EXECUTIVE SUMMARY

This study examines the life cycle of greenhouse gas (GHG) emissions from the use of renewable fuel oil and biodiesel in the power generation and transportation sectors in the state of Hawai‘i. The study calculates the GHG emissions from each step of the value chain (feedstock production, feedstock logistics, conversion, distribution, and end-use) to determine:

- What is the potential reduction in GHG emissions if biofuels replace fossil fuels?
- What is the difference in GHG emissions between locally produced and imported biofuels?
- Which biomass crops offer the best potential for GHG emission reductions?
- What are the potential fuel supply chain pathways?
- To what extent can biofuels reduce Hawai‘i’s consumption of oil?

The study examines three land-based crops (oil palm, soybeans, and jatropha). The results indicate that:

- Biofuels reduce GHG emissions but the reduction varies depending on the choice of feedstock where jatropha offers the most GHG emissions reduction;
- Imported biofuels reduce GHG emissions by only 2% relative to locally produced biofuels;
- Local production of all the biofuels specified in the two scenarios may not be feasible due to limited land availability. Based on the HBMP’s estimate of 53,000 acres available for biofuel crop production, the State can produce less than a half of the expected consumption of 20% substitution from petroleum counterparts;
- With the current GHG legislation, producing biofuels in Hawai‘i leads to approximately $0.2/MMBtu in cost savings compared to importing biofuels;
- If Hawai‘i chooses to grow crops for biofuels, then the reduction in oil imports may not be as great because Hawai‘i will need imported sources of energy to process the crops into biofuels.

The methodology for the life cycle analysis (LCA) is drawn from various national and international studies conducted by Argonne National Laboratory, the California Air Resources Board, the Intergovernmental Panel on Climate Change (IPCC), the US Environmental Protection Agency (US-EPA), and the UK Renewable Fuels Agency (UK-RFA).

Based on an examination of the existing legislation and previous studies of biofuels and LCA methodology, this study; i) draws a baseline scenario and two hypothetical scenarios for the expected consumption of biofuels in Hawai‘i, ii) explain the selection of feedstock crop types, and iii) describes five distinct fuel pathways. The study offers insights that are relevant to the State’s energy and GHG emissions reduction policies.

The impacts to the land use change are not clear. If biofuel crop production causes changes in land use, GHG emissions could be massive and may negate the positive projections of this study. Future study should address issues related to land use decisions to improve the results provided by this study.
1 Introduction

In conjunction with efforts to reduce both fossil fuel use and greenhouse gas (GHG) emissions, the State of Hawai‘i also seeks to increase renewable energy development and use. Among various state, county and city plans and policies, the Hawai‘i Global Warming Solutions Act (Act 234, Session Law of Hawai‘i (SLH) 2007), the Hawai‘i Clean Energy Initiative (HCEI), and the Hawai‘i Bioenergy Master Plan (HBMP) specify targets for meeting the State’s fossil fuel and GHG reduction goals.

Hawai‘i currently derives 90% of its energy from fossil fuels. HCEI calls for Hawai‘i to meet 70% of its energy demand through renewable energy and energy efficiency measures by the year 2030 (DBEDT 2008). This will result in significant changes to Hawai‘i’s electricity generation and transportation sectors and the state’s energy usage habits.

Since HCEI’s introduction, a number of key energy policies have been put in place to codify its goals and facilitate its achievement. Of particular note are such new policies as the State’s adoption of a 40% Renewable Portfolio Standard (RPS) by 2030, the dollar per barrel tax, and a new state goal to have 30% of highway fuel needs supplied by alternative fuels by 2030 (DBEDT). All these measures make biofuels and other alternate energy sources more attractive.

Biofuels have the potential to play a significant role in helping Hawai‘i achieve its renewable energy and GHG emission reduction goals. There are two major types of liquid biofuels: bioethanol and biodiesel. Bioethanol derives from crops that contain sugar, such as sugarcane and corn. Bioethanol is often used as gasoline blend for motor vehicles. Biodiesel derives from crops that contain oil or fat, such as oil palm and soybeans, or animal fat. Biodiesel can substitute petroleum diesel without major changes to existing capital equipment. Biodiesel is a refined product from vegetable oil or animal fat. Un-refined vegetable oil, or crude vegetable oil, can be used to substitute heavier petroleum product such as residual fuel oil.\(^1\) This study focuses on biodiesel and crude vegetable oil for reasons we will discuss later.

It is important to assess the financial and technical viability and effectiveness of different biofuels and, in particular, their different supply chain pathways. Towards this end, this study discusses the potential of crop-based biofuels, specifically, renewable fuel oil and biodiesel, to support the State’s energy and GHG reduction goals. In this paper, we attempt to answer the following key questions:

- What is the potential reduction in GHG emissions if biofuels replace fossil fuels?
- What is the difference in GHG emissions between locally produced and imported biofuels?
- Which biomass crops offer the best potential for GHG emission reductions?
- What are the potential fuel supply chain pathways?
- To what extent can biofuels reduce Hawai‘i’s consumption of oil?

\(^1\) Crude vegetable oil can be refined into various products as crude oil can be refined into various petroleum products. For instance, jet fuel may be substituted by jet biofuel.
To answer these questions, this study utilizes a uniform methodology to account for the life cycle of GHG emissions and how to properly account/credit for emission reductions. We review various studies and standards on biofuel life cycle analysis (LCA) and compute life cycle GHG emissions for Hawai‘i’s specific fuel pathways. We also show land requirements for biofuel crop production by deriving per acre energy yield for different biofuels. A comparison of the GHG emissions associated with biofuels and petroleum products are also presented.

Though we recognize other potential feedstocks such as animal waste or waste, this study focuses on crop-based biofuels. We are also aware that there are many other renewable energy options such as wind, solar heater, solar PV, and geothermal. We recognize the significance of conducting life cycle analysis of such technologies, but we choose to reserve such studies for the future.

In deciding whether biofuels can replace fossil fuels and which biofuel is best, one needs to consider their viability and feasibility with respect to competition for food, their production costs, and resource availability. Although we recognize the importance of such concerns, this study does not discuss them due to data availability.

In Section 2, we discuss previous work on biofuel LCA and their relevance to our study. In Section 3, we introduce the five fuel pathways that this paper considers and define the scope of study. In Section 4, we introduce our methodology for computing life cycle GHG emissions. Section 5 presents our research results and offers some discussion. In Section 6, we discuss limitations and uncertainties in account. Section 7 concludes the report.

2 Previous LCA studies

Many groups have undertaken studies to compute the LCA for various biofuels. Much of the work however, has mainly focused on biofuels for the transportation sector. In this section, we highlight five prominent studies performed by: Argonne National Laboratory, California Air Resources Board, Intergovernmental Panel on Climate Change (IPCC), US Environmental Protection Agency (US-EPA), and UK Renewable Fuels Agency (UK-RFA). Compared to the continental United States, Hawai‘i has a unique energy structure and is geographically distinct. We therefore found it insufficient to refer only to US studies and thus examined both national and international studies on LCA. These studies contributed to our understanding of which pathways would be probable for delivering biofuels to Hawai‘i. The results from these studies provide a source of comparison for our findings of life cycle emissions from various pathways.

2.1 Argonne National Lab

Argonne National Laboratory developed the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model. This model lets computation of life cycle GHG emissions from the various types of fuels used in transportation. The model has been used in many projects including California’s Low Carbon Fuel Standard Program (California Air Resource Board), which is described in detail in the next section. The model provides a comprehensive analysis of the different fuel mix and fuel pathways. For instance, the model allows for modifying the percentage of different types of fuel used for electricity production. This is important when conducting an LCA for different types of electric vehicles. The model also allows choice among various vehicle types for transportation end-use combustion. GREET
has an added advantage in allowing for multi-year projections. Users can specify such projections as combustion engine efficiencies. The GREET fuel pathways include three types of crops: corn, sugarcane, and soybeans, as inputs for the first generation biofuels (Argonne National Laboratory).

### 2.2 California Air Resources Board

In its efforts to develop a low carbon fuel standard, the California Air Resources Board (CARB) considered a number of biofuel pathways. Although this analysis is concerned with the transportation sector, following pathways are relevant to our study:

- Conversion of waste oils (used cooking oil) to biodiesel (fatty acid methyl esters - FAME) where “cooking” is required;
- Biodiesel conversion of waste oils (used cooking oil) to biodiesel where “cooking” is not required;
- Conversion of tallow to renewable diesel, using a higher energy use for rendering;
- Renewable diesel conversion of tallow to renewable diesel, using a lower energy use for rendering, and;
- Midwest soybeans to biodiesel.

Table 1 reports the carbon intensity for the different pathways. Though the first four may have very low emission factors, the availability of their feedstocks (used cooking oil or tallow) is quite low. It is also important to note that the efficacy of this fuel and fuels from similar pathways depends greatly on land-use changes involving soybean production. These processes could make use of these local waste products to satisfy a small percentage of diesel demand, but the volumes are too small to satisfy a significant demand, and therefore, were not pursued for this analysis.

Depending on the price of soybeans, Hawai‘i may want to source biodiesel from Midwest crops. In our study, we derived estimates of the direct emissions to produce biodiesel from soybeans as well as other biofuels not considered by CARB.

**Table 1: Carbon intensities from various pathways put forth by the Air Resources Board**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Pathway</th>
<th>Direct Emissions</th>
<th>Total Emissions Incl. Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>Average of California refinery</td>
<td>94.7</td>
<td>94.7</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Used cooking oil to FAME w/ cooking</td>
<td>15.8</td>
<td>15.8</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Used cooking oil to FAME w/o cooking</td>
<td>11.8</td>
<td>11.8</td>
</tr>
<tr>
<td>Renewable</td>
<td>Tallow to renewable biodiesel using higher energy</td>
<td>39.3</td>
<td>39.3</td>
</tr>
<tr>
<td>Diesel</td>
<td>Tallow to renewable biodiesel using lower energy</td>
<td>19.6</td>
<td>19.6</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Soy oil transesterified to biodiesel</td>
<td>21.2</td>
<td>83.2</td>
</tr>
</tbody>
</table>
(California Environmental Protection Agency Air Resources Board 2008)

2.3 Intergovernmental Panel of Climate Change

The IPCC provides guidelines for calculating GHG emissions from different fuels via various combustion activities. Our analysis follows their 2006 guidelines to calculate CO₂-eq emission of methane and nitrous oxide by using Global Warming Potential (GWP). We use IPCC’s emission factor database to calculate GHG emissions from combustion activities.

2.4 US Environmental Protection Agency

The US-EPA has elaborate work on LCA within the framework of its RFS. US-EPA’s methodology is based on the existing models to supplement LCA. For instance, it uses FASOM Economic modeling by Texas A&M University to project changes in domestic agriculture sectors and the FAPRI-CARD model by Iowa State University to evaluate the impacts of the biofuel crop production on international agricultural and livestock production (Us Environmental Protection Agency 2010). In a collaborative effort with Winrock International, they also examine land use changes due to biofuels production. Although their methodology is comprehensive, their crop choice is limited to corn, switchgrass, sugarcane, and soybean. Given Hawai‘i’s unique climate and geography, we need to expand the crop choice.

2.5 UK Renewable Fuel Agency

The UK Renewable Fuels Agency (UK-RFA) specifies the methods for reporting the carbon intensity of biofuel derived from various types of crops to meet its Renewable Transportation Fuel Obligation (RTFO) (Uk Renewable Fuels Agency 2008). While most US studies focus on biofuel derived from corn and soybeans, the UK-RFA analysis includes other crops such as oil palm and jatropha. Their framework accounts not only for the domestically produced crops and fuels but also for the imported ones. For those reasons, we employ their value chain as the basis for calculating GHG emissions, from the production of the crops to fuel conversion.

3 Scenarios Analyzed

3.1 Fuel Demand

Three lines of inquiry frame the scope of this analysis: i) how much biofuel the state requires; ii) which crops are used for biofuel production; and iii) where activities take place along the biofuel value chain.

Before discussing the details of how these value chains were chosen, it is important to note that ethanol is not included in the scope of this analysis. This decision was driven by several considerations:

- HECO is pursuing a strategy to retrofit their existing generation units to burn biodiesel to incorporate biofuels into their electricity generation mix. This strategy appears more economical than building new units that burn ethanol.
- The success of electric vehicles could depress the forecasted demand for ethanol, minimizing the value of a GHG LCA of the alcohol fuel.
- At present the market lacks commercial scale development of second-generation sources of ethanol.
For these reasons, ethanol is excluded from the current study. Also excluded is fiber (inclusive of forest residues, wood, albezia, and sugar cane bagasse). While our methodology would support analysis of GHG LCA for ethanol and fiber, we elect to focus on the most viable biofuels available at this time.

Table 2: Expected Fuel Consumption

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1: 20% Residual Fuel and Diesel Oil Replacement</th>
<th>Scenario 2: 100% Residual Fuel and Diesel Oil Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TJ</td>
<td>MM Bbl</td>
</tr>
<tr>
<td>Residual Fuel Oil</td>
<td>58,246</td>
<td>9.36</td>
</tr>
<tr>
<td>Diesel</td>
<td>15,451</td>
<td>2.69</td>
</tr>
<tr>
<td>Renewable Fuel Oil</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Biodiesel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Diesel Substitution)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Biodiesel (New Gen Unit)</td>
<td>2,987</td>
<td>0.56</td>
</tr>
<tr>
<td>Power Sector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (Non-Hwy Use)</td>
<td>32,133</td>
<td>5.60</td>
</tr>
<tr>
<td>Diesel (Hwy-Use)</td>
<td>7,206</td>
<td>1.25</td>
</tr>
<tr>
<td>Biodiesel (Non-Hwy Use)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transportation Sector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel (Hwy-Use)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: 2007 Fuel Consumption by County/Island in millions of barrels per year

<table>
<thead>
<tr>
<th></th>
<th>Honolulu</th>
<th>Maui</th>
<th>Lanai</th>
<th>Molokai</th>
<th>Hawaii</th>
<th>Kauai</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>8.10</td>
<td>0.47</td>
<td>0.55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9.36</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.10</td>
<td>1.36</td>
<td>0.06</td>
<td>0.07</td>
<td>0.28</td>
<td>0.82</td>
<td>2.69</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel Oil (Non-Hwy)</td>
<td>4.43</td>
<td>0.28</td>
<td>0</td>
<td>0</td>
<td>0.35</td>
<td>0.53</td>
<td>5.60</td>
</tr>
<tr>
<td>Diesel Oil (Hwy Use)</td>
<td>0.60</td>
<td>0.22</td>
<td>0</td>
<td>0</td>
<td>0.31</td>
<td>0.11</td>
<td>1.25</td>
</tr>
</tbody>
</table>

(Hawaii Natural Energy Institute 2009)
Baseline
The Baseline includes the 2007 residual fuel oil and diesel use for power generation: residual fuel (9.36 MM Bbl) and diesel (2.69 MM Bbl); and diesel use in 2007 diesel use for transportation: diesel (non-highway use) (5.60 MM Bbl) and diesel (highway use) (1.25 MM Bbl). The biodiesel for existing planned power generation (0.56 MM Bbl) is also included here. This choice reflects the desire and expectation that this analysis will be useful for comparisons beyond decisions already made.

Scenario 1
Scenario 1 adopts the HBMP “‘significant’ bioenergy scenario” to calculate GHG emissions when substituting 20% of oil-based fuels for power generation and transportation in 2007. 20% of residual fuel will be replaced by renewable fuel oil and 20% of diesel will be replaced by biodiesel. We assume that residual fuel replacement will occur entirely in Oahu generators and diesel fuel replacement will occur entirely in Maui generators for this scenario. This assumption is made based on fuel use in 2007 (described in Table 3). Since Oahu and Maui use more than 20% of the State’s residual fuel oil and diesel oil for power production, we assume biofuel substitution will occur in their systems first. This decision will impact GHG emissions from the distribution value chain point, as this scenario will not result in energy spent on distribution of biodiesel to all islands (more on this point later in this paper).

In summary, Scenario 1 displaces 1.88 MM Bbl of residual fuel oil with 2 MM Bbl of renewable fuel oil and displaces 0.55 MM Bbl of diesel with 0.58 MM Bbl of biodiesel².

Scenario 2
Scenario 2 extends the HBMP approach by substituting 100% of residual fuel oil and diesel in 2007. In summary, Scenario 2 displaces 9.36 MM Bbl residual fuel oil with 10 MM Bbl of renewable fuel oil and 2.69 MM Bbl of diesel with 2.9 MM Bbl of biodiesel.

3.2 Crop Selection
This analysis includes three crops as the source for biofuel production: oil palm, soybean, and jatropha. We chose these crops because they are repeatedly discussed and recommended by the HBMP project and Poteet (2006). These crops are also discussed in other methodologies developed and used by the UK-RFA, the US-EPA, Argonne National Laboratories and CARB.

Oil palm
Oil palm grows in tropical climates. Malaysia and Indonesia are the two main countries producing palm oil, and Biodiesel production from oil palm is commercially established (United Nations Food and Agriculture Organization 2008). Palm oil is expected to account for half the growth in world vegetable oil production between now and 2017; 88% of this will be from Indonesia and Malaysia (Edwards, R, S Szekers, F Neuwahl, and Vm Ies 2008). About 27% of palm oil concessions (planned plantations) in Indonesia are on peat-forest, with about 10% of present plantations in Malaysia on former peat-forests (Edwards, R, S Szekers, F Neuwahl, and Vm Ies 2008).

² Note: each fuel has a different energy content per volume.
Jatropha
Jatropha also grows in tropical climates. Jatropha is not a widely used crop for biodiesel production but it is commercially produced in India and some parts of Africa. (Whitaker, M, G Heath, and National Renewable Energy Laboratory 2009). Since this crop is not edible, the demand for this crop comes solely from biofuel production. One of the advantages of growing jatropha is that it can grow in a dry climate (Poteet, MD 2006). As water becomes scarcer and its cost is not negligible, this characteristic makes jatropha more attractive.

Soybean
Used to produce ethanol, soybean is the next major fuel crop in the United States to corn. Soybeans could be grown in Hawai‘i, however, a large initial investment would be required. Poteet highlights the costliness of soybeans in Hawai‘i, stating, “the water costs alone would likely be greater per acre than the value of the crop, making the economics of soybean production in dry microclimates unfeasible (Poteet, MD 2006).” Although soybean production would not be suitable for Hawai‘i, it would be feasible for the State to import soybean-based biofuels from the US Mainland.

3.3 Pathways Selected
Our choice of pathways is summarized in Table 4. In Pathway 1, we import crude palm oil from Malaysia. In this pathway, biofuel conversion takes place in Hawai‘i. In Pathways 2 and 3, we import biofuels derived from oil palm and soybean from Malaysia and the US Mainland respectively. In Pathways 4 and 5, the entire production of biofuel takes place in Hawai‘i. We choose oil palm and jatropha as the feedstock for local production.

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Crop</th>
<th>Value Chain Activity</th>
<th>Locale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Production</td>
<td>Logistics</td>
</tr>
<tr>
<td>Pathway 1</td>
<td>Oil Palm</td>
<td>Malaysia</td>
<td>Malaysia</td>
</tr>
<tr>
<td>Pathway 2</td>
<td>Oil Palm</td>
<td>Malaysia</td>
<td>Malaysia</td>
</tr>
<tr>
<td>Pathway 3</td>
<td>Soybean</td>
<td>US Mainland</td>
<td>US Mainland</td>
</tr>
<tr>
<td>Pathway 4</td>
<td>Oil Palm</td>
<td>Hawai‘i</td>
<td>Hawai‘i</td>
</tr>
<tr>
<td>Pathway 5</td>
<td>Jatropha</td>
<td>Hawai‘i</td>
<td>Hawai‘i</td>
</tr>
</tbody>
</table>

4 Methodology and Data
This study determines life cycle GHG emissions from the use of biodiesel and renewable fuel oil in power generation and the transportation sector. Figure 1 represents the five-step value chain of the life cycle emissions from the use of biofuels. We followed the standard convention of dividing the biofuel value chain into five steps: Feedstock production, Feedstock logistics, Conversion, Distribution, and End-use. First, we calculate GHG emissions at each of the step in the value chain, then we add the emissions from each step to show the life cycle of GHG emissions.
In our analysis, we include the three major GHG contributors of global warming: carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O). By following the IPCC’s guideline of each of the three gases’ GWP, the total GHG is shown in terms of the CO$_2$-equivalent (IPCC 2007). Table 9 shows the 100-year GWP (or CO$_2$ equivalent factors) of each gaseous molecule.

**Table 5: CO$_2$-eq factor**

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Global Warming Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>1</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>25</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>298</td>
</tr>
</tbody>
</table>

(Source: IPCC 2006)

4.1 Input Data

Table 5 summarizes the input data we used in our calculation of life cycle GHG emission. At each step of the life cycle value chain, emission factors are presented along with the data source. At the first three phases of the life cycle, Feedstock Production, Feedstock Logistics, and Conversion, emission factors are determined for each of the crops and petroleum separately. For Distribution, emission factors are given by different transportation mode and their units, kg CO$_2$-eq/MT-km, represent the emission from per mass of fuel used per distance. For End-use stage, emission factors are presented for biofuel and petroleum for electricity production and for transportation.

4.2 Treatment of Land Use Change

In most traditional biofuel LCA of GHG emissions, the assumption is made that no land use change has occurred; land use change is a subcategory of the first stage of the value chain entitled Feedstock Production. Where analyses did consider the impacts of land use change, there are significant net GHG emissions; their results indicate a significant release of carbon stocks that usually eliminates any GHG savings that would otherwise be derived from the biofuel (Pearson, T, S Walker, and S Brown 2005). GHG emissions from land use change vary between biotic community and specific locations. Generally the calculation of the carbon content of an
area about to be cleared for bioenergy crop production according to the IPCC Guidelines consists mainly of two parts: the carbon content in the living and dead biomass; and the carbon content in the soil carbon.

Edwards et al. (2008) explored biofuel made from palm oil and the land use change of peat-forest associated with it. The CO2 losses from oil palm plantations on drained peat-forest are about 170 tonnes/ha/y and would cause the GHG savings from biofuel to be cancelled out (Edwards, R, S Szekers, F Neuwahl, and Vm Ies 2008).

We recognize that the acceleration of the production of biofuels will reduce the quantity of land available for farming biofuel feedstock. We agree that land use change should be included as a possible scenario, the environmental trade-offs should be fully characterized and analysis should be properly account for the GHG impacts of biofuels. GHG net emissions equations will need to be changed accordingly. For example, one concern about importing biofuels from Malaysia arises when forests are clear cut or burned to create land on which biocrops can be grown.

Our study could not include land use due to a lack of uniform calculations/equations and absence of information specific to Hawaiian soils.

4.3 Treatment of Carbon Sequestration

One of the major benefits of using biofuels is the carbon sequestration by biomass crops. The notion of carbon sequestration is derived from the process of photosynthesis by plants, during which plants sequester atmospheric carbon. As the crops grow, the generated biomass that will supply biofuels used for electricity generation and transportation comes from sequestered carbon. In our analysis, we assume that CO2 emissions during biofuel end-use (combustion) equals the amount sequestered by growing biomass crops -i.e., CO2 mass sequestered during feedstock production equals CO2 mass emitted during end-use. Therefore the GHG emission differences between fossil fuel and biofuel result from points along the value chain.
Table 6: Input Data

<table>
<thead>
<tr>
<th></th>
<th>Oil Palm</th>
<th>Soybean</th>
<th>Jatropha</th>
<th>Petroleum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feedstock Production</strong></td>
<td>313 kg CO₂-eq/MT</td>
<td>2393 kg CO₂-eq/MT</td>
<td>169 kg CO₂-eq/MT</td>
<td>8467 kg CO₂-eq/TJ</td>
</tr>
<tr>
<td><strong>Feedstock Logistics</strong></td>
<td>570 kg CO₂-eq/MT</td>
<td>-713 kg CO₂-eq/MT</td>
<td>293 kg CO₂-eq/MT</td>
<td>2293 kg CO₂-eq/TJ</td>
</tr>
<tr>
<td><strong>Conversion</strong></td>
<td>828 kg CO₂-eq/MT</td>
<td>471 kg CO₂-eq/MT</td>
<td>471 kg CO₂-eq/MT</td>
<td>5132 kg CO₂-eq/TJ</td>
</tr>
</tbody>
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<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Ship</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distribution</strong></td>
<td>0.005 kg CO₂-eq/MT-km</td>
<td>0.011 kg CO₂-eq/MT</td>
<td>0.114 kg CO₂-eq/MT</td>
<td></td>
</tr>
</tbody>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Berge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>End-use (NET) Data Source</strong></td>
<td>254 kg CO2e/TJ</td>
<td>1480 kg CO2-eq/TJ</td>
<td>74354 kg CO2e/TJ</td>
<td>77654 kg CO2e/TJ</td>
</tr>
</tbody>
</table>


[2] Key Assumptions for the GHGenius Model Run of the HECO CT1 Biodiesel Project.


[4] Canadian National Railway Company [Source: The truck emission factor was calculated using diesel fuel consumption data from Statistics Canada's Trucking in Canada 1995 survey for for-hire trucking companies with revenues greater than $1M, combined with tonne-km data from Statistics Canada's For-Hire Trucking Commodity Origin/Destination Survey 1995 that was modified by Transport Canada to include an estimated tonne-km amount for smaller freight carriers.]


## 5 Results

**Table 7: Reduction in emissions and oil imports under different pathways and scenarios**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pathway</th>
<th>Petroleum Imports Reduction (MM Bbl)</th>
<th>Emission Reduction (MM MT CO$_2$-eq)</th>
<th>Emission Reduction compared to Baseline (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Oil Palm</strong>, imports crude (Malaysia)</td>
<td>3.79</td>
<td>1.24</td>
<td>13.70</td>
</tr>
<tr>
<td>2</td>
<td><strong>Oil Palm</strong>, imports final product (Malaysia)</td>
<td>3.79</td>
<td>1.23</td>
<td>13.67</td>
</tr>
<tr>
<td>3</td>
<td><strong>Soybean</strong> (US Mainland)</td>
<td>3.79</td>
<td>0.78</td>
<td>8.87</td>
</tr>
<tr>
<td>3b</td>
<td><strong>Soybean</strong>, excludes soy meal credit (US Mainland)</td>
<td>3.79</td>
<td>0.21</td>
<td>3.32</td>
</tr>
<tr>
<td>4</td>
<td><strong>Oil Palm</strong> (Local)</td>
<td>1.97</td>
<td>1.28</td>
<td>14.19</td>
</tr>
<tr>
<td>5</td>
<td><strong>Jatropha</strong> (Local)</td>
<td>2.81</td>
<td>1.7</td>
<td>17.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2: 100% Residual Fuel and Diesel Oil Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>3b</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

Table 6 reports the reduction in petroleum use and GHG emissions by substituting biofuels for residual fuel and diesel oil under the two scenarios, 20% and 100% residual fuel and diesel oil substitution, for three different feedstock crops.

By substituting 20% and 100% of diesel and residual fuel oil with imported biofuels, Hawai‘i can displace 3.79 MM Bbl and 18.9 MM Bbl, respectively, from the electricity and transportation sectors. However, if Hawai‘i chooses to grow crops to convert into biofuels locally, then the reduction in petroleum imports may not be as great because Hawai‘i will need sources of energy to process the crops into biofuels. For imported fuels, the petroleum use is reduced by 3.79 MM bbls for Scenario 1 and 18.9 MM bbls for Scenario 2. On the other hand for locally produced oil palm- and jatropha-based biofuels, we assume petroleum is the fuel used to process the biocrops. The reduction is then limited to 1.97 MM Bbls (oil palm) and 2.81 MM
Bbls (jatropha) for Scenario 1 and 9.83 MM Bbls (oil palm) and 14.0 MM Bbls (jatropha) for Scenario 2. Presumably, biofuels could be used in the conversion of feedstock crops to biofuels, but doing this would lower the effective yield per acre of fuel because some of the crop would be needed for energy to convert the crops to biofuels and therefore would be unavailable for end-use consumption.

The GHG emission reduction ranges from 0.21 to 1.70 MM MT CO₂-eq for Scenario 1 and 1.05 to 8.04 MM MT CO₂-eq for Scenario 2. Among other crops and pathway alternatives, locally produced jatropha emits the least amount of GHG. This result derives from low level of emissions at the Feedstock Production phase of the life cycle. Table 7 reports the emission factors for each step in the life cycle of the specified pathways. In the table, it shows that jatropha only emits 4.4 g CO₂-eq/MJ during the feedstock production phase, which is the least amount of emissions among other crops in the production phase.

It is clear from Table 7 that bulk of emission for petroleum derives from the burning of the fuel (i.e. end use). On the other hand, for biofuels, the crop sequesters entire CO₂ emission. The emissions in the End-use phase come from NH₄ (methane) and N₂O (nitrous oxide) emissions.

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Feedstock Production</th>
<th>Feedstock Logistics</th>
<th>Conversion</th>
<th>Distribution</th>
<th>End-use (Net)</th>
<th>Net GHG Emissions</th>
<th>Ratio to Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Palm, import crude palm oil (Malaysia)</td>
<td>8.1</td>
<td>15.6</td>
<td>10.4</td>
<td>1</td>
<td>0.2</td>
<td>35.3</td>
<td>0.40</td>
</tr>
<tr>
<td>Oil Palm, import biofuel (Malaysia)</td>
<td>8.1</td>
<td>14.7</td>
<td>10.4</td>
<td>2.1</td>
<td>0.2</td>
<td>35.4</td>
<td>0.40</td>
</tr>
<tr>
<td>Soybean (US Mainland)</td>
<td>61.8</td>
<td>-18.4</td>
<td>5.9</td>
<td>3.7</td>
<td>0.2</td>
<td>53.2</td>
<td>0.60</td>
</tr>
<tr>
<td>Soybean, exclude soy meal credit (US Mainland)</td>
<td>61.8</td>
<td>7</td>
<td>5.9</td>
<td>3.7</td>
<td>0.2</td>
<td>78.6</td>
<td>0.89</td>
</tr>
<tr>
<td>Oil Palm (Local)</td>
<td>8.1</td>
<td>14.7</td>
<td>10.4</td>
<td>0.1</td>
<td>0.2</td>
<td>33.4</td>
<td>0.38</td>
</tr>
<tr>
<td>Jatropha (Local)</td>
<td>4.4</td>
<td>7.6</td>
<td>5.9</td>
<td>0.1</td>
<td>0.2</td>
<td>18.1</td>
<td>0.20</td>
</tr>
<tr>
<td>Petroleum Products</td>
<td>8.5</td>
<td>2.3</td>
<td>2.4</td>
<td>0.1</td>
<td>74.9</td>
<td>88.2</td>
<td>1</td>
</tr>
</tbody>
</table>

Comparing the emissions from imported oil palm based biofuel from Malaysia and locally produced oil palm based biofuel, the difference in GHG emissions is only 2.17%. This indicates that the transportation of the fuel from Malaysia to Hawaii does not contribute much to the overall GHG emissions. This is clear in Table 7, where difference in the emissions from distribution between imported and locally produced biofuel is about 2 g CO₂-eq/MJ. This is roughly 5% of the overall net emission for the imported fuel.

Among other crop choices, soybean based biofuel has the highest level of GHG emissions. For Scenario 2, it leads to the emission reduction of 44.47% with the byproduct credits and 16.72% without byproduct credits. As a fully developed agricultural product, all byproducts of soybeans
are utilized. One way to account for this bi-product, you can credit parts of the greenhouse gas emissions back to the byproduct. In the table 7, negative number shows this byproduct credit in Feedstock Logistics.

It is clear from the table 7 that the major cause for soybean based biofuel having the largest amount emission derives from the production phase of the crop. While other crops only emit 4.4 to 8.1 g CO$_2$-eq/MJ during the production of feedstock, soybean emits roughly 7.5 to 13 times as much GHG. The share of the emission from the feedstock production is 79% of the overall life cycle emission, accounting for the byproduct. This happens because of the difference in harvesting practice, while you only need to harvest fruits when harvesting oil palm or jatropha, you need to harvest the entire crop to harvest soybean.

GHG emissions do not vary much by changing the location of fuel conversion from raw oil to biofuel. In Table 6, comparing the biofuels derived from oil palm produced in Malaysia, the difference in GHG emissions is minimal when we import crude palm oil and when we import the final product.

Conversion of crude palm oil to the biofuel emits more GHG emissions than the other crops. This is because crude palm oil first needs to be processed into refined oil, then converted into biofuels via esterification. Meanwhile, soybean and jatropha oil can directly be converted into biofuel via transesterification.

As mentioned earlier, distribution of the fuel is a minor part of overall GHG emissions. However, it is worth noting that soybean biofuel imported from US Mainland has larger emissions than oil palm biofuel imported from Malaysia. The marine transportation distance between Malaysia and Oahu is more than twice as long as the distance between US Mainland and Oahu. The reason for higher emission from distribution comes from the ground transportation distance. Ground transportation emits more than twenty times as much GHG as marine transportation. In the US Mainland, the ground transportation distance from the refinery to the port is eight times as long as in Malaysia.

6 Discussion

The results indicate that feedstock production and feedstock logistics phases are the key to reduce GHG emission. Locally produced jatropha-based biofuel achieves the most emission reduction for its low emission during feedstock production, while soybean-based biofuel has the lowest emission reduction for its high emission during feedstock production. Byproduct establishment is another key to reduce overall GHG emission. This is clear from the comparison from the soybean-based biofuel. These results suggest the potential emission savings from the improved farming practice. Achieving higher yield and reduced fertilizer and energy use during feedstock production can further reduce GHG emissions. On the other hand, transportation of the fuel does not contribute much to the life cycle GHG emissions. Their share in the entire life cycle emission is big. This section offers further discussions of the results and their implications.
6.1 Local vs. Imports

Life cycle emissions are one element to consider in determining the best biofuel pathway. Costs and resource usage (e.g., water and land requirements) also need to be considered in the final decision of which feedstock to grow and where to grow it.

Over the past few years, several legislators have pushed for Hawai‘i to produce its own biofuels because of the belief that this would reduce Hawai‘i’s dependence on foreign oil and boost its economy.

In this analysis, we investigated Hawai‘i’s capacity for producing biofuels, achieving GHG reduction benefits, and reducing oil imports. Table 8 reports the energy yield of different crops under different watering conditions and the potential amount of energy that could be produced from Hawai‘i’s lands.

<table>
<thead>
<tr>
<th>Biocrop/Water Source</th>
<th>Yield (MMBtu/ha)</th>
<th>Energy Potential Using All Plantation Lands (MM Bbl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BioEnergy Master Plan Optimistic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Palm/rain fed</td>
<td>66</td>
<td>0.24</td>
</tr>
<tr>
<td>Oil Palm/irrigated</td>
<td>88</td>
<td>0.32</td>
</tr>
<tr>
<td>Jatropha/rain fed</td>
<td>33</td>
<td>0.12</td>
</tr>
<tr>
<td>Jatropha/irrigated</td>
<td>85</td>
<td>0.31</td>
</tr>
</tbody>
</table>

There are important land use and water resource issues associated with growing feedstock crops. Hawai‘i grown biofuels have the least amount of emissions, but Hawai‘i’s capacity for producing energy from land-based crops is limited. The HBMP concluded that optimistically, there are 53,000 acres available for growing biocrops. Even if all plantation lands were irrigated and used for growing feedstock crops, the land would produce less than one million barrels of biofuels or less than half the demand of 20% diesel and residual fuel oil substitution.

---

3 "137,000 acres of former plantation lands are available for bioenergy crop production with extensive infrastructure development. However, with the consideration of various limitations, the optimistic projection is that only 53,000 acres statewide can be utilized for bioenergy crop production." HNEI Bioenergy Master Plan Vol. II Land & Water Resources, (2009)

4 Based on The Potential for Biofuels Production in Hawaii (Black & Veatch Corporation and Economic Development and Tourism State of Hawai‘i Department of Business. 2010. "Potential for Biofuel Production in Hawai‘i." , biodiesel production from oil palm: 203 gallons per acre (= 1901.15 liters per ha), from jatropha: 103 gallons per acre (= 964 liters per ha) on rainfed land; from oil palm: 270 gallons per acre (=2528.54 liters per ha), from jatropha 261 gallons per acre (=2444 liters per ha).
Thus to replace significant quantities of oil with biofuel (i.e., going from 20% to 100% substitution) would require substantial imports of biofuels. It is also important to point out that the emission from transporting the fuel from overseas is minor. As noted in the previous section, local production of the biofuel only achieves 2% reduction in GHG emissions compared to the import.

Though locally grown jatropha has the least amount of life cycle emissions, it requires more water than palm oil. In addition producing any fuel in Hawaii will likely demand large supplies of water. These resource issues as well as life cycle emissions need to be considered in the final decision of which feedstock to grow.

6.2 Likely Impacts of Cost Adder from a Carbon Policy (Implications for CO₂ Policy)

As Hawaiiʻi moves forward with its climate change policy and HCEI, the State will be required to reduce its GHGs, and in particular, CO₂ emissions. These policies will result either directly or indirectly in a cost for these emissions. As this cost increases, the State will transition to less carbon and less GHG intensive activities.

What these transitions mean for biofuels production in Hawaiiʻi could depend on how the State decides to account for emissions associated with biofuels. If the State accounts for the full life cycle emissions associated with biofuels, then all else being equal, as the cost of emitting GHGs rises, local production of biofuels will become slightly more cost-effective; biofuel will have fewer emissions, avoiding the emissions associated with importing the finished biofuel.

To assess the value of these emissions savings from not importing biofuels, one needs to multiply the emissions savings by a representative CO₂ price and then compare these cost savings to the likely cost of biofuels. The Waxman-Markey legislation is probably the most representative GHG legislation. In the EPA’s analysis of this climate change legislation, they estimated carbon prices to range from $20/mt of CO₂e to $85 in 2005$ from 2020 to 2050 (Us Environmental Protection Agency 2009). Using the high end of the range means that the additional 2% reduction in emissions from producing biofuels in Hawaiiʻi equates to about a $0.18/MMBtu cost savings. The Energy Information Agency forecasts fossil diesel to sell for about $25/MMBtu in 2020. Biodiesel is likely to be priced above fossil diesel in 2020. Using the fossil diesel price says that if there were a GHG policy with an effective price for GHG emissions of $85/MT of CO₂e, the transport cost adder would amount to less than 1% of the price of the biofuels. Therefore, from a GHG cost perspective there is virtually no difference between importing biofuels and producing them locally. Given the higher land and labor costs in Hawaiiʻi relative to those in developing countries, production costs would likely remain higher in Hawaiiʻi. Therefore this carbon advantage is too small to affect the relevant economics.

If, however, the state accounts only for emissions occurring in Hawaiiʻi, and excludes emissions associated with combustion under the assumption that these represent CO₂ that had been sequestered, then there will be an additional disincentive to producing biofuels locally. Under this case, however, biofuels in general would experience a cost advantage relative to fossil fuels. Using the EPA cost estimates for permit prices, the biofuels considered in this analysis would receive a cost advantage of between $1/MMBtu to $6/MMBtu or about a 4-24% edge relative to the corresponding fossil fuel.
In comparing the costs of different biofuels along different pathways, one should incorporate all costs, including those associated with GHG emissions. This ensures that fuel purchase decisions would be based on the total production costs.

6.3 Limitations and Uncertainty in Accounting

In all of the 5 pathways, there are great uncertainties. In this section, we attempt to discuss such uncertainties and future research needed to reduce these uncertainties.

Ignoring emissions associated with changes in land use, one sees significant emissions savings via biofuel use, ranging from 10-80% reductions in fossil fuel emissions. But as highlighted by others analyses (e.g., CARB), emissions from changes in land use are quite unclear. Originally, CARB found these emissions could be three or four times the amount of emissions from all other processes in the value chain. Recently however, an analysis conducted by the Global Trade Analysis Project found that emissions from land use changes for corn-based ethanol were only 13.9 gCO$_2$/MJ (Tyner, We, F Taheripour, Q Zhuang, D Birur, and U Baldos). Just as land use changes could significantly increase life cycle emissions, byproduct credits could significantly reduce life cycle emissions. As discussed in the Section 4.1, due to the lack of available data, the impacts from land use change were not considered in this study. Therefore, to determine the full life cycle emissions of the various biofuels pathways considered in this study, one must perform further analysis to compute the emissions associated with land-use change and byproduct credits for each specific proposed pathway.

This study assumes homogeneous land. In other words, various soil types and geographical characteristics are not considered. The study also does not discuss 2nd and 3rd generation biofuels such as cellulosic biofuels and algae based biofuels. This is due to limited data and their market not being well established.

7 Conclusion

This study calculated the life cycle GHG emissions from replacing oil with biofuels in the state of Hawai‘i. This analysis concerned itself with analyzing life cycle emissions of fuels and the possible emissions savings of, and reduced oil imports from, biofuels. The work revealed several key findings, many of which point to Jatropha as an ideal biofuel feedstock.

Generally, the value chain point feedstock production has the highest level of GHG emissions, followed by feedstock logistics, conversion, and lastly distribution. Therefore, jatropha is a very attractive feedstock given its emissions per energy yield is lowest within Feedstock Production (Table 7). It is, however, critical to note that a comprehensive land-use change analysis could alter these results. Future studies in this area are important.

The jatropha pathway also emits relatively very few GHGs at the feedstock logistics point, though when byproducts are considered for soybean oil its GHG emissions are the lowest at that value chain point. It is therefore critical to maximize byproduct development, and future research should investigate possible jatropha co-products that would even further reduce its feedstock logistics emissions. Byproducts or no, soybean oil has the highest emissions out of all the crops.
evaluated because the plant is completely harvested every year, rather than harvesting a portion of the tree as in a palm oil tree.

*Distribution* surprisingly does not significantly contribute to gross emissions. This fact is most apparent when comparing imported Malaysian oil palm to locally produced oil palm - a 60% reduction compared to a 62% reduction, respectively (Table 7). This result emphasizes the need to evaluate the economics of imported versus locally produced biofuels. These results indicate that the *distribution* GHG emissions do not heavily influence net emissions.

As pointed out above, our results call for at least three areas of future investigation:

- A cost-benefit analysis, which would compare differences in agricultural output, labor cost, land value, processing, and infrastructure requirements for both various crops and locations.

- An impact assessment of monetizing GHG emission reductions from substituting biofuels - i.e. attaching a price on carbon. UHERO EGGS is well poised for such a study, having demonstrated proficiency in both economic modeling and complex life cycle analysis, which includes GHG accounting. This could include evaluating other energy options - e.g. wind, solar, energy efficiency, etc.

- An evaluation of land-use change elements that would not only include resulting GHG emissions, but also added value from preserving or increasing open lands. This idea of preserving or expanding open lands is particularly important in Hawai‘i where both residents and visitors gain from land use, which allows views out to the surrounding environment.
REFERENCE

Argonne National Laboratory. "GREET Model."


California Air Resource Board Website.

California Environmental Protection Agency Air Resources Board. 2008. "Detailed California-GREET Pathway for Biodiesel (Esterified Soyoil) from Midwest Soybeans."

DBEDT. "Hawaii - DOE Clean Energy Initiative."


Tyner, We, F Taheripour, Q Zhuang, D Birur, and U Baldos. 2010. "Land use changes and consequent CO2 emissions due to US corn ethanol production: A comprehensive analysis." Department of Agricultural Economics, Purdue University.


APPENDIX A: METHODOLOGY

The total GHG emissions from biodiesel in pathway \( i \) for scenario \( j \) can be given by

\[
\text{Total GHG emission}^{ij} = \sum_{k \in K} V_k^{ij}
\]

where

\( V_k^{ij} \): kg CO\textsubscript{2}-eq emitted from component \( k \) of the value chain for pathway \( i \) for scenario \( j \)

\( k = \text{Step of the value chain: \{Production (P), Feedstock Logistics (L), Conversion (C), Distribution (D), End-use (Net) (U)\}} \)

\( i \in I = \text{Pathway: \{Oil Palm grown in Malaysia, ship crude palm oil to Hawai'i (1); Oil Palm grown in Malaysia, ship biofuel to Hawai'i (2), Soybean US (3), Oil Palm Hawaii (4), Jatropha Hawai'i (5)\}} \)

\( j \in J = \text{Scenario: \{Baseline, Scenario 1, Scenario 2\}} \).

In our analysis, we include the following three major GHG contributors of global warming: carbon dioxide (CO\textsubscript{2}), methane (CH\textsubscript{4}), and nitrous oxide (N\textsubscript{2}O). By following the IPCC’s guideline of each of the three gases’ GWP, the total GHG is shown in terms of the CO\textsubscript{2}-equivalent (IPCC 2007). We have

\[
E_{CO2}^k: \text{CO}_2\text{-eq factor for CO}_2 \ \forall k \in K
\]

\[
E_{CH4}^k: \text{CO}_2\text{-eq factor for CH}_4 \ \forall k \in K
\]

\[
E_{N2O}^k: \text{CO}_2\text{-eq factor for N}_2\text{O} \ \forall k \in K
\]

Table 9 shows the 100-year GWP (or CO\textsubscript{2} equivalent factors) of each gaseous molecule.

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Global Warming Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2}</td>
<td>1</td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>25</td>
</tr>
<tr>
<td>N\textsubscript{2}O</td>
<td>298</td>
</tr>
</tbody>
</table>

(IPCC 2006)

STEPS IN VALUE CHAIN

We followed the standard convention of dividing the biofuel value chain into five steps: Feedstock production, Feedstock logistics, Conversion, Distribution, and End-use. The calculation of GHG emissions from Feedstock production and Conversion strictly follow the specification by UK’s Renewable Transportation Fuel Obligation (RTFO). For the Feedstock logistics, a modified version of RTFO is used to calculate the emissions. In this section, we detail how GHG emissions from each step of the value chain are calculated.
Feedstock production

Feedstock production includes the process of producing biomass crops. Following RTFO, the emissions from the production of biomass crops can be calculated as:

\[ V_p^{ij} = EF_n^{P} * B_j \]

where:
- \( n \in N = \text{Feedstock type: \{Oil Palm, Soybean, Jatropha\}} \)
- \( EF_n^{P} : \text{Oil palm crop production emissions factor} \)
- \( EF_n^{SB} : \text{Soybean crop production emissions factor} \)
- \( EF_n^{JT} : \text{Jatropha crop production emissions factor} \)
- \( B_j : \text{Amount of biodiesel needed to satisfy demand in Scenario } j \)

Feedstock logistics

*Feedstock logistics* includes the emissions from the transportation of feedstock from the farm to a conversion station, extraction of vegetable oil from raw crops, and the drying and storage of the feedstock. Particularly for Pathway 1, the shipment of oil palm-derived vegetable oil from Malaysia to Oahu is included in this value chain. Hence, the GHG emissions from feedstock logistics can be given as follows:

\[ V_L^{ij} = \sum_{l \in L} (EF_n^{l} * B_j) + SHIP_{ij} \]

where
- \( l \in L = \{\text{Feedstock Transportation (FS), Oil Extraction (OX), Drying and Storage (DS)}\}. \)
- \( SHIP_{ij} = OTD_{ij} * EF_n^{FS} * \alpha * B_j \)

Also,

\[ EF_n^{l} = \sum_{g \in G} EF_n^{l} * EQ_g \]

where:
- \( EF_n^{FS} : \text{Oil palm feedstock transportation emission factor} \)
- \( EF_n^{SB} : \text{Soybean feedstock transportation emission factor} \)
- \( EF_n^{JT} : \text{Jatropha feedstock transportation emission factor} \)
- \( EF_n^{OX} : \text{Palm oil extraction emission factor} \)
- \( EF_n^{OX} : \text{Soy oil extraction emission factor} \)
- \( EF_n^{DS} : \text{Oil palm drying and storage emission factor} \)
- \( EF_n^{DS} : \text{Drying and storage emission factor} \)

\( G=\{\text{CO}_2, \text{N}_2\text{O}, \text{CH}_4\} \) provides the emission from each stages of the feedstock logistics. We must also note that

\[ SHIP_{ij} = OTD_{ij} * EF_n^{FS} * \alpha * B_j \]
where:

OTD: Overseas transportation distance
α: added weight for the conversion of weight for vegetable oil
  • $t'$ = marine transportation
  • $n'$ = oil palm

$SHIP$ is only applicable to Pathway 1 (i.e. $SHIP_i = 0 \ \forall i \neq 1$) because all other Pathway conversions take place in close proximity to where the biomass crops are produced.

**Conversion**

Conversion of fuels takes different forms depending on the crop type. For instance, crude palm oil is first refined then converted into biodiesel by esterification; whereas, soybean oil and jatropha oil are converted into biodiesel through a step of transesterification. By considering such factors, we represent the emissions from conversion in the following form:

$$V_{ij}^c = EF_n^C * B_j .$$

To show emissions from different types of biomass crops, we have

$$EF_n^C = \sum_{g \in G} EF_{ng}^C * EQ_g$$

where for oil palm

$EF_{OP}^C$: Palm oil conversion emission factor

$EF_{OP}^C = \sum_{c \in C^*} EF_{OP}^c$

$C^* = \{\text{Palm oil refining (RF), Palm oil transportation (TR), Esterification (EST)}\}$

for soybean oil,

$EF_{SB}^C$: Soybean oil conversion factor

$EF_{SB}^C = EF_{SB}^{TEST}$

for jatropha,

$EF_{JT}^C$: Jatropha oil conversion factor

$EF_{JT}^C = EF_{JT}^{TEST}$

where

TEST: Transesterification emission factor.

Note that conversion of the fuel is a necessary step only for the biodiesel production. Renewable fuel oil does not require further conversion from crude vegetable oil.

**Distribution**

Distribution includes the transportation of biofuel from the conversion station to the power plant and fueling station. In our analysis, we chose trucking for ground transportation and large ships for the transportation of fuel from Malaysia and the US Mainland to O’ahu and barges for inter-
island marine transportation. Hence, we can represent the emissions from the distribution of biodiesel as follows:

\[
V_D^{ij} = \sum_{t \in T} \sum_{h \in H} (LCD_{ht} \ast EF_t^{D} \ast B_{jh} ) + SHIP_{ij}
\]

where

- \( LCD \): Local transportation distance
- \( T = \{\text{Marine transportation, Ground transportation}\} \)
- \( H = \{\text{O'ahu, Moloka'i, Lāna'i, Kaua'i, Hawai'i, Maui}\} \)

and

\[
EF_t^{D} = \sum_{g \in G} EF_{tg}^{O} \ast EQ_g
\]

where

- \( SHIP_{ij} = OTD_{ij} \ast EF_t^{D} \ast \alpha \ast B_j \)
- \( EF_{t'}^{L} = EF_{t'}^{D} \)
- \( t' = \text{Marine transportation.} \)

Again, we must note that \( SHIP \) only applies to Pathways 2 and 3, which involve shipment of fuel from overseas locations to Hawai'i. The allocation of biofuel among the six islands is based on the fuel consumption of each island in 2007, and our assumption described in Section 4.1.

**End-use**

End-use emissions include combustion of biofuel for the production of electricity and for transportation. Our calculation of these emissions follows the IPCC’s guidelines (IPCC) and emission factors, which can be represented by the following:

\[
V_U^{ij} = \sum_{g \in G} TEC(TJ)^{ij} \ast EF_{ng}^{U} \ast EQ_g
\]

where

- \( G = \{\text{CO}_2, \text{N}_2\text{O}, \text{CH}_4\} \)

We assume that biodiesel derived from different crops via different conversion processes share the same characteristics in terms if what types of chemicals are emitted when we burn the biodiesel. Hence, we suppose

\[
EF_{ng}^{U} = EF_{ng}^{U}; \quad \forall n \in N
\]

where

- \( N = \{\text{Oil Palm (OP), Soybean (SB), Jatropha (JT)}\} \).
- \( EF_{CO_2}^{U} \): \( \text{CO}_2 \) emission factor for biofuel
- \( EF_{CH_4}^{U} \): \( \text{CH}_4 \) emission factor for biofuel
- \( EF_{N_2O}^{U} \): \( \text{N}_2\text{O} \) emission factor for biofuel
APPENDIX B: HAWAI‘I BIOENERGY MASTER PLAN

HBMP Results

The HBMP results were presented in five sections and are summarized below.

Outcome I: Evaluation of Hawai‘i’s potential to rely on biofuels as a significant renewable energy resource

Having defined a 20% displacement of 2007 consumption as “significant,” the HBMP report concluded that Hawai‘i has the potential to rely on biofuels as a significant renewable energy source.

Outcome II: A plan or roadmap to implement commercially viable biofuels development

In brief, the HBMP report identified and expanded upon eight immediate, near-term action items:

1. Establish a bioenergy program
2. Establish a bioenergy technical advisory group
3. Develop clear and consistent policy for use of state lands
4. Develop methodology for evaluation of bioenergy projects
5. Require LCA for use of state lands or funding support.
6. Provide a tax credit for irrigation systems
7. Provide a tax credit for infrastructure systems
8. Appropriate funds for a research position

Outcome III – Strategic partnerships for the research, development, testing, and deployment of renewable biofuel technologies and production of biomass crops

Several partnering arrangements arose from the HBMP project. Additionally, as well as various private companies and other research institutions the following groups and initiatives were identified that promote strategic partnering: i) The Hawai‘i Clean Energy Initiative, ii) the Hawai‘i Renewable Energy Development Venture, iii) the Hawai‘i State Energy Office, iv) the University of Hawai‘i, v) the Hawai‘i Agriculture Research Center. Future partnerships are expected to form and, depending on the purpose, they could occur within the same industry and/or across industries.

Outcome IV - Biofuels Demonstration Projects

Several stakeholder demonstration projects were analyzed in the report, which reinforced the value chain theme and use/need of the LCA approach to judge system performance. The analysis identified feedstock production as a key bottleneck in the value chain. New projects for consideration were raised that would examine specific technologies and allow for assessment—not only of the technology but also operating costs, overall system performance and reliability, bioproduct yield, conversion efficiency, and maintenance requirements. In addition, new projects related to transportation were described that would include monitoring and analysis of prime mover performance, changes in required maintenance, and acceptance and satisfaction by vehicle operators.
OUTCOME V – Promotion of Hawai’i’s Renewable Biofuels Resources to Potential Partners and Investors for Development in Hawai’i as Well as for Export Purposes

The HBMP process and report provided the groundwork for a program that will appeal to research, business, and investment partners. An on-going program must incorporate an outcome-oriented approach to link bioenergy industry needs with the interests of appropriate partners. Among a variety of suggestions, the report stressed the value of the following activities: legislative actions that reduce the regulatory burden and create financial incentives for project development; maintenance of the HBMP website; continued and active engagement by master plan participants in conferences and workshops that provide opportunities for establishing contacts; and keeping the state energy office staff engaged and informed about the bioenergy landscape.