Biofuel Production Methods Based on Icelandic Feedstocks: An Environmental and Economic Comparison

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HÁSKÓLI ÍSLANDS

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ABSTRACT

Due to rising concerns of energy security and the environmental implications of using fossil fuels, there is a need to explore other fuel options. The objective of this thesis is to compare different biofuel production methods from an environmental and economic perspective and to evaluate potential implications for Iceland. The environmental implications are assessed using a “well-to-tank” (WTT) perspective, meaning in general terms the boundaries extend from the cultivation and harvest, feedstock transport, biofuel production, and finally biofuel transport. Economic implications are assessed using conventional break-even point analysis.

Results indicate that when bioethanol is produced from timber employing a biochemical conversion method, this yields the least impact (7.26 CO₂ eq. g/MJ) to environmental categories such as global warming potential (GWP), however if using the thermal-chemical platform, the utilization of timber to produce Fisher-Tropsch biodiesel (FTD) has the least impact to acidification potential (AP) (01 to .14 SO₂ eq. g/MJ). At the same time, FTD had the highest and lowest impact to POCP, depending on the feedstock (.01 to .09 C₂H₄ eq. g/MJ). Both types of technology reported the same in regard to eutrophication potential (EP) and that the application of fertilizer from cultivation had the largest impact. In contrast, when the organic fraction of municipal solid waste is used to make bioethanol and biodiesel from rapeseed this yielded the largest impact to GWP (86 to 80 CO₂ eq. g/MJ) explained by the high moisture content, transportation and low lignin content. However, more research is needed to estimate the environmental impact in the production of biofuels in Iceland, based on Icelandic circumstances.

In conclusion based on quantity estimates of the selected Icelandic feedstocks and assuming that equal hectares of land as already cultivated land, is transformed to producing energy crops and increasing forest cover by 300%, beyond what is already planned, the potential quantity of displaced petroleum products in Iceland ranges from <0.1 % (FTD-recycled newspaper) to 68% (second generation bioethanol from wheat).
ACKNOWLEDGEMENTS

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AP</td>
<td>Acidification Potential</td>
</tr>
<tr>
<td>B20</td>
<td>80% diesel, 20% biodiesel</td>
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<td>B100</td>
<td>100% biodiesel</td>
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<tr>
<td>CPI</td>
<td>Consumer price index</td>
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<td>E85</td>
<td>85% gasoline, 15% bioethanol</td>
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<td>EP</td>
<td>Eutrophication Potential</td>
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<td>FTD</td>
<td>Fisher-Tropsch diesel</td>
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<td>GHG</td>
<td>Greenhouse gases</td>
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<td>GWP</td>
<td>Global Warming Potential</td>
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<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>LCI</td>
<td>Life Cycle Inventory</td>
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<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<td>LHV</td>
<td>Lower heating value</td>
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<tr>
<td>MJ</td>
<td>Mega joule</td>
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<tr>
<td>OFMSW</td>
<td>Organic fraction of municipal solid waste</td>
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<tr>
<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
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<tr>
<td>POCP</td>
<td>Photochemical oxidant potential</td>
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<tr>
<td>RME</td>
<td>Rapeseed Methyl Ester</td>
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<tr>
<td>RON</td>
<td>Research octane test</td>
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<tr>
<td>RTFO</td>
<td>Renewable Transport Fuel Obligation</td>
</tr>
<tr>
<td>WTT</td>
<td>Well-to-tank perspective</td>
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<tr>
<td>WTW</td>
<td>Well-to-Wheels perspective</td>
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1 INTRODUCTION

Estimates from the Organization of Petroleum Exporting Countries (OPEC) state that global economic growth is expected to rise 50% between 2006 and 2030\(^1\). Accordingly, this growth will lead to an increase in energy demand and thus far fossil fuels have been the main source for fueling 85% of the world’s need for energy. Due to concerns such as resource depletion, environmental degradation, economic and energy security, attention has been redirected to alternative renewable energy sources.

Within the transportation sector, production and use of alternative fuels is one option to counter the rising concerns associated with climate change. Of the different options for different fuels are the so-called biofuels. Biofuels are derived from renewable energy sources and according to United Nations Framework Convention on Climate Change have been defined as carbon neutral. As a result, an increase in the share of biofuels is expected to significantly contribute to the mitigation of climate change. As a fraction of total emissions of greenhouse gasses, and as one of the largest consumers of primary energy the transportation sector consumes 27% of the world’s primary energy (Antoni, Zverlov et al. 2007) and its importance is growing as less developed countries build their transportation infrastructure. The sector is responsible for emitting 15% of anthropogenic energy-related GHG emissions and its share is expected to increase (Schafer 2000).

The increase in demand for transportation fuels and its corollary increase in greenhouse gas emissions have prompted enhanced pressures on increased biofuel use in the transportation sector. At present, bioethanol is the most widely used alternative transportation fuel, and numerous countries are encouraging the penetration of biofuels into their markets. For example, under the Renewable Transport Fuel Obligation (RTFO), the British government had said that by 2010, 5% of UK’s fossil fuel derived transportation fuels be displaced by biofuels where the feedstock used is harvested using sustainable sources. The European Union has commitments of incorporating biofuels by 10% into its portfolio of

transportation fuels by volume. In the United States, bioethanol production has increased from 4 billion liters in 1996 to 14 billion in 2006, and is expected to continue to increase (Dufey 2006).

In contrast to e.g. Norway, Iceland imports all petroleum products, while there is only one landfill piping system capturing biogas to convert to methane. Consequently the cost of fuel purchases was 27.6 billion ISK in 2005, up from 17.8 billion ISK in the year 2000\(^2\). Since 1990 the vehicle fleet has increased by 70% and according to Statistics Iceland gas-powered registered vehicles had reached approximately 240 thousand in 2007 (Hagstofa Íslands). This has led to an increase in greenhouse gas emissions, but emissions from the transportation sector has increased by 74% between 1990 and 2006 (Umhverfisstofnun official data, www.ust.is).

Figure 1 illustrates the distribution of greenhouse gas emissions by source in Iceland in 2006. The figure illustrates that almost one third of all emissions are linked to the transportation sector.

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2 http://eng.umhverfisraduneyti.is/media/PDF_skrar/Stefnumorkun_i_loftslagsmalum_en.pdf
3 http://eng.umhverfisraduneyti.is/media/PDF_skrar/Stefnumorkun_i_loftslagsmalum_en.pdf
In total, the National Inventory Report for 2008 stated that in 2006, greenhouse gas emissions were estimated to be 4.234 Gg CO₂-equivalents. Iceland’s total emissions in 2006 were 24.3% above 1990 levels and 8.5% above the 1990 levels when activities under Article 3, paragraph 3 and 4 of the Kyoto Protocol are accounted for.

Actions to lower Iceland’s emissions lead to the adoption of a new climate change strategy by the Icelandic government in February 2007. The Ministry for the Environment formulated the strategy in close collaboration with the ministries of Transport and Communications, Fisheries, Finance, Agriculture, Industry and Commerce, Foreign Affairs and the Prime Minister’s Office. The long-term vision of the strategy is to reduce net greenhouse gas emissions in Iceland by 50 – 75% by 2050, compared to 1990 levels. Yet within this Strategy there are no mechanisms in place that introduces a solid plan to dramatically decrease the use of fossil fuels in the transportation sector and therefore Iceland’s dependence on oil for its transportation sector.

1.1 Research Questions
These issues provide the grounding for this research project, which is to focus on three main research questions:

1. Based on suitable Icelandic biomass feedstocks, what are the environmental implications of different biofuel conversion technologies and feedstocks?
2. Based on the most environmentally benign technology, current and future oil prices, and productions costs, when does producing biofuels become profitable?
3. Based on Iceland’s current oil consumption patterns within the transportation sector, what percentage of total energy use in the transportation sector can be displaced at a maximum if Iceland’s chooses to begin producing it owns biofuels?

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4 http://www.ust.is/media/ljosmyndir/mengun/National_Inventory_Report_2008.pdf
5 http://eng.umhverfisraduneyti.is/media/PDF_skrar/Stefnumorkun_i_loftslagsmalum_en.pdf
To approach the first question earlier studies that evaluated the environmental implementations of biofuel production from a Well-to-Tank (WTT) life cycle perspective were compared and analyzed. Afterwards the results from the studies are standardized into a format that presents the environmental burden expressed in the form of different types of emissions, when one MJ is delivered to the tank. The WTT perspective in regard to biofuel production includes the production of inputs, agriculture and harvesting, transport of material, and the conversion process. The second question will be addressed by a general economic assessment that estimates a potential period when certain biofuel production platforms become profitable based on retail price of biofuel, productions costs, and potential quantity estimates. Finally, to assess if Iceland can self sufficiently produce its own biofuels, a comparison will be made between current consumption patterns within the Icelandic transportation sector and potential production of biofuels derived from Icelandic feedstock.

Results from this analysis will be fed into a larger project that is investigating alternative fuel options in Iceland and in an upcoming study, focus will be placed on the use of the fuels or a “tank-to-wheel” study. The combination of these two reports will provide key decision makers in Iceland about possible outcomes based on the production and use of alternative fuels.

1.2 Thesis structure
To address these research questions the structure of this report will be organized by first discussing general trends related to the consumption and production of biofuels, leading into an overview of three general conversion platforms for biomass into biofuels. This is followed by an identification of viable options for biofuel feedstocks in Iceland, leading into a description of what a life cycle assessment is and the methodology that was developed in this analysis to allow an environmental comparison between different studies. To compliment these results, an economic evaluation is included followed by a discussion that contrasts the environmental and economic implications of using different feedstocks and biofuel production methods.
2 General Introduction to Biofuel Production Methods

The upcoming sections are divided into two main parts. The first serves the role of describing recent trends in consumption and production that are related to biofuels followed by a discussion of different conversion technologies for biofuel production.

Biofuels are generally classified as either being a first generation biofuel or a second generation biofuel, the distinguishing factor being its biomass input source, which may also determine the production pathway. First generation biofuels are based on mature technology and are produced from energy crops, and according to Zinoviev (2007) bioethanol, biodiesel, and biogas (from anaerobic digester) are considered to be the most important. Although biogas is not from an energy crop because the technology is well established it is often categorized as a first generation fuel. Biofuels produced from food crops are commercial today with almost 50 billion liters of bioethanol and 5.4 million tons of biodiesel produced worldwide in 2006 (Zinoviev November 2007). For these types of fuels only easily extractable parts are used and the by-products such as press cake, the remains of the converted biomass from vegetable oil production, for example, are typically used for fodder or chemical purposes.

Second generation biofuels are of wider range and are essentially based on non-crop feedstocks. The fuel can be converted either through a bio-chemical process (hydrolysis) or a thermo-chemical process (pyrolysis). The raw gas produced from the thermal-chemical process is then treated and conditioned into synthesis gas (syngas), which mainly consists of carbon monoxide and hydrogen. Syngas can then be further processed into different types of liquid and gaseous fuels. Hence, fuels produced from this route are called ‘synthetic biofuels’. “The most promising liquid synthetic biofuels, also called BtL: biomass to liquids, are biomethanol and Fisher-Tropschs fuels” (Zinoviev 2007, p.22). However, the status of second generation biofuels is still in developmental stages and has not reached commercial scale to date.
One main objective of this thesis is to provide a comparison between different biofuels and the environmental implications that are associated with each production system. In order for this to occur there must be a complete introduction of general production routes, creating an awareness of potential energy requirements and environmental outputs of the different conversion platforms. By providing these descriptions of different biofuel conversion methods it provides the reader with a general background to clearly understand the stages and possible levels of energy requirements to convert the raw material to biofuel.

The next sections provide background information that establishes the patterns in demand for different types of biofuels. This will then lead into a discussion describing general production routes for biofuel production methods.

2.1 Liquid Biofuels
Biofuels, in solid form such as wood, for example, have long been used by man, but it wasn’t until the late 1800’s when two German inventors, Nikolaus August Otto and Rudolf Diesel first suggested the use of liquid biofuels as options for automobiles. Despite these developments related to liquid biofuels, the discovery of crude oil, which at that the time was a cheaper and more efficient option, forced this interest to shift from liquid biofuels to fossil fuels.

Today we return to seeking alternative fuel options due to the possibility of scarce supplies, rising costs of petroleum products and the environmental implications from extraction and use. In this attempt, focus has been redirected to biofuels. Thus far bioethanol and biodiesel (1st generation) have made a solid stance in the market because these biofuels fill the criteria of what constitutes a good motor fuel: preferably a liquid or easy to handle gas, stable, easy to transport and store, having a high energy to mass ratio, and inexpensive (Wackett 2008). For these underlying reasons, biofuels that are produced from food crops are commercial today with almost 50 billion liters of bioethanol and 5.4 million tons of biodiesel produced worldwide in 2006 (Zinoviev November 2007).
Currently the European Union is the world leader in the production and consumption of biodiesel with the primary feedstock being rapeseed, while Brazil is the world leader in producing bioethanol from sugar cane. In both cases production and consumption has increased over the past few years. Error! Reference source not found. illustrates the dramatic increases in production for both bioethanol and biodiesel in the EU -27 most notably between 2005 and 2006. Comparatively, 6,400 million liters of biodiesel were produced in 2007 and on average a + 35% per annum between 1992 -2007⁶.

![Graph of bioethanol and biodiesel production in EU-27](image)

**Figure 2: Evolution of bioethanol and biodiesel production in EU -27. Bioethanol is represented in the first graph and biodiesel is depicted on the right (ML/year).**

These increases in production are linked to the ease at which these fuels may be transformed and their ability to be blended in any ratio with conventional diesel and gasoline which can extend the supplies of petroleum products and increase the octane content. Certain countries such as Austria and Germany are using pure biodiesel (B100) as a fuel for agricultural tractors and road vehicles. B20 and B100 are the two most often used bio-diesel variants.

The B20 (20% biodiesel and 80% conventional diesel) was originally chosen as an optimum blend, achieving both reductions in exhaust emissions and fuel cost, as no investment is required in new infrastructure when switching to biodiesel. Studies showed that B20 provided about a 14% decrease in particulate matter emissions, a 9% decrease in CO and a 7% decrease in hydrocarbons, compared with conventional diesel. However, emission tests revealed it also entailed a 2%

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increase in NOx. To correct this problem a small adjustment to the engine’s injection timing must be made.  

Like biodiesel and its variants, using ethanol reduces emissions and particulate matter because of its chemical properties. Bioethanol contains 35% oxygen and has a lower heating value (LHV) of 21.1 MJ/L which is lower than petrol (32.2 MJ/L). When blended with gasoline as E85 (15% bioethanol and 85% gasoline) this increases the octane value and its efficiency in combustion and replaces 28 MJ/L of petrol. Thus 1 L of E85 displaces .84 L of petrol while, biodiesel replaces approximately .80 L of diesel.

The combination of displacement from fossil fuels, environmental gains from use, and ease of production for biofuels from food crops has pushed bioethanol and biodiesel to the forefront and explains their status in today’s market.

2.2 Compressed Natural Gas

Like bioethanol and biodiesel, biogas is another biofuel option. Sources of biogas include landfills, manure, or dedicated energy crops such as maize. In 2007, the Biogas Barometer, a study by the European Commission-backed EurObserv'ER research organization showed that the amount of biogas produced in 2006 was 20.5% higher than in 2005, at 5.9m tons of oil equivalent (5.9mtoe). Of this amount, biogas from landfill accounted for 49.2%. Another reason why the use of biogas has gained more attention is because the gas may be cleaned and used for the production of energy and electricity. Error! Reference source not found. is a map illustrating the primary production of biogas from landfills, sludge, and agricultural waste. Of these three sources, biogas captured from landfills accounted for the largest percentage in 2007. In the case of Europe, most are using the methane to produce electricity. Overall, the production of electricity from biogas grew by 28.9% in 2006 and Germany remains the European leader and noted a 55.9% growth in 2006 in electricity generated from the renewable gas.

Already 99% of Iceland’s electricity is generated from renewable geothermal and

Already 99% of Iceland’s electricity is generated from renewable geothermal and hydropower with an installed capacity of 2,243MW\(^9\). However, according to Björn Halldórsson (Personal communication, November, 2008), approximately 15% of captured methane is used for transport fuel while the remaining 85% is either flared or delivered to the grid for electricity production. Lack of demand from consumers for methane filled vehicles explains this distribution (Personal communication, Björn Halldórsson, November 2008).

As a transportation fuel the gas has a very high octane (RON = 110-130) giving it the potential for use in a high compression engine. Consequently engine performance is reduced with methane because the volume of the gas reduces

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\(^9\) http://www.os.is Accessed November 2008

the air breathing capacity of the engine\textsuperscript{11}. Despite this, production and utilization is increasing due to the positive gains relating to waste treatment issues and the environmental benefits of capturing a potent greenhouse gas. As a result in Sweden, for example, roughly 600 buses and 10,000 light and heavy vehicles use biogas, and currently in Iceland a platform has been established that captures biogas from a landfill, Álfsnes, which has the potential to fuel 3 to 4 thousand smaller vehicles\textsuperscript{12}.

\textsuperscript{11} \url{www.wikipedia.com} Accessed February 2008.
\textsuperscript{12} \url{http://www.metan.is/bindata/documents/Driving_sep07A_00064.pdf} Accessed October 2008
3 CONVERSION TECHNOLOGIES FOR BIOFUEL

Biofuels are deemed to be a renewable energy source and may be produced from biomass and organic waste. Biomass is a renewable resource that is constantly being made from the interaction of water, air, soil, and sunlight. If biomass is not harvested for energy purposes, then microorganisms break down the biomass into basic elements, releasing CO$_2$ or methane depending on aerobic conditions. When biomass is harnessed for energy purposes, technology is attempting to mimic the natural process that occurs in nature. In fact, depending on the input source and technological conversion methods required to produce the desired fuel, this determines how the biofuel will be classified.

Figure 4 provides the fundamentals for understanding biofuel conversion platforms. Mature and established technology can harness the energy that is stored in the simple sugars (i.e. cellulose) and what newer technology is attempting to do is to capture all components, thereby increasing conversion efficiency and achieving economies of scale.


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13 http://genomics.energy.gov/gallery/biomass/thumbnails/552.jpg
Biofuels in general are classified into three categories commonly known as first generation, second generation and third generation fuels\textsuperscript{14} and the classification system has already been discussed in a previous section. To lead into a discussion of general biofuel production and why focus has shifted to second generational biofuel Figure 4 must be described. There are three main components of biomass: cellulose, hemicelluloses, and lignin. Cellulose is the most common form of carbon in biomass, accounting for 40%-60% by weight, depending on the biomass source. It is a complex sugar polymer, or polysaccharide, made from the six-carbon sugar (C6), glucose. Its crystalline structure makes it resistant to hydrolysis. Hemicelluloses is also a major source of carbon in biomass, at levels of between 20% and 40% by weight. It is a complex polysaccharide made from a variety of five- and six-carbon sugars (C5). It is relatively easy to hydrolyze into simple sugars but the sugars are difficult to ferment to ethanol. Lignin is a complex polymer, which provides structural integrity in plants. It makes up 10% to 24% by weight of biomass. It remains as residual material after the sugars in the biomass have been converted to ethanol. It contains a lot of energy and can be burned to produce steam and electricity for the biomass-to-ethanol process.

Put simply, first generation fuels capture less than a third of the biomass content, greatly limiting potential quantity. Second generation fuels are of wider range, are based on non-crop feedstocks and can include by-products, residues from organic matter, or organic waste in addition their production methods include ways to capture and utilize the remaining biomass content.

To capture this remaining biomass, it may be converted to fuel either through a bio-chemical process (hydrolysis) or thermo-chemical process (pyrolysis), and both techniques have not reached maturity. Figure 5 depicts the numerous production routes for both 1\textsuperscript{st} and 2\textsuperscript{nd} generation biofuels. A key observation from Figure 5 is that there are many intermediate steps involved for the production of biofuel, especially for second generation biofuels. Consequently

\textsuperscript{14} Third generation fuels will not be discussed in this report for they are only in the very beginning stages of R&D, but these are fuels that are produced from feedstocks that have been chemically engineered to enable faster and more efficient breakdown of required compounds.
each process will require energy and produce either valuable or negative coproducts.

To evaluate these processes the upcoming sections are organized into three parts discussing the three main platforms for biomass conversion to biofuel and these include: Thermo-Chemical Conversion; Physical-Chemical Conversion; and Bio-Chemical Conversion. The intent is to provide an overview and to introduce the possible environmental concerns that are associated with each process.

3.1 Physical-Chemical Conversion
Under this particular platform either vegetable oil or biodiesel derived from oil plants such as rapeseed are the general outputs. Figure 6 illustrates the general inputs and outputs required for biodiesel production.
Biomass that has a high free fatty acid content must undergo a pretreatment using distillation. More specifically, it goes through an acid esterification process to increase the yield of biodiesel. These feedstocks are also filtered and preprocessed to remove water and contaminants, and then fed to the acid esterification process. The catalyst, sulfuric acid, is dissolved in methanol and then mixed with the pretreated oil. The mixture is heated and stirred, and the free fatty acids are converted to biodiesel. Once the reaction is complete, the mixture is dewatered and then fed to the transesterification process.

Within this process, the pressing and extraction by organic solvents are performed. Compared to cold pressing (at temperatures not higher than 60 °C), hot pressing at temperatures of 110–120 °C yields a larger quantity of oil. However, 6–7% of oil is left in the cake, the remains of the pressed biomass, even when slow presses are used. Cold pressing method requires less energy for processing of 1 t of seeds and there are less phospholipids in the oil, which is desirable in the production of the biodiesel fuel. However, 12–14% of oil is left in the cake. Using the extraction method, only 0.1–0.8% of oil is left in the cake (Unger 1990). However, the quantity of phospholipids in the hexane-extracted oil is twice as high compared to that in the pressed oil (Makareviciene 2001). For this reason, additional energy consuming operation of oil degumming is required before transesterification.

To complete the transesterification process, an alcohol (like methanol) reacts with the triglyceride oils forming biodiesel and glycerin. This stage requires

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approximately 110 kg of alcohol per 1000 kg oil and is carried out at approximately 60 °C under atmospheric pressure, as alcohol boils off at higher temperatures. Under these conditions, the reaction takes about 90 min to complete. To expedite the process, a higher temperature can be used in combination with higher pressures, but at added cost (Chisti 2007). If the feedstock required acid esterification an extra base catalyst must be added to neutralize the acid added in the beginning of the process, in addition to potassium hydroxide which is dissolved in methanol and then mixed with and the pretreated oil (Chisti 2007). Once the reaction is complete, the major co-products, biodiesel and glycerin, are separated into two layers.

After this reaction the methanol may be recovered from the biodiesel and recycled into the process. In addition to the methanol recovery, the biodiesel goes through a clean-up or purification process to remove excess alcohol, residual catalyst and soaps. This consists of one or more washings with clean water. It is then dried and sent to storage. Sometimes the biodiesel goes through an additional distillation step to produce a colorless, odorless, zero-sulfur biodiesel.

The glycerin must also undergo refining to remove unreacted catalyst and soaps that were neutralized with an acid. One by-product is cake, the remains of the rapeseed plant, which may be used for animal meal. Once the water and alcohol are removed the product is 50%-80% crude glycerin. If the glycerin is to be used for market applications it must be further purified to remove the remaining contaminants of unreacted fats and oils.

3.2 Thermal-Chemical Conversion

Under this category, two types of conversion technologies that yield biofuels, from a wide range of sources exist for gasification and pyrolysis. If gasification is employed then biomass may be converted only to biomethane. Pyrolysis involves producing syngas, which is a combination of carbon monoxide and hydrogen which may further be synthesized into a liquid biofuel by employing Fisher-Tropsch synthesis, for example. Therefore processes that are related to gasification serve as the building blocks for pyrolysis.
In the process of gasification, methane is produced. Methane (CH₄) is a biogas that is produced natural gas or biomass waste under different anaerobic conditions and is 21 more times potent than carbon dioxide in terms of global warming potential. Energy content is higher for municipal waste and that is mainly because the sludge digestion contains about 60 to 70% methane with an energy content of about .63 MJ per cubic foot (MacLean and Lave 2003).

There are two main ways to capture biogas, which may then be processed to meet the same specifications as compressed natural gas. One option is to collect municipal waste, sewage, or manure for example, and to place the contents into an anaerobic digester. In the absence of oxygen, this step serves the purpose of extracting the methane gas that is formed from this process. The other option is to collect the biogas from a landfill using a piping system, which Iceland has already established.

In either case once the biogas has been captured it must undergo two main processes. First the moisture must be removed by the use of dryers. After the water is removed the three main elements that found are carbon, (50% by weight), hydrogen (5% by weight), and oxygen (45% by weight). Secondly before the methane is transformed to pipeline quality it must be cleaned of impurities such as hydrogen sulfide (H₂S), using water scrubbers and filters removing them (see Figure 7).

It is important to remove these impurities because of their adverse affect on the fuel. For example, hydrogen sulfide (H₂S), will affect the vehicle engine by causing corrosiveness. Despite this, from extraction to use it is generally accepted that biogas will provide a 95% reduction in CO₂ and 80% lower emissions of NOx in addition to other environmental benefits.
Pyrolysis is classified as a thermal chemical platform because it not only employs high temperature gasification but also requires chemical processes for the pretreatment of the biomass material, and if the syngas (carbon monoxide and hydrogen) is going to undergo synthesis a catalyst will be required. One note regarding pretreatment is that the material must be generally be microcrushed to break down the biomass, making it more amiable for the acid to break down the cells’ wall. This can be a very energy intensive process. Afterward the remains are then fed into a boiler along with gasifying agents that include oxygen and steam.

During the gasification typical operating temperatures are around 850°C are used and through this process the gases produced this route will include hydrogen (47.7%), carbon monoxide (18.7%), carbon dioxide (29.3%). After the syngas has been created it is cleaned removing the tar and ash which are the main by-products. Biomass ash has also the potential to be used as a clarifying agent in water treatment, as a wastewater adsorbent, as a liquid waste adsorbent, as a hazardous waste solidification agent, as a lightweight fill for

**Figure 7:** A general production scheme for landfilled captured biogas. Source: Zionoviev et al. (2007).
roadways, parking areas, and structures, as asphalt mineral filler, while the tar must be removed and disposed of.

The removal of the by-products produces a suitable gas that may then be converted into a Fisher-Tropsch Diesel or methanol. Fisher-Tropsch synthesis is a catalyzed chemical process that converts the syngas into liquid hydrocarbons. Most generally the common catalysts used for this process involve iron and cobalt. Methanol via pyrolysis demands extreme pressurization of the syngas. This option to produce different types of liquid biofuel demonstrates one advantage of pyrolysis over the bio-chemical platform, which will be discussed next. Figure 8 is a schematic illustration showing the production flow employing pyrolysis technology and Fisher-Tropsch synthesis.

![Figure 8: BTL production process employing thermal chemical technology. Link to view animation of process](http://www.choren.com/swf/carbo_v_en.htm)

3.3 Bio-Chemical Conversion
Under this platform, the sugars that are produced by the plants such as sugar cane and sugar beet can be fed directly into the fermentation process, while starches such as corn or grain require a hydrolysis reaction, known as saccharification, to convert starches to sugars before fermentation. Recent research indicates among the different technologies that dilute acid hydrolysis

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followed by enzymatic hydrolysis is less expensive and more efficient (Chandel, Chan et al. 2007).

The draw to lignocellulosic biomass can be explained giving three reasons. First, there are a greater number of possible input sources. Chandel, Chan et al. (2007) reviewed possible input sources for second generation ethanol and found 28 different input options, including banana pulp waste, industrial waste, aspen, municipal solid waste, and paper products. Secondly, there are more sugars that may be derived, which is a vital step towards increasing lignocellulosic yield (Huber and Corma 2007). Finally, depending on the type of biomass and its lignin content, it has the potential to supply electricity to support the biofuel production (Kemppainen and Shonnard 2005).

Figure 9 is a general illustration of the steps involved in bioethanol production. The first step is biomass handling, which involves harvesting, storage, and transport, all of which demand resources and energy. Depending on the area of land and size of facilities will contribute either positively or negatively from those three processes (Bernesson, Nilsson et al. 2004). Of these three, storage of plant material can be a critical issue because storing can lead to loss of material and leaching of materials can cause problems requiring wastewater treatment (Gislerud 1990). Storage may provide opportunity for reducing the impact of some pre-treatment methods for second generation ethanol because while in storage agents that help make the plant material more amenable to processing and reducing costs can be introduced.
Figure 9: Schematic illustrating the ethanol fuel production17.

Because this material is chemically complex it must undergo pretreatment before hydrolysis (See Figure 9). The purpose of pretreatment is to alter the size and structure of the chemical composition increasing the efficiency and supporting higher yields created from the process of hydrolysis (Mosier, Wyman et al. 2005). Of the four major operations, pretreatment is the most expensive processing step with cost as high as 30 cents/gallon ethanol produced (Mosier, Wyman et al. 2005).

Once the pretreatment is completed, the feedstock must be hydrolyzed into monomeric sugar constituents required for fermentation into ethanol. There are different methods available to employ, but the most commonly used are enzymatic and dilute acid hydrolysis (Chandel, Chan et al. 2007). Essentially to improve enzymatic hydrolytic efficiency the goal is to loosen the lignin-hemicellulose network and improve the amenability of celluloses to residual carbohydrate fraction for sugar recovery. The other option mentioned is the use

of acid which degrades the hemicelluloses leaving only the lignin and cellulose network.

After hydrolysis has been employed the sugar syrup is used for ethanol fermentation. Typically yeast is the agent which is used to ferment sucrose or glucose from starch. In some cases bacterium may be used because it offers higher specific productivity, ethanol yield (grams per gram) and high alcohol tolerance. Unfortunately neither of these organisms can convert pentose (C5) sugars derived from hemicellulose. Currently there are different variations available or being researched. For example, researchers are focusing on recombinant yeast, which can greatly improve the ethanol production yield by metabolizing all form of sugars (C6 and C5 sugars), and reducing the cost of operation. In order for this to occur the yeast must be genetically engineered (Chandel, Chan et al. 2007). In general the process can take about 45-70 hours (see Figure 9).

Theoretically the maximum conversion efficiency of glucose to ethanol is 35%\textsuperscript{18}. In practice, assuming moisture content of 12% 1,000 kilograms of fermentable sugar produces roughly 300 liters of pure ethanol.

After the sugars have been fermented, ethanol must be separated from a dilute solution which is a particular energy intensive step\textsuperscript{19}. Ethanol and water form an azeotrope, or constant boiling solution, of about 95 percent alcohol and five percent water. The five percent water cannot be separated by conventional distillation. The production of pure, water-free ethanol requires a dehydration step following distillation. Dehydration, a relatively complex step in ethanol fuel production, is accomplished in one of two ways. The first method uses a third liquid, most commonly benzene, which is added to the ethanol/ water mixture. This changes the boiling characteristics of the solution, allowing separation to pure ethanol. The other method employs molecular sieves that selectively absorb water on the basis of the difference in molecular size between water and ethanol.

\textsuperscript{18} This conversion ratio also applies to second generation biodiesel. www.iea.org.

\textsuperscript{19} royalsociety.org/displaypagedoc.asp?id=28914 Accessed February 2008
The by-product of this process is wastewater, also known as effluent, occurring both from the fermentation processes and distillation, although the water can be recycled back into the process once treated to recover the chemical or biological catalysts and remove other impurities. About 9 liters of effluent are produced for each liter of ethanol. Effluent can have a high biological oxygen demand (BOD), which is a measure of organic water pollution potential, and it is acidic. Treatment requirements depend on feedstock and local pollution control regulations. Because of the acid content, care must be taken if the effluent is spread over fields.

One co-product of this production method is mash or the remains of the biomass that may be used as animal meal. Mash typically contains between 50 and 100 grams of ethanol per liter (5 to 10 percent weight per volume) when fermentation is complete. The non-fermentable solids in distilled mash (stillage) contain variable amounts of fiber and protein, depending on the feedstock. The liquid may also contain soluble protein and other nutrients. The recovery of the protein and other nutrients in stillage for use as livestock feed can be essential for economical ethanol fuel production. If the processing equipment is constructed of stainless steel and processing is carried out under well-controlled conditions, the protein by-products can also be consumed by humans.

Other intermediate products, including glucose, galactose, mannose, xylose, and arabinose may be relatively easily processed into value-added bioproducts (Mabee 2006).
4 BIOMASS FEEDSTOCKS AND QUANTITY ESTIMATES

One objective of this analysis is to assess Iceland’s potential to achieve energy independence by producing its own biofuels and thereby eliminating the need to import oil for transportation needs. To fulfill this objective entails identifying potential biomass options for biofuel production. Through personal communication with agricultural experts (Jón Guðmundsson, Ólafur Eggertsson 2008) in Iceland and a literature review, five biomass inputs suitable to Icelandic conditions were selected. These include:

- Timber
- Newspaper
- Municipal Solid Waste
- Winter wheat
- Rapeseed

This however, does not imply that there are not others that potentially could be included such as manure. Below are brief summary statements corresponding with each feedstock that was selected to fall within the study boundaries and include the amount of biomass (kg) that will be used to calculate potential yield for the selected fuels. The potential quantity of each feedstock and derived biofuel quantities are estimated for the year 2030 by pushing the potential quantity up to its limits to provide a clear understanding what the maximum quantities may be. In all cases, the forecasts were based on information derived from either agricultural and forestry experts, or from the consulting firm Mannvit, who specialize among other things in waste management.

4.1 Timber
Timber is one renewable biomass option that may be used to produce biofuels. In 2007 approximately 5.5 thousand tons of unstained timber were sent to Sorpa, which is an independent firm responsible for waste disposal in six municipalities in Iceland. Based on weight and assuming 12% moisture content and a 35% conversion ratio this yields 1,694 liters of bioethanol. Timber is already utilized to produce ferra-silicon which may exclude this as a viable option. Another
option is to convert arable land that is available for cultivation and set it aside to
grow trees to be used as a feedstock. Currently there is approximately 10,000
m³ available for wood fuel and this number is expected to rise to 30,000 m³ in
2030 providing timber to become a viable option for biofuel production (Personal
communication, Ólafur Eggertsson, January 2009).

4.2 Newspaper
The utilization of newspaper, which can be classified as municipal solid waste is
one option that may be used to produce biofuels. In 2007 2.7 thousand tons
were sent to Sorpa to be sent to Sweden where it is recycled into other paper
products. Biofuel derived from newspaper may either be produced via the bio-
or thermochemical pathway. If hydrolysis is employed to convert the feedstock
the final product will be bioethanol, while the other conversion route (pyrolysis)
may be used to produce other biofuel options.

4.3 Municipal Solid Waste
According to Sorpa, a study conducted in 2005 revealed that for Sorpa,
Suðurnes, Suðurland, and Vesturland, 223,992 tons of organic biomass was
mixed in MSW and for the entire country was around 297 thousand tons
(Mannvit 2008, Unpublished report). This includes 24 different categories for
biomass such as slaughter, food, hay, and yard waste and newspaper that is not
recycled. If it is assumed that the organic fraction of MSW is expected to stay at
61%, and that MSW per capita will increase by 0.6% per year, and using
population size estimates from Hagstofan (as cited by Mannvit, 2008) - the
organic fraction of MSW is expected to increase by 44% by 2030. Based on this

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21 To be more specific, Iceland plans to predominately reforest by planting either pine or birch.
Between these two birch has a higher density between the range of (481 to 494 kg/m³) while pine
has a lower density of 407kg/m³ to 435 kg/m³ [Lindblad, J. and E. Verkasalo (2001). "Basic
density and conversion factors for industrial and pulpwood chips." Paperi ja puu 83(6): 458-461.].
For increased quantities it is obviously better to use timber that has a higher density which in this
case is birch. In this analysis potential quantity was estimated assuming the lower density for
birch because according to Lindblad and Verkasalo (2001) there is a regional difference and trees
that grew in the southern part of Finland had a higher density. Since Iceland is geographically
higher in latitude it was decided to use the lower density value.
assumption, the organic fraction of MSW is expected to be approximately 428 thousand tons. This value is used to calculate the potential yield for different types of biofuels in 2030.

4.4 Winter Wheat
Current research has concluded that winter wheat may be grown in Iceland but currently only in the most southern regions as it does not survive the winter elsewhere in Iceland. The harvest ranges from 4.5-6.0 tons (dry matter) of wheat per hectare, applying 120 kilograms of Nitrogen per hectare (Personal communication, Jón Guðmundsson). However given potential climatic changes due to climate change, the growing range is likely to expand. According to Jon Guðmundsson approximately 130 thousand hectares are cultivated in Iceland.

Assuming at a maximum, a land area equal to this size, either derived from transforming already cultivated land to producing winter wheat or by cultivating new land, in addition to using the lower range for yield per hectare, sets upper boundary conditions for the amount of wheat being produced and used as a feedstock in 2030.

4.5 Rapeseed
According to Jón Guðmundsson (2008), rapeseed is a possible feedstock and is available in both winter sawn and spring sawn variants. The spring sawn variant does not develop mature seeds but the winter sawn does, and it has survived the two winters tested so far (Jón Guðmundsson, personal communication). The harvest is 2.8-3.2 tons (dry matter) per hectare, applying 120 tons of Nitrogen per hectare (personal communication, Jón Guðmundsson). Assuming the lower yield value, that the dried oil seeds have a 45% oil content and oil extraction efficiency of 98%, this yields approximately 1164 L per hectare (3000 kg of dry matter). Assuming at a maximum, as was done for winter wheat, a land area equal to already cultivated land, either derived from transforming already cultivated land to producing rapeseed or by cultivating new land, sets upper

boundaries on the amount of rapeseed possible to produce in 2030 to be used as a feedstock.

4.6 Potential Quantity Estimates
In the introduction a question that was posed asking, “What percentage of imported petroleum products used for transportation could be displaced if Iceland began producing its own biofuels?” To answer this question, potential quantities must be estimated and then compared to the total amount imported for the transportation sector.

According to statistics provided by Orkustofnun (the Icelandic National Energy Authority), in 2007 total consumption of oil was approximately 330 million liters. The energy forecast published in 2008 foresees oil consumption to be below the 2007 value in 2030. However, due to large uncertainties in for example future fuel prices the 2007, value places a potential maximum in fuel consumption. Therefore, potential quantity estimates of biofuels are compared to the 2007 value.
Table 1: Main assumptions used to calculate potential quantities for different types of biofuels (this is an expansion of Table 5) \(^{a}\) includes 24 different organic biomass. This accounts for everything including newspaper, paper, yard waste, food, slaughter, hay for example.\(^{25}\) \(^{b}\) Newspaper recycled to Sorpa for 2007.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Assumptions</th>
<th>Potential Quantity 2030 (million liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed Methyl Ester</td>
<td>1164 L/ha(^{m}) 130 thousand ha</td>
<td>151.4</td>
</tr>
<tr>
<td>Bioethanol (timber)</td>
<td>10,000m(^{3}) of timber in 2008, 30,000m(^{3}) -2030 12% moisture content 3.2 kg dry biomass/liter of bioethanol(^{27})</td>
<td>3.97</td>
</tr>
<tr>
<td>Bioethanol (wheat)</td>
<td>1718 L per hectare 5.5 tons of dry biomass/ha 130 thousand ha 3.2 kg of dry biomass/liter of bioethanol</td>
<td>223.3</td>
</tr>
<tr>
<td>Fisher-Tropsch Diesel (timber)</td>
<td>10,000m(^{3}) of timber in 2008, 30,000m(^{3}) -2030 12% moisture content 3.7 kg dry biomass/liter of biodiesel</td>
<td>3.43</td>
</tr>
<tr>
<td>Fisher-Tropsch Diesel (wheat)</td>
<td>1486.5 L per hectare 5.5 tons of dry biomass/ha 130 thousand ha 3.7 kg of dry biomass/liter of biodiesel</td>
<td>193.24</td>
</tr>
<tr>
<td>Bioethanol (Organic Fraction of Municipal Solid Waste)(^{a})</td>
<td>428,000 tons of organic biomass. 30% moisture content 3.2 kg of dry biomass/liter of bioethanol</td>
<td>93.63</td>
</tr>
<tr>
<td>Fisher Tropsch Diesel (Organic Fraction of Municipal Solid Waste)</td>
<td>428,000 tons of organic biomass. 30% moisture content 3.7 kg of dry biomass/liter of biodiesel</td>
<td>80.97</td>
</tr>
<tr>
<td>Bioethanol (Recycled Newspaper)(^{b})</td>
<td>2700 tons of NP 5% moisture content 3.2 kg of dry biomass/liter of bioethanol</td>
<td>.8</td>
</tr>
<tr>
<td>Fisher Tropsch Diesel (Recycled Newspaper)</td>
<td>2700 tons of NP 5% moisture content 3.7 kg of dry biomass/liter of bioethanol</td>
<td>.7</td>
</tr>
</tbody>
</table>


\(^{26}\) Bernesson et. al. (2005)

\(^{27}\) Kemppainen and Shonnard (2005)
Based on this figure, the following comparisons can be presented corresponding to the quantities provided in Table 1. All feedstocks in Table 1 require land to produce the feedstock, excluding MSW and NP.

According to Table 2 between the range of 68 to <0.01% of petroleum products consumed in the Icelandic transportation sector could be potentially displaced based on the quantities estimated in this thesis. Second generation bioethanol using wheat as the feedstock has the highest potential to displace imported fuels followed by Fisher Tropsch diesel (wheat). The second best is Rapeseed Methyl Ester displacing approximately 46%. It must however be noted that the quantity values assumed possible to produce of both rapeseed and wheat are based on assumptions that are highly uncertain. However it was deemed appropriate to follow the information given by agricultural experts. In addition, it also should be emphasized that the increase in forest cover used for the production of biofuels is expected to increase by 300% beyond what is already planned for other purposes. Yet, the lowest percentages are both associated with using Icelandic timber.

Table 2: Percentage capacity of selected biofuels to fulfill total Icelandic consumption of petroleum for automobiles based on 2008 statistics. a assuming 130 thousand hectares are converted, employing second generation technology

<table>
<thead>
<tr>
<th>Fuel</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed Methyl Ester</td>
<td>46</td>
</tr>
<tr>
<td>Bioethanol (timber) a</td>
<td>.56</td>
</tr>
<tr>
<td>Bioethanol (wheat) a</td>
<td>68</td>
</tr>
<tr>
<td>Bioethanol (Organic Fraction of MSW)</td>
<td>28</td>
</tr>
<tr>
<td>Fisher Tropsch Diesel (timber)</td>
<td>.47</td>
</tr>
<tr>
<td>Fisher Tropsch Diesel (wheat)</td>
<td>58</td>
</tr>
<tr>
<td>Fisher Tropsch Diesel (Organic Fraction of MSW) a</td>
<td>25</td>
</tr>
<tr>
<td>Bioethanol (recycled newspaper)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Fisher Tropsch diesel (recycled newspaper)</td>
<td>&lt;.01</td>
</tr>
</tbody>
</table>
5 methodology

The objective of this study is to compare and rank different biofuel production methods. To complete this goal a comparative table is created that standardizes previous life cycle studies by expressing the environmental burden, expressed in emissions, when one MJ of energy is delivered to the tank. The upcoming section describes in detail what constitutes a life cycle assessment followed by the methodology behind the creation of this comparative analysis, and finally a description of the parameters estimated to complete the economic analysis and potential quantity estimates.

The section is organized as follows:

- Description of life cycle assessment,
- Methodology for environmental comparative analysis,
- Methodology for economic section.

5.1 Description of Life Cycle Assessment

Several different factors interplay and affect the environmental footprint of biofuels. For example, different energy crops will demand different levels of fertilizer and pesticides per hectare than others. These differences will thereby indirectly affect the level of water consumption, the impact on land use, and biodiversity. One tool that is available and that can provide a total environmental assessment is life cycle assessment (LCA) which was standardized by the International Organization for Standardization (ISO) in 1998. Life cycle assessment (LCA) is a practical tool because it measures the environmental burden of a particular product or process from a “cradle to grave” perspective, eliminating the option to shift the burden from one stage to another. Thus, the result is a holistic view of the entire system.

The evaluation of the system must meet a standardized format established by the ISO and according to the ISO 14040–14049 a full LCA is divided into four main stages:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)

4. Life cycle interpretation of the result

The goal and scope definition defines the purpose of the study, sets the boundaries of the system, and defines the functional unit. The functional unit allows the cross comparison and analysis between alternative products or processes and is defined as the measure of performance that is delivered by the product. In practice this is an equivalent amount, so in the case of biofuels this could be 1 ha of arable land producing biomass in order to compare the environmental performance of the different fuel systems.

The next stage is the life cycle inventory analysis (LCI). The LCI is a methodology for estimating the consumption of resources and the quantities of waste flows and emissions caused by product’s life cycle. The processes within the life cycle and the associated material and energy flows as well as other exchanges are modeled to represent the product system and its total inputs and outputs from and to the natural environment, respectively. It results in a product system model and an inventory of environmental exchanges related to the functional unit.

Figure 10: Material flow and environmental interventions across the life cycle stages in a biofuel system\textsuperscript{28}.

Within the realm of biofuels Figure 10 illustrates the main stages at which the LCI measures the exchanges between the product and the natural environment. The depiction is from a “well-to-wheel” perspective (WTW) evaluating; the extraction and production of input materials, the harvesting of the crop, the production of the biofuel, the transportation to different locations for dispensing, and the combustion of the fuel. At each stage there occurs a carbon input from fossil energy resulting in emissions to the environment. This thesis evaluates the environmental burden from a “well-to-tank” perspective (WTT) (excluding combustion of fuel).

The life cycle impact assessment (LCIA) is the third stage and takes the quantities of material and energy flows that were evaluated in the LCI stage and organizes the output into different environmental indicators. Due to the functional unit the results can be compared between the different fuels. There are many environmental categories that should be evaluated in the case of biofuels but most LCAs report only greenhouse gas emissions (measured as global warming potential), energy consumption, and pollution assessments measured as acidification potential (AP), eutrophication potential (EP) and photochemical smog potential (POCP) (Anderson and Fergusson 2006). This conclusion was confirmed by a recent review of previous bioethanol life cycle assessments where land use, water consumption and ecological toxicity were never measured in any of the reviewed studies despite their importance in a total assessment (Blottnitz and Curran 2007). Therefore due to unavailability of a broad number of environmental indicators only those that are described in will be standardized in this thesis. Further research is needed on land use and water consumption.
Table 3: Environmental categories selected and adapted by ISO\textsuperscript{29}

<table>
<thead>
<tr>
<th>Environmental Impact</th>
<th>Pollutants and main sources</th>
<th>Examples of impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>CO\textsubscript{2}: carbon dioxide, from fossil fuel combustion and destruction of forests. CH\textsubscript{4}: methane, from livestock, landfill sites, extraction of natural gas or oil and coal.</td>
<td>Climate change affecting agricultural and forest productivity and increasing the likelihood of extreme weather events such as flood and hurricanes.</td>
</tr>
<tr>
<td>Acidification Potential (AP):</td>
<td>SO\textsubscript{2}: sulfur dioxide, from smelters, combustion of coal or oil. NO\textsubscript{x}: nitrogen oxides, from transportation or any combustion</td>
<td>Negative impact of lakes, forests, and materials.</td>
</tr>
<tr>
<td>Eutrophication Potential (EP)</td>
<td>Nitrogen and Phosphorous: nutrients and limiting agents that increase plant’s primary productivity from increased use of fertilizer.</td>
<td>Lead to algal blooms and fish kills.</td>
</tr>
<tr>
<td>Photochemical smog (POCP): formation of ozone and other toxic pollutants in the atmosphere</td>
<td>NO\textsubscript{x}: nitrogen oxides, from transportation or any combustion VOC: Volatile organic compounds from transportation, refineries, oil and wood heating</td>
<td>Affects human health at local and regional levels and reduces productivity of agriculture.</td>
</tr>
</tbody>
</table>

The environmental indicators produced from the LCIA may be tested to see how changes in the products life cycle may alter the impact categories. This sensitivity analysis is crucial because it allows a comparison between alternative trade-offs, while exploring opportunities for improvement in the system. For example, less use of fertilizers may decrease the impact of eutrophication but may require more land to provide the same level of energy output thereby possibly increasing GWP from the increased demand of transportation. This may be important for key decision makers who must prioritize amongst the different environmental impact categories.

Overall the LCA is a valuable tool that evaluates the environmental burden of different products and processes. However within the construction of the model the method enables flexibility with regard to system and study boundaries which

\textsuperscript{29} http://www.iso.org/iso/catalogue_detail?csnumber=29834
creates inconsistency between different studies that evaluating the same product or system.

5.2 Methodology for Environmental Comparison
As described above the main thrust behind this study is to prepare a format that allows a comparative analysis between different biofuels from a “well-to-tank” perspective. To do this, each fuel has a corresponding lower heating value (LHV). The LHV is determined by subtracting the heat of vaporization of the water vapor from the higher heating value. This treats any H₂O formed as a vapor and the energy required to vaporize the water therefore is not realized as heat. In other words, it is the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C. LHV is useful in comparing fuels where condensation of the combustion products is impractical, or heat at a temperature below 150 °C cannot be put to use³⁰.

Table 4 lists the corresponding lower heating values that have been used in this thesis to convert the selected impact categories (GWP, AP, EP, POCP) from the selected life cycle assessments into a standardized format. The units of the impact categories are given by a specific quantity (g) per kilogram of the biofuel produced and therefore when the impact categories are divided by the values that are listed in Table 4 a new factor is created that expresses the environmental burden when one MJ is delivered to the tank.

Table 4: The corresponding lower heating values (MJ/L) used in thesis to create standardized table³¹.

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Gasoline</th>
<th>Petro- diesel</th>
<th>Bioethanol</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Density (MJ/L)</td>
<td>32.2</td>
<td>36.4</td>
<td>21</td>
<td>32.1</td>
</tr>
</tbody>
</table>

³⁰ http://en.wikipedia.org/wiki/Lower_Heating_Value
³¹ http://bioenergy.ornl.gov/papers/misc/energy_conv.html
This same approach to compare automobile fuels was also completed by MacLean, Lave et al. (2000) but the authors only reported the differences in greenhouse gases. This study will not only be an update but an expansion to the study published by MacLean, Lave et al (2000) and more importantly offering a comparison between first and second generation technology.

5.3 Methodology for Economic Analysis

In addition to preparing an environmental comparison of different biofuels produced from various raw materials, the intention of the economic analysis is to provide an assessment of the potential period when the production of selected biofuels in Iceland may become profitable, assuming no changes in policies and applying the predicted price changes of crude oil provided by the Energy Information Administration (EIA). The selection was based on which biofuel yielded the lowest impact under the environmental analysis.

To complete this evaluation a break-even analysis was performed on three specific biofuels, including rapeseed biodiesel, Fisher-Tropsch biodiesel and second generation bioethanol. Two primary feedstocks, timber and winter wheat, were considered to assess the potential quantity for the latter two biofuels, as the environmental results indicated that these may be the most advantageous inputs in comparison to the feedstocks that were reviewed.

To complete these general analyses three main parameters were estimated and then presented by showing the total cost and revenue corresponding to the production of each specific type of biofuel. To produce these graphs, retail price, production costs, and potential quantity were estimated. Below are three sections describing the methodology used to calculate these specific parameters.

5.3.1 Potential Quantity

In the framework of the economic analysis potential quantity values were used for three types of biofuels. These were selected based on the environmental results, which indicated that these three had lowest impact in the environmental categories that were evaluated. These include:
• Rape Methyl Ester (rapeseed)\textsuperscript{32}
• Bioethanol (timber/wheat)
• FT-Diesel (timber/wheat)

Table 5 is an overview of the main assumptions and the estimated yield in 2030. Under scenarios that demand land use, it is assumed that the land that is currently cultivated is transformed to produce crops that may be converted to biofuels. In total this is approximately 130 thousand hectares.

\textsuperscript{32} Minimal impact due to lower amounts of nitrogen used (104 kg/ha) and small scale farming.
Table 5: Main assumptions used to calculate potential quantity of biofuels for specific feedstocks and technology.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Assumptions</th>
<th>Potential Quantity 2030 (million liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed Methyl Ester</td>
<td>1164 L/ha&lt;sup&gt;33&lt;/sup&gt;</td>
<td>151.4</td>
</tr>
<tr>
<td></td>
<td>130 thousand ha</td>
<td></td>
</tr>
<tr>
<td>Bioethanol (timber)</td>
<td>10,000 m&lt;sup&gt;3&lt;/sup&gt; of timber in 2008 to 30,000 m&lt;sup&gt;3&lt;/sup&gt; in 2030</td>
<td>3.97</td>
</tr>
<tr>
<td></td>
<td>12% moisture content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.2 kg dry biomass/liter of bioethanol&lt;sup&gt;34&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Bioethanol (wheat)</td>
<td>5.5 tons of dry biomass/ha</td>
<td>223.3</td>
</tr>
<tr>
<td></td>
<td>1718 L ha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>130 thousand ha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.2 kg of dry biomass/liter of bioethanol</td>
<td></td>
</tr>
<tr>
<td>Fisher-Tropsch Diesel (timber)</td>
<td>10,000 m&lt;sup&gt;3&lt;/sup&gt; of timber in 2008 to 30,000 m&lt;sup&gt;3&lt;/sup&gt; in 2030</td>
<td>3.43</td>
</tr>
<tr>
<td></td>
<td>12% moisture content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.7 kg dry biomass/liter of biodiesel</td>
<td></td>
</tr>
<tr>
<td>Fisher-Tropsch Diesel (wheat)</td>
<td>5.5 tons of dry biomass/ha</td>
<td>193.24</td>
</tr>
<tr>
<td></td>
<td>1486.5 L ha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>130 thousand ha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.7 kg of dry biomass/liter of biodiesel</td>
<td></td>
</tr>
</tbody>
</table>

In Table 5, all of the calculations are based on second generation conversion ratios (excluding RME). The ratio of required dry biomass (timber) to produce bioethanol via hydrolysis was applied from the Kemppainen and Shonnard (2005) study (3.2 kg dry biomass/liter), while the first large-scale plant in Germany (www.Choren.com) is producing FT-Diesel and base requirements are

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<sup>33</sup> Bernesson et. al. (2005)

<sup>34</sup> Kemppainen and Shonnard (2005)
3.7 kg of dry biomass/liters of biodiesel. These ratios were applied to calculate potential quantity for the corresponding fuels listed in Table 5.

5.3.2 RETAIL PRICE
In Table 6 there are two types of general biofuels: bioethanol and biodiesel. Each fuel has different characteristics and one way to evaluate fuels is to compare lower heating values (LHV). A fuel's LHV indicates a specific quantity of heat that is transferred when the temperature is increased from 25°C and returned to 150°C. In theory, depending on the difference between the biofuel and the reference case (gasoline or petro-diesel) LHV can determine the percentage change of what price per liter the biofuel could be sold at the pump. For example, E85 is a blend of 85% gasoline and 15% bioethanol with a LHV of 27. In comparison to gasoline and in competitive terms this implies that E85 should sell for approximately 16% lower price than gasoline at the pump because it only has 84% of the LHV of gasoline (see Table 6).

Table 6: Fuels and corresponding lower heating values (LHV).

<table>
<thead>
<tr>
<th>Gasoline</th>
<th>Petro-Diesel</th>
<th>Ethanol</th>
<th>E85</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.1</td>
<td>34.2</td>
<td>21.1</td>
<td>27</td>
<td>32.8</td>
</tr>
</tbody>
</table>

In the case of biodiesel it was assumed that there was no significant difference in LHV so there were no differences between retail prices.

Future retail price was calculated based on the following assumptions and methodology:

1) To calculate the retail price for gasoline and petro-diesel the twelve month average of the retail price for gasoline and petro-diesel was estimated, which were 3.17 USD/gallon (.84 USD/L) and 3.89 USD/gallon (1.02 USD/L) in 2008 provided by the EIA. These prices include taxes.

2) The estimated retail values were converted to 2005 USD real dollars per liter using 1.032 as the CPI factor.

35 http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp
36 It was decided to convert these to 2005 since the EIA released a forecast predicting prices of crude oil until 2030. http://www.bls.gov/cpi/tables.htm
3) To access changes in retail price, the rate of change in crude oil prices predicted by the EIA for the reference case until 2030 (See Figure 11) was applied to calculate expected changes in the retail price for gasoline and petro diesel.

4) To convert retail prices to Icelandic Kronur for gasoline and diesel (2005 USD) the exchange rate based on December 31, 2005 which was 1 Iceland Krona = 0.01575 US Dollar; 1 US Dollar (USD) = 63.49500 Iceland Krona (ISK) was applied.

Based on the assumption that Iceland adheres to the same fluctuations in oil prices provided by the EIA, an index can be created for the retail price of gasoline as well biofuel (applying a LHV ratio). This index was calculated using the corresponding rate for the reference scenario, which assumes no changes in policy that could affect projections (see Figure 11).

Table 7: Retail price for E85 and biodiesel (RME and FT-Diesel) for 2008.

<table>
<thead>
<tr>
<th>Retail Price ISK/liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioethanol (E85)</td>
</tr>
<tr>
<td>Biodiesel</td>
</tr>
</tbody>
</table>

Of course, the prices given are lower than prices derived ultimately in Iceland, and therefore neither total revenue values nor total cost values, represent directly Icelandic reality. However, since the cost and revenue values are derived from and based on information from comparable sources that is the IEA and the EIA, the break-even point analysis is valid.
5.3.3 PRODUCTION COST

Biofuel production cost has been estimated by the International Energy Agency (IEA) and has presented two different scenarios; optimistic and pessimistic (see Table 8). These costs are expressed in 2005 real dollars.

Table 8: IEA 2nd-generation biofuel cost assumptions for 2010 and 2030 (lge: liter of gasoline equivalent).

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Production Cost - By 2010 USD/lge</th>
<th>Production Cost - By 2030 USD/lge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioethanol</td>
<td>Optimistic</td>
<td>.80</td>
</tr>
<tr>
<td></td>
<td>Pessimistic</td>
<td>.90</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Optimistic</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Pessimistic</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Both scenarios have been analyzed for second generational biofuels. The exchange rate of 1 Iceland Krona = 0.01575 US Dollar; 1 US Dollar (USD) = 63.49500 Iceland Krona (ISK) was used to convert these prices to ISK. In regard to first generation biodiesel, the technology is mature and well established and for this reason production costs are assumed to stay constant (Williamson and Badr 1998).
6 ENVIRONMENTAL RESULTS

Life cycle studies that were chosen to be evaluated in this thesis were selected based on the criteria that the study assessed a crop that was suitable to Icelandic growing conditions. Research has confirmed that rapeseed and winter wheat are possible options. In addition, a piping system is already in place that collects biogas from waste in Álfsnes, and the gas is reformed to methane. One other way to utilize the organic fraction of municipal solid waste is to produce liquid biofuels. Finally, timber grown in Iceland is another possible option. In this section the environmental results between the different combinations of technology and selected feedstocks will be presented.

The presentation of the four life cycle environmental impact categories (GWP: Global Warming Potential, AP: Acidification potential, EP: Eutrophication potential, POCP: photochemical oxidant creation potential) are illustrated by the amount of pollution (by weight) that is generated when one MJ is delivered to the tank in regards to feedstock: NP: newspaper; W: wheat; MSW; municipal solid waste; C; classification, T:timber; R: rapeseed; the corresponding technology: H:Hydrolysis, F:Fermentation, P:Pyrolysis, T:Transesterfication.and the output: E:bioethanol; and D:biodiesel. 

Accordingly, there will be four upcoming sections for each environmental category with the abbreviations listed above under the corresponding figures. Under each environmental category there are different numbers of studies included. The absence is explained by the fact that the author of each respective study did not evaluate all four categories. As will be seen, there are more results corresponding to GWP than EP for example.

6.1 Global Warming Potential (GWP)

Global warming may be enhanced by the dramatic increase in greenhouses gases such as CO₂, CH₄, CO, N₂O which can be induced from anthropogenic sources. Global warming potential (GWP) is a LCA impact category that measures the environmental performance that can result at different stages of the biofuel production chain and that evaluates the possible impact to global warming. When the results are presented in LCA studies they are presented as
a unit expressed as CO₂ equivalents (kg) per hectare or liter, for example. The results here will be presented similarly but based on the unit of energy (MJ) delivered to the tank.

Figure 12 shows the potential impact to global warming for different production routes and feedstocks. This evaluation assesses both second generation production methods (hydrolysis and pyrolysis). Bioethanol that is produced using timber as the raw material and employing hydrolysis in comparison to all other feedstocks, yields the lowest impact to GWP of approximately 7.26 CO₂ eq. g/MJ. This is due to the fact that timber has a high lignin biomass fraction and the energy from this content may be recycled into the system by providing electricity (Kemppainen and Shonnard 2005). Since Iceland uses renewable, nearly carbon neutral sources for its electricity production, these results directly apply to Iceland. Using the same feedstock, timber, but employing pyrolysis in comparison to the bio-chemical route this yields an impact of 18.30 CO₂ eq. g/MJ as shown in Figure 12 (Jungbluth 2007). This particular production route demands high temperature levels (800°C) and to improve the conversion ratio hydrogen must be produced. These demand high levels of electricity and if the energy source is fossil fuels this will increase the potential impact to global warming. However Jungbluth (2007) assumed that renewable energy was used as the energy source, and thus the result does apply to Iceland.

Figure 12: Results comparing the impact to global warming potential (GWP) based on feedstock, technology, Fuel. NP: Newspaper, T: Timber, W: Winter wheat, MSW: Municipal Solid Waste, C: Classification, R: Rapeseed, H: Hydrolysis, F: Fermentation, P:Pyrolysis, T:Transesterification, E:bioethanol, D:biodiesel. *: cases of allocation.
In contrast to these favorable results, this analysis indicates that the production of first generation biodiesel using rapeseed and employing general cultivation and harvesting practices, such as applying 140 kg of nitrogen per hectare, generates the largest impact to GWP (86 CO₂ eq. g/MJ) (Kaltschmitt, Reinhardt et al. 1997). The second highest in this category was linked to 2nd generation bioethanol production and the utilization of municipal solid waste (MSW). Under this platform, bioethanol produced from waste yielded an impact of 80 CO₂ eq. g/MJ. Kalogo, Habbibi et al. (2007) explain in their study the pivotal role that classification (incorporating recycling into the LCA boundaries) plays and when it is included into the boundaries of the LCA it can negatively affect results due to the high demands of energy for separation and the transportation requirements for pick-up as fossil fuels generally are used for transportation. When classification was not considered the impact was reduced by 25 CO₂ eq. g/MJ. Despite this reduction, the utilization of MSW to produce bioethanol based on parameters set by Kalogo, Habbibi et al. (2007) still generated the largest impact in comparison to the other types of production methods for bioethanol.

6.2 Acidification Potential (AP)

Although acidification is a natural process, it may also be associated with atmospheric pollution arising from anthropogenically derived sulphur (S) and nitrogen (N) as NOₓ or ammonia. Anthropogenically derived pollutant deposition enhances the rates of acidification, which may then exceed the natural neutralizing capacity of soils. Within the LCA, the acidification potential (AP) impact category evaluates the different stages of the life cycle and how these processes may illicit an impact to acidification.

Figure 13 shows the potential impact to acidification due to different production routes. The most benign production route was when the thermal-chemical platform is employed yielding an impact of .01 to .14 SO₂ eq. g/MJ (Jungbluth 2007). According to Jungbluth (2007) the actual biomass production contributed approximately 60% to the total acidification impact under the study while the other sub-processes accounted for the other 40%. This is in agreement with Kemppainen and Shonnard (2005) who calculated that most acidification is a result of processes related to manufacturing and not premanufacturing.
operations. In theory, the bio-chemical route should have a slightly lower AP in comparison to the thermal-chemical platform; however, under the Kemppainen and Shonnard (2005) study, the authors assumed the electricity was produced from natural gas rather than using renewable energy. For this reason, production route that yields the lowest impact to acidification is Fisher-Tropsch biodiesel using wheat (W/T/D) as a feedstock. In addition FTD requires less ammonia for pretreatment than second generation bioethanol.

![Figure 13: Results comparing the potential impact to acidification based on feedstock, technology, Fuel. NP: Newspaper, T: Timber, W: Winter wheat; MSW: Municipal Solid Waste, C:Classification R: Rapeseed, H: Hydrolysis, P:Pyrolysis, T:Transesterification, E:bioethanol, D:biodiesel, *:allocation](image)

In contrast, whenever hydrolysis is employed, it generates the highest impact ranging between 1.27 to 1.42 SO\textsubscript{2} eq. g/MJ (Kempainnan and Shonnard 2005). Kempainnan and Shonnard (2005) claim this is derived from actual manufacturing of the ammonia where flue gases escape and the actual production of the bioethanol. The slight difference between newspaper and timber may be explained by the fact that newspaper requires less ammonia for the pretreatment process.

Despite the fact that Jungbluth (2007) still included agricultural production, while Kemppainen and Shonnard (2005) did not evaluate this stage, Kemppainen and Shonnard (2005) values are still higher. This may indicate that if hydrogen is produced from a renewable energy source to enhance the conversion efficiency,
which is one major hurdle under the hydrolysis scheme, that even when biomass production is included it does not outweigh the benefits achieved by improving the conversion efficiency. Transportation distances could also affect this impact category.

6.3 Eutrophication Potential (EP)
Eutrophication can either be a natural process or accelerated by the excessive release of nutrients into lakes. Excessive amounts of plant nutrients (primarily phosphorus, nitrogen, and carbon) are emitted in various ways such as agricultural runoff, leading algal blooms. As a result, this leads to algal blooms. When the algal blooms die and decompose they demand higher levels of oxygen leading to anoxic environments resulting in fish kills. Eutrophication Potential (EP) measure the possible impact of a product on eutrophication.

Figure 14 expresses the result of biofuel production as phosphate eq. g/MJ. When comparing these results, the use of timber to produce FTD is the most benign (0.05 PO$_4^{3-}$ eq. g/MJ) followed by rapeseed biodiesel which yields an impact of 0.09 PO$_4^{3-}$ eq. g/MJ. The worst production route is FTD using wheat as a raw material. Jungbluth (2007) and Bernesson (2004) both agree that the application of fertilizers is the great culprit to this environmental category.

![Figure 14: Results comparing the impact to Eutrophication based on feedstock, technology, Fuel. T: Timber, W: Winter wheat, R: Rapeseed. H: Hydrolysis, P:Pyrolysis, T:Transesterification, E:Bioethanol, D:Biodeisel. *:allocation](chart)

**Figure 14:** Results comparing the impact to Eutrophication based on feedstock, technology, Fuel. T: Timber, W: Winter wheat, R: Rapeseed. H: Hydrolysis, P:Pyrolysis, T:Transesterification, E:Bioethanol, D:Biodeisel. *:allocation
Jungbuth (2007) concluded that a share of more than 85% of the release of eutrophication emissions can be attributed in most cases directly to the agricultural production process due to the application of fertilizers. The other important sources of emissions are from the conversion process and power plant.

6.4 Photochemical oxidant creation Potential (POCP)
Photochemical ozone formation is caused by degradation of organic compounds (VOC) in the presence of light and nitrogen oxide (NOx). Photochemical ozone affects environmental and human health. Exposure of plants to ozone may result in damage of the leaf surface, leading to damage of the photosynthetic function, discoloring of the leaves, dieback of leaves and finally the whole plant. Exposure of humans to ozone may result in eye irritation, respiratory problems, and chronic damage of the respiratory system.

To quantify this impact, photochemical oxidant creation potential is used by LCAs. Figure 15 presents the results expressed as ethylene (C₂H₄) equivalents i.e. their impacts are expressed relative to the effect of (C₂H₄).

![Figure 15: Results comparing the impact to photochemical ozone formation based on feedstock, technology, Fuel. T: Timber, W: Winter wheat, R: Rapeseed, H: Hydrolysis, P: Pyrolysis, T: Transesterification, E: Bioethanol, D: Biodeisel.*: allocation](image-url)
Of the different production routes considered in Figure 15, first generation biodiesel from rapeseed and FTD using timber appear to be the most environmentally benign in comparison to the other options (.01 C₂H₄ eq. g/MJ). This may be explained by the less demanding conversion process of rapeseed biodiesel in comparison to the newer technologies. However, this also indicates that choosing the appropriate feedstock is critical because the different physical properties of the biomass greatly affect the potential impact. This is illustrated by the fact that depending on the feedstock (timber versus wheat) will yield either the best or worst, as timber requires less hydrogen in contrast to wheat straw.

6.5 Summary of Environmental Results
Grouping and consolidating the results from Figure 12, Figure 13, Figure 14, Figure 15 produces Table 9 which ranks the different biofuel production methods according to environmental impact. In some circumstances there was more than one study that evaluated the same feedstock. In the case of rapeseed, there were three studies (Kaltschmitt, Reinhardt et al. 1997; Elsayed, Matthews et al. 2003; Bernesson, Nilsson et al. 2004; Fredriksson, Baky et al. 2006) that evaluated the environmental load for RME production, but only Bernesson, Nilsson et al. (2004) assessed all four categories. Their results were chosen to be included in Table 9. In the cases where the same feedstock was evaluated in different studies, the most environmentally (e.g., timber) results were chosen to be include in Table 9.

Table 9: Environmental ranking of selected biofuels based on performance in each environmental category.

<table>
<thead>
<tr>
<th>Feedstock/Technology/Biofuel</th>
<th>GWP CO₂</th>
<th>AP SO₂</th>
<th>EP PO₄₃</th>
<th>POC OP C₂H₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber/Hydrolysis/bioethanol</td>
<td>1</td>
<td>5</td>
<td>NA</td>
<td>3</td>
</tr>
<tr>
<td>Wheat/Pyrolysis/Fisher-Tropsch Diesel</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>MSW/hydrolysis/bioethanol</td>
<td>4</td>
<td>2</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Newspaper/hydrolysis/bioethanol</td>
<td>2</td>
<td>4</td>
<td>NA</td>
<td>2</td>
</tr>
<tr>
<td>Rapeseed/transesterification/biodiesel</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

1…5: Best….Worst
According to Table 9 there are particular platforms that yield less impact to selected environmental LCA categories, but when examining an entire process and all environmental categories there is no significant difference between production methods and it appears there are environmental trades-offs with each conversion method. Some differences could be attributed to the different assumptions that are built into the different studies as discussed before.

When hydrolysis is employed the lignin biomass content is utilized to support the electricity for the production of the biofuel. Timber in particular has enough lignin content to support its entire system. When other products such as newspaper or MSW are used as the primary feedstock both of which have lower lignin content, this requires electricity being drawn from outside sources increasing the impact to acidification and global warming potential if conventional fossils fuels are the source of energy for the electricity production.

A major assumption built into Jungbluth (2007) was that hydrogen that is used to increase the conversion efficiency ratio was produced using renewable energy sources, which directly applies to Iceland.

Another characteristic that is important to recognize is the corresponding moisture content of each feedstock. In comparison to the other feedstocks when MSW was used it produced unfavorable results for GWP. Excluding the role of classification, one explanation may be due to the high moisture content of the material. For example, mixed food waste and mixed yard waste are components of MSW and their corresponding moisture contents are 72% and 62%. These are high percentages which imply that high levels of energy will be demanded to remove excess water. In contrast timber as moisture content of approximately 12%.

In either hydrolysis or pyrolysis, raw material must undergo pretreatment that involves using ammonia. If Iceland uses any type of feedstock that must be cultivated and harvested, the impact to GWP, AP, EP and POCP could dramatically increase because not only would there be the impact from production and application of fertilizers but also from the production of ammonia which is used for pretreatment which was excluded form the analysis.
Kemppainin and Shonnard (2005) demonstrated that when evaluating the entire biofuel production chain for bioethanol (timber and newspaper), the production of ammonia contributed significantly to global warming potential, acidification potential and photochemical oxidant potential mainly due to the release of flue gases from actual production and the authors suggested finding alternatives options in lieu the usage of ammonia.

One consistency between both technologies is the potential impact to eutrophication. This is due to the soil emissions from the fertilizer.

Overall from an environmental perspective and based the ranking system in Table 9, there is not a distinguishable difference between the different generations of technology.
7 ECONOMIC RESULTS

The intent of this economical analysis is to estimate a potential period when the production of selected biofuels could become profitable in Iceland. Calculations were based on retail price (2005 ISK/L), production costs (2005 ISK/L) as derived from EIA and IEA, and potential quantity estimates according to Icelandic quantities for the selected feedstocks (see Table 1). In total, nine different break-even scenarios are presented. They were selected based on the criteria that the worst and most environmentally friendly production methods were represented and also to incorporate a comparison between older and newer technology. In setting this criterion, two general types of biofuels were evaluated, bioethanol (E85) and biodiesel. Three primary feedstocks are considered: rapeseed, wheat, and timber, all of which are based on Icelandic conditions and parameters.

Figure 16 - Figure 20 were produced based on potential quantity estimates, retail price (ISK/L), and production costs (ISK/L) and are all presented in 2005 ISK. Where ever bioethanol is estimated, it is assumed to be E85, a blend of 85% gasoline and 15% ethanol. E85’s LHV is 84% of gasoline’s LHV. This implies that E85 must sell at a price at least 16% less than the retail value of gasoline which is built into the cost calculations.

Figure 16: Break-even analysis of rapeseed biodiesel production in Iceland, assuming no changes in production.

Results indicate that the production of rapeseed biodiesel in Iceland could be potentially profitable today between the range of 10,000 million ISK to 8,000
million ISK, due to the lower production costs in comparison to the new biofuel technology (see Figure 16). Changes in total revenue may be explained by the changes in world oil prices. It must however be emphasized, that since both prices and costs are based on values from the United States, that total cost and revenue values are likely to be higher in Iceland. In addition total quantity values for rapeseed and wheat production are likely to represent an upper extreme in possible production quantities. Therefore one must be cautious when interpreting total cost and revenue values in addition to the break-even analysis. However, the break-even analysis is valid for the assumptions used in the analysis.

Figure 17: Break-even analysis of second generation bioethanol (E85) produced from Icelandic timber using IEA optimistic cost scenario.
Figure 18: Break-even analysis of second generation bioethanol (E85) produced from Icelandic wheat using IEA optimistic production cost scenario.

Figure 17 and Figure 18 indicate that when employing second generation technology to produce bioethanol using timber or wheat, a breakeven point is not reached during the time period evaluated. This may be explained by the high production costs and the lower retail price. However, the production of Fisher Tropsch diesel using either timber or wheat is potentially a profitable option for Iceland in 2020 (see Figure 19 and Figure 20).

Figure 19: Break-even analysis of second generation FT-Diesel produced from Icelandic timber, using IEA optimistic production cost scenario.
Figure 20: Break-even analysis of second generation FT-Diesel produced from Icelandic wheat, using IEA optimistic production cost scenario.

Between these two feedstocks, Fisher Tropsch diesel from Icelandic wheat has higher total revenue (4,000 million ISK) versus Fisher Tropsch diesel using timber (80 million ISK). This is due to the higher potential quantity.
8 DISCUSSION

The intent of this thesis is to evaluate the potential environmental impact of different production methods in Iceland. To do this specific crops and organic raw materials suitable to Icelandic conditions were identified. Based on this criterion, earlier studies that had evaluated the environmental impact of biofuel production using these specific feedstocks were selected and placed into a standard format to provide an opportunity to compare and rank the different conversion methods based on their impact to four different environmental categories: global warming potential (GWP); acidification potential (AP); eutrophication potential (EP); and photochemical oxidant potential (POCP).

In addition to the environmental assessment of different conversion methods, a general economic analysis was conducted based on potential quantities estimates, which were calculated using Icelandic feedstocks, the retail price (2005 ISK), and production costs for the different conversion technologies also in ISK.

In doing this it addresses the three research questions that were posed at the beginning of the thesis which were:

1. Could Iceland achieve self-sufficiency within the transportation sector if it started producing its own biofuels based on current/potential resources?
2. What would be the potential environmental impact of different production methods?
3. Based on productions costs, the future price of oil, and the potential amount of biofuel that could be produced at what point would the production become profitable in Iceland?

Given these questions each biofuel production method has environmental, economical, and numerical attributes that may make some more favorable or suitable than others. Each attribute influences decision making when deciding on possible future transportation fuel options for Iceland.

The feedstocks that were evaluated in this study represent options that may be used to produce biofuels. Based on potential quantity limits and the percentage
of total fuel displaced in Iceland was in the range of 68 to < 0.01 percent. The highest percentages were those methods that employed second generation technology using wheat as the feedstock. However, from an economical perspective, the productions cost per liter of gasoline equivalent is still very high so despite the higher quantity a break-even point would not be met until approximately 2030. Despite this drawback, this newer production method yields less of an impact to global warming potential (GWP), with the lowest value being 7.26 CO2 eq. g/MJ for the production of bioethanol from timber.

In contrast, the production of rapeseed biodiesel yielded the highest impact to GWP (86 CO2 eq. g/MJ). Processes responsible for this value include the production of fertilizers, on farm fuel use and transportation. These processes also affect the other three environmental categories.

Rapeseed biofuel production in comparison to the other methods does not require the same amount of energy for production. The greatest contributor to acidification potential and photochemical oxidant potential was the actual production for these second generation biofuels and as a result flue gases would escape affecting air quality.

Rapeseed biofuel production differs because the greatest contributor to these environmental categories is the production of fertilizers, on-farm fuel use and transportation to the refinery. Under all three processes there are options to alleviate the environmental burden. For example, organic waste placed into an anaerobic digester produces methane that may be used as transportation fuel or electricity. This action can reduce fecal coliform bacteria in manure by more than 99%, eliminating a major source of pollution. Since the emission of CH4 is affected by temperature, duration of storage, precipitation, etc., reducing the storage time to 1 day reduces emissions to approximately 15%. Another advantage is that the digested manure is a higher quality fertilizer since organic-bound nitrogen is converted into ammonium available to plants. Results show that nitrogen leaching may be reduced by 20% when digested manure replaces undigested manure (Börjesson and Berglund 2007). This indicates potential for Icelandic producers of rapeseed to incorporate the utilization of waste as a fertilizer.
Another option which might further reduce the environmental burden of biofuel derived from rapeseed would be to use bioethanol in place of using synthetic methanol. Usually, rapeseed oil is transesterified by synthetic methanol however the methanol energy ratio R1 is 0.76 in comparison to 1.34 for ethanol when appropriate selected raw materials and technology are used (Janulis 2004). More importantly, methanol is extremely toxic in comparison to bioethanol.

Another consideration is the use of renewable energy for rapeseed biofuel production. In this thesis there was only one study included that evaluated the impact of biofuel production using renewable energy. In this study, Jungbluth (2007) evaluated the pyrolysis method producing Fisher-Tropsch from timber or wheat. Jungbluth (2007) explains the great importance of using renewable energy thereby greatly lowering the impact to all four environmental categories. This certainly applies to Iceland since 99% of its electricity is produced from either geothermal or hydropower.

In addition to the options that are available to potentially reduce the environmental burden for rapeseed production, from an economic perspective the production could be profitable today (given the large potential production quantities). In contrast to the newer technology rapeseed production is based on a mature technology. In addition, glycerin, a valuable by-product of rapeseed production has many market applications. Approximately 115 kilograms of glycerin per hectare is the expected yield (Bernesson, Nilsson et al. 2004). Based on the assumption that Iceland transforms 130 thousand hectares this is approximately 17.25 million kilograms of glycerin annually, along with potentially 194.75 million kilograms of animal meal. Of course it must be emphasized that the amount possible to produce in 2030 is highly uncertain.

Further economies of scales could be reached by having a large-scale refinery plant yet these gains may be overshadowed by environmental and economic costs due to transportation of feedstock. More importantly an increase in emissions from rapeseed production cannot exceed the benefits from use. In 2007 there were an estimated 934 giga grams (Gg) of CO₂ eq. from transportation and 516 in 1990. Based on the results in this analysis (86 to 46 CO₂ eq. g/MJ) rapeseed production exceeds the 2007 level by 5% corresponding
to the highest value while 57% lower using the lower number. In terms of 1990 levels (516 Gg) and according to the highest GWP value, rapeseed production is 91% higher in emission than use (2% above if using 46 CO2 eq. g/MJ).

Under these circumstances, and when taking a life-cycle perspective, rapeseed production has higher emissions than use, which should warrant serious consideration.

Within the category of organic waste and in this thesis, two potential options for Icelandic feedstocks were evaluated, the organic fraction of municipal solid waste (OFMSW) and newspaper. This does not indicate that these are the only options available in Iceland as there could be other options such as manure or fish waste for example but these were the two that were included in this thesis.

The Waste Management Law no. 55/2003 and Regulation no. 737/2003 on waste treatment transpose the following EU targets into Icelandic law:

- To reduce the total weight of other organic waste, such as biodegradable organic waste to be landfilled, by 25 per cent by no later than 1 January 2009, by 50 per cent by no later than 30 June 2013 and by 65 per cent by no later than 30 June 2020.

According to the results in this analysis and in comparison to the other options, using MSW solid waste to produce liquid bioethanol is the least optimal use of this material but a more optimal route is to capture the potent biogas that can escape and convert it to either electricity or methane, which is already occurring at one landfill, Álfsnes, in Iceland.

An interesting observation can be made regarding MSW. According to the literature review and the results the optimal use of OFMSW is to put it in a landfill and capture the biogas rather than using it to produce bioethanol. The separation of the OFMSW and non-organic material can be extremely energy intensive (Kalogo, Habibi et al. 2007) leading to large GWP impact. For all of these reasons, the conditions set by the waste management law may be sub-optimal.
In addition to the potential impact to the selected environmental categories large quantities of waste water are associated with the production of biofuels. For every liter of second generation bioethanol, nine liters of effluent are created. Although this waste stream may be recovered, treated and then recycled back into the system, it still requires energy for the treatment process. Results from Kalogo, Habibi et al. (2007) indicate that waste water treatment plays a critical role in air pollutant emission (AP), especially carbon monoxide, NOx and VOC all of which can negatively affect the quality of air.

For all of these reasons, when there is no market for heat or electricity as derived from the process, as this may apply to Iceland, enriched methane is the most advantageous scenario in comparison to producing ethanol via hydrolysis from MSW (Murphy and Power 2007). If Iceland must separate the OFMSW then one option for Iceland to optimize the system could be to use the recycled newspaper that is normally sent to Sweden and instead place it in anaerobic digester with the OFMSW. When this is done the rate of biogas produced increases from 79 m³ per ton of OFMSW to 115 m³ per ton. This improvement is because the addition of newspaper improves the C:N ratio and slow biodegradability improves the gasification of wet organics (De Wilde, Six et al. 1989).

Thus far explanations have been put forward identifying methods that could reduce the environmental impact for selected biofuel production methods in Iceland. Due to very high production costs, the second generation technology is extremely limited in comparison to the older technology. In order to reduce costs, subsidizes would have to be provided to make the technology competitive. This brings the attention to energy carriers such as hydrogen or electricity to power vehicles. According to Jón Björn Skúlasson (personal communication, 2008), in 2008 when the price of oil greatly fluctuated and reached 100 USD per bbl (2008 USD), hydrogen could be produced and sold at competitive prices in Iceland.

However, production costs of second generation technology are expected to decline due to learning effects and expected increased economies of scale as larger quantities of feedstocks such as timber are produced. Yet use of timber
as a feedstock limits the sequestering potential of forestry as one use excludes the option of the other.
9 CONCLUSION

This thesis is part of a larger project that seeks to understand the environmental, economical and social implications of producing and using alternative transportation fuels in Iceland. Before Iceland engages in the production of its own biofuels, it is important to assess from an environmental and economic perspective the potential impacts that biofuel production may have. Ultimately, there are many unknown factors such as total land space available for cultivation, for example, and it is imperative, that Iceland conduct its own research before engaging in the production of biofuels.

The main outcome of this analysis is that there may be a great opportunity for producing biofuels in Iceland assuming the large potential quantity estimates, however in some cases there is a large tradeoff between environmental and economic gains such as in the case of using rapeseed as a feedstock. However, if Iceland could find ways to alleviate the environmental burden relating specifically to global warming potential and eutrophication, and given the large estimates then the production of rapeseed biodiesel seems to be the best choice for liquid fuels.

In regard to biogas, since in Iceland 99% of the electricity is produced from renewable energy, the optimal method to produce methane is to install a piping system in a landfill that captures the biogas. This is already taking place at one landfill in Iceland. This in turn provides strong environmental benefits because methane in terms of global warming potential is 21 more times potent than carbon dioxide, does not escape into the atmosphere and there are not the social and economical issue that surround certain feedstocks.

Currently only 15% of the methane that is captured from the landfill in Álfsnes is being used for transportation purposes, while the remaining percentage is either flared or sold and put on the grid, according to Bjorn Halldórsson (personal communication, December 2008). This low percentage may be attributed to lack of demand (Bjorn Halldórsson, December 2008). Although there are tax incentives in place for alternatively fuel vehicles, there needs to be a more
outspoken and proactive approach to encourage demand of the type of vehicles that run on this type of fuel.

In conclusion when considering all three aspects such as potential environmental impacts, economic costs, and potential quantities, it would be in Iceland’s best interest to find ways to alleviate the environmental burden associated with rapeseed production and to move cautiously forward with this option.
10 STUDIES LIMITATIONS AND FUTURE RESEARCH

In this study only five feedstocks were evaluated. This does not imply, however, that there are not others. As technology develops this will widen the range of options, which should be analyzed.

Another weakness of this analysis is the limited number of environmental factors considered. This result is due to inherent limitation of the LCA methodology which does not include impact on for example, land and water use. Those factors should be included to provide a holistic view of environmental implication of different biofuel options.

Due to the high potential of rapeseed biodiesel further research is needed to investigate methods to reduce the environmental burden associated with the production.


**Verbal Sources**

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