher for maximum diesel and $221 million higher for maximum jet fuel if it is located in Mexico.

		Mexico	**US**
Max Diesel	NPV	$83.78	$(90.54)
Max Jet Fuel	NPV	$73.79	$(148.09)

Table 5.9: NPV results in Mexico and US based on the baseline case. Values reported are in millions of dollars.

5.2.2 Waste Vegetable Oil Sensitivity Analysis

A waste vegetable oil sensitivity cost analysis was conducted for both locations. As mentioned above, a plant operating in Mexico reaches an NPV of zero at a 15% discount rate at a vegetable oil prices of $0.75 per liter in the case of maximum diesel and of $0.76 per liter for maximum jet fuel. For the US, as shown in figure 5.2, the break-even waste vegetable oil price in the US is $ 0.65 per liter for maximum diesel and $0.59 per liter for maximum jet fuel.

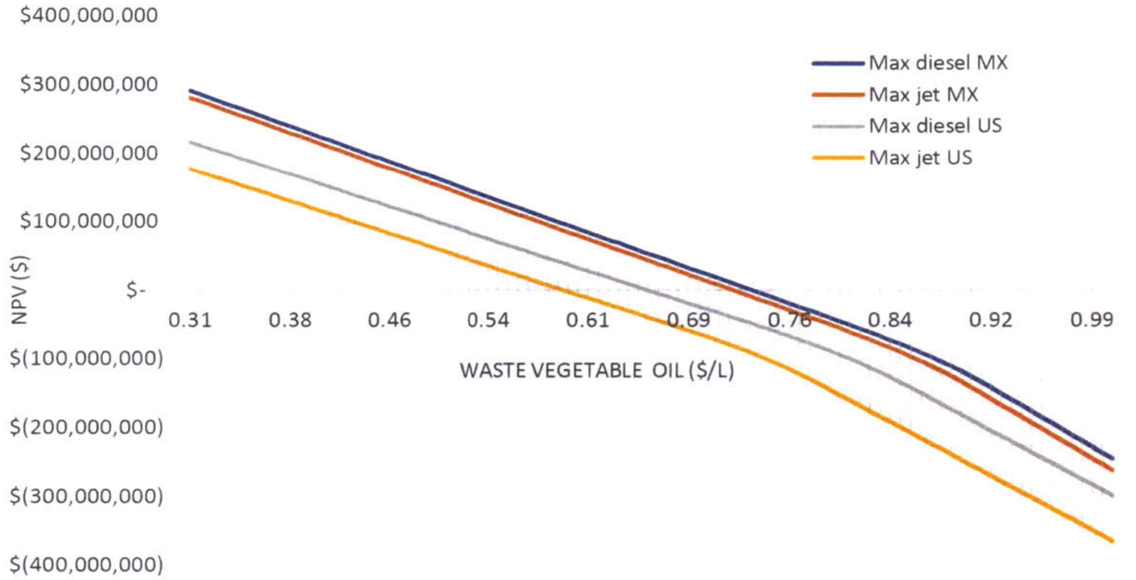


Figure 5.2: Waste vegetable oil cost sensitivity analysis for Mexico and US baseline case.

As shown above, a plant located in Mexico could afford to pay higher waste vegetable oil prices. The differences between break-even prices among locations are $0.10 for maximum diesel and $0.17 per liter of waste vegetable oil for maximum jet fuel.

5.2.3 Production in Mexico and Export of Fuel to the US

Mexico's significantly lower labor costs, coupled with geographical proximity and free trade agreements between the US and Mexico make the scenario of producing in Mexico and selling in the US worth exploring. The following analysis shows the results of the economic evaluation of producing biofuels in Mexico and selling them in the US.

As discussed in Chapter 4, the US Government provides incentives for the use of biofuels. For this analysis two scenarios are evaluated: high incentives, which includes a high RIN price of $1.13 per gallon and low incentives, which includes a low RIN price of $0.465. For both scenarios, a blenders' credit of $1.00 per gallon of diesel is considered. Table 5.10 shows the minimum selling price required for the NPV of the plant to be zero at 15% discount rate.

Minimum Selling Price[$/gal]		**Without Incentives**	**With Incentives**	
			High incentives	**Low incentives**
Max Diesel	Diesel	$2.44	$0.31	$0.98
	Jet Fuel	$2.45	$1.32	$1.99
Max Jet Fuel	Diesel	$2.65	$0.52	$1.19
	Jet Fuel	$2.66	$1.53	$2.2

Table 5.10: Minimum selling prices considering production in Mexico and selling in the US with and without incentives.

In terms of NPV, table 5.11 shows that the profitability of exporting the fuels to the US is dependent on the existence of subsidies. Without incentives, a negative NPV of $90 million in case of max diesel production and $148 million in case of max jet fuel production is reached. With incentives, NPV values range from $ 252 million USD to $ 462 million USD depending on production and incentive scenario.

Minimum Selling Price[$/gal]		**Without Incentives**	**With Incentives**	
			High RIN Price	**Low RIN Price**
Max Diesel	NPV	$(33.68)	$461.66	$294.46
Max Jet Fuel	NPV	$(79.44)	$401.34	$252.00

Table 5.11: NPV results considering the production in Mexico and the selling in the US with and without incentives.

Overall, locating the plant in Mexico to sell in the US increases NPV by between 300% and 551% if incentives can be secured, compared to the case in which the fuels are sold in Mexico.

6 Conclusion and Future Work

This thesis is the first to quantify the economic feasibility of producing renewable jet fuel and diesel fuel from waste vegetable oil using the HEFA technology in Mexico. The economic analysis finds that the construction and operation of a biofuels plant in Mexico can be economically feasible. The analysis shows that a 4,000 BPD plant located in Mexico can reach a positive NPV of approximately $80 million over a 20-year operating period at an internal rate of return of 15% percent. The minimum selling price for reaching this internal rate of return is $2.21 per gallon for diesel and $2.36 per gallon for jet fuel. The economies of scale analysis shows that if the capacity of the plant is increased to 6,500 BPD, the NPV increases to approximately $180 million. The sensitivity analysis shows that NPV reaches zero at an internal rate of return of 24% discount rate and that the maximum buying price of the waste vegetable oil at the baseline internal rate of return of 15% percent the plant can afford to procure is $0.73 per gallon, which is 36% higher than the 2013 year average price. In addition, the economic analysis shows that if the biofuels are exported to the US, NPV could increase up to $294 million for the 4000 bpd facility, using the incentives currently offered by the US Government. The plant investigated will produce up to 980,000 barrels per year of biofuels, helping to reduce GHG emissions and contributing to Mexico's GHG reduction goals.

Given the recent energy sector reform approved by the Mexican Congress,[93] which partially and progressively deregulates the oil and electricity industries and opens them to private investment, the energy industry in Mexico will substantially change. These changes will modify the production and selling prices that were used in this analysis; therefore, the data should be adjusted accordingly when used for future projections. Moreover, an in-depth analysis of regulation and taxation applicable for production in Mexico should be conducted. Finally, future work could investigate the economics of building a first-of-its kind biorefinery as opposed to the Nth plant analysis conducted in this thesis, the logistical challenges in securing reliable waste vegetable oil feed for the biorefinery and the actual GHG emissions of the fuel production pathway as proposed in the Mexican context.

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