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Life Cycle Assessment of the Use of Jatropha Biodiesel in Indian Locomotives

Technical Report
NREL/TP-6A2-44428
Revised March 2009

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Symbiotic Engineering

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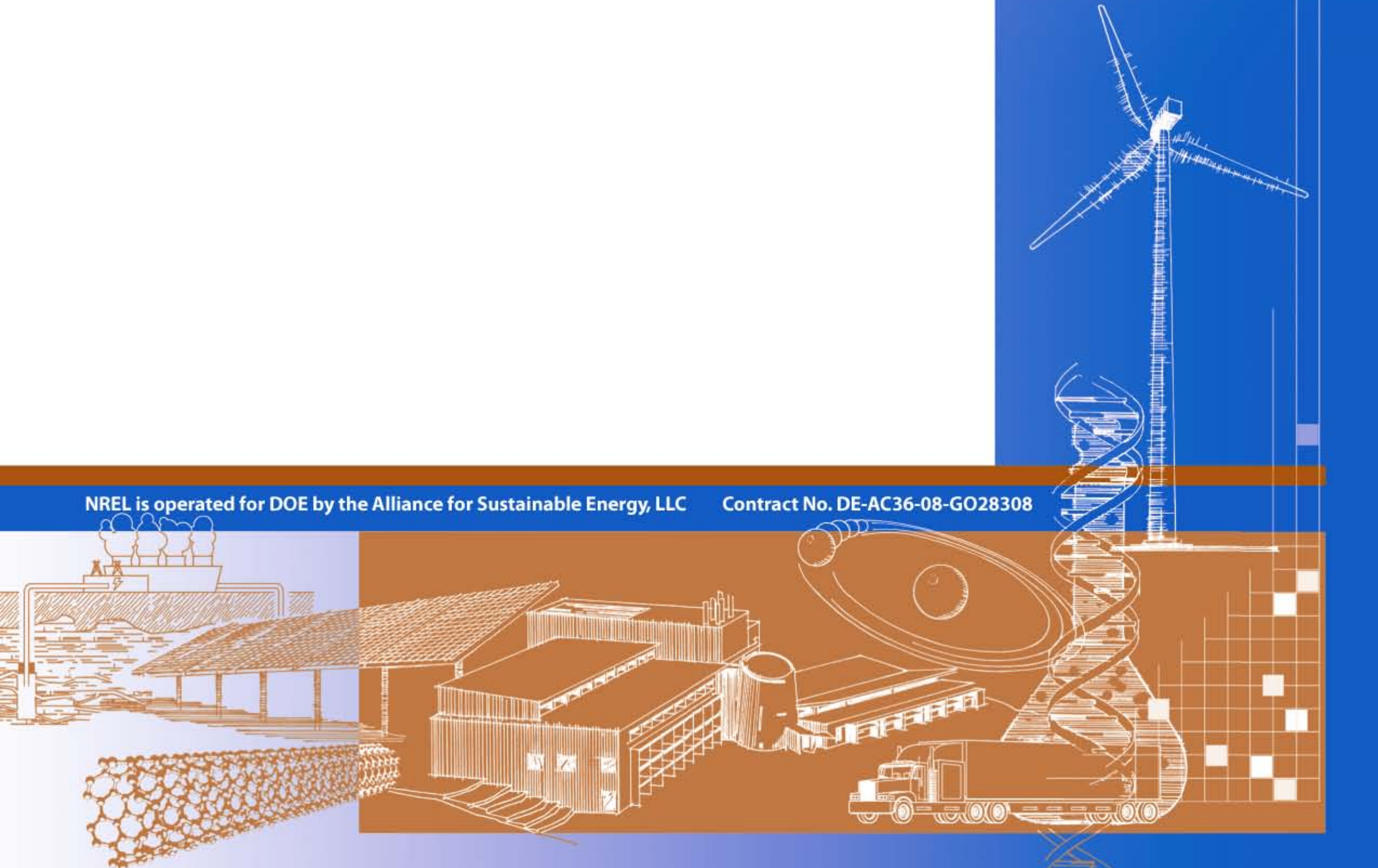

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The following corrections were made to this report:

Table 21, pages 47-49 – entire table replaced, due to an editing error

Tables 20-22, pages 43-52 – explanatory note added

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The authors would first like to thank our local partners in this work, the Indian Oil Corporation, Ltd. (IOC). Rakesh Sarin, chief research manager of the IOC, provided timely and helpful guidance and data to focus our modeling on the large-scale Jatropha biodiesel systems that India and the IOC envision. Margaret Mann and Anelia Milbrandt, both of NREL, provided their expertise in life cycle assessment (LCA) modeling and Jatropha production. Guido Reinhardt of the Institute for Energy and Environmental Research Heidelberg GmbH provided an early release version of an updated report summarizing valuable Jatropha production data.

List of Acronyms

B5	5% biodiesel blend with diesel
B10	10% biodiesel blend with diesel
B20	20% biodiesel blend with diesel
B100	100% biodiesel (neat biodiesel)
CH	Switzerland
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent in terms of global warming potential
$MtCO_2e$	Metric ton carbon dioxide equivalent
DOE	United States Department of Energy
EPA	United States Environmental Protection Agency
GB	United Kingdom
GHG	Greenhouse gas
GJ	Giga joules
GTK	Gross tonne-kilometer
GWP	Global warming potential
ha	Hectare
HFCs	Hydrofluorocarbons
IOC	Indian Oil Corporation, Ltd.
IPCC	Intergovernmental Panel on Climate Change
IR	Indian Railways
ISO	International Organization for Standardization
KOH	Potassium hydroxide
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
N_2O	Nitrous oxide
NaOH	Sodium hydroxide
NEG	Net energy gain
NER	Net energy ratio
NG	Nigeria
NREL	National Renewable Energy Laboratory
OCE	Oceanic
PFCs	Perfluorocarbons
RER	Europe
RME	Middle East
S	SimaPro System process
SF_6	Sulfur hexafluoride
T&D	Transmission and distribution of electricity
Tonne	Metric ton
UCPTE	Union for the Coordination of Production and Transmission of Electricity (predecessor to UCTE)
UCTE	Union for the Coordination of Transmission of Electricity
VIZAG	Visakhapatnam Oil Refinery

Executive Summary

India's transportation sector relies heavily on petroleum-based fuels, which account for more than 95% of the transportation sector's energy use. In 2003, the Planning Commission of India recommended increasing the use of biodiesel blended with petroleum diesel in transportation fuels with the goal of reducing greenhouse gas (GHG) emissions and petroleum consumption. The Planning Commission of India selected Jatropha curcas L. (Jatropha) as the most suitable plant for the production of biodiesel in India due to its high oil yielding seeds and ability to grow in a variety of agro-climatic conditions. Also in 2003, Indian Oil Corporation, Ltd. (IOC) signed a memorandum of understanding with Indian Railways (IR) to explore the use of biodiesel in the Indian rail system (Ministry of Railways 2003). IR offered land to the IOC for the cultivation of Jatropha trees to produce Jatropha oil, which can be extracted and transesterified into biodiesel for use in IR locomotives. Based on recommendations from the Planning Commission of India and the IOC-IR agreement, Jatropha-based biodiesel is poised to take an increasingly large role in the Indian transportation sector. Initially, IR plans to use 5% biodiesel blends with diesel (B5) in its locomotive fleet. The Indian government passed a new standard in 2008 that also requires the use of 20% biodiesel blends (B20) in Indian diesel-based transport fuels by 2017 (Padma 2008).

To help evaluate the potential for Jatropha-based biodiesel in achieving sustainability and energy security goals, this analysis estimates the life cycle impacts of substituting petroleum diesel with biodiesel blends in Indian locomotives. In addition, this study identifies the parameters that have the greatest impact on the sustainability of the system.

The life cycle of Jatropha biodiesel examined here includes Jatropha cultivation, Jatropha oil extraction, base-catalyzed Jatropha oil transesterification to biodiesel, and combustion of blends of 5% (B5), 10% (B10), and 20% (B20) biodiesel in Indian locomotives. B100 (100% biodiesel) results are also presented for reference. The petroleum diesel reference system, to which the results for Jatropha biodiesel are compared, includes crude oil extraction and transportation, crude oil refining to diesel fuel, and diesel fuel combustion in Indian locomotives. Jatropha biodiesel is compared to petroleum diesel based on three metrics: net changes in life cycle GHG emissions, petroleum consumption, and the net energy ratio (ratio of energy produced by the system to the net energy demand of the system).

The results of the base case analysis in this study are summarized in Table ES-1. GHG emissions and petroleum displacement results are presented per gross-tonne kilometer (GTK) of train transport to mitigate the influence of many system boundary assumptions of this study. The results suggest that substituting petroleum diesel with biodiesel blends yields reductions in both net GHG emissions and petroleum consumption. Under base case conditions, this study finds that substituting petroleum diesel with B5 could reduce net GHG emissions per GTK by 3%, by 12% for B20, and, for reference, by 62% for B100. The life cycle stages that made the greatest contribution to net GHG emissions for biodiesel blends were locomotive operation, petroleum diesel production and distribution, and Jatropha cultivation. In terms of petroleum consumption by IR locomotives, B5 could displace 4% of petroleum use, B20 17%, and B100 86%, under the base case conditions evaluated in this study. The base case net energy ratio for Jatropha biodiesel (B100) is estimated in this study to be nearly 2, meaning nearly two units of energy are produced for every one unit of energy consumed in the production process. When blended with petroleum diesel, the net energy ratio is less than 1 for blends of 20% biodiesel and lower, owing to the high proportion of diesel whose net energy ratio is estimated to be approximately 0.8.

Table ES-1. Net Life Cycle GHG Emission Intensity, Net Energy Ratio, and Petroleum Displacement Intensity for the Base Case

Metric	Units	Diesel	B5	B10	B20	B100
GHG Emission Intensity	g CO_2e / GTK	13	13	12	12	5.1
Change from Diesel	%	--	-3%	-6%	-12%	-62%
Net Energy Ratio	Energy out / energy in	0.79	0.81	0.84	0.89	1.9
Change from Diesel	%	--	3%	6%	13%	140%
Net Petroleum Displacement Intensity	g crude oil / GTK	--	0.17	0.34	0.69	3.6
Change from Diesel	%	--	-4%	-8%	-17%	-86%

Note: Assumes a 20 year system lifetime with 2 billion GTK transported over that time. Uses values for global warming potential (GWP) in carbon dioxide equivalents (CO_2e) for each of the six Kyoto GHGs based on the IPCC's 1997 guidance for consistency with the LCA literature. Results are rounded to two significant figures as an indication of their uncertainty. Petroleum consumption for the diesel reference system was estimated to be 4.2 g crude oil/GTK. Percent change values are rounded to the nearest integer.

Sensitivity analyses on selected parameters show that, per unit change in the value of an individual parameter, the tree planting density, seed yield, locomotive efficiency, and seed oil content are the parameters that have the greatest influence on all three results. The sensitivity analysis also evaluated alternative scenarios for the value of individual parameters. In some cases, these alternative scenarios are plausible and in others they tested the extreme best/worst case boundaries. Considering just the most plausible alternative scenarios evaluated, one robust conclusion of this study appears to be that the net energy ratio of Jatropha biodiesel will most likely be greater than 1. The net GHG emissions could vary more considerably—up to 50-100%—depending on the value of certain key parameters such as number of years of irrigation required, whether co-products are used, the nitrous oxide (N_2O) volatilization rate, as well as other factors listed above. And the estimation of petroleum consumption could vary even more, depending on the value of three parameters in particular: the amount of fertilizer required, the fuel economy of the locomotive, and the seed yield.

Given the embryonic state of Jatropha research, there is considerable uncertainty in modeling Jatropha biodiesel production systems. Therefore, it is advisable to interpret the findings of this report as indicative of the direction and scale of impacts relative to the diesel reference system rather than accurate point estimates of the magnitude of impacts. Because the focus of this study is on large-scale Indian plantations and biodiesel production processes, as well as on the use of biodiesel in rail transport, the results presented here are not necessarily broadly applicable to other locations, production processes, or uses. For instance, other locations might require more fertilizer or irrigation, other production processes may have different oil yields and energy input requirements, and motor vehicles have different engine efficiencies. Finally, two potentially important factors were not included in the analysis of this study: the impacts of direct and indirect land use change. However, this study's results—along with the results of other reviewed studies—suggest that, under plausible growing conditions and production scenarios, Jatropha-based biodiesel shows promise for helping India and possibly other nations achieve their GHG emission reduction and petroleum-displacement goals.

While this study was designed to evaluate Jatropha biodiesel production systems under Indian conditions to the greatest degree possible, the lessons learned from this study also will benefit other countries, including the United States. Petroleum-based transportation fuels are traded on an international market. Reduction in consumption anywhere in the world, but particularly in countries with growing demand like India, will reduce pressure on world petroleum demand and, ultimately, prices. While countries like India are at the leading edge of research on alternative transportation fuel feedstocks such as Jatropha, the plant also may be a suitable biofuel feedstock for the United States (e.g., in Florida) (Layden 2008), and lessons learned from the Indian context can be applied to the United States. Finally, to the extent that this study can help optimize the Jatropha biodiesel production process and reduce greenhouse gas emissions, there are worldwide benefits for climate change mitigation.

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1.0 Introduction

At the behest of the Department of Energy's Office of Energy Efficiency and Renewable Energy, and in cooperation with Indian Oil Corporation, Ltd. (IOC), the National Renewable Energy Laboratory (NREL) has performed a life cycle assessment (LCA) on the biodiesel made from the Jatropha plant seeds grown in India and used in India's existing rail transport system. In 2003, the IOC signed a memorandum of understanding with Indian Railways (IR) to explore the potential use of biodiesel in the Indian rail system (Ministry of Railways 2003). The initial agreement resulted in IR offering 500 hectares (ha) of land to the IOC for plantation and cultivation of Jatropha curcas L. (Jatropha) to yield oil that will be extracted and transesterified to produce biodiesel for use in IR locomotives. IR's stated intention is to initially use 5% biodiesel blends with diesel (B5), later increasing to10-20% biodiesel blends (B10-B20) as more biodiesel becomes available and tests establishing the good performance of locomotives using higher blends are completed (Ministry of Railways 2003).

1.1 Background

Oil provides more than 95% of the energy required for India's transportation sector while only 22% of future projected demand can be met by domestic supplies (Planning Commission of India 2003). In 2003, the Planning Commission of India established the Committee on Development of Bio-Fuels to explore how India can use ethanol and biodiesel blended with motor spirit (gasoline) and diesel, respectively, to reduce vehicle emissions and to decrease the country's reliance on petroleum-based fuels. Based on its ability to thrive in a variety of agro-climatic conditions, a low gestation period, and high seed yield relative to other plants with oil-bearing seeds, Jatropha was selected as the most suitable for the production of biodiesel in India. In September 2008, the Indian government passed a new standard requiring that by 2017, all transport fuels in India must contain at least 20% biofuels (Padma 2008). It has been determined that biodiesel can be used in diesel engines at a blend of up to 20% (B20) without substantial engine modifications and generally results in reductions of hydrocarbon, carbon monoxide, particulate matter, and sulfur dioxide emissions (Planning Commission of India 2003). Figure 1 shows the preferred regions in India for Jatropha growth. Green areas are most likely to be targeted for Jatropha cultivation.

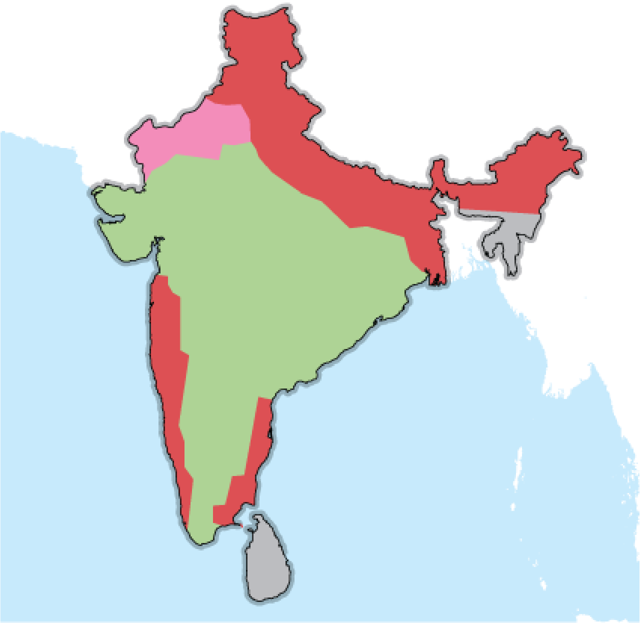

Figure 1. Jatropha cultivation zones. Green areas indicate good Jatropha cultivation potential in India; red areas are fertile agricultural lands unlikely to be used for Jatropha cultivation; pink areas are deserts with poor growing conditions
Source: Lele 2008b

1.2 India Rail Sector and Existing Fuels

The rail sector in India, operated by IR, is vital to the domestic transport of both passengers and freight. Approximately two billion liters of diesel fuel (representing more than 3% of total Indian diesel fuel consumption) are consumed annually in the operation of almost 4,000 freight and passenger locomotives at a cost of almost $1.3 billion per year (Kathpal 2008). IR adds an average of 100-120 locomotives to its fleet every year and is beginning to test and apply biodiesel blends with its fleet to reduce its reliance on petroleum diesel. In laboratory tests, IR compared the engine power, brake specific fuel consumption, and emissions of locomotives operating on conventional diesel to B100 and to biodiesel blends of B10, B20, and B50 (Kathpal 2008). The study found negligible penalties in maximum engine power and fuel consumption for B10 and B20 compared with petroleum diesel.

On December 31, 2002, IR used B5 in a test run of the prestigious Shatabdi Express (Figure 2) (Kathpal 2008). The test revealed no adverse effect on hauling capacity, no unusual deposits on the filters, and no deterioration of the condition of the fuel injection system. In May 2004, following the positive results of the initial laboratory and field trials, IR ran a test using B10 to operate the Jan-Shatabadi express for five days. IR observed no adverse effects in terms of hauling capacity, lube oil consumption, engine performance, or filter deposits. Additionally, fuel injection pumps and injector nozzles were found in satisfactory condition and free from any gum or resinous deposits (Kathpal 2008).

Figure 2. Shatabdi Express used in biodiesel trial

Source: Kathpal 2008

Based on the early positive experimental results with biodiesel blends, IR decided to expand the use of biodiesel in its system. In 2003, IR signed a 15-year memorandum of understanding with the IOC to provide about 500 hectares of land to the IOC for the plantation of Jatropha to generate oil for processing into biodiesel (Ministry of Railways 2003). The IOC will direct the plantation and cultivation of Jatropha, oil extraction, and transesterification aspects of the project. One of the pilot project's goals is to develop better baseline data on plant growth, seed yield, oil yield, and biodiesel production and performance. In total, IR seeks to have Jatropha planted on about 43,000 hectares of its land and will begin operating on blends of 1-5% with expansion up to 20% depending on field experience (Kathpal 2008).

In addition to the IOC agreement, IR is also considering establishing a set of transesterification plants to produce biodiesel for use by its zonal railways. The Southern Railway, headquartered in Chennai, owns a transesterification plant and operates two diesel locomotives on B5. The Northern Railway, headquartered in New Delhi, recently set up two transesterification plants and will begin field trials with 3,000 kiloliters of B10. The Southeastern and Northeast Frontier Railways are also operating trains on B10. The Railway Board is requesting proposals for the supply of 50,000 kiloliters of biodiesel (Kathpal 2008). If biodiesel blending is fully integrated into IR operations in the future, diesel fuel savings could range from 100 million liters per year for B5 to 400 million liters per year for B20 (Kathpal 2008).

1.3 Related Literature

As Jatropha's potential as a feedstock for significant biofuel production has become apparent in recent years, studies examining potential impacts have emerged. Reinhardt and colleagues (2007) conducted a screening LCA examining the advantages and disadvantages of Indian Jatropha biodiesel compared with conventional diesel. Biodiesel blends were apparently not evaluated. The study evaluated the environmental impact categories of consumption of energy resources, greenhouse gas (GHG) emissions, acidification, eutrophication, summer smog formation potential, and nitrous oxide ozone depletion potential. As a functional unit, the authors selected the use of Jatropha fruit harvested from one hectare of land in one year (i.e., land use efficiency). The diesel reference system was not clearly specified as to whether it represents diesel as sold in India or a world average stock. Data on many of the upstream processes were taken from the Institute for Energy and Environmental Research Heidelberg GmbH internal database and is therefore not accessible for comparison to other databases. Consideration of impacts from the manufacture, construction, and maintenance of infrastructure was not included in this study. Jatropha-specific cultivation data was compiled largely through primary research from field and laboratory measurements or from expert judgments and was recently published (Reinhardt et al. 2008). The study evaluated Jatropha-based biodiesel production in the province of Bhavnagar, where poor soil conditions were assumed. The published cultivation data are among the most extensive and complete available data at this time and are used to define many of the base case parameters in this report. The screening LCA evaluated biodiesel use to replace diesel in passenger cars and concluded that Jatropha biodiesel generally shows an energy balance savings of about 50% (8 GJ of primary energy per hectare year) and also has a small greenhouse gas emission advantage of about 10% (approximately 100 kg CO_2e per hectare year). The study also determined that Jatropha cultivation and processing made the greatest contribution to net GHG emissions, while the contribution of material transportation was minimal.

Prueksakorn and Gheewala (2008) conducted an LCA to evaluate the net energy gain (NEG) and net energy ratio (NER) of biodiesel produced from Jatropha cultivated in Thailand. This study excluded the impacts of facilities construction (i.e., infrastructure). NEG was defined as the difference between total energy outputs and total energy inputs while NER was calculated as the ratio of total energy outputs (including co-products energy content) to total energy inputs (including offsets such as avoided fertilizer production energy). The functional unit for this study was the production of one hectare of land over 20 years, and data was gathered from 14 research sites and 10 practical sites in Thailand. For average Jatropha cultivation and biodiesel production conditions, the authors calculated an NEG of 4,720 GJ/ha and an NER of 6.03 for biodiesel, plus co-products and a NER of 1.42 for biodiesel without consideration of co-products. The study was not designed to evaluate GHG emissions or to make comparisons to conventional diesel.

Achten et al. (2008) published a detailed literature review of available studies regarding Jatropha biodiesel production and use. The article gives an overview of the published data on Jatropha biodiesel production processes ranging from cultivation and oil extraction to biodiesel conversion and use. Data reported in the article serve to define many parameter values for the sensitivity analyses of this report. Based on the literature reviewed, the article concludes that the energy balance for Jatropha biodiesel is likely positive with the extent of the positive balance dependent on the efficiency of co-product use and on fertilization and irrigation requirements. The authors also confirm the reduction in GHG emissions that result from the substitution of biodiesel for conventional diesel while identifying irrigation, fertilization, and transesterification as the processes with the greatest influence on net GHG emissions. The authors determined that the overall global warming potential for the production and use of 100% Jatropha biodiesel (B100) is 77% less than for conventional diesel based on another study by Prueksakorn and Gheewala (2006) and a life cycle assessment by Tobin and Fulford (2005). However, neither of the two reviewed studies considered N_2O release from nitrogen fertilizer during cultivation, thereby underestimating, likely considerably, the GWP of Jatropha biodiesel production.

Finally, two rich resources for India-specific data are Satish Lele's books on Jatropha cultivation (2008b) and biodiesel (2008a). They provide primary data for developing study parameters related to typical conditions encountered in India. The books also contain excellent discussions of where data is lacking, particularly regarding fertilization, chemical application, and irrigation requirements.

1.4 System Description

1.4.1 General Jatropha Biodiesel Description

Figure 3. Jatropha curcas trees
Source: JatrophaWorld 2008

Biodiesel production begins with the cultivation of Jatropha (Figure 3), a small tree or large shrub that grows to an average height of 3-5 meters (with heights exceeding 7 meters in optimal conditions) and bears fruit containing seeds rich in non-edible oil suitable for conversion to biodiesel. Jatropha grow in a variety of environmental conditions, including poor soils, but generally prefer heat of the tropics and subtropics. Jatropha grow without irrigation in a wide range of rainfall conditions, from 300-3,000 mm per year (Achten et al. 2008). It grows in the wild throughout India with a 50-year life expectancy.

For commercial production, Jatropha is grown in plantations with tree densities ranging from 1,100 to 2,500 trees per hectare (Achten et al. 2008 and Lele 2008b). Jatropha is often established through the planting of seedlings grown at nurseries in plastic bags (Achten et al. 2008). Irrigation and fertilization requirements are highly dependent on location-specific conditions. Even under adequate rainfall, irrigation may be required for the first three years to help plant establishment (Reinhardt et al. 2008). If fertilization is required, nitrogen and phosphorus tend to be the nutrients of greatest need (Achten et al. 2008). Jatropha fruit (Figure 4) can be harvested at least once per year, often using human labor (Lele 2008b).

Once harvested, the Jatropha fruit is de-husked to isolate the oil bearing seeds (Figure 5) through use of either a mechanical decorticator or manual labor. The husks can be collected as a co-product and used to generate energy (heat or electricity) by combustion. Chemicals in the seed render the oil toxic to humans and animals but appropriate for conversion into biodiesel. The yield of Jatropha trees is highly uncertain. According to Achten et al. (2008), reliable data on the anticipated dry Jatropha seed yield per hectare per year for a given set of environmental conditions and inputs does not exist. However, Achten and colleagues suggest 4-5 metric tons (tonnes) of dry seed per hectare per year as a reasonable yield estimate for a well-managed plantation with good environmental conditions.

Jatropha seeds contain an average of 25-40% oil by mass which can be extracted using either mechanical systems such as a screw press or chemical-based processes such as solvent extraction. Solvent extraction is more efficient (90-99% oil extraction) but also more expensive and is only economical for commercial-scale processing. Hexane is the primary solvent being used for commercial extraction at this time (Adriaans 2006). Seed cake remaining after oil extraction is rich with nutrients and can be returned to the field as fertilizer with an average nitrogen : phosphorous : potassium NPK ratio of 40:20:10 (Prueksakorn and Gheewala 2008).

Figure 4. Jatropha fruit
Source: Lele 2008b

To produce a usable biofuel, Jatropha oil is transesterified to biodiesel and glycerine using methanol as the alcohol and either sodium hydroxide (NaOH) or potassium hydroxide (KOH) as a base catalyst. Glycerine is a marketable co-product whose value depends on the quantity available from alternative suppliers, its purity, and other attributes like its odor (Glycerine produced as a co-product of biodiesel production is known to have a strong odor, which can affect its marketability). The India Oil Company suggests that the market is robust in India for glycerine obtained from biodiesel production, though that may not be the case in other countries (Sarin 2008c).

Figure 5. Jatropha seeds
Source: Lele 2008b

Biodiesel can be used in both heavy-duty road vehicles such as buses and in locomotives. Biodiesel is initially being used in India in blends of B5, B10, and B20 and has shown no adverse impacts on engine performance in blends of up to B10 in Indian Railways trials (Kathpal 2008). Biodiesel can be blended with diesel at regional storage or at the point of fueling.

1.4.2 Analysis Approach

Several options were available for developing a comparative analysis of Jatropha biodiesel and conventional diesel in India based on scenarios for cultivation, extraction, processing, and use in locomotives. One option was to form a base case scenario from parameters that were independently averaged based on point estimates and ranges reported in the literature. A motivation for using this approach is to attempt to make the scenario under consideration as generalizable as possible. However, because many of the parameters are causally related, a scenario comprised of averages formed independently could be implausible. For instance, because the amount of irrigation and annual rainfall should sum to the total water requirement of the site considered, if averaged independently, and depending on the conditions of the site, this sum might actually provide more or less than the total water requirement for Jatropha cultivation

Therefore, the authors chose an alternative approach. A narrative was developed coherently linking all key parameters into a base case scenario. The robustness of this base case scenario was tested by a thorough sensitivity analysis that examines reasonable alternative values of each parameter independently. Because so many key parameters, especially for Jatropha cultivation, are dependent on site conditions, the authors, following recommendations from the IOC, selected a specific region of India for consideration, matching certain agronomic parameters to the typical conditions of that location. The following sections describe the most important aspects of the base case scenario for both Jatropha biodiesel and conventional diesel production and use in Indian locomotives.

1.4.3 Jatropha Biodiesel Base Case Scenario Description

1.4.3.1 Jatropha Cultivation

As Jatropha is capable of being grown throughout India (Figure 1) and numerous production pathways are possible, a base case narrative was developed to guide the analysis. The base case narrative is based on guidance from the IOC regarding likely future development scenarios (Sarin 2008a,b,c,d).

Figure 6. The Chhattisgarh state of India is highlighted in brown. The approximate location of the city of Raipur is indicated with the arrow.
Source: Chhattisgarh Online 2008

This analysis assumes that the Jatropha trees are grown on a 50,000 hectare plantation for a period of 20 years in the Raipur area of the Chhattisgarh state of India where the average annual rainfall is 1,385 mm per year. The state of Chhattisgarh is identified in red in Figure 6 and falls within the prime Jatropha cultivation zones of India displayed in Figure 1. To correspond to available plantation management data, the plantation is modeled as five separate 10,000 hectare units. Seeds are harvested at the plantation manually and are transported via truck to a hypothetical oil extraction facility in Raipur. Raipur, the capital of Chhattisgarh, is well connected to the region via road and rail and is one of India’s fastest growing industrial cities.

1.4.3.2 Summary of Jatropha Cultivation and Processing Plant Assumptions

The base case Jatropha cultivation and biodiesel processing characteristics are taken from the Planning Commission of India’s (2003) assumptions used in its biofuels assessment report. The following is a list of some of the most important base case assumptions.

Base Case Assumptions

- Jatropha cultivation via nursery
- 2,500 trees per hectare density at planting
- Average quality soils and agro-climatic conditions (e.g., temperature, rainfall) at the plantation site

- Jatropha plants reach maturity within three years from planting when full seed yield is expected
- 1,500 grams of seed harvested per tree at full yield, or 3.75 tonnes of seed per hectare year
- Seed oil content is 35% by weight
- Solvent extraction efficiency is 91%
- Jatropha oil recovery efficiency is 32% (i.e., 35% oil content multiplied by 91% recovery efficiency)
- Based on above conditions, 3.125 kg seed is required to produce 1 kg Jatropha oil
- Based on assumed oil recovery efficiency, 1.2 tonnes of Jatropha oil is expected / hectare – yr
- Anticipated Jatropha oil recovery for the full plantation is approximately 60,000 tonnes per year.

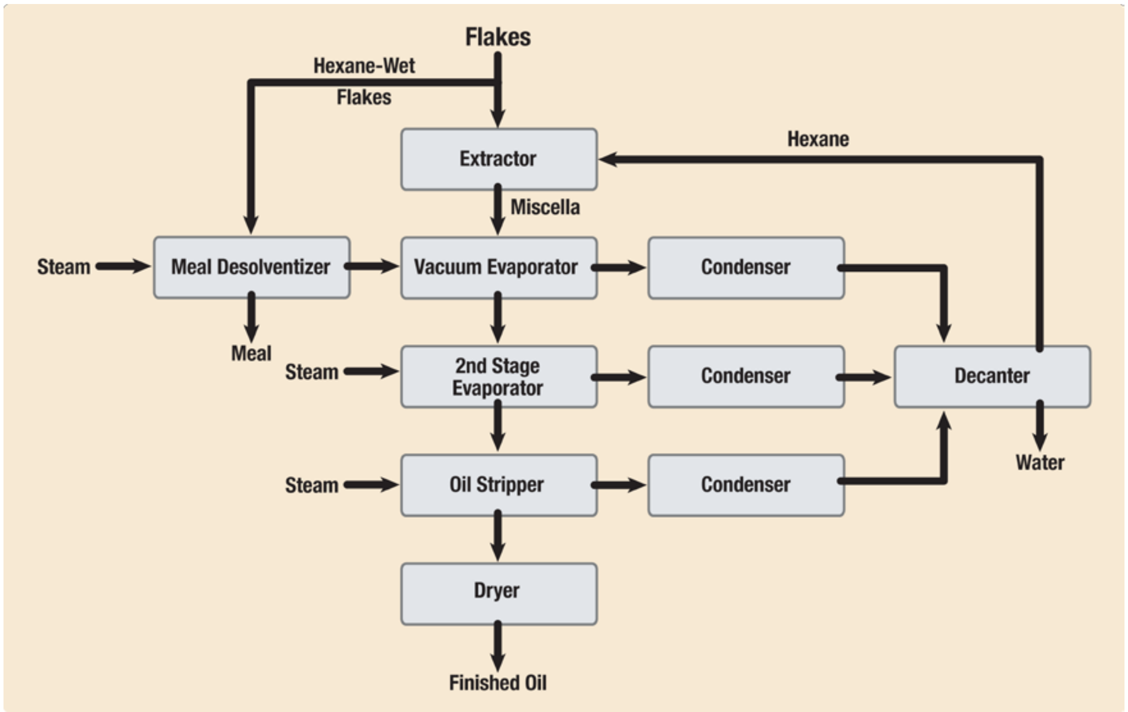

Figure 7. Schematic for continuous solvent oil extraction
Adapted from: Adriaans 2006

1.4.3.3 Jatropha Oil Extraction

The analysis assumes that the oil extraction facility has a capacity of 200 tonnes oil per day, giving it the ability to process up to 625 tonnes of seeds per day in a continuous solvent extraction process with 91% extraction efficiency. According to Adriaans (2006), continuous solvent extraction of Jatropha oil requires processing at least 200 tonnes of seed per day to be economical. Solvent extraction plants can process up to 4,000 tonnes per day making the base assumption of a 625 tonnes per day capacity well within the current technology range. Hexane is currently the only solvent used commercially on a large scale (Adriaans 2006). Based on the size of the facility, the extraction is assumed to be continuous (Figure 7). Not all of the individual processes shown in Figure 7 are specifically modeled in this analysis, though their impacts and results are included in summary fashion.

1.4.3.4 Biodiesel Production via Jatropha Oil Transesterification

The Jatropha oil extraction facility is co-located with the biodiesel transesterification plant for logistical reasons. This study assumes both are located in Raipur. The transesterification unit capacity is assumed to be 100,000 tonnes of biodiesel / yr with a 95% conversion efficiency of Jatropha oil to biodiesel. If the 200 tonnes / day oil extraction unit operated continuously throughout the year, it would generate 73,000 tonnes of Jatropha oil per year. The excess plant capacity could be used to process Jatropha oil generated by other extraction units in the area. The transesterification process is assumed to be base-catalyzed using potassium hydroxide with methanol as the alcohol.

1.4.3.5 Locomotive Operation

Based on discussions with the IOC (Sarin 2008b) and statements by IR (Kathpal 2008), the base case compares blends of B5, B10, and B20 to conventional diesel. The base case assumes that the locomotives are fueled 20 kilometers from Raipur in Bhilai, and that the biodiesel blending with petroleum diesel occurs at the IOC's Bhilai petroleum depots. The base case analyzes the fuel requirements for 100,000 gross tonne-kilometers of locomotive travel per year. An IR study found a negligible negative effect for volumetric fuel consumption for locomotives operated on B5, B10, or B20 (Kathpal 2008). The base case assumes no negative fuel consumption impacts, while the sensitivity analysis tests for the impacts of fuel economy reductions with increases in biodiesel percentages. This study assumes that the combustion of biodiesel results in no net carbon dioxide emissions; carbon sequestered from the atmosphere during the growth of biomass offsets the carbon dioxide emissions from combustion of the same biomass. This concept is described further in the base case assumptions section of this report.

1.4.4 Reference System – Petroleum Diesel Production and Distribution

Figure 8. Visakhapatnam (VIZAG) oil refinery is located near the Bay of Bengal in eastern India
Source: Maps of India 2008

As biodiesel is used primarily in blended applications with conventional, petroleum-based diesel (diesel), the diesel life cycle serves a dual purpose in this analysis. First, the 100% diesel scenario serves as a benchmark against which the biodiesel blends (B5, B10, and B20) are compared. Second, the entire diesel life cycle is contained within the blended biodiesel life cycle as 80% of the fuel in the highest blending scenario (B20) comes via the diesel pathway.

Crude oil used in India is of both domestic and foreign origin. For the base case, foreign oil is assumed to be extracted from Saudi Arabia and transported to the Visakhapatnam Oil

Refinery (VIZAG) on the east coast of India near the Bay of Bengal (Figure 8). Domestic oil is assumed to be extracted from the Bombay High oil field off the west coast of India near Mumbai and transported via oil tanker to VIZAG. Refined diesel is transported from VIZAG to the oil depots in Bhilai near Raipur via rail for fueling IR locomotives at the Bhilai depots. A complete set of data regarding the operations of the VIZAG refinery was not made available in time for completion for this study; therefore, a pre-established diesel fuel refining module based on Western European average refining impacts from the Ecoinvent 2.0 database (Swiss Centre for Life Cycle Inventories 2008) was used as a substitute. If the Western European refinery operates more efficiently than the Indian refinery, results may be biased in favor of the diesel system. If, however, tighter environmental regulations results in the Western European refinery using more energy for fuel processing, results may be biased in favor of the biodiesel system. Also, the Ecoinvent diesel refining module contains multiple transport steps. It is unclear whether these transport steps might double count the rail transport modeled (in a custom module) between VIZAG and the Bhilai depots. However, any overestimate of impacts determined in this report owing to potential double counting of the transport of refined diesel to the regional storage site at Bhilai is expected to be small.

2.0 Methods

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is an analysis method designed to evaluate the potential environmental impacts of a product or process starting from raw material extraction, through production and use, to an end-of-life scenario. As defined by the International Organization for Standardization (ISO) 14044:2006 standard (ISO 2006), LCA studies are comprised of four phases:

1. **Goal and scope definition** requires defining the system boundary and level of detail required for input data. Depth and breadth of LCA studies can vary greatly depending on the target subject, quality of data, available time and budget, and intended use of the results.

2. **Inventory analysis** includes the collection and processing of all input/output data required to define and analyze the system. Data can be collected from established life cycle inventory (LCI) databases, primary documentation, academic studies, or other high quality, verifiable sources. Connections must also be formed between components of the study system to determine how changes in one process are propagated upstream or downstream through the LCA. Results are reported using many units of measure, depending on what materials and metrics are tracked in the LCA. For instance, mass of individual greenhouse gases emitted, area of land occupied or transformed, and volume of crude oil consumed could all be tracked and reported as the results of the LCI.

3. **Impact assessment** is designed to translate the environmental significance of a system's impacts. The life cycle impact assessment (LCIA) phase takes raw input and output data (such as emissions of carbon dioxide and methane) and converts them to common metrics such as global warming potential (GWP). Impacts can be assessed at either the midpoint, where flows are characterized based on their expected environmental impacts such as GWP, or at their endpoint where actual environmental changes such as temperature increase, are predicted.

4. **Interpretation** is an ongoing process of analyzing the results of the LCI and LCIA as a basis for conclusions, recommendations, and discussions.

This study focuses on inventory and midpoint impact assessment analysis, as endpoint analysis introduces additional uncertainty and assumptions. LCI results are classified according to their relevance for petroleum displacement and cumulative energy demand. Midpoint impact assessment characterizes inventory greenhouse gas emissions according to their GWPs. The following sections outline the assumptions and methodologies used to conduct this study in accordance with ISO 14044:2006 requirements.

2.2 Goal of the Study

The purpose of this study is to compare the environmental impacts of using Jatropha biodiesel for rail transportation to the conventional diesel baseline. The methodology used in this study is consistent with that described by ISO 14044:2006 standards for LCA, and particularly those standards that cover inventory analysis (ISO 2006). The study is intended to lend guidance regarding the potential impacts of a significant increase in biodiesel production from Jatropha plants to offset a portion of the diesel fuel currently being used in the Indian rail system. LCA is used to evaluate the relative impacts throughout the life cycle phases including resource extraction, crop cultivation, processing, and use in order to develop as complete a picture as possible of the likely impacts. The study also seeks to identify which key parameters and uncertainties are most likely to influence the ultimate conclusions of the study. The intended audience includes policy-makers, industry executives, academics, and any interested members of the public.

2.3 Scope of the Study

The scope of this study is the evaluation of the production of conventional petroleum diesel and the production of biodiesel from Jatropha for use in the operation of IR locomotives. The functional unit for the study is GTK of rail transportation. GTK includes both the weight of the train and the weight of any passengers or cargo on board. The functional unit assumes that the primary goal of the Indian rail system is to move passengers or cargo and that diesel and biodiesel should be evaluated in terms of their ability to provide that function. An overview of the processes included in the system evaluations are detailed in Figures 9 and 10. The diesel and biodiesel production pathways are evaluated beginning with resource extraction, through transportation and processing, to use in the locomotives.

The diesel life cycle is required for analyzing both the combustion of conventional petroleum diesel and blended biodiesel in locomotives.

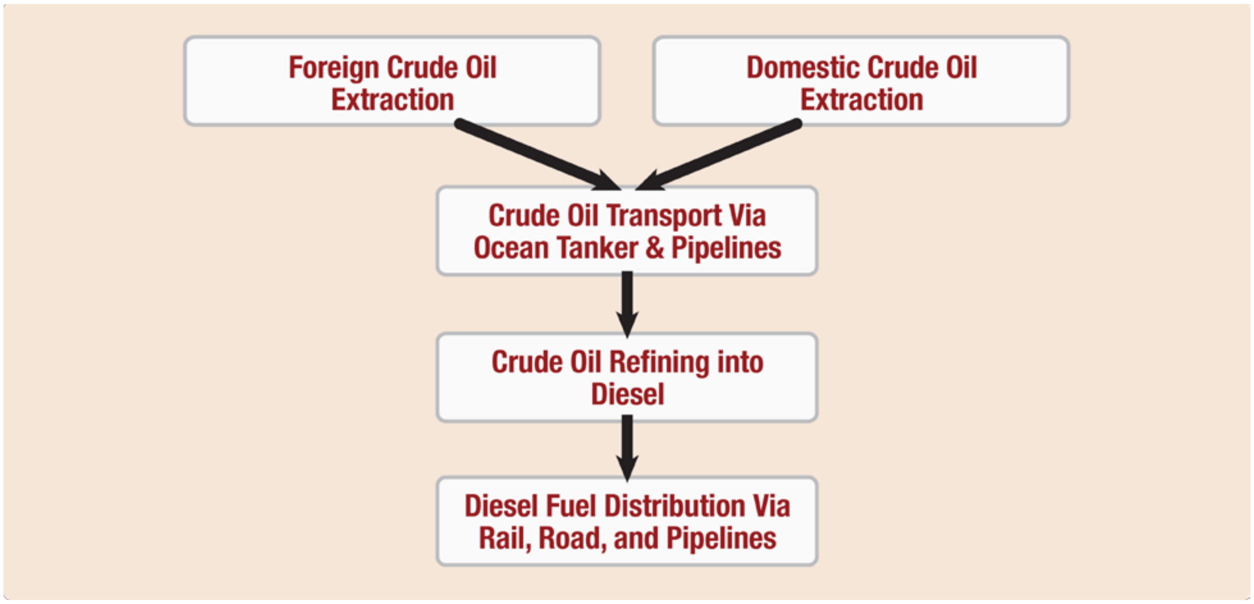

Figure 9. Petroleum diesel life cycle process map

The entire petroleum diesel production and distribution life cycle outlined in Figure 9 is contained in the blended biodiesel life cycle shown in Figure 10. Supporting processes include Indian transportation systems and electricity generation, transmission, and distribution.

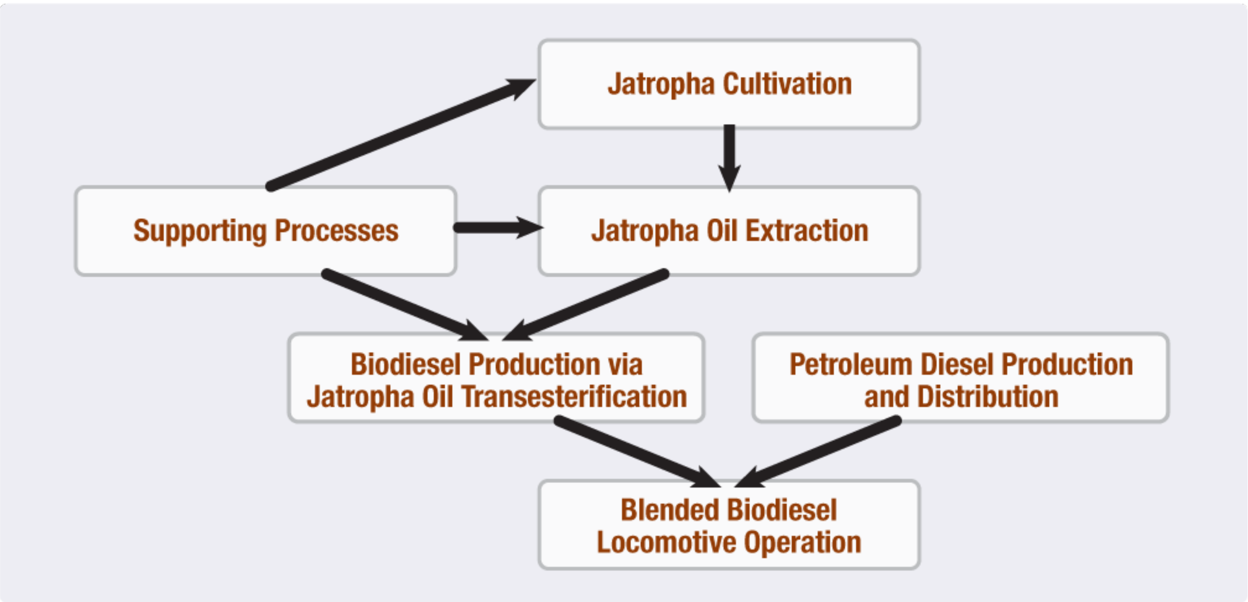

Figure 10. Blended biodiesel life cycle process map. The entire petroleum diesel production and distribution life cycle (Figure 9) is contained within the blended biodiesel life cycle. Supporting processes include Indian transportation systems and electricity generation, transmission, and distribution.

2.4 System Boundaries

The study analyzes both petroleum-diesel and biodiesel production and use pathways in India and identifies resource consumption, energy use, and emissions for the following life cycle stages and sub-processes:

- Petroleum diesel production and distribution (reference system)
    - Foreign and domestic crude oil extraction
    - Crude oil transport
    - Crude oil refining into diesel fuel
    - Diesel fuel distribution to rail depots for use and for blending with biodiesel
- Jatropha cultivation
    - Seedling production and planting
    - Plantation operation and management
    - Seed harvesting and transport to extraction facility
- Jatropha oil extraction
    - Solvent-based extraction of oil
    - De-oiled seed cake use as fertilizer substitute
- Biodiesel production via Jatropha oil transesterification
    - Base-catalyzed transesterification to biodiesel
    - Transport of biodiesel to railways for blending with petroleum diesel
- Locomotive operation
    - Locomotive operation on conventional petroleum diesel
    - Locomotive operation on blended biodiesel

- Supporting processes
    - Indian transportation vehicles and infrastructure
    - Indian electricity and transmission and distribution infrastructure
    - Local generation of steam for use in Jatropha oil extraction and biodiesel transesterification processes

While the amortized impacts from manufacturing, assembling, and/or constructing infrastructure related to most processes are included in the analysis, railroad construction and equipment infrastructure are omitted because the existing rail system is assumed to be utilized. Operation of the locomotives is included as the use phase of the study for both the petroleum-diesel and biodiesel pathways.

The geographic boundary for the study is India, with a focus on biodiesel and diesel use by IR, except where resources are extracted and transported to India from other countries.

The system vintage boundary for the study is set for present day technologies and systems. No efforts are made to project future technology advances. The most recent, quality data is used whenever possible.

The impacts are evaluated over a 20-year timeframe. The selection of timescale should not significantly impact results as it is consistent between the diesel and biodiesel systems and the results are normalized by GTK. The 20-year time frame is consistent with analyses conducted in other studies (Reinhardt et al. 2007, Prueksakorn and Gheewala 2008).

2.5 Allocation Procedures

Many options are available within LCA for the allocation of impacts (Scientific Applications International Corporation 2006). Allocation is necessary when a process produces more than one valuable product. For example, the extraction of Jatropha oil from the seeds produces two valuable products: Jatropha oil and the seed cake. The Jatropha oil is processed into biodiesel while the seed cake can be used in the fields as fertilizer, offsetting some chemical fertilizer requirements. It would be inaccurate to assign all of the impacts associated with the energy and materials required to extract the oil to the Jatropha oil when the seed cake is also a valuable product. Allocation procedures typically divide process impacts among co-products using mass, energy, or economic value as the metric.

While each of these allocation procedures has its merits, the preferred methodology for LCAs is boundary expansion where all process impacts are included but credits are taken for the impacts that are avoided by the production and use of the co-product (ISO 2006). Using the oil extraction example, the full process impacts are included in the analysis; however, credit is taken for avoided impacts such as when chemical fertilizer production is offset by the application of the nutrient-rich, de-oiled seed cake to the fields. Other co-product boundary expansions considered in this study include biomass from pruning Jatropha plants being used to generate electricity, offsetting the Indian grid electricity, and glycerine produced during transesterification offsetting synthetic glycerine production.

2.6 Impact Categories

Table 1. Global Warming Potentials (Relative to CO_2) of a Subset of the GHGs Evaluated in this Study

Greenhouse Gas	GWP ($mtCO_2e$)*
CO_2	1
CH_4	21
N_2O	310
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_3F_8	7,000
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

*$mtCO_2e$ = metric tons CO_2 equivalent
Source: IPCC 1995

The study focuses on three primary impact categories:

1. **Greenhouse gas emissions** from all GHGs identified and characterized by the Intergovernmental Panel on Climate Change (IPCC) are considered cumulatively and weighted according to their 100-year global warming potential relative to CO_2, in metric tonnes of carbon dioxide equivalent ($mtCO_2e$). The GWPs of the GHG emissions are calculated according to the IPCC's Second Assessment Report (1995), detailed in Table 1. GWPs revised in more recent IPCC reports were not used in order to maintain consistency with previous LCAs that have used the earlier factors.
2. **Net energy ratio** *i*s evaluated by dividing the energy output of the system in the form of fuel energy delivered to the locomotive by the cumulative energy demand of the system. Energy credits for the use of biodiesel system offsets are accounted for in the cumulative energy demand calculation.
3. **Net petroleum displacement** is tracked in terms of reduced crude oil consumption for the analyzed biodiesel blend life cycle relative to the reference conventional petroleum diesel system.

Efforts were made to gather information on criteria pollutants, toxic air pollutants, and water consumption, but not enough India-specific, quality data were available throughout the life cycle processes to provide a consistent, complete analysis of these impacts.

2.7 Data Requirements

Whenever possible, India-specific data from literature or the IOC are used for the base case analysis. When Indian data are not available, preference is given to regional studies from South or Southeast Asia with data gaps filled by established LCI data from Europe and North America when required. The sensitivity analysis is used to test the importance of using non-regional data in the study.

2.8 Model

The diesel and biodiesel systems are modeled using SimaPro 7.1 LCA software from Product Ecology Consultants (http://www.pre.nl/simapro/default.htm). The SimaPro software allows the modeling of complex life cycles and the running of detailed sensitivity studies to determine the importance of parameter uncertainty and variability. Whenever possible, custom SimaPro process modules were developed to meet Indian-specific operating conditions. Modules within the SimaPro model are designed to define material, energy, and environmental inputs and outputs that are required for a specific process within the life cycle. For example, a module may define the electricity, steam, and water required for Jatropha oil extraction along with the required seeds that must be delivered from the plantation and the impacts of constructing the facility infrastructure.

When Indian data was unavailable or insufficient, gaps were filled using data from the Ecoinvent v2 LCI database (http://www.ecoinvent.org/) included with the SimaPro software. Because of the depth and breadth of the data modules and the consistent inclusion of infrastructure impacts, Ecoinvent system processes were used to maintain consistency throughout the process. For these and other reasons, Ecoinvent data are commonly used in LCAs from other researchers, improving the comparability of our results to others in the literature. Infrastructure impact data are lacking for Indian-specific conditions and therefore are taken from the available datasets in Ecoinvent. Ecoinvent data is primarily focused on European conditions but contain many worldwide modules with datasets ranging from energy, building materials, and transport to chemicals, agriculture, and waste management.

2.9 Uncertainty

As with all LCAs, this analysis encountered a great deal of uncertainty. Lloyd and Ries (2007) provide an excellent discussion of how uncertainty is characterized, addressed, and analyzed in LCA studies, along with the various types of uncertainty likely to be encountered. Uncertainty is particularly relevant to the outcomes of this study because the model is deterministic, using single value parameters to generate single point output estimates each time the model is run. A deterministic model that produces point estimates can yield a false perception of certainty in results that are generated from uncertain inputs. The authors' approaches for addressing uncertainty are discussed in the introduction to the sensitivity analysis section.

The study is faced with three primary types of uncertainty:

1. **Parameter uncertainty** – uncertainty in the numerical value assigned to a particular data point.
2. **Scenario uncertainty** – uncertainty related to developing the analysis scenarios for the study, including selection of functional units, time horizons, allocation procedures, use of co-products, and technology trends.
3. **Model uncertainty** – uncertainty in the mathematical relationships that drive the calculations in the model that is designed to represent real world systems. Model uncertainty is minimized in this study for impacts such as GHG emissions from fuel combustion where the mathematical relationships between fuel consumption and GHG

emissions are well-established. The primary model uncertainty stems from random error and statistical variation related to the projected outputs of the Jatropha cultivation processes based on defined inputs.

Applicable to each of these three types of uncertainty, Lloyd and Reis list seven major sources of uncertainty and variability. The five major sources of uncertainty and variability in this study are highlighted below, with examples representing one or more of the three types of uncertainty.

1. **Data unavailability:** At a fundamental level, high-quality, consistent, and coherent data is not available for many of the project parameters, particularly related to the cultivation of Jatropha. Comprehensive data sets detailing anticipated Jatropha seed and oil production given a particular set of environmental conditions are not yet developed. Moreover, required inputs related to fertilizer, pesticides, and irrigation water are also not well defined, nor is the likely impact of these inputs on expected outputs well characterized.

2. **Measurement uncertainty:** Even when important parameters are identified and analyzed, it may be difficult to precisely and accurately estimate their value(s). For instance, precise and accurate measurements of N_2O volatilization rates from soils after fertilization are extremely difficult to obtain. As N_2O is a potent GHG, the uncertainty in the measurement of N_2O volatilization rate contributes substantially to uncertainty in the prediction of GHG emissions from Jatropha cultivation.

3. **Inherent variability:** Many of the parameters in this study are strongly influenced by temporal and geographical conditions which vary over time, such as rainfall and the mix of foreign and domestic crude oil entering India. Moreover, while some of the parameters have well-established relationships, such as anticipated CO_2 emissions from combusting a given amount of diesel fuel, several of the parameters in this study lack direct deterministic correlations. For example, seed and oil yield are challenging to predict with a great degree of certainty even if all environmental and man-made inputs and conditions of the system are known. These particular parameters are inherently variable, with many other parameters exhibiting similarly variable numerical estimates.

4. **Systematic errors and subjective judgment:** Scenarios evaluated in this study reflect current practice. However, the markets for the products and co-products of Jatropha-based biodiesel production are immature in India, making it likely the scenario evaluated in this study will change over time. No technology advancement is assumed over the analysis lifetime as predictions for the likely evolution of technology are not available.

5. **Expert uncertainty and disagreement:** There is no “most likely” scenario that experts agree on for how Jatropha cultivation and transformation into biodiesel will develop in India. Multiple scenarios are plausible and vary greatly in terms of geographical location, production pathways, and co-product use even before the uncertainty of input parameters is included. The lack of expert agreement makes the development of a coherent analytical narrative challenging. As multiple competing scenarios could be proposed, the applicability of the results outside of the developed scenarios is uncertain.

2.10 Sensitivity Analysis Approach

Reasons to conduct a sensitivity analysis are at least twofold. First, sensitivity analysis can test the robustness of conclusions to parameter uncertainty and variability. Second, sensitivity analysis can determine and rank the influence a given parameter has on model outputs. This report attempts to achieve both of these goals in its sensitivity analysis. It focuses on a set of key parameters judged to be the most likely influential on model outcomes.

Sensitivity analysis is distinct from uncertainty analysis. One method of uncertainty analysis propagates the uncertainty and variability of parameters through model calculations to estimate the uncertainty (error bounds) of model results. This study does not conduct a formal uncertainty analysis because the uncertainty and variability of parameter values for many parameters is not known and the web of modeled processes is so complex that propagation is challenging. However, a sense of the outer boundaries of model results is determined based on analyzing a compilation of best- and worst-case parameter values into what this report refers to as best- and worst-case scenarios. These scenarios are not likely or even necessarily plausible, but inform the reader of the likely extremes of model outcomes.

3.0 Base Case Assumptions

Developing a coherent narrative for a base case analysis is among the most difficult tasks in an LCA of Jatropha biodiesel in India. As Achten and colleagues noted in their literature review, a quality set of data identifying anticipated Jatropha yields for specific environmental conditions and detailed irrigation and fertilization scenarios does not exist (Achten et al. 2008). Developing such a coherent set of primary data inputs was outside the scope of this study. Consequently, the authors had to make many assumptions to define the scenarios and estimate values for all parameters and scenarios. In addition, LCAs require decisions about modeling approaches and calculation methods in order to complete the analysis. These decisions do not necessarily have a correct answer. It is critical for interpretation of the results produced from an LCA that the assumptions and decisions of the analysts be transparent to the reader. Below, 10 major base case assumptions and modeling decisions are outlined:

1. **Fuel economy does not decrease with increasing biodiesel blends.** According to initial IR trials of biodiesel in their locomotives, no difference in volumetric fuel consumption was observed for operation using B5, B10, or B20 compared to operation using conventional diesel (Kathpal 2008). If a fuel economy decrement is in fact experienced, then this study's impacts will have been underestimated. Therefore, the sensitivity analysis examines the impact of assuming a small fuel economy decrement with the use of biodiesel based on evidence from the U.S. Environmental Protection Agency that the use of B20 may result in a fuel economy decrement of approximately 2% (U.S. EPA 2008).

2. **The biodiesel fuel combusted in the locomotives is assumed to have no CO_2 emissions.** At some point in this biofuel LCA, the carbon sequestered by the growth of the Jatropha trees must be credited as a reduction in GHG emissions from the biodiesel system. This study incorporates that credit by assuming an emission factor of zero for all biofuels combustion, including the portion of the locomotive fuel composed of biodiesel and the Jatropha biomass. The alternative assumption would be to account for carbon sequestration during the plantation operation phase. Data sets are not well established to define the rate Jatropha plants sequester carbon. Therefore, the authors chose to credit the sequestration at the point and time of use. Assuming no net GHG emissions from biofuels combustion is based on an assumption of complete combustion—negligible emissions of other carbon-containing compounds such as carbon monoxide and methane. Consequently, by first principles, carbon dioxide emissions from the complete combustion of the biomass (in the form of solid or liquid fuel) must equal the carbon dioxide sequestered from the atmosphere. This assumption should not bias results toward diesel or biodiesel.

3. **Potential land use changes were not evaluated.** The location of the hypothetical Jatropha plantation considered in this study was not specified in enough detail to ascertain its prior land use and above and below-ground carbon content. Therefore, determining net change in carbon content of the plantation site was not feasible. The carbon emissions from direct land use change could be zero, small or significant, and could be either positive or negative, depending on the prior land use. Utilizing lands that are abandoned or degraded are best from a GHG perspective. Direct land use change

should be accounted for when specific plots of land are being considered as plantation sites.

4. **A 20-year time horizon is assumed.** A time horizon of greater than one year is required to analyze Jatropha biomass systems in order to include upfront activities like the development of land into a plantation and also the time for Jatropha plants to mature. The life cycle length should not bias results as most results are normalized to the functional unit (GTK) for reporting. Twenty years is well within the lifetime of most pieces of infrastructure in the study and is the value used in comparable studies (Reinhardt et al. 2007, and Prueksakorn and Gheewala 2008). However, it is likely that technological innovations will occur over this time period, particularly for the immature biodiesel production industry and are not accounted for in the study.

5. **The amount of rainfall required to avoid the need for irrigation is 2,500 mm per year.** The circumstances where irrigation is required for the establishment of Jatropha trees is very poorly defined in literature as Jatropha has been known to grow in places with rainfall ranging from approximately 300 mm per year to 3,000 mm per year. However, Prueksakorn and Gheewala (2008) identify 2,500 mm per year as a rainfall level where no irrigation is required for Jatropha grown in Thailand. This study calculates the required irrigation as the difference between 2,500 mm per year and the average rainfall at the plantation location. If the water requirement for Jatropha plants is in fact greater than 2500 mm per year, this study's results will have underestimated the true impacts. Likewise, if Jatropha's water requirement is less than 2500 mm per year, then this study's results will have overestimated the true impacts.

6. **Irrigation is assumed to be required for only the first three years of cultivation.** Reinhardt and colleagues (2008) suggest that irrigation is only required when the plantation is establishing itself, which they report as three years. If irrigation turns out to be necessary for longer than three years, the impacts estimated in this study will be underestimated. However, the sensitivity analysis does evaluate the impacts of requiring irrigation for the full life cycle.

7. **Initial tree density is 2,500 trees per hectare in a 2 m x 2 m planting grid.** Tree planting densities reported in the literature range from 1,100 to 2,500+ trees per hectare with the appropriate planting grid largely dependent on local conditions. The Planning Commission of India (2003) uses 2,500 trees per hectare as the density for its calculations, taken as the base case assumption for this study. This assumption will tend to increase both seed and biomass yields per hectare compared to cases of lower densities reported in the literature, benefiting the biodiesel system in comparison to the diesel reference system.

8. **No pesticides, insecticides, or herbicides are applied to the crops.** Some literature suggests that the use of protective chemicals on the trees may not be necessary (Reinhardt et al. 2008; Prueksakorn and Gheewala 2008) due, in part, to the toxic nature of the plant. Other studies have cited pests that do impact Jatropha crop yields (Lele 2008b). Data sets recommending the appropriate amounts of chemicals to apply over tree life cycles are not

well developed, therefore this study assumes no protective chemicals are necessary. This assumption would lead to underestimated impacts for biodiesel production if protective chemicals are necessary.

9. **Seed cake is used to offset fertilizer use on the plantation.** The Jatropha seed cake has multiple potential uses once the oil has been extracted. This study assumes the seed cake is returned to the plantation to offset an amount of NPK fertilizer equal to the nutrient content of the seed cake. Combustion to produce useable heat or power, an alternative use of the seed cake, is not considered.

10. **Biomass removed from the plantation is combusted to generate electricity.** Biomass removed from the plantation via pruning and clipping is assumed to be combusted to generate electricity (Reinhardt et al. 2008). The electricity generated from the plantation biomass offsets Indian grid electricity. No CO_2 emissions are assumed for the biomass combustion to account for the credit that should be given for CO_2 sequestration during Jatropha cultivation. Efficiency of conversion from biomass combustion to electricity generation is assumed to be 25% (U.S. CCTP 2005). An alternative assumption is that the energy produced by combusting the biomass offsets heat required in some local industrial process. This study did not evaluate that alternative use since no literature reports Jatropha biomass used for this purpose, and it is unclear whether a local process requiring heat would exist where the biodiesel processing facility is located.

4.0 Base Case Scenario

The subsequent sections report important data inputs that define the base case scenario. Input data are separated into the six primary categories listed below. Additional details on the included data and processes are highlighted in each section:

- Petroleum diesel production and distribution (Reference System)
- Jatropha cultivation
- Jatropha oil extraction
- Biodiesel production via Jatropha oil transesterification
- Locomotive operation
- Supporting processes.

Each category is defined in SimaPro by several modules, as shown in Figures 11-16. Many of the modules were developed by the authors (referred to hereafter as "custom" modules). The exact coding of the custom modules is reported in Appendix A. Where India-specific data were not available, Ecoinvent 2.0 modules were used. The detailed coding of these modules is proprietary and cannot be reported.

4.1 Petroleum Diesel Production and Distribution (Reference System)

Both the conventional petroleum diesel reference system and the biodiesel pathways include the life cycle impacts of diesel fuel production and distribution. The overview of the petroleum diesel production and distribution pathways was shown in Figure 9. Figure 11 displays the modules used to model the petroleum diesel production and distribution system in SimaPro in more detail.

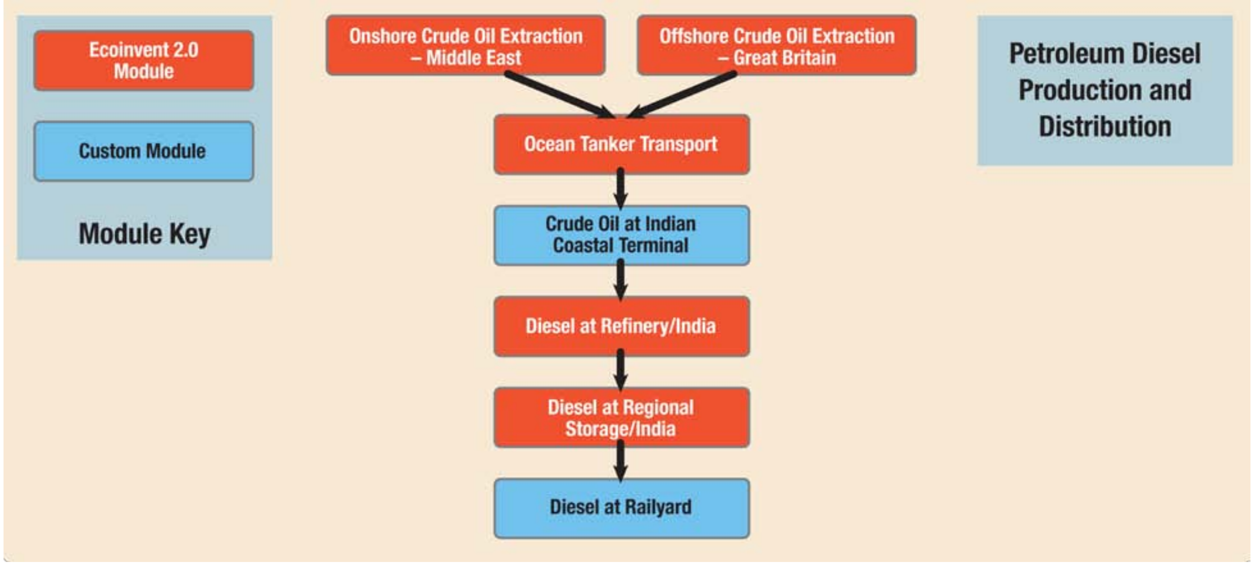

Figure 11. Modeling schematic for petroleum diesel production and distribution processes

Table 2 describes the purpose of each custom and Ecoinvent 2.0 module utilized in modeling the petroleum diesel production and distribution processes.

Table 2. Simapro Module Descriptions for Petroleum Diesel Production and Distribution Processes

Module Name	Module Purpose	Comments
Onshore Crude Oil Extraction – Middle East	This Ecoinvent 2.0 module calculates the impacts of onshore oil production in the Middle East. As the largest percentage of Indian foreign crude oil originates in the Middle East, this module is used to represent the 70% of Indian crude oil that is from foreign sources.	Indian oil may also come from foreign offshore sources, Africa (particularly Nigeria), or other foreign places. Oil from these sources is not considered in this study.
Offshore Crude Oil Extraction – Great Britain	This Ecoinvent 2.0 module calculates the impacts of offshore oil production near Great Britain. The module is used as a proxy for the impacts of domestic offshore oil production from the Bombay High oil fields in India.	The largest share of domestically-produced Indian crude oil is produced offshore at the Bombay High oil fields. The Ecoinvent module for offshore crude oil production in Great Britain is used as a proxy for Indian production.
Ocean Tanker Transport	This Ecoinvent 2.0 module calculates the impacts of the transport of foreign and domestic crude oil via ocean tanker to the coastal terminal in India.	Crude oil is assumed to be delivered to the port at Visakhapatnam, India, adjacent to the VIZAG refinery. Foreign oil originates in Saudi Arabia, domestic oil from Bombay High.
Crude Oil at Indian Terminal	This custom module aggregates crude oil produced domestically and from foreign sources at the port at Visakhapatnam, India prior to refining.	
Diesel at Refinery / India	This modified Ecoinvent 2.0 module quantifies the impacts of refining crude oil into high speed diesel. This module represents an average European refinery from year 2000.	The only aspect modified to India-specific conditions in this module is the source of crude oil.
Diesel at Regional Storage / India	This modified Ecoinvent 2.0 module quantifies the impacts distributing diesel to regional storage via road, rail, and pipeline.	By using the diesel at regional storage module, losses that occur during diesel distribution and filling are included in the analysis. The only modification to India-specific conditions is the source of crude oil to the refinery.
Diesel at Railyard	This custom module aggregates diesel fuel at the railyard prior to fueling locomotives or blending with biodiesel.	

Key data used to develop the custom module for Indian crude oil is reported in Table 3. Seventy percent of Indian crude oil comes from foreign sources with the greatest percentage originating in the Middle East (Bureau of Energy Efficiency 2008). Domestically, the largest percentage of Indian oil is extracted from the offshore oil fields at Bombay High (Ministry of Petroleum and Natural Gas 2006). Because tracing a specific drop of oil through the Indian system is not possible, this study constructs a plausible base case scenario based on country averages, where foreign oil is extracted in Saudi Arabia and domestic oil is extracted from Bombay High with both locations shipping the crude oil via ocean tanker to the VIZAG refinery on the east coast of

India. Refined diesel is then shipped via rail to the rail terminals and depot at Bhilai, near Raipur, for use in IR locomotives.

Table 3. Base Case Data Inputs for Petroleum Diesel Production and Distribution

Parameter	Value	Units	Assumptions/Notes	Source
Foreign Crude Oil	0.75	Mass fraction	Fraction of India's crude oil from foreign sources.	Sarin 2008e
Domestic Crude Oil	0.25	Mass fraction	Fraction of India's crude oil from domestic sources.	Sarin 2008e
Domestic Offshore	1	Mass fraction	Fraction of domestic oil from offshore fields. Base case assumes all oil is derived from the Bombay High offshore oil field.	Base case assumption
Domestic Onshore	0	Mass fraction	Fraction of domestic oil from onshore fields. Base case assumes no crude oil generation from onshore fields in locations such as Assam.	Base case assumption
Fraction Middle East	1	Mass fraction	Fraction of foreign oil from Middle East. Largest percentage of Indian foreign crude oil comes from Saudi Arabia. Nigeria is another potential source.	Base case assumption
Foreign Crude Oil Transport	7,000	km	Transport distance by ocean tanker between Middle East and VIZAG Refinery.	World News Network 2008
Domestic Crude Oil Transport	3,200	km	Transport distance by ocean tanker between Bombay High and VIZAG Refinery.	World News Network 2008
Diesel Rail Transport	600	km	Distance crude oil travels by rail from VIZAG oil terminal to Bhilai.	LiveIndia 2008

4.2 Jatropha Cultivation

Modeling the cultivation of Jatropha trees and operation of the plantation requires data on numerous inputs and outputs including fertilizer use, irrigation water, electricity, and diesel fuel, along with parameters such as the rate of N_2O release from nitrogen fertilizer. This portion of the model carried the greatest uncertainty as deterministic correlations amongst cultivation parameters, including environmental conditions and human inputs, are not well established. Figure 12 outlines the processes included in the modeling of Jatropha cultivation.

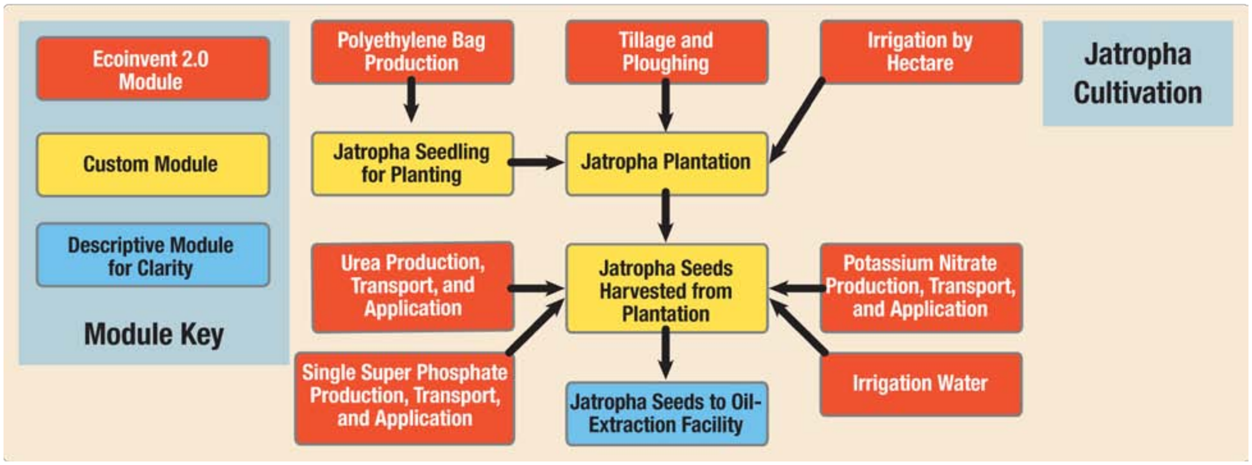

Figure 12. Modeling schematic for Jatropha cultivation processes

Table 4 describes the purpose of each module utilized in the analysis of Jatropha cultivation. Table 5 summarizes key base case input parameters for Jatropha cultivation.

The nitrous oxide release rate in Table 5 represents the default value of 0.01 g N_2O/g N in fertilizer reported by IPCC (2006) from a stated range of 0.003 – 0.03 g N_2O / g N in fertilizer. The emission factor accounts for direct emissions from a variety of organic and synthetic nitrogen fertilizers and accounts for crop residue and mineralization of organic carbon in the soil due to land management and use changes. The emission factor does not include secondary or indirect emission sources of N_2O such as leaching N entering water systems, crop residue being plowed into the fields for successor crops, or dung and urine from animals that feeding on the crops. Crutzen et al. (2008) use a top-down calculation method to suggest that the actual N_2O-N emission factor may be three to five times larger than the default IPCC value (ranging from 0.03 – 0.05 g N_2O per gram N in fertilizer). The impact of the uncertainty in this parameter on overall study results is tested in the sensitivity analysis.

The plantation electricity parameter is also uncertain as Lele (2008e) does not explicitly state what plantation operations are included in this estimate. Therefore, plantation electricity use is considered a conservative value as it may double count some of the electricity required for plantation processes such as irrigation and oil extraction that are modeled separately.

Table 4. SimaPro Module Descriptions for Jatropha Cultivation

Module Name	Module Purpose	Comments
Polyethylene Bag Production	This Ecoinvent 2.0 module calculates the impacts of producing and transporting the polyethylene used in the Jatropha seedling bags at the nursery.	Each Jatropha seedling is generally raised in a polyethylene bag for the first few months.
Tillage and Ploughing	This Ecoinvent 2.0 module calculates the impacts of clearing and preparing the required land for developing the Jatropha plantation.	The base case assumes that 50,000 hectares are cleared for plantation land based on IOC guidance.
Irrigation by Hectare	This Ecoinvent 2.0 module calculates the impacts of irrigating the plantation area during initial planting of the trees to aid establishment.	Irrigation data is not well established for Jatropha plantations.
Jatropha Seedling for Planting	This custom module is designed to represent the requirements for the cultivation of Jatropha seedlings at the nursery. Nursery is likely to be located at or near the plantation. Better data is needed to identify energy requirements of the nursery.	Module information is incomplete as only polyethylene bag requirement is known. However, impacts are very small.
Jatropha Plantation, Planted, India	This custom module calls the required number of seedlings, fertilizer, tillage and ploughing, and irrigation water to establish the Jatropha trees on the plantation. The output is a hectare of planted Jatropha plantation.	The impacts for operating and managing the plantation are separately tracked in the "Jatropha Seeds Harvested from Plantation" module.
Jatropha Seeds Harvested from Plantation	This custom module quantifies all of the impacts associated with operating and managing the plantation over the entire life cycle. Plantation management impacts are normalized per tonne of seeds produced. Jatropha fruit harvesting and de-husking are assumed to be done with manual labor. Jatropha husk combustion is used to offset Indian electricity delivered.	This module calls the required inputs from the fertilizer and irrigation modules along with electricity and diesel fuel for plantation operation and contains much of the model's uncertainty.
Urea Production, Transport, & Application	This Ecoinvent 2.0 module quantifies the impacts of producing, transporting, and applying urea to provide the required amount of nitrogen to the plantation.	Required fertilizer levels are not well defined for the management of Jatropha plantations.
Single Super Phosphate Production, Transport, & Application	This Ecoinvent 2.0 module quantifies the impacts of producing, transporting, and applying single super phosphate to provide the required amount of phosphate to the plantation.	Required fertilizer levels are not well defined for the management of Jatropha plantations.
Potassium Chloride Production, Transport, & Application	This Ecoinvent 2.0 module quantifies the impacts of producing, transporting, and applying potassium chloride to provide the required amount of potassium.	Required fertilizer levels are not well defined for the management of Jatropha plantations.
Irrigation Water Required	This Ecoinvent 2.0 module accounts for the impacts of applying the required levels of irrigation water to the plantation.	The required amount of water is assumed to be the rainfall deficit between the rainfall on the site and a threshold of 2,500 mm/yr for no irrigation.

Table 5. Base Case* Data Inputs for Jatropha Cultivation

Parameter	Value	Units	Assumptions / Notes	Source
Life cycle	20	Years	Defines the lifetime over which the study is conducted.	Reinhardt et al. 2007
Plantation Location	Raipur Area	Chhattisgarh India	Target plantation location selected by IOC.	Sarin 2008b
Plantation Rainfall	1,385	mm/yr	Average rainfall for Raipur, used to calculate required irrigation.	Chhattisgarh Online 2008
Rainfall Required for No Irrigation	2,500	mm	Irrigation data is difficult to find. 2,500 mm per year cited as amount of rainfall where no irrigation is needed in Thailand. This rainfall value is compared with site average rainfall to determine irrigation requirement.	Prueksakorn and Gheewala 2008
Plantation Size	50,000	Hectares	Based on IOC anticipated plantation size.	Sarin 2008b
Seedling Survival Rate	0.8	Surviving seedlings per total seedling planted	Represents Jatropha seedling survival rate of 80% under average planting conditions.	Lele 2008b, Renewable Energy 2008
Tree Density	2,500	Trees per hectare	Assumed initial Jatropha tree density based on Planning Commission of India assumptions.	Planning Commission of India 2003
Years Required for Irrigation	3	Years	Reinhardt et al.'s optimized scenario assumes irrigation is only required for the first three years of plantation establishment.	Reinhardt et al. 2008
Fertilizer Application	2	Applications per year	Assumes one fertilizer application at the beginning and end of the rainy season.	Lele 2008b
Urea Fertilizer Required	81	kg per ha-year	Urea fertilizer use based on the Optimized scenario of Reinhardt et al. Reinhardt assumes density of 1,667 trees / hectare which is scaled to base case density.	Reinhardt et al. 2008
P_2O_5 Fertilizer Required	31	kg per ha-year	P_2O_5 fertilizer use based on the Optimized scenario of Reinhardt et al.	Reinhardt et al. 2008
K_2O Fertilizer Required	89	kg per ha-year	K_2O fertilizer use based on the Optimized scenario of Reinhardt et al.	Reinhardt et al. 2008
Diesel Fuel Required	86	liters per ha-year	Diesel fuel use based on the Optimized scenario of Reinhardt et al.	Reinhardt et al. 2008
Nitrous Oxide Release	0.01	g N_2O per g N in fertilizer	Fraction of nitrogen contained in fertilizer that is released to the air based on IPCC's default value for N_2O emissions from nitrogen fertilizers.	IPCC 2006
Oil Content of Jatropha Seed	0.35	Mass oil per mass total seed	Assumed average oil content of dry seed on mass basis. Matches assumption in Indian Planning Commission calculations.	Achten et al. 2008
Plantation Electricity	12,000	MWh per year	Approximate electricity required to operate a 50,000 hectare plantation for one year.	Lele 2008c

Parameter	Value	Units	Assumptions / Notes	Source
Seed Husk Yield	1,429	kg sun dried husks per ha-year	Estimated seed husk yield after seed extraction and assuming a water content of 9%. Based on the Optimized scenario of Reinhardt et al.	Reinhardt et al. 2008
Seed Husk Energy Density	15.5	MJ per kg	Gross energy content of the dry matter of Jatropha seed husks.	Reinhardt et al. 2008
Jatropha Seed Yield	2,382	kg sun dried seeds per ha-yr	Estimated Jatropha seed yield assuming 5.8% water content. Based on the Optimized scenario of Reinhardt et al.	Reinhardt et al. 2008
Biomass Yield, Year 1	2.5	kg biomass per tree	IOC supplied estimate of first year biomass yield from pruning.	Sarin 2008c
Biomass Yield Year 2	4.5	kg biomass per tree	IOC supplied estimate of second year biomass yield from pruning.	Sarin 2008c
Biomass Yield from Mature Jatropha Plants	8.5	kg biomass per tree	IOC supplied estimate of biomass yield from pruning mature Jatropha trees.	Sarin 2008c
Mass Fraction Stems	0.67	Mass fraction	Based on approximate breakdown of dried Jatropha plant biomass. Remaining mass fraction is comprised of leaves.	Nivitchanyong 2007
Energy Density of Leaves	3,624	kJ per kg	Gross specific energy content of Jatropha leaves.	Nivitchanyong 2007
Energy Density of Stems	3,932	kJ per kg	Gross specific energy content of Jatropha stems.	Nivitchanyong 2007
Seed Transportation	50	km	Assumed distance for Jatropha seeds to be transported by truck from plantation to oil extraction unit.	Calculated for base case narrative

*Base case assumes no application of pesticides, herbicides, or insecticides.

4.3 Jatropha Oil Extraction

The Jatropha oil extraction process considered in this study is a continuous solvent extraction process with 91% extraction efficiency. Limited data is available on the use of this solvent extraction process for Jatropha oil collection in India. The base case data represents India-specific published data. Figure 13 highlights the processes used to model Jatropha oil extraction while Table 6 describes the modules.

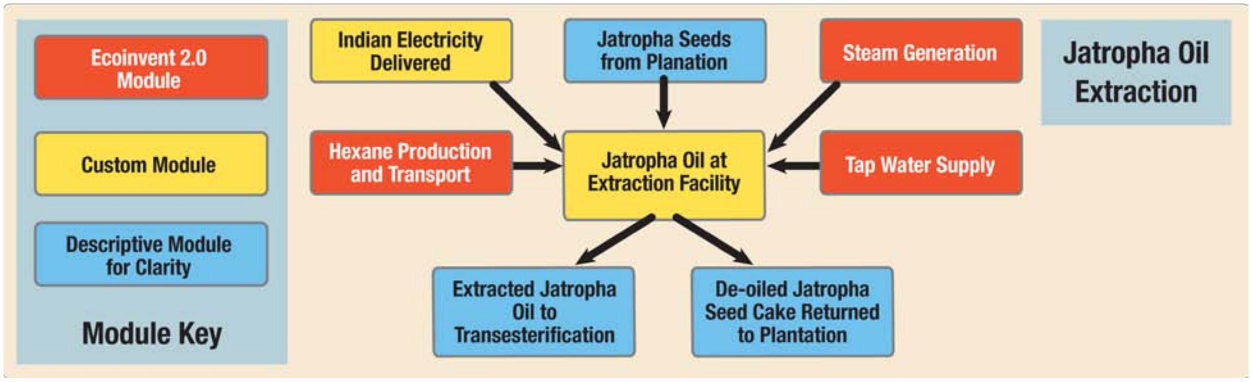

Figure 13. Modeling schematic for Jatropha oil extraction processes

Table 6. SimaPro Module Descriptions for Jatropha Oil Extraction

Module Name	Module Purpose	Comments
Indian Electricity Delivered	This custom module represents the Indian electric grid mix supplied to the oil extraction unit.	See the section "Supporting Processes" for more details on the Indian Electricity module.
Jatropha Oil at Solvent Extraction Facility, India	This custom module calculates the impacts of continuous solvent-based Jatropha oil extraction. Infrastructure of an oil extraction facility in Western Europe is included. The process produces Jatropha oil that is transported to the transesterification plant and de-oiled seed cake that is returned to the plantation as a fertilizer.	This module calls the required inputs for electricity, steam, hexane, and water needed to operate continuously.
Steam Generation	This Ecoinvent 2.0 module calculates the impacts of generating and delivering the steam required for the oil extraction process.	Generic steam production is used due to a lack of information on India-specific processes for generating steam for oil extraction.
Hexane Production and Transport	This Ecoinvent 2.0 module quantifies the impacts of producing and transporting the hexane that is used as the solvent in the Jatropha oil extraction process.	Hexane is the only solvent used on a commercial scale for oil extraction at this time.
Tap Water Supply	This Ecoinvent 2.0 module quantifies the impacts of supplying tap water to the oil extraction facility for use in the oil extraction process.	The module is based on Western European data as India-specific water production and delivery data is unavailable.

Table 7 reports key base case data inputs used to model Jatropha oil extraction via a continuous solvent extraction process.

Table 7. Base Case Data Inputs for Jatropha Oil Extraction

Parameter	Value	Units	Assumptions/Notes	Source
Extraction Efficiency	91%	Mass percent	Percent of Jatropha oil available in seeds extracted via solvent extraction.	Planning Commission of India 2003
Electricity Use	55	kWh per tonne of seed input	Average electricity use for continuous solvent extraction per tonne of Jatropha seed input.	Adriaans 2006
Hexane Use	4	kg per tonne of seed input	Average amount of hexane used in continuous solvent extraction; 99% is recycled.	Adriaans 2006; Sarin 2008c
Steam Use	280	kg per tonne of seed input	Average amount of steam required for continuous solvent extraction.	Adriaans 2006
Water Use	12	m^3 per tonne of seed input	Average amount of water required for continuous solvent extraction (consumed and discharged to sewer).	Adriaans 2006
Jatropha Oil Transportation	0	km	Assumes oil extraction facility is co-located with the transesterification plant.	Sarin 2008c

4.4 Biodiesel Production via Jatropha Oil Transesterification

The study focuses on base-catalyzed transesterification of Jatropha oil to biodiesel as the process promoted by the Planning Commission of India (2003). Figure 14 outlines the important processes included in the model while Table 8 describes each module.

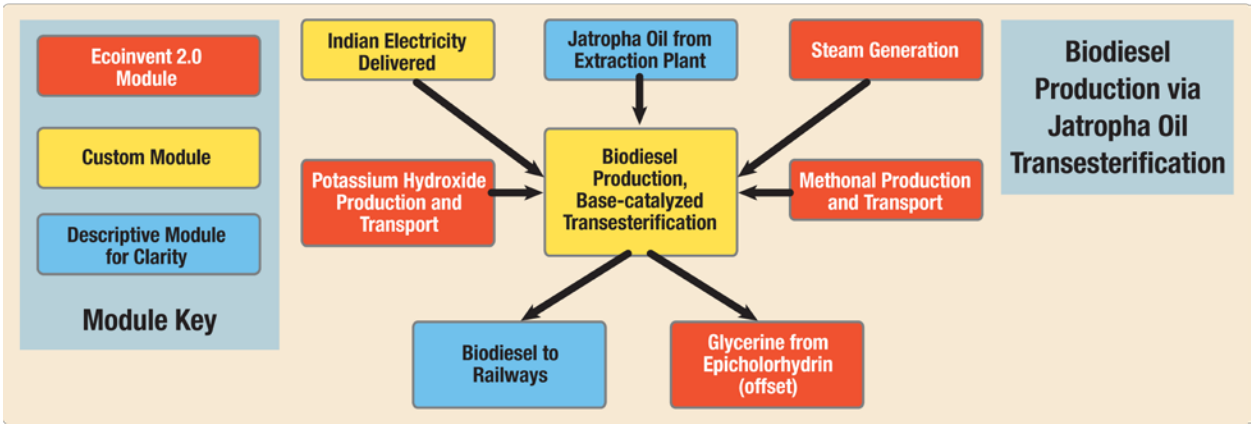

Figure 14. Modeling schematic for biodiesel production via Jatropha oil transesterification processes

Table 8. SimaPro Module Descriptions for Biodiesel Production via Jatropha Oil Transesterification

Module Name	Module Purpose	Comments
Indian Electricity Delivered	This custom module represents the Indian electric grid mix supplied to the biodiesel production unit.	See the section "Supporting Processes" for more details on the Indian Electricity module.
Biodiesel Production, Base-catalyzed Transesterification, India	This custom module calculates the impacts of biodiesel production via base-catalyzed Jatropha oil transesterification. Infrastructure of a transesterification facility in Western Europe is included. The process produces biodiesel to be transported to railways and glycerine to offset synthetic glycerine production.	This module calls the required inputs for electricity, steam, potassium hydroxide, and methanol, and water needed to operate.
Steam Generation	This Ecoinvent 2.0 module calculates the impacts of generating and delivering the steam required for the oil extraction process.	Generic steam production is used due to a lack of information on India-specific processes for generating steam for transesterification.
Potassium Hydroxide Production and Transport	This Ecoinvent 2.0 module quantifies the impacts of producing and transporting the potassium hydroxide that is the base catalyst for the transesterification process.	Potassium hydroxide production is modeled based on Western European conditions due to a lack of data on Indian production.
Methanol Production and Transport	This Ecoinvent 2.0 module quantifies the impacts of producing and transporting the methanol that is used as the alcohol for the transesterification process.	Methanol production is modeled based on Western European conditions due to a lack of data on Indian production.
Glycerine from Epicholorhydrin	This Ecoinvent 2.0 module quantifies the impacts that are offset through the generation of the co-product glycerine replacing some synthetic glycerine production.	The module is based on Western European conditions due to a lack of Indian data.

Table 9 reports key base case data inputs for the modeling of biodiesel transesterification.

Table 9. Base Case Data Inputs for Biodiesel Transesterification via Jatropha Oil Transesterification

Parameter	Value	Units	Assumptions/Notes	Source
Conversion Efficiency	95%	Mass percent	Conversion efficiency of Jatropha oil to biodiesel	Lele 2008d
Electricity Use	36	kWh per tonne of biodiesel produced	Electricity use based on a 100,000 tonne biodiesel / year plant	Planning Commission of India 2003
Steam Use	660	kg per tonne of biodiesel produced	Steam use based on a 100,000 tonne biodiesel / year plant	Planning Commission of India 2003
Water Use	55	m^3 circulated	Water is circulated, not consumed, so the amount reported here is for initial loading of the system.	Planning Commission of India 2003
Base Catalyst Required (KOH)	18	kg per tonne of biodiesel produced	KOH used as base catalyst for a 100,000 tonne biodiesel / year plant	Planning Commission of India 2003
Methanol Required	110	kg per tonne of biodiesel produced	Methanol use based on a 100,000 tonne biodiesel / year plant	Planning Commission of India 2003
Glycerine Yield	0.08	Mass fraction	Mass fraction yield of glycerine as co-product during production of biodiesel	Lele 2008a
Biodiesel Transportation	20	km	Distance between Raipur and Bhilai depots	LiveIndia 2008

4.5 Locomotive Operation

Both the reference petroleum diesel life cycle and the comparison blended biodiesel scenarios end with the fuels being combusted to operate IR locomotives. Figure 15 displays the primary SimaPro modules for analyzing the locomotive combustion while Table 10 describes each process.

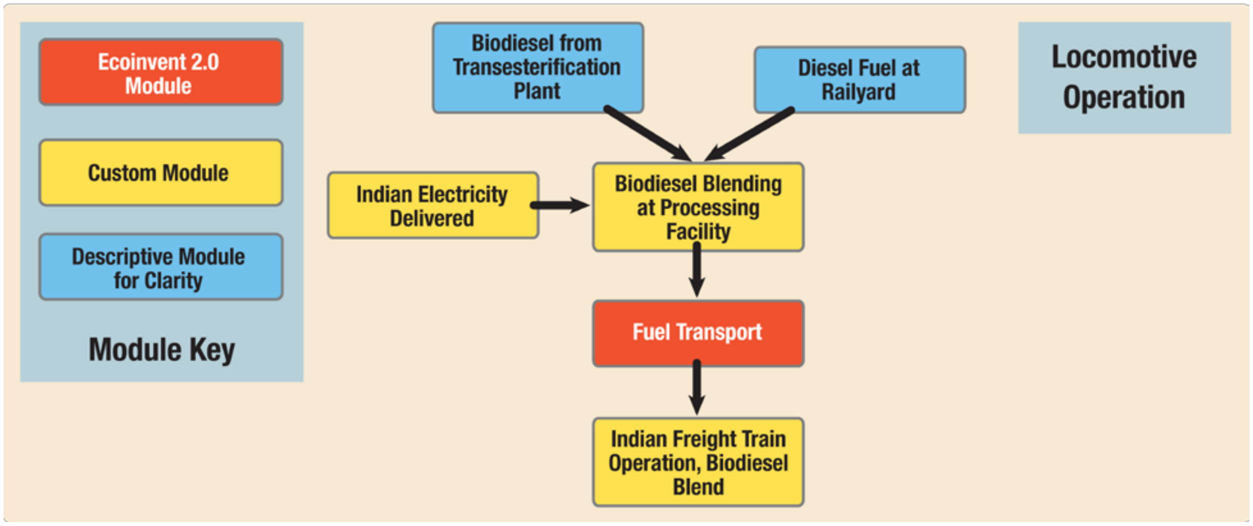

Figure 15. Modeling schematic for locomotive operation

Table 10. SimaPro Module Descriptions for Locomotive Operation

Module Name	Module Purpose	Comments
Indian Electricity Delivered	This custom module represents the Indian electric grid mix supplied to the biodiesel blending unit.	See the section “Supporting Processes” for more details on the Indian Electricity module.
Biodiesel Blending, India, At Processing Facility	This custom module calls biodiesel from the transesterification plant and diesel fuel at the rail yard and blends them using Indian electricity into the desired mix for the analysis.	Analyzed biodiesel blends include 0%, 5%, 10%, and 20%.
Fuel Transport	This Ecoinvent 2.0 module calculates the impacts of transporting the blended biodiesel a short distance via truck from the Bhilai depot to the railway fueling location.	Blended biodiesel transport is a small impact in the overall life cycle.
Indian Freight Train Operation, Biodiesel Blend	This custom module calls the required amount of blended biodiesel to operate the locomotive over the entire life cycle. Carbon dioxide emissions from the diesel portion of the blended biodiesel are also calculated in this module.	The base case analysis assumes an operating life time of 2 billion GTK.

Table 11 reports key base case data inputs for locomotive operation including CO_2 emission factors, fuel consumption, and biodiesel efficiency.

Table 11. Base Case Data Inputs for Locomotive Operation

Parameter	Value	Units	Assumptions/Notes	Source
Biodiesel Blend	0.05, 0.1, 0.2	Fraction biodiesel	Base analysis covers 5%, 10%, and 20% biodiesel blends.	Sarin 2008a; Kathpal 2008
Biodiesel Efficiency	1	Biodiesel fuel consumption per diesel fuel consumption	Preliminary IR field trials showed a negligible negative effect in volumetric fuel consumption for B5, B10, and B20 (checked with sensitivity).	Kathpal 2008; Skinner et al. 2007
Specific Gravity Biodiesel	0.88	kg per liter	Specific gravity of 100% biodiesel used in model conversions.	Planning Commission of India 2003; Gubler 2006
Specific Gravity Diesel	0.84	kg per liter	Specific gravity of diesel fuel used in the model conversions.	Planning Commission of India 2003; Gubler 2006
Diesel Fuel Consumption (Locomotive)	4.38	liters diesel per 1,000 GTK	Average fuel consumption for Indian Railways passenger and freight trains. Gross tonnage includes both the weight of the train and the passengers/cargo.	Indian Railways 2007
Lifetime Gross Tonne Kilometers (GTK)	2 billion	Total GTK analyzed over locomotive life cycle	GTK is the functional unit for this study. The lifetime of this study is 20 years.	Indian Railways 2007
Diesel CO_2 Emission Factor	2.68	kg CO_2 per liter of diesel combusted	CO_2 emission factor for the combustion of diesel fuel in the locomotives.	Climate Registry 2008
Biodiesel CO_2 Emission Factor	0	kg CO_2 per liter of biodiesel combusted	Combustion of 100% biodiesel assumed to emit no CO_2 emissions to account for the carbon sequestered in Jatropha during cultivation.	By definition

4.6 Supporting Processes

Many of the biodiesel processes, including cultivation, oil extraction, and transesterification require supporting processes such as electricity or transportation. An Indian specific electricity generation profile was created based on the national average annual proportion of electricity generation by fuel type. The impacts of each generating technology were calculated using Ecoinvent 2.0 data modules as outlined in Figure 16 and described in Table 12. The proportion of electricity generation by source is reported in Table 13. The Indian electric grid suffers from significant electricity transmission and distribution (T&D) losses. The base case assumes T&D losses of 32% (Indian Central Electricity Authority 2008) and includes impacts from T&D infrastructure in the calculations to test the potential impact of electricity infrastructure on the results. The inclusion of the T&D infrastructure had a negligible impact on model results.

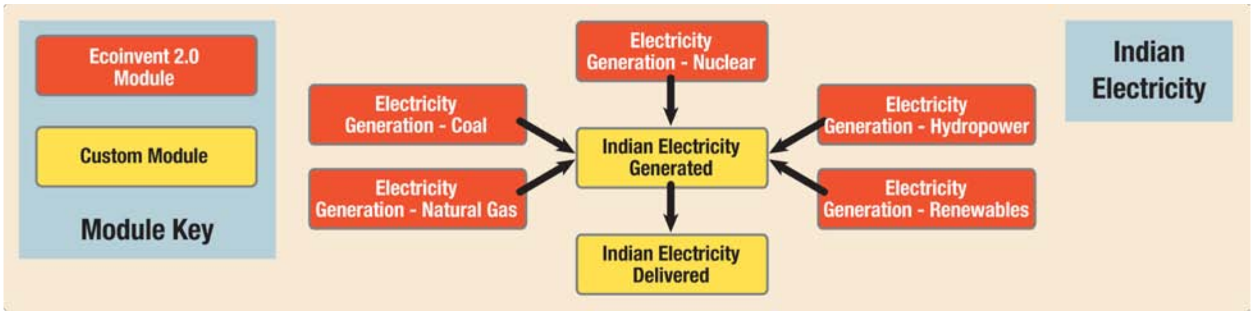

Figure 16. Modeling schematic for Indian electricity

Table 12. SimaPro Module Descriptions for Indian Electricity

Module Name	Module Purpose	Comments
Electricity Generation – Natural Gas	This Ecoinvent 2.0 module calculates the impacts of electricity generation from natural gas in Western Europe. Indian data was unavailable.	The amount of natural gas used in the Indian Electricity module is based on average annual electricity generation by fuel type in India.
Electricity Generation – Coal	This Ecoinvent 2.0 module calculates the impacts of electricity generation from coal in Western Europe. Indian data was unavailable.	The amount of coal used in the Indian Electricity module is based on average annual electricity generation by fuel type in India.
Electricity Generation – Nuclear	This Ecoinvent 2.0 module calculates the impacts of electricity generation from nuclear energy in Western Europe. Indian data was unavailable.	The amount of nuclear power used in the Indian Electricity module is based on average annual electricity generation by fuel type in India.
Electricity Generation – Hydropower	This Ecoinvent 2.0 module calculates the impacts of electricity generation from hydropower in Western Europe. Indian data was unavailable.	The amount of hydropower used in the Indian Electricity module is based on average annual electricity generation by fuel type in India.
Electricity Generation – Renewables	This module calls two Ecoinvent 2.0 modules that calculate the impacts of electricity generation from solar and wind energy in Western Europe. Indian data was unavailable.	Indian electricity generation data were listed with renewables as a category. In order to match with existing Ecoinvent 2.0 modules, the authors assumed that 50% of the renewable electricity came from solar and 50% came from wind.
Indian Electricity Generated	This custom module defines the source mix for Indian electricity using Ecoinvent 2.0 modules for each generation type.	
Indian Electricity Delivered	This custom module includes impacts from T&D infrastructure and accounts for transmission and distribution losses in India.	Transmission and distribution losses in India can be greater than 30%.

Table 13 reports key base case data inputs for calculating the Indian electricity SimaPro module.

Table 13. Base Case Data Inputs for Indian Electricity

Fuel	% Generation	Source
Coal	70%	Indian Electricity 2008
Natural Gas	12%	EIA 2008
Hydroelectric	15%	EIA 2008
Nuclear	2%	EIA 2008
Renewable (solar, wind, etc)	1%	EIA 2008
Transmission & Distribution Loss*	32% (loss)	Indian Central Electricity Authority 2008

*Transmission & Distribution Loss refers to national average electricity that is lost between generation and delivery to end users.

Note: Impacts from electricity infrastructure is included in the analysis.

Table 14 describes the SimaPro modules that are used to represent transportation impacts throughout the model.

Table 14. SimaPro Module Descriptions for Transportation

Module Name	Module Purpose	Comments
Truck - Lorry	This Ecoinvent 2.0 module is used to calculate the impacts of road transport and associated infrastructure whenever truck transport is required in the model.	Data is for Western European conditions; India-specific data was not available.
Ocean Tanker	This Ecoinvent 2.0 module is used to calculate the impacts of transoceanic transport and associated infrastructure whenever ocean tanker transport is required in the model.	Data is for Western European conditions; India-specific data was not available.
Rail	This Ecoinvent 2.0 module is used to calculate the impacts of rail transport and associated infrastructure whenever railcar transport is required in the model.	Data is for Western European conditions; India-specific data was not available.
Pipeline	This Ecoinvent 2.0 module is used to calculate the impacts of pipeline transport and associated infrastructure whenever pipeline transport is required in the model.	Data is for Western European conditions; India-specific data was not available.

5.0 Base Case Results

The base case results are presented using three impact assessment metrics:

1. **Net GHG emission intensity:** net emissions of the IPCC-identified GHGs are calculated with results grouped according to the six Kyoto Protocol gas classifications (CO_2, CH_4, N_2O, PFCs, HFCs, SF_6) expressed in carbon dioxide equivalents (grams CO_2e per GTK).

2. **Net energy ratio:** useful fuel energy delivered to the locomotive divided by the cumulative energy demand of the system (including offset credits).

3. **Petroleum displacement intensity:** reduction in crude oil use per GTK for the biodiesel analysis scenarios compared with the conventional diesel baseline.

Base case results are presented for conventional diesel and biodiesel blends of B5, B10, and B20. Results for B100 (neat biodiesel), although not envisioned for use in the Indian rail system, are shown for informational purposes and to help the reader calculate results for other blends. The sensitivity analysis section explores the relative influence of certain key parameters.

5.1 Net Greenhouse Gas Emissions

Table 15 presents the net life cycle GHG emissions normalized by the functional unit of the study (GTK). The percent change for each biodiesel blend compared with conventional diesel is also reported. The results suggest that, for the case considered, life cycle GHG emissions will decrease by approximately 3% for B5, 6% for B10, 12% for B20, and 62% for B100 compared with conventional diesel emissions. Note that GHG emissions trend proportionally with increasing biodiesel blend percent as expected.

Table 15. Net Life Cycle Greenhouse Gas Emissions

	Units	Diesel	B5	B10	B20	B100
GHG Emission Intensity	g CO_2e per GTK	13	13	12	12	5.1
Change from Diesel	**%**	**--**	**-3%**	**-6%**	**-12%**	**-62%**

Assumes a 20 year system lifetime with 2 billion gross tonne-kilometers (GTK) transported over that time. Uses IPCC 1997 GWP values for consistency with the LCA literature. Results are rounded to two significant figures as an indication of their uncertainty. Percent change values are rounded to the nearest integer.

Based on the analysis of the case considered in this study, Jatropha-based biodiesel has a significant greenhouse gas emission benefit compared to petroleum diesel. The results indicate that there is not a significant negative impact on the biodiesel system's net GHG emissions due to the cultivation and processing of the Jatropha crop, at least for the base case conditions considered here. While this benefit may be reduced if the impact of direct land use change were evaluated, a slight benefit remains when site-specific carbon content changes are accounted for in prior work (Reinhardt et al. 2008).

The results of Table 15 demonstrate that net GHG emissions reductions compared to petroleum diesel are proportional to the biodiesel content of the fuel. This result is mainly a consequence of the modeling assumption that all CO_2 emissions emitted during the combustion of biodiesel in the locomotive are offset by CO_2 uptake during the growing of the plants, whereas considerable CO_2 is emitted during combustion of diesel fuel by the locomotive.

Beyond reporting the GHG emissions intensity and the anticipated percent change compared to petroleum diesel for each biodiesel blend, it is informative to identify the life cycle processes responsible for the greatest amount of GHG emissions. Identifying the key processes can better focus the sensitivity analyses to test the assumptions in those modules and to determine which parameters are likely to be critical in potentially changing the conclusions of the study.

Table 16 reports the percent contribution of each stage to total GHG emissions. Each major stage is separated, where appropriate, into sub-processes to provide more detail on the source of GHG emissions. Owing to limitations of the LCA software used in this study, the impacts of two supporting processes—Indian electricity and steam production—are aggregated into combined sub-processes instead of their contributions being determined separately for each stage they support. For instance, Indian electricity supports Jatropha cultivation, Jatropha oil extraction, and base-catalyzed transesterification stages, while steam production supports Jatropha oil extraction and base-catalyzed transesterification stages. Negative percentages represent GHG emission credits resulting from co-product boundary expansion.

Table 16. Life Cycle Greenhouse Gas Process Contributions

Process	Diesel	B5	B10	B20	B100
Locomotive Operations	**89%**	**87%**	**85%**	**81%**	**0%**
Crude Oil Production, Transport, and Refining	**10%**	**10%**	**9.9%**	**9.4%**	**0%**
Jatropha Cultivation	**--**	**0.83%**	**1.7%**	**3.7%**	**44%**
N_2O Release from Fertilizer	--	0.32%	0.66%	1.4%	17%
Irrigation	--	0.53%	1.1%	2.4%	28%
Fertilizer Application and Offset	--	<-0.1%	<-0.1%	<-0.1%	-0.83%
Jatropha Oil Extraction	**--**	**<0.1%**	**<0.1%**	**<0.1%**	**0.93%**
Hexane Production	--	<0.1%	<0.1%	<0.1%	0.93%
Base-catalyzed Transesterification	--	**-0.42%**	**-0.87%**	**-1.9%**	**-22%**
Methanol Production	--	0.13%	0.26%	0.56%	6.7%
Potassium Hydroxide Production	--	<0.1%	0.10%	0.22%	2.7%
Glycerine Offset	--	-0.60%	-1.2%	-2.7%	-32%
Supporting Processes	**--**	**1.4%**	**2.8%**	**6.1%**	**72%**
Indian Electricity	--	0.78%	1.6%	3.4%	40%
Truck Transport	--	<0.1%	0.16%	0.35%	4.2%
Steam Production	--	0.53%	1.1%	2.4%	28%

Note: Percent contributions for each process to total GHG emissions are displayed. Negative percentages represent emission credits due to boundary expansion (co-product offsets). Column totals may not sum to 100% due to rounding and contribution of minor processes throughout the life cycle. Indian electricity and steam production contribute to impacts for multiple life cycle stages but are aggregated separately due to model limitations. Results are rounded to two significant figures as an indication of their uncertainty.

The results show that life cycle GHG emissions are primarily driven by the combustion of diesel in the locomotive, followed by the conventional diesel production process. As a reminder, combustion of biodiesel in locomotives is assigned a zero emission factor to account for the carbon sequestered during the cultivation of the Jatropha trees. Therefore, all GHG emissions in the freight train transport process result from the combustion of the portion of the fuel that is diesel. For the diesel scenario, locomotive transport accounts for nearly 90% of total life cycle GHG emissions, decreasing to 81% for B20. The contribution of crude oil extraction, transport, and processing into diesel fuel accounts for approximately 10% of the GHG emissions for the conventional diesel scenario, down to 9.4% for B20.

As the percentage of biodiesel increases, the proportionate contribution of the Jatropha cultivation, oil extraction, biodiesel transesterification, and supporting processes increases. Reducing the net impacts of the Jatropha biodiesel production process are the three major offsets considered in this study: 1) glycerine production, which receives a GHG credit for offsetting synthetic glycerine production; 2) seed cake reused as fertilizer, which reduces the use of urea fertilizer; and 3) excess biomass combusted to produce electricity thereby offsetting grid electricity (which mainly is derived from fossil fuels). The most significant of these offsets is glycerine production, providing a 32% offset in the case of neat biodiesel.

Two parameters that deserve particular attention are irrigation and N_2O release from nitrogen fertilizer. These processes contribute 28% and 17% to B100 net life cycle GHG emissions, respectively. However, the parameter values modeled for each are highly uncertain. The base case scenario assumes irrigation for only the first three years of the life cycle while the plantation is being established, as suggested by Reinhardt and colleagues (2008). No other published source confirmed this assumption. Also, available literature provides little guidance on the relationship between rainfall and irrigation water requirements, nor the correlation amongst irrigation requirements and soil conditions, fertilizer usage, and other important agronomic information. While the best available information was used to develop the base case scenario, the impact to this report's conclusions owing to changes in irrigation-related assumptions is examined through a sensitivity analysis. N_2O, which is released after application of nitrogen fertilizers, is a potent GHG. Both the amount of nitrogen fertilizer required and the fraction of nitrogen in the fertilizer that is volatized to N_2O are highly uncertain owing to challenges regarding the measurement and modeling of the fate and transport of N_2O. The sensitivity analysis section shows how different assumptions regarding these parameters can significantly alter the estimate of biodiesel life cycle GHG emissions.

In addition to examining the contribution of each process to GHG emissions, it is also informative to analyze the proportionate contribution of each major GHG to net carbon dioxide equivalent emissions and how those contributions vary across different biodiesel blends. The categories of gases considered in this analysis include CO_2, CH_4, N_2O, perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6). As shown in Table 17, CO_2 has the greatest contribution in all scenarios, as would be expected for a life cycle that heavily relies on combustion of fossil fuels. CO_2 contributes from 99% of life cycle net GHG emissions for diesel to 76% for B100. Methane and N_2O emissions constitute the majority of the remainder depending on biodiesel blend, where methane emissions are a greater contributor to total net GHG emissions for diesel through B10. Table 17 highlights the increasing contribution of agricultural N_2O emissions as the percentage of biodiesel increases. N_2O contribution is negligible for the diesel case, increasing to 1.5% for B20 and 18% for B100. The sensitivity analyses show that this contribution can increase even further if different assumptions are used for the volatilization rate of N_2O from nitrogen fertilizer during plantation operation. HFCs, PFCs, and SF_6 combined contribute less than 0.1% to overall life cycle GHG emissions for both diesel and all biodiesel blends.

Table 17. Percent Contribution by Greenhouse Gas to Total Global Warming Potential

Greenhouse Gas	Diesel	B5	B10	B20	B100
CO_2	99%	99%	98%	97%	76%
CH4	0.68%	0.78%	0.89%	1.1%	6.0%
N_2O	0.61%	0.39%	0.74%	1.5%	18%
HFCs, PFCs, SF6 (combined)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%

Results are rounded to two significant figures as an indication of their uncertainty.

5.2 Net Energy Ratio

The net energy ratio (NER) is used to compare the useful energy produced by the system to the net energy consumed by the system. As described in the supporting materials to Farrell et al.

(2006), NER is a problematic metric. Chiefly, the NER is difficult to compare between studies as it is often poorly defined and strongly influenced by the analyst's method of calculation (i.e., whether energy offsets produced by the system are added to the energy output or subtracted from the energy input). Nevertheless, it is used in this study because its meaning is intuitive and for the sake of comparison to other studies that have used this metric.

In this study, NER is calculated as

$$\text{NER} = \frac{\text{Energy Out (MJ)}}{\text{Net Energy Demand (MJ)}} \tag{1}$$

where, *Energy Out* is defined as the useful energy delivered to the locomotive to produce motion, and *Net Energy Demand* is defined as all energy consumed by the system minus energy saved or produced due to system offsets such as biomass combustion.

The results of the NER analysis are reported in Table 18. The diesel reference case shows an NER of less than one. Fossil fuel based systems have NERs less than one because energy out is always less than energy in due to energy consumed during processing and transport. By contrast, the B100 case shows an NER of greater than one which indicates a favorable energy balance. Owing to the greater contribution of diesel, blends up to B20 still show an NER of less than one. The robustness of the B100 NER base case result is tested in the sensitivity analyses.

Table 18. Net Energy Ratio

	Units	Diesel	B5	B10	B20	B100
Net Energy Ratio	Energy out per net energy demand	0.79	0.81	0.84	0.89	1.9
Change from Diesel	**%**	**--**	**3%**	**6%**	**13%**	**140%**

Assumes a 20 year system lifetime with 2 billion gross tonne-kilometers (GTK) transported over that time. Results are rounded to two significant figures as an indication of their uncertainty. Percent change values are rounded to the nearest integer.

5.3 Net Petroleum Displacement

Biodiesel use is often cited as a means for decreasing dependence on petroleum. This issue is particularly important to India as approximately 70% of all crude oil used in India is imported. IR estimates that use of B20 for all diesel locomotive operations could save approximately 400 million liters of diesel fuel per year (Kathpal 2008). Reduction in petroleum use is defined as the consumption of petroleum by the reference system (here, diesel), minus the amount of petroleum consumed in an alternative scenario (here, various biodiesel blends), often termed petroleum displacement. By examining petroleum displacement over the full life cycle, this study analyzes what degree the reduction in diesel fuel combustion in the locomotive is offset by petroleum consumption during the cultivation of Jatropha and transportation and processing of Jatropha oil and biodiesel. Table 19 shows petroleum consumption and displacement over the life cycle normalized by the functional unit, GTK. The percent decrease in petroleum consumption is also tabulated for each scenario examined.

Table 19. Life Cycle Net Petroleum Consumption and Displacement Intensity

	Units	Diesel	B5	B10	B20	B100
Net Petroleum Consumption Intensity	g crude oil per GTK	4.2	4.0	3.8	3.5	0.58
Net Petroleum Displacement Intensity	g crude oil per GTK	--	0.17	0.34	0.69	3.6
Change from Diesel	**%**	**--**	**-4%**	**-8%**	**-17%**	**-86%**

The study life cycle assumes two billion GTKs of train transport. Petroleum consumption is measured in terms of mass of crude oil consumed. Results are rounded to two significant figures as an indication of their uncertainty. Percent change values are rounded to the nearest integer.

If upstream life cycle phases for the diesel and biodiesel production systems were identical in terms of petroleum consumption, one would expect to see a percent decrease in petroleum consumption equal to the percent biodiesel blended in the fuel (e.g., 20% biodiesel would reduce diesel requirements by 20%). As Table 19 shows, the overall life cycle petroleum displacement is close to, but slightly less than the percent biodiesel used. B5 yields a 4% reduction, B10's reduction is 8%, and B20 displaces 17% of petroleum use. These results indicate that diesel use during Jatropha cultivation, transport, and processing into biodiesel offsets a small percentage of the gains from reducing diesel use in the locomotives.

6.0 Sensitivity Analyses

The sensitivity analyses focus on determining the influence of individual parameters on the overall study results and on establishing best and worst case bounding estimates for net GHG, net petroleum displacement, and net energy analyses. In this analysis, each parameter (or set of parameters) is tested individually, while other parameters are held at their base case values.

This sensitivity analysis focuses on 15 parameters or sets of parameters that were selected because they met two criteria: 1) they were judged likely to influence one or more of the model outputs significantly, and 2) their values are uncertain, as determined by a review of the available literature. The uncertainty of values was due in some cases (such as N_2O volatilization) to expert uncertainty and disagreement while other parameters (such as fertilizer required) were subject to data unavailability uncertainty due to lack of information on India-specific requirements. Appendix B details the parameter values used in each sensitivity case.

The sensitivity analyses are reported in Tables 20-22 for net global warming potential, net energy ratio, and net petroleum consumption, respectively. In addition to reporting the difference between the result of the sensitivity run and the base case result, Tables 20-22 also rank the scenarios according to how sensitive the model output is to changes in the value of individual parameters. The sensitivity of the model to changes in the value of individual parameters is evaluated using the local sensitivity coefficient, $S_{i,j}$. $S_{i,j}$ is defined as the partial derivative of the model prediction with regard to a specific input parameter:

$$S_{i,j} = \frac{\partial C_j}{\partial \lambda_i}, \tag{2}$$

where C is the set of model outputs, with j representing a specific output, and λ is the set of model input parameters, with i representing a specific input parameter. C is a function of λ.

The finite difference approach is used to estimate the local sensitivity coefficient. This approach estimates the local derivative as the ratio of the difference between two model runs, where the two runs are distinguished by a change in the value of only one model input parameter, and the change in value of that one parameter:

$$\frac{\partial C_j}{\partial \lambda_i} = \frac{C_j(\lambda_i + \Delta\lambda_i) - C_j(\lambda_i)}{\Delta\lambda_i}. \tag{3}$$

Note that the local sensitivity coefficient is undefined for sensitivity cases where the value of more than one parameter was changed, and therefore will not be reported for a few sensitivity scenarios tested.

The local sensitivity coefficient can be presented unnormalized (in units of model output per model input), as above, or normalized (dimensionless), as below:

$$\frac{\partial C_j / C_j}{\partial \lambda_i / \lambda_i} = \frac{\lambda_i}{C_j} \frac{\partial C_j}{\partial \lambda_i} . \tag{4}$$

The normalized local sensitivity coefficient can be interpreted as the fractional change in model output resulting from a 100% change in model input. Local sensitivity coefficients greater than one in absolute value indicate input parameters with outsized influence on the model result; local sensitivity coefficients less than one indicate parameters that have proportionally less influence on model outcomes. Negative local sensitivity coefficients indicate that the model output and input are anti-correlated (e.g., the value of the model output decreases as the value of the model input increases); positive local sensitivity coefficients can be interpreted in the opposite manner. As LCAs are typically linear models, the local sensitivity coefficient is expected to remain consistent throughout the likely range of input parameter values.

The sensitivity cases evaluated in Tables 20-22 are presented in decreasing order of the absolute value of the normalized S_{ij} parameter. Although S_{ij} could be determined for diesel fuel and any biodiesel blend, it is only presented in Tables 20-22 for the case of neat biodiesel (B100) because the parameters tested in the sensitivity scenarios primarily impacted the biodiesel production system. The biodiesel production system used the least certain data in the study; the diesel reference system largely relied on peer-reviewed life cycle inventory databases produced by Ecoinvent (Swiss Centre for Life Cycle Inventories 2008). The only parameter tested in the sensitivity analyses that impacted the diesel reference system was the diesel fuel consumption requirement. Results from this analysis are presented separately in Table 23.

Table 20. Results of the Global Warming Potential (GWP) Sensitivity Analyses

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 GWP[B]	Change from Base Case GWP for Given Biodiesel Blend[C] (g CO_2e/GTK)			
					B5	B10	B20	B100
		Base case GWP (g CO_2e/GTK)			**13[D]**	**12**	**12**	**5.1**
1	Tree planting density	Low tree density	Set to low tree density with a 3m x 3m planting grid (Lele 2008b)	-1.4	0.22	0.44	0.88	4.6
		Medium tree density	Set to medium tree density with a 2.5m x 2.5m planting grid (Lele 2008b)		<0.1	0.17	0.35	1.8

Rank[A]	**Parameter Category Tested**	**Sensitivity Scenario Name**	**Sensitivity Scenario Description**	**Normalized Local Sensitivity Coefficient (S_{ij}) for B100 GWP[B]**	**Change from Base Case GWP for Given Biodiesel Blend[C] (g CO_2e/GTK)**			
					B5	**B10**	**B20**	**B100**
		Base case GWP (g CO_2e/GTK)			**13[D]**	**12**	**12**	**5.1**
2	Dry seed yield	High seed yield	Set to high end of future projections (Reinhardt et al. 2008)	-1.3	-0.13	-0.27	-0.53	-2.8
		Low seed yield	Set to low end of future projections (Reinhardt et al. 2008)		0.20	0.39	0.79	4.1
3	Biodiesel efficiency compared to diesel	Medium biodiesel efficiency decrement	Set to middle of the range of reported efficiency decrement for biodiesel blends (EPA 2008)	1.0	0.26	0.25	0.23	0.10
		High biodiesel efficiency decrement	Set to high end of the range of reported efficiency decrement for biodiesel blends (EPA 2008)		0.64	0.62	0.58	0.25
4	Diesel fuel consumption requirement	Low diesel fuel consumption	Set to low end of reported range (Indian Railways 2008)	1.0	-5.1	-5.0	-4.7	-2.0
		High diesel fuel consumption	Set to double the base case locomotive diesel fuel consumption		13	12	12	5.1
5	Seed oil content	High seed oil content	Set to high end of reported range (Jongschaap et al. 2007)	-0.94	<-0.1	<-0.1	-0.10	-0.52
		Low seed oil content	Set to low end of reported range (Lele 2008b)		<0.1	0.16	0.32	1.7
6	Jatropha oil extraction efficiency	High oil extraction efficiency	Set to high end of reported range (Achten et al. 2008)	-0.78	<-0.1	<-0.1	<-0.1	-0.34
		Medium oil extraction efficiency	Set to middle of reported range (Achten et al. 2008)		<-0.1	<-0.1	<-0.1	-0.18

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 GWP[B]	Change from Base Case GWP for Given Biodiesel Blend[C] ($g CO_2e/GTK$)			
					B5	B10	B20	B100
		Base case GWP ($g CO_2e/GTK$)			**13[D]**	**12**	**12**	**5.1**
7	Seed cake offset	No seed cake offset	Eliminates the benefits of seed cake used as fertilizer	-0.51	0.12	0.25	0.50	2.6
8	Fertilizer use	No fertilizer use	Sets the use of fertilizer to zero	0.44	-0.11	-0.21	-0.43	-2.2
		Double fertilizer use	Sets the use of fertilizer to double the base case value		0.11	0.21	0.43	2.2
9	Rainfall	No annual rainfalll	Assumes irrigation provides all water requirements	-0.34	<0.1	0.16	0.33	1.7
10	Glycerine production offset	No glycerine offset	Eliminates the benefits of the glycerine co-product offsetting synthetic glycerine production	-0.32	<0.1	0.15	0.31	1.6
11	Irrigation	Full irrigation years	Plantation is irrigated for all life cycle years	0.27	0.37	0.75	1.5	7.8
12	Plantation electricity consumption	Half plantation electricity	Sets plantation electricity to half the base case value assuming that half is already accounted for by other processes	0.20	<-0.1	<-0.1	-0.10	-0.51
		No plantation electricity	Sets plantation electricity use to zero assuming all of it is already accounted for in other processes		<-0.1	-0.10	-0.20	-1.0
13	N_2O volatilization rate	Low N_2O volatilization rate	Set to low end of reported range for volatilization rate (IPCC 2006)	0.17	<-0.1	<-0.1	-0.12	-0.60
		High N_2O volatilization rate	Set to high end of reported range for volatilization rate (Crutzen et al. 2008)		0.12	0.25	0.49	2.6

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 GWP[B]	Change from Base Case GWP for Given Biodiesel Blend[C] (g CO_2e/GTK)			
					B5	B10	B20	B100
		Base case GWP (g CO_2e/GTK)			**13[D]**	**12**	**12**	**5.1**
14	All offsets	No offsets	Benefits of offsets (glycerine production, biomass combustion, and seed cake used as fertilizer) are not included	-	0.20	0.40	0.81	4.2
15	Biomass offsets	No biomass offset	Eliminates the benefits of biomass combustion offsetting grid electricity	-	< 0.1	<0.1	<0.1	<0.1

[A] This column ranks the absolute value of B100 S_{ij} value from greatest to least.

[B] Normalized S_{ij} represents the percent change in model output per 100% percent change in an input parameter. Greater absolute S_{ij} values indicated greater model sensitivity to change in the specified input parameter.

[C] To calculate the GWP per GTK of a sensitivity scenario, sum the sensitivity “change from” value reported in these columns and the base case value.

[D] Model results, S_{ij} values, and sensitivity run differences are rounded to two significant figures as an indication of their uncertainty.

The results displayed in Table 20 identify tree planting density and dry seed yield as the two parameters with the greatest influence on the model’s GWP results for B100, followed by biodiesel efficiency and locomotive diesel fuel consumption requirement. By increasing trees per hectare and seed yield per tree, more seeds are produced from the same fertilizer and energy inputs. Even if this result accurately reflects the sensitivity of the modeled system, its relevance to an actual Jatropha plantation is less understood. There are no published data correlating plantation inputs to either plantation configuration parameters or outputs. Plantation operational energy consumption or fertilizer requirements may in fact increase as tree density or seed yield increases. Further research is needed to establish these relationships and to better define the Jatropha plantation processes.

The reason the B100 scenario results are sensitive to the diesel fuel consumption requirement is that the fuel consumption requirement of biodiesel-fueled locomotives is calculated by multiplying the diesel fuel consumption requirement by the biodiesel efficiency value. Among the system offsets considered in this study, Table 20 shows that the GWP results are more sensitive to the offset that accounts for seed cake substituting for fertilizer than to the glycerine production. The local sensitivity coefficient for the biomass combustion offset could not be determined since it is characterized by multiple input parameters. However, one can easily see that its influence is small since the difference in GWP between base case and sensitivity model runs is negligible. Interestingly, N_2O volatilization rate, which is subject to significant expert uncertainty, is the least influential single parameter tested in the sensitivity analyses on GWP. For other biofuels, this parameter has been found to be highly influential (Farrell et al. 2006). The same set of sensitivity cases as tested on GWP were evaluated for affect on NER (Table 21). As for GWP, the Jatropha biodiesel (B100) NER is shown to be most sensitive to seed yield, the locomotive diesel fuel consumption requirement, biodiesel efficiency, and tree density, in that order. The most notable result in this table can be seen by examining the column presenting the difference in B100 NER from the sensitivity case to the base case. Only the high locomotive diesel consumption requirement scenario and the scenario that requires irrigating the plantation for every year in the life cycle bring the B100 NER below one. This result suggests that the irrigation requirement for the plantation may be critical in determining if the production of biodiesel has a favorable net energy ratio.

Table 21. Net Energy Ratio (NER) Sensitivity Analyses

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 NER[B]	Change from Base Case NER for Given Biodiesel Blend[C]			
					B5	B10	B20	B100
		Base case NER			**0.81[D]**	**0.84**	**0.89**	**1.9**
1	Dry seed yield	High seed yield	Set to high end of future projections (Reinhardt et al. 2008)	1.2	0.0088	0.019	0.044	2.0
		Low seed yield	Set to low end of future projections (Reinhardt et al. 2008)		-0.013	-0.026	-0.057	-0.82
2	Diesel fuel consumption requirement	Low diesel fuel consumption	Set to low end of reported range (Indian Railways 2008)	-1.1	0.54	0.56	0.59	1.3
		High diesel fuel consumption	Set to double the base case locomotive diesel fuel consumption		-0.41	-0.42	-0.45	-0.94
3	Biodiesel efficiency compared to diesel	Medium biodiesel efficiency decrement	Set to middle of the range of reported efficiency decrement for biodiesel blends (EPA 2008)	-0.97	-0.016	-0.016	-0.017	-0.037
		High biodiesel efficiency decrement	Set to high end of the range of reported efficiency decrement for biodiesel blends (EPA 2008)		-0.039	-0.040	-0.042	-0.090

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 NER[B]	Change from Base Case NER for Given Biodiesel Blend[C]			
					B5	B10	B20	B100
		Base case NER			**0.81[D]**	**0.84**	**0.89**	**1.9**
4	Tree planting density	Low tree density	Set to low tree density with a 3m x 3m planting grid (Lele 2008b)	0.75	-0.013	-0.027	-0.060	-0.84
		Medium tree density	Set to medium tree density with a 2.5m x 2.5m planting grid (Lele 2008b)		-0.0052	-0.011	-0.024	-0.45
5	Seed oil content	High seed oil content	Set to high end of reported range (Jongschaap et al. 2007)	0.72	0.0015	0.0031	0.0071	0.18
		Low seed oil content	Set to low end of reported range (Lele 2008b)		-0.0047	-0.098	-0.022	-0.41
6	Jatropha oil extraction efficiency	High oil extraction efficiency	Set to high end of reported range (Achten et al. 2008)	0.69	<0.001	0.0020	0.0046	0.11
		Medium oil extraction efficiency	Set to middle of reported range (Achten et al. 2008)		<0.001	0.0011	0.0024	0.057
7	Fertilizer use	No fertilizer use	Sets the use of fertilizer to zero	-0.59	0.0078	0.017	0.039	1.6
		Double fertilizer use	Sets the use of fertilizer to double base case value		-0.0077	-0.016	-0.036	-0.60
8	Seed cake offset	No seed cake offset	Eliminates benefits of seed cake used as fertilizer	0.35	-0.0089	-0.019	-0.041	-0.66
9	Rainfall	No annual rainfalll	Assumes irrigation provides water requirements	0.26	-0.0058	-0.012	-0.027	-0.49
10	Glycerine production offset	No glycerine offset	Eliminates the benefits of the glycerine co-product offsetting synthetic glycerine production	0.24	-0.052	-0.011	-0.025	-0.45

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 NER[B]	Change from Base Case NER for Given Biodiesel Blend[C]			
					B5	B10	B20	B100
		Base case NER			**0.81[D]**	**0.84**	**0.89**	**1.9**
11	Plantation electricity consumption	Half plantation electricity	Sets plantation electricity to half base case value assuming half is accounted for by other processes	-0.16	0.0012	0.0026	0.0060	0.15
		No plantation electricity	Sets plantation electricity use to zero assuming it is accounted for in other processes		0.0025	0.0052	0.012	0.32
12	Irrigation	Full irrigation years	Plantation is irrigated for all life cycle years	-0.11	-0.026	-0.053	-0.11	-1.2
13	N_2O volatilization rate	Low N_2O volatilization rate	Set to low end of reported range for volatilization rate (IPCC 2006)	0.0	0.0	0.0	0.0	0.0
		High N_2O volatilization rate	Set to high end of reported range for volatilization rate (Crutzen et al. 2008)		0.0	0.0	0.0	0.0
14	All offsets	No offsets	Benefits of offsets (glycerine production, biomass combustion, and seed cake used as fertilizer) are not included		-0.014	-0.029	-0.064	-0.87
15	Biomass offsets	No biomass offset	Eliminates the benefits of biomass combustion offsetting grid electricity		0.0	0.0	0.0	-0.01

[A] This column ranks the absolute value of B100 S_{ij} value from greatest to least.

[B] Normalized S_{ij} represents the percent change in model output per 100% percent change in an input parameter. Greater absolute S_{ij} values indicated greater model sensitivity to change in the specified input parameter.

[C] To calculate the NER of a sensitivity scenario, sum the sensitivity "change from" value reported in these columns and the base case value.

[D] Model results, S_{ij} values, and sensitivity run differences are rounded to two significant figures as an indication of their uncertainty.

As shown in the petroleum consumption results in Table 22, this outcome is most sensitive to tree density, seed yield, and seed oil content, all with absolute S_{ij} values greater than one. These results highlight that most of the petroleum consumption during the production of B100 occurs during plantation maintenance and operation activities.

Table 22. Petroleum Consumption Sensitivity Analyses

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 Petroleum Consumption[B]	Change from Base Case Petroleum Consumption for Given Biodiesel Blend[C] (g crude oil/GTK)			
					B5	B10	B20	B100
		Base case petroleum consumption (g crude oil/ GTK)			**4.0[D]**	**3.8**	**3.5**	**0.58**
1	Tree planting density	Low tree density	Set to low tree density with a 3m x 3m planting grid (Lele 2008b)	-1.7	0.032	0.065	0.13	0.68
		Medium tree density	Set to medium tree density with a 2.5m x 2.5m planting grid (Lele 2008b)		0.013	0.025	0.051	0.27
2	Dry seed yield	High seed yield	Set to high end of future projections (Reinhardt et al. 2008)	-1.5	-18	-35	-71	-370
		Low seed yield	Set to low end of future projections (Reinhardt et al. 2008)		26	52	100	540
3	Seed oil content	High seed oil content	Set to high end of reported range (Jongschaap et al. 2007)	-1.2	<0.01	<-0.01	-0.015	-0.077
		Low seed oil content	Set to low end of reported range (Lele 2008b)		0.012	0.024	0.048	0.25

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 Petroleum Consumption[B]	Change from Base Case Petroleum Consumption for Given Biodiesel Blend[C] (g crude oil/GTK)			
					B5	**B10**	**B20**	**B100**
		Base case petroleum consumption (g crude oil/ GTK)			**4.0[D]**	**3.8**	**3.5**	**0.58**
4	Biodiesel efficiency compared to diesel	Medium biodiesel efficiency decrement	Set to middle of the range of reported efficiency decrement for biodiesel blends (EPA 2008)	1.0	72	68	61	0.012
		High biodiesel efficiency decrement	Set to high end of the range of reported efficiency decrement for biodiesel blends (EPA 2008)		180	170	150	0.029
5	Diesel fuel consumption requirement	Low diesel fuel consumption	Set to low end of reported range (Indian Railways 2008)	1.0	-1600	-1500	-1400	-230
		High diesel fuel consumption	Set to double the base case locomotive diesel fuel consumption		3900	3800	3400	570
6	Jatropha oil extraction efficiency	High oil extraction efficiency	Set to high end of reported range (Achten et al. 2008)	-0.99	<-0.01	<-0.01	-0.010	-0.050
		Medium oil extraction efficiency	Set to middle of reported range (Achten et al. 2008)		<-0.01	<-0.01	<-0.01	-0.026
7	Seed cake offset	No seed cake offset	Eliminates benefits of seed cake used as fertilizer	-0.45	0.012	0.025	0.050	0.26
8	Fertilizer use	No fertilizer use	Sets use of fertilizer to zero	0.43	-12	-24	-48	-250
		Double fertilizer use	Sets use of fertilizer to double the base case value		12	24	48	250

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 Petroleum Consumption[B]	Change from Base Case Petroleum Consumption for Given Biodiesel Blend[C] (g crude oil/GTK)			
					B5	B10	B20	B100
		Base case petroleum consumption (g crude oil/ GTK)			**4.0[D]**	**3.8**	**3.5**	**0.58**
9	Rainfall	No annual rainfall	Assumes irrigation provides all water requirements	-0.40	0.011	0.023	0.045	0.24
10	Glycerine production offset	No glycerine offset	Eliminates benefits of glycerine co-product offsetting synthetic glycerine production	-0.37	0.010	0.021	0.042	0.22
11	Irrigation	Full irrigation years	Plantation is irrigated for all life cycle years	0.33	0.052	0.10	0.21	1.1
12	Plantation electricity consumption	Half plantation electricity	Sets plantation electricity to half the base case value assuming half is accounted for by other processes	0.02	<-0.01	<-0.01	<-0.01	-0.01
		No plantation electricity	Sets plantation electricity use to zero assuming it is accounted for in other processes		<-0.01	<-0.01	<-0.01	-0.010
13	N_2O volatilization rate	Low N_2O volatilization rate	Set to low end of range for volatilization rate (IPCC 2006)	0.00	0.00	0.00	0.00	0.00
		High N_2O volatilization rate	Set to high end of range for volatilization rate (Crutzen et al. 2008)	--	0.00	0.00	0.00	0.00

Rank[A]	Parameter Category Tested	Sensitivity Scenario Name	Sensitivity Scenario Description	Normalized Local Sensitivity Coefficient (S_{ij}) for B100 Petroleum Consumption[B]	Change from Base Case Petroleum Consumption for Given Biodiesel Blend[C] (g crude oil/GTK)			
					B5	B10	B20	B100
		Base case petroleum consumption (g crude oil/ GTK)			**4.0[D]**	**3.8**	**3.5**	**0.58**
14	All offsets	No offsets	Benefits of offsets (glycerine production, biomass combustion, seed cake used as fertilizer) are not included	--	0.023	0.046	0.092	0.48
15	Biomass offsets	No biomass offset	Eliminates benefits of biomass combustion offsetting grid electricity	--	< 0.01	< 0.01	< 0.01	< 0.01

[A] This column ranks the absolute value of B100 S_{ij} value from greatest to least.

[B] Normalized S_{ij} represents the percent change in model output per 100% percent change in an input parameter. Greater absolute S_{ij} values indicated greater model sensitivity to change in the specified input parameter.

[C] To calculate the petroleum consumption per GTK of a sensitivity scenario, sum the sensitivity “change from” value reported in these columns and the base case value.

[D] Model results, S_{ij} values, and sensitivity run differences are rounded to two significant figures as an indication of their uncertainty.

The sensitivity analyses of this study primarily evaluate the biodiesel system. The sensitivity of the diesel base case is only tested by varying the locomotive diesel fuel consumption requirement. The local sensitivity coefficients for GWP, NER, and petroleum consumption are shown in Table 23 to yield changes in model ouputs that are approximately proportionate to the change in the diesel fuel consumption requirement parameter.

Table 23. Local Sensitivity of Diesel Model Output

Sensitivity Scenario	Diesel Global Warming Potential S_{ij}	Diesel Net Energy Ratio S_{ij}	Diesel Petroleum Consumption S_{ij}
Locomotive diesel fuel consumption requirement	1.0	-1.1	1.0

As a final sensitivity check on the model results, best and worst case sensitivity scenarios were developed by combining together 35 model parameters set to their optimum (best) and least advantageous (worst) values, respectively; the results are presented in Table 24. Details of the values assigned to each of the 35 parameters are reported in Appendix C. The table shows the base case value along with the best and worst case bounding values for each model output. Note that the scenarios modeled in the best/worst cases are unlikely to be seen in real world conditions but are presented as bounding scenarios. Results to note are that the best case scenario for B100 NER results in net negative energy inputs as the life cycle offsets are greater than the required inputs. This unlikely scenario leads to the large negative number in the table. Also, the best case scenario for GWP and petroleum consumption yield net negative life cycle values for B100.

Table 24. Best-/Worst-Case Scenario Analysis

Metric	Units	Case	Diesel	B5	B10	B20	B100
Global Warming Potential Intensity	g CO_2e per GTK	**BASE**	**13**	**12**	**12**	**12**	**5.1**
		Best	7.9	7.5	7.1	6.2	-1.3
		Worst	26	47	66	100	430
Net Energy Ratio	NER	**BASE**	**0.79**	**0.81**	**0.84**	**0.89**	**1.9**
		Best	1.3	1.4	1.5	1.7	-8.5
		Worst	0.40	0.23	0.16	0.10	0.026
Petroleum Consumption Intensity	g crude oil per GTK	**BASE**	**4.2**	**4.0**	**3.8**	**3.5**	**0.58**
		Best	2.5	2.3	2.2	2.0	-0.15
		Worst	52	67	79	100	310

7.0 Discussion

This section reviews several critical aspects of this study that are important to keep in mind when interpreting its results. This study has significant limitations that constrain the generalizability and certainty of its findings.

7.1 Study Limitations

The study faced several limitations that constrain the interpretation and certainty of the results presented in this report. Categories of limitations include technological and geographical scope, methods, data availability, metrics evaluated, and state of the science. Each category of limitation is discussed in further detail in the following sections.

7.1.1 Uncertainty Analysis

Data limitations prevented a thorough evaluation of uncertainty. Many important parameters have not been studied in enough detail to enable proper characterization of variability and uncertainty, to identify causal relationships between parameters, and, in some cases, to even establish plausible value ranges for the parameters under a given scenario. While investigating the sensitivity of our model to alternative input parameter values provides useful insight to the system studied and our model of it, plausible and internally consistent sets of alternative parameter estimates need to be developed to provide reasonable boundaries to the model output estimates. Our best and worst case scenarios are not internally consistent, and therefore only provide an estimate of the extreme boundary which we would not expect to occur. Due to the limited data available to define base case parameter values and to develop internally consistent modeling scenarios, considerable uncertainty remains in our estimates of parameter inputs and model outputs.

7.1.2 Technological and Geographic Scope

- The study focuses on locomotive transport as the ultimate end use of the biodiesel. A much larger market for biodiesel exists in the road transport sector. Much of the analysis of this study is applicable to road transport, though adjustments for the ultimate end use of the product would need to be made.

- In order to produce a coherent narrative, the study’s base case focused on specific locations in India, with sensitivity analysis used to explore the impact of plausible, alternative parameter estimates. It is unclear how well the results of this study can be generalized to Jatropha biodiesel production in other regions of India, or of the world. This limitation is largely due to a paucity of data that accurately relates Jatropha seed and oil yield to specified environmental conditions and levels of artificial assistance through fertilization and irrigation.

- The scope of this study is also limited in terms of the technologies evaluated. Upon the advice of the IOC, this study focused on large-scale methods of Jatropha cultivation and biodiesel production technologies. This study did not evaluate alternative methods and technologies; therefore, its results should not be considered reflective of the impacts or benefits of alternative systems.

- Clearly, the results of this study are not applicable to biodiesel production systems using other feedstocks nor to other biofuels as cultivation and processing requirements can vary greatly amongst biofuels and feedstocks.

7.1.3 Modeling Approach

- This study is prospective in that it attempts to evaluate biodiesel production systems as they would be built in the near future in India. It is not based on data collected from an already established system. Consequently, it is unclear how well the narrative evaluated actually describes systems as they will be built.

- This analysis was conducted using secondary data collected from many disparate sources. No primary research was conducted to better establish site-specific data parameters. Thus, it is not clear how well the parameter values evaluated in this study are applicable to the specific site selected, nor how internally consistent they are in describing a biodiesel production system as it would be built.

7.1.4 Data Availability and Certainty

- India has not yet developed a comprehensive LCI database covering the production of basic materials, energy and fuels, transportation, and the ultimate disposal of goods based on India-specific conditions. As a result, many life cycle stages required inputs from better established European databases, particularly to obtain infrastructure impacts. A key limitation of this study is that the authors were required to use non India-specific data to represent Indian processes where data was lacking. Specific examples of substituting non-Indian data included diesel refining, truck transport, and crude oil extraction. It is unclear how relevant the non-Indian data is to Indian processes, and also how much influence on the final results the use of Indian-specific data would have.

- Limited data was available for India-specific waste generation and end-of-life scenarios for both the biodiesel and diesel pathways. Facing this limitation, this study omitted impacts associated with the ultimate disposal of process waste. Inclusion of these impacts would likely not affect the conclusions of this study since additional GHG emissions, petroleum use, or energy demand for waste disposal in India is likely very small relative to the processes already included.

7.1.5 Metrics Evaluated

- The full extent of the environmental impacts of switching from conventional diesel to Jatropha biodiesel is not fully represented by the metrics evaluated in this study. Other impacts such as hazardous waste generated; pollutant emissions to air, water, and soil, land use changes; and socio-economic impacts are also important consideration in a full impact assessment. However, adequate data was not available to include an analysis of these metrics in this study.

7.1.6 State of the Science

- Biodiesel cultivation and production systems in India are still immature. This study represents the current state of knowledge and data availability. Changes to the systems and improvements in the quality and quantity of data available are expected as the technologies and procedures mature. A reassessment using new data as they become available may alter the findings of this study.

7.2 Generalizability of Results

The previous section discussed limits to how applicable the results of this study are to other locations, technologies, etc. Nevertheless, there are also reasons to believe that the results of this study might be indicative to how other systems would perform. For instance, while this study was designed to address Indian-specific conditions, the results may be generalizable to other locations because much of the input data either originated from studies of other regions (e.g., use of Ecoinvent datasets describing European systems) or are based on parameters whose value was not made site-specific (e.g., N_2O volatilization rate). Furthermore, some parameter values reflect the crude state of the science more than they do a detailed reflection of site-appropriate values, (e.g., fertilization rates).

Nonetheless, the relative results from this study are most easily generalized to other regions than the absolute results. For instance, the rankings of which parameters are most influential to the model outcomes are likely applicable to other situations.

7.3 Interpretation of Sensitivity Analyses

As many of the model's input parameters are uncertain, the sensitivity analyses are most useful in focusing future research on the parameters most likely to impact study results and policy decisions. To evaluate the net GHG impacts of proposed biodiesel production from Jatropha cultivation, assumptions related to tree density, dry seed yield, and seed oil content are the most critical. These three parameters are also some of the most influential for determining NER and petroleum displacement, along with diesel and biodiesel fuel efficiency . Tree density, dry seed yield, and seed oil content directly determine the amount of Jatropha oil that can be extracted from one hectare of land. As these values are improved through optimal cultivation, required inputs of fertilizer and irrigation water per liter of Jatropha oil extracted decrease leading to lower resource use impacts throughout the system. Optimal tree density varies with the quality of the land while dry seed yield and seed oil content are functions of not only land quality and location but also of human inputs such as fertilizer and irrigation water. Unfortunately, the current literature does not contain correlated sets of data that accurately predict dry seed yield and seed oil content given a set of agro-climatic conditions and a selected tree density. Further research is needed in this area to improve the predictive quality of models that evaluate systems with Jatropha cultivation.

7.4 Displaced Petroleum and Net GHG Emission Reduction Projections from Utilization of Jatropha Biodiesel in Indian Railways

IR freight and passenger trains travel in excess of 500 billion GTK per year (Kathpal 2008). If all IR trains were to switch to B20 instead of petroleum diesel, the potential savings in GHG emissions and petroleum consumption are great. Considering the base case results produced in this study, a switch to B20 would reduce IR's annual net GHG emissions by 750,000 $mtCO_2e$ per year and petroleum consumption by 350,000 tonnes of crude oil per year. The potential GHG emission reductions represent 0.04% of India's total GHG emissions from 2005 (Pew Center on Global Climate Change 2008) while the potential petroleum displacement represents 0.3% of India's 2006 total annual crude oil consumption and is in line with IR's own estimate of potential crude oil savings per year (Kathpal 2008).

7.5 Comparison of Results to Other Studies

The results of LCA studies can be difficult to compare directly due to differences in selection of system boundaries, site-specific conditions, different functional units, and other variations in modeling assumptions. However, attempts were made to compare the results of this study to the two most comprehensive Jatropha biodiesel LCAs previously published: Reinhardt et al. (2007) and Prueksakorn and Gheewala (2008).

Reinhardt and colleagues evaluated biodiesel use in passenger cars as opposed to locomotives and expressed the results on a per hectare-year (ha-yr) basis as opposed to per gross tonne-kilometer transported. Our results were converted to their functional unit by dividing the net life cycle GHG emissions (over the entire system lifetime) and energy consumption by the 20-year life cycle and the 50,000 hectare study plantation size. Their study calculated the net GHG emissions from the conventional diesel reference system as approximately 1,200 kg CO_2e per ha-yr. The diesel reference system for this study estimates the net GHG emissions as 26 kg CO_2e per ha-yr. Reinhardt calculates net GHG emissions from B100 production and use of approximately 1,100 kg CO_2e per ha-yr, an 8.3% reduction from the diesel reference system.. In contrast, this study calculates B100 net GHG emissions of 10 kg CO_2e per ha-yr, a 62% reduction from our reference system. For net energy, Reinhardt and colleagues calculated energy consumption of 16 GJ per ha-yr for the diesel reference system compared with 8 GJ per ha-yr for the B100 case, a 50% reduction. In comparison, this study calculates net energy consumption as 0.7 GJ per ha-yr for the diesel reference system compared with 0.5 GJ per ha-yr for the B100 case, a 32% reduction.

It is difficult to identify the precise reasons for the discrepancy between this study's results and those of Reinhardt et al. Possibilities include use of a proprietary data set by Reinhardt, Reinhardt's inclusion of pre-existing vegetation stocks in the calculation, and Reinhardt's assigning of a CO_2 emission factor to biodiesel combustion in the vehicle as opposed to zeroing out that factor. Further investigation into the source(s) of the discrepancy is a high priority for future research on this topic.

Prueksakorn and Gheewala reported NERs for Jatropha biodiesel production in Thailand ranging from 1.93 (worst case) to 11.99 (best case) with an average of 6.03 when seed cake was combusted as fuel stock, and 0.53 (worst case) to 2.70 (best case) with an average of 1.42 when co-product benefits were omitted. They cited co-product yield assumptions, fertilizer and irrigation requirements, and transportation distances as having the greatest impact on NER. This study calculated a base case NER (including offsets) for Jatropha-based B100 in India of 1.9. This result is slightly below the low end of Prueksakorn and Gheewala's NER range with offsets but above the average of their no offset range. While closer than the comparison of this study's results to Reinhardt's, there is still a discrepancy with the results of Prueksakorn and Gheewala. Again, it is difficult to determine exact reasons that account for the discrepancy.

A favorable comparison of this study's petroleum displacement results to those made by IR was made in the sensitivity analyses section of this report.

8.0 Conclusions

With India's transportation sector relying heavily on imported petroleum-based fuels, the Planning Commission of India and the Indian government recommended the increased use of blended biodiesel in transportation fleets, identifying Jatropha as a potentially important biomass feedstock. The Indian Oil Corporation and Indian Railways are collaborating to increase the use of biodiesel blends in Indian locomotives with blends of up to B20, aiming to reduce GHG emissions and decrease petroleum consumption. To help evaluate the potential for Jatropha-based biodiesel in achieving sustainability and energy security goals, this study examines the life cycle, net GHG emission, net energy ratio, and petroleum displacement impacts of integrating Jatropha-based biodiesel into locomotive operations in India. In addition, this study identifies the parameters that have the greatest impact on the sustainability of the system.

This study was designed to evaluate Jatropha cultivation, biodiesel production, and biodiesel blend use under Indian conditions to the greatest degree possible. However, the lessons learned from this study also will benefit other countries, including the United States. Petroleum-based transportation fuels are traded on an international market. Reduction in consumption anywhere in the world, but particularly in countries with growing demand like India, will reduce pressure on world petroleum demand and, ultimately, prices. While countries like India are at the leading edge of research on alternative transportation fuel feedstocks such as Jatropha, the plant also may be a suitable biofuel feedstock for the United States (e.g., in Florida) (Layden 2008), and lessons learned from the Indian context can be applied to the United States. Finally, to the extent that this study can help optimize the Jatropha biodiesel production process and reduce greenhouse gas emissions, there are worldwide benefits for climate change mitigation.

For the base case considered, this study has found that a blend of B20 would reduce GHG emissions by 1.5 g CO_2e per GTK (12%) and displace 0.69 g crude oil per GTK (17%) while increasing the net energy ratio by 0.10 (13%). These results suggest that the Jatropha-based biodiesel system under consideration could potentially achieve the identified sustainability goals of reducing net GHG emissions, displacing petroleum consumption, and improving the net energy ratio. Through the use of sensitivity analyses, this study also identified tree density, dry seed yield, and seed oil content as critical parameters that influence the system's overall sustainability.

It is important to note, however, not only that the data used to produce the results of this study are uncertain, but also that the potential impacts of direct and indirect land-use change, particularly to net GHG emissions, were not considered. Therefore, it is advisable to interpret the findings of this report as indicative of the direction and scale of impacts relative to the diesel reference system rather than accurate point estimates of the magnitude of impacts. Because agro-climatic conditions and optimal biodiesel feedstocks vary widely throughout the world, no one study can definitively determine the sustainability of biofuels in all scenarios. However, this study's results, along with the results of other reviewed studies, suggest that under plausible growing conditions and production scenarios, Jatropha-based biodiesel shows promise for helping India and possibly other nations achieve their GHG emission reduction and petroleum-displacement goals.

8.1 Research Recommendations

Based on the results of this study and the influence of uncertain individual parameters as shown in the sensitivity analyses, the following seven research topics are recommended.

1) The accuracy of the results produced by this study was hampered by the lack of prior, quality research on the requirements and performance of Jatropha cultivation systems. When considering cultivation parameters individually, knowledge gaps exist; but more importantly, there are major knowledge gaps regarding how individual parameters relate to each other across a range of agro-climatic conditions. The following are specific, key parameters that should be the focus of future research efforts, though not to the exclusion of consideration of other parameters.
    a. The individual parameters with the most influence on all three metrics evaluated in this study are seed yield, tree density, and seed oil content. They each also have considerable influence on the economic viability of Jatropha cultivation and biodiesel production, but more research is needed to better relate these parameters to site-specific, agro-climatic conditions. However, these parameters should not be considered in isolation because, for example, the sustainability benefits of increased yield are mitigated by any resulting requirements for increased fertilization and irrigation. Once robust data sets are completed, these trade-offs should be evaluated on a life cycle basis.

    b. The amount of irrigation has an influence on whether the substitution of diesel fuel with blended biodiesel results in a net increase or decrease in GHG emissions. Quality irrigation data are lacking in the literature. Research is needed to define how much irrigation is required based on site-specific, agro-climate conditions; how many years irrigation is required after plantation establishment; and what level of rainfall is necessary to no longer require irrigation.

    c. Fertilizer use impacts all three metrics evaluated in this study. The literature lacks quality data on required fertilizer levels and application rates for site-specific conditions and also lacks quality studies that correlate fertilizer-use levels to anticipated seed yields and N_2O volatilization rates. Future research should target these gaps.

2) Future research that would produce data sets and models that could predict seed yield, oil content, fertilizer use, and irrigation requirements based on specific agro-climatic conditions of a proposed Jatropha plantation site would be especially useful. This information would help analysts, project developers, and decision makers accurately forecast the economic and environmental viability of a proposed project. Such predictive models should include the ability to assess and track changes in land use and carbon stocks on specific land parcels, which could determine the potential impacts of direct land use change on net GHG emissions. This research would have direct benefits to other countries, including the United States, in defining how and where Jatropha should be used to produce biodiesel.

3) Viable scenarios for the use of co-products produced from all Jatropha cultivation activities and biodiesel production processes need to be developed for India-specific economic and technological conditions. Removing the offsets in this study changes GHG emissions from net reductions to net increases and, therefore, changes the overall conclusions of the study's GHG emission analysis. Future research should aim to better characterize issues such as: the glycerine co-product yield and the robustness of localized markets; the feasibility of distributed electricity generation using seed husks and the potential for local heat demand to make combined heat and power (or simply combustion for heat production) viable alternatives; and to document the amount of synthetic fertilizer that Jatropha seed cake actually offsets when the practices of farmers are monitored.

4) The impacts of indirect land-use change have been shown to potentially significantly alter the net GHG balance of biofuels (Searchinger et al. 2008). If lands previously used to produce useful products were to be transformed to Jatropha, it is possible (partly depending on the elasticity of demand for those products) that new lands would be sought to fill the previous demand. The net GHG emissions from transforming those other lands should be included on the balance sheet of Jatropha biodiesel production. While the concept of indirect land-use change is logical, the determination of its net GHG emissions that are attributable to an individual decision to plant biofuel feedstock is currently both difficult and highly uncertain, leading to considerable controversy. The science is immature in this area and urgently needs attention because, for example, legislation in the United States (EISA 2008) already demands that regulatory decisions be based on consideration of this effect.

5) The accuracy of this study's comparison between biodiesel blends and petroleum diesel would be greatly improved if India-specific data were available on petroleum refining. Future Indian LCAs would be improved with the development of Indian-specific inventory modules for energy and material production to decrease the reliance on European data.

6) An examination of impacts on net GHG and petroleum displacement for use of Jatropha-based biodiesel in the road sector (automobiles, trucks, and buses) would be a useful extension to this study. The Indian biofuels mandate applies to all transportation fuels, not just the rail sector, making an evaluation of the road sector an important area for future research.

7) Examining Jatropha biodiesel production systems, or potential ones, in the United States (in Florida, for example) (Layden 2008) also would be a useful extension to this study. Potential use of co-products; origin; and manufacturing impacts of cultivation inputs, scale of operations, and many other attributes of the Jatropha biodiesel production system could differ, and perhaps significantly alter the results found here for India. Research in this context is justified even though results of the sensitivity analyses in this study could provide indications of the scale of impacts to be expected in other locations.

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Appendices

Appendix A – Details About the SimaPro Model and Base Case Model Parameter Values

Appendix A contains tables detailing the contents of the custom modules developed to construct the SimaPro model and the base case model parameter values. These custom modules were introduced in the Base Case Scenario Section of the main body of the report. Tables A-1 and A-2 list all relevant parameters in the study along with their abbreviations, values, units and descriptions to facilitate understanding of the custom modules. The parameters are listed in alphabetical order by abbreviation, with parameters that have specific values assigned listed first and those with values that are calculated based on formulas calling other parameters listed second. Tables A-3 through A-14 show how the custom modules are coded.

Table A-1. List of Input Parameters that Have Assigned Values

Input Parameters	Value	Description
annual_rain	1,385	mm, average rainfall in Raipur province, India, the plantation's assumed location
bio_blend_elec	0.00086	kWh/kg, energy required to blend ethanol with gasoline, assuming similar requirement for blending biodiesel with diesel
bio_elec_eff	0.25	Assumed efficiency of converting solid biofuel to electricity
bio_fuel_switch	1	Set value to "1" if analyzing blended biodiesel, set value to "0" if analyzing diesel operation
bio_plant_life	50	Years, lifetime of biodiesel transesterification facility in Ecoinvent database
bio_plant_prod	63	MT/day, daily production of biodiesel in Ecoinvent database
biodiesel_blend	0.05	Biodiesel / (biodiesel + diesel) for defining the blending ratio of the biodiesel mix.
biodiesel_dist	25	km, distance biodiesel must be transported from the production facility in Raipur to rail depots in Bhilai where blending occurs
biodiesel_eff	1	Fuel consumption of B5 compared with conventional diesel, "1" indicates no significant change in volumetric fuel consumption as indicated by Indian Railway studies
cal_val_bio	39,500	kJ/kg, calorific value of biodiesel produced from Jatropha
cal_val_diesel	42,000	kJ/kg, calorific value of diesel (IOC)
cal_val_husk	4.6	MJ/m^3, calorific value of the JCL husk if used as a feedstock for gasification
cal_val_kernel	30.4	MJ/kg, calorific value of the JCL kernel if it is combusted
cal_val_scake	18.2	MJ/kg, calorific value of Jatropha seed cake if combusted
cal_val_shell	19.4	MJ/kg, calorific value of the JCL shell if it is combusted
chem_per_yr	0	Assumption is that application of protective chemicals occurs this many times per year. We are assuming that no protective chemicals are applied.
CO_2_bio	0	kg CO2 / liter of B100 combusted. Zero value assumes that carbon sequestered during growth of plant is offset by combustion for no net carbon emissions
CO_2_dies	2.68	kg CO_2 / liter of diesel combusted (from The Climate Registry Data)
crude_foreign	0.75	Fraction of IOC crude oil from foreign sources (Middle East and Nigeria)
crude_offshore	1	Mass fraction of Indian domestic crude oil produced offshore

Input Parameters	Value	Description
crude_oil_trans	600	km, approximate distance crude oil travels via rail between Vizag crude oil terminal on the east coast of Andhra Pradesh to the Bhilai rail depots near Raipur
degum_elec	1.69	kWh electricity required to degum the oil extracted from 1 MT of Jatropha seeds
degum_steam	16,354	kCal steam required to degum the oil extracted from 1 MT of Jatropha seeds
diesel_fuel_con	4.38	Liters diesel / 1000 gross tonne kilometers transported via locomotive
diesel_fuel_cul	86	l/ha-yr of diesel used for cultivation
diesel_loss	0.006	Grams diesel lost at filling
domestic_offsh	1	Fraction of domestic crude from offshore field (country-wide average is 66%)
domestic_onsh	0	Fraction of domestic crude produced onshore (country-wide average is 34%)
elec_gen_coal	0.7	Fraction of Indian electricity generated from coal
elec_gen_hydro	0.15	Fraction of Indian electricity generated from hydro power
elec_gen_ng	0.12	Fraction of Indian electricity generated from natural gas
elec_gen_nuclea	0.02	Fraction of Indian electricity generated from nuclear power
elec_gen_renew	0.01	Fraction of Indian electricity generated from renewables
elec_TD_loss	0.32	Fraction of Indian electricity generated that is lost due to transmission and distribution losses
elec_tran_dist	1,000	km, length of electricity transmission infrastructure included in inventory, can be checked for relevance with sensitivity
fert_app_num	2	Fertilizer applications per year, one each at the beginning and end of the rainy seasons
fert_switch	1	"1" uses Reinhardt numbers, "0" uses Lele, IOC numbers for fertilizer use. Default is using Reinhardt's values.
foreign_advan	0.03	Fraction of foreign crude produced using advanced recovery techniques
foreign_offshor	0.2	Fraction of foreign crude produced in offshore fields
foreign_onshore	0.77	Fraction of foreign oil produced in onshore fields
frac_mid_east	1	Assumed fraction of foreign crude oil arriving from Middle East
frac_stem	0.67	Mass fraction of Jatropha biomass comprised of stems
fuel_econ_inrl	2.63	liters/1,000 gross tonne kilometers, average fuel econ for rail cargo transport in India
full_seed_yield	3	Years estimated for trees to achieve full seed yield, supplied by Indian Oil Corporation (IOC)
glyc_cool_wat	17	m^3 cooling water required to purify 100 kg glycerine
glyc_elec	2	kWh electricity required to purify 100 kg glycerine
glyc_energy	25.6	MJ/kg, energy content of glycerine
glyc_feed	100	kg, raw glycerine feed for glycerine purification
glyc_steam	230	kg steam required to purify 100 kg glycerine
glyc_yield	0.079	Fraction yield of glycerine during jatropha oil conversion to biodiesel
glycerol_yield	0.97	Fraction of glycerol produced during glycerine purification
harvest_per_yr	1	Assumes one harvest per year at given seed yield per hectare
husk_energy_con	15.5	MJ/kg energy content of husks
irr_years	3	Years, number of years irrigation is required
jat_husk_wt	0.375	Mass fraction of jatropha husk weight compared with jatropha fruit
jat_oil_grav	0.92	kg/liter, specific gravity of crude jatropha oil

Input Parameters	Value	Description
jatoil_extract	63	MT/day, daily production of extracted oil in Ecoinvent database
jatoil_life	50	Years, lifetime of oil extraction facility in Ecoinvent database
K2O_fert_req	89	kg/ha-yr requirement for K2O fertilizer
life_cycle_yr	20	Years, defines the lifetime of the study being analyzed
loco_gtk	1E+08	Gross tonne kilometers per locomotive - year (based on IR averaging 400 billion gtk transported each year with 4000 locomotives)
mat_KCL_app	80	Grams KCl / tree per application for mature Jatropha plantation
mat_KNit_app	25	Grams K Nitrate per tree per application for mature Jatropha plantation
mat_SSP_app	100	Grams single super phospate per tree per application for mature Jatropha plantation
mat_urea_app	150	Grams urea per tree per application for mature Jatropha plantation
mature_biomass	8.5	kg biomass per tree
N_fert_req	81	kg/ha-yr requirement for N fertilizer
N_2O_release	0.01	Fraction of nitrogen contained in fertilizer that is released to the air as N_2O, fraction is on a mass basis
oil_content	0.35	Percent oil content of seed, weight oil per weight total seed
oil_domestic	3,200	km, transport distance for domestic oil between Bombay High and VIZAG per sea route
oil_extract_cap	200	MT oil/day, assumed capacity of the oil extraction unit based on IOC guidance and assumption that extraction unit will meet more than just the IOC plantation seed demand
oil_mid_east	7,000	km, approximate distance traveled for transport of crude oil by tanker from Middle East to Vizag
oil_Nigeria	13,000	km, approximate distance traveled for transport of crude oil by tanker from Nigeria to Salaya
oil_tanker_CO_2	4.9	Grams CO_2 per tonne-km transported by transoceanic oil tanker
P2O5_fert_req	31	kg/ha-yr requirement for P2O5 fertilizer
plant_manure	4.5	kg manure per planting hole (Lele only, not mentioned by IOC)
plant_MOP	16	Grams of muriate of potash (common name for KCl) per planting hole
plant_SSP	120	Grams single super phosphate per planting hole
plant_urea	20	Grams urea per planting hole (IOC estimate, comparable to Lele estimates)
plantation_elec	2,431,620	kWh electricity per yr required to operate a 10,000 hectare plantation
plantation_tot	50,000	Total hectares, to be split into five 10,000 hectare units for management
plantation_unit	10,000	Hectares, used as manageable unit based on available data
poly_bag	1	polyethylene bag per seedling
poly_eth_bag	7	Grams, weight of LLDPE bag for seedling cultivation
rail_CO_2	20.7	Grams CO_2 per tonne-km transported for railcar transport
reinhardt_dens	1,667	Assumed trees per hectare for Reinhardt's calculations
required_rain	2,500	mm/yr, amount of rain required to avoid irrigation
seed_cake_K	0.1	Fraction potassium of fertilizer replaced by seed cake
seed_cake_N	0.4	Fraction Nitrogen of fertilizer replaced by seed cake
seed_cake_P	0.2	Fraction phosphorus of fertilizer replaced by seed cake

Input Parameters	Value	Description
seed_cake_rep	0.15	kg of NPK (40:20:10) fertilizer replaced by 1 kg jatropha seed cake
seed_drying	0	Energy used to dry seeds (assumed 0 at this point for sun drying, could also use an oven)
seed_husk_yield	1,429	Yield of kg sun dried husk per ha-yr
seed_survive	0.8	Fraction of planted seedlings that survive
seed_tran_dist	50	km, transport distance for Jatropha seeds to processing facility, seed transport via truck
seed_yield_tot	2,382	Yield kg sun dried seeds per ha-yr
seed_yield_tree	1.5	kilograms dry seed per tree, assumed seed yield based on India Planning Commission (IPC) estimates
solv_extract_n	0.91	Percent, extraction efficiency for solvent extraction, weight oil extracted per weight oil available in seed
solvent_elec	55	kWh electricity per tonne of seed required for continuous solvent extraction
solvent_hexane	4	kg hexane-n per tonne of seed required for continuous solvent extraction
solvent_recycle	0.99	Mass fraction of hexane recycled during solvent extraction
solvent_steam	280	kg steam per tonne of seed required for continuous solvent extraction
solvent_trans	0	Tonne-km transport for oil extracted at solvent extraction facility to reach biodiesel transesterification facility. Assumption is that the oil extraction and transesterification units are co-located
solvent_water	12	m^3 water per tonne of seed required for continuous solvent extraction (consumed and discharged to sewer)
spec_ener_leaf	3,624	kJ/kg specific energy of Jatropha leaf
spec_ener_stem	3,932	kJ/kg specific energy of jatropha stem
spec_grav_biod	0.88	kg/L, specific energy of biodiesel; within reasonable range, more specific IOC data would be useful
spec_grav_dies	0.84	kg/L, specific energy of diesel; within reasonable range, more specific IOC data would be useful
transest_cap	100,000	MT biodiesel produced per year
transest_eff	0.95	Conversion efficiency of jatropha oil to biodiesel
transest_elect	36	kWh electricity required per tonne of biodiesel produced
transest_KOH	18	kg KOH required per tonne of biodiesel produced
transest_meth	110	kg methanol required per tonne of biodiesel produced
transest_minacd	6	kg mineral acid required per tonne of biodiesel produced
transest_steam	660	kg steam required per tonne of biodiesel produced
transest_water	55	m^3 circulating water required (not consumed)
tree_density	2,500	Trees/hectare, initial plantation density of Jatropha trees
truck_CO_2	51.2	Grams CO_2 per tonne-km transported by lorry
yr_1_biomass	2.5	kg total biomass yield per tree in Year 1
yr_2_biomass	4.5	kg total biomass yield per tree in Year 2

Table A-2. List of Calculated Input Parameters that Have Values Determined by Formulas Based on Other Parameters

Name	Formula	Description
b5_fuel_cons	diesel_fuel_con*biodiesel_eff	Liters B5 per 1000 gross tonne kilometers transported via locomotive
bio_blend_sg	spec_grav_dies*(1-biodiesel_blend) +spec_grav_biod*biodiesel_blend	kg per liter, specific gravity of blended fuel
bio_fuel_con	biodiesel_eff*diesel_fuel_con	Liters biodiesel per 1000 gross tonne kilometers
bio_plant_piece	1/bio_prod_life	Piece of a biodiesel transesterification plant allocated to each tonne of biodiesel produced based on Ecoinvent numbers. This value is used to represent the infrastructure contribution of the transesterification facility in the Indian case study
bio_prod_life	bio_plant_life*bio_plant_prod*365	Lifetime biodiesel fuel production assumed in Ecoinvent inventory calculation
CO_2_biodiesel	CO_2_bio/spec_grav_biod	CO_2 emissions for biodiesel on a kg CO_2 per kg biodiesel basis
CO_2_diesel	CO_2_dies/spec_grav_dies	CO_2 emissions for diesel on a kg CO_2 per kg diesel basis
crude_assam	(1-crude_foreign)*(1-crude_offshore)	Fraction of Indian crude oil produced onshore at Assam
crude_bombay	(1-crude_foreign)*crude_offshore	Fraction of total crude oil from domestic fields (Bombay High)
crude_mid_east	crude_foreign*frac_mid_east	Fraction of total crude oil from Middle East
crude_Nigeria	crude_foreign*(1-frac_mid_east)	Fraction of total crude oil from Nigeria
crude_ocean_trn	crude_Nigeria*oil_Nigeria+crude_mid_east* oil_mid_east+crude_bombay*oil_domestic	t-km, tonne kilometer of oil tanker transport required to deliver 1 tonne of total crude oil to the Indian coastal oil terminal
frac_leaf	1-frac_stem	Mass fraction of biomass that is leaves
frac_nig	1-frac_mid_east	Assumed fraction of foreign crude oil arriving from Nigeria
husk_tot_mass	seed_husk_yield*plantation_tot*harvest_per_yr * life_cycle_yr	kg seed husks produced per plantation lifetime
jatoil_ext_life	jatoil_extract*jatoil_life*365	Lifetime oil extraction assumed in Ecoinvent inventory calculation
jatoil_plnt_pce	1/jatoil_ext_life	Piece of an oil extraction facility plant allocated to each tonne of oil extracted based on Ecoinvent numbers. This value is used to represent the infrastructure contribution of the solvent extraction facility in the Indian case study
jatoil_required	1/transest_eff	kg jatropha oil required to produce 1 kg of biodiesel
life_biomass_el	(life_biomass_en+life_husk_en)*0.000278* bio_elec_eff	kWh electricity offset over lifetime (converted from kilojoules)
life_biomass_en	life_biomass_to*(frac_stem*spec_ener_stem+ frac_leaf*spec_ener_leaf)/1000	MJ leaf and stem energy per plantation lifetime
life_biomass_pl	yr_1_biomass+yr_2_biomass+ (mature_biomass*(life_cycle_yr-2))	Total kg biomass per plant over plantation lifetime
life_biomass_to	life_biomass_pl*tree_density*plantation_tot	kg, total biomass produced on plantation over lifetime
life_husk_en	husk_tot_mass*husk_energy_con	MJ husk energy produced per plantation lifetime

loco_bio_fuel	bio_fuel_con*bio_blend_sg	kg biodiesel blend used per 1000 gross tonne kilometer transported, locomotive
loco_dies_fuel	diesel_fuel_con*spec_grav_dies	kg diesel used per 1000 gross tonne kilometer transported, locomotive
loco_life_gtk	loco_gtk*life_cycle_yr	Lifetime gross tonne kilometer analyzed in the study
locomotive_CO_2	CO_2_diesel*(1-biodiesel_blend)+ CO_2_biodiesel*biodiesel_blend	(kg CO_2/kg fuel) Adjusted CO2 emission factor for the locomotive based on the biodiesel blend being used
N_2O_release_ioc	N_2O_release*(1-fert_switch)*urea_tot_lele	kg N_20 release under IOC fertilizer scenario
N_2O_release_rei	N_2O_release*fert_switch* (N_fert_req*plantation_tot*life_cycle_yr)	kg N_2O release in Reinhardt fertilizer scenario
N_2O_volatized	N_2O_release_rei+N_2O_release_ioc	kg N_2O volatized from N fertilizer over plantation lifetime
oil_per_hectare	seed_yield_hect/seed_required/1000	Metric tonnes (MT) of oil yield expected per hectare calculated from anticipated seed and oil yields
oil_produced_yr	oil_per_hectare*plantation_tot	MT of anticipated oil produced by the crops on the plantation and solvent extraction in an average year
oil_recov_eff	oil_content*solv_extract_n	Weight of oil that is available and recovered per total weight of seed
rainfall_def	required_rain-annual_rain	mm/yr rainfall deficit
req_irrigation	rainfall_def/1000*10000	m^3 irrigation water required per hectare-yr
seed_process_dy	oil_extract_cap*seed_required	MT of seeds per day processed in a continuous process if oil extraction unit is operating at full capacity (200 MT seed per day considered minimum for economically viable continuous solvent extraction of jatropha oil; top end of solvent extraction capacity is 4000 MT seed per day)
seed_required	1/oil_recov_eff	Amount of dry seed required in kilograms to generate 1 kg of jatropha oil when oil content and extraction efficiency are taken into account
seed_tran_tot	seed_tran_dist*seed_yield_hect* plantation_tot/1000	Tonne-km of truck transport service required to transport all Jatropha seed produced on the plantation in one year to the oil extraction facility
seed_yield_hect	seed_yield_tree*tree_density	Kilograms dry seed expected per hectare based on tree density and seed yield per tree
seedling_plant	tree_density/seed_survive	Total trees required to be planted to achieve desired mature tree density based on seedling survival rate
solvent_req	(1-solvent_recycle)*solvent_hexane	kg hexane required to be replenished per kg seeds processed
tot_biomass_en	life_biomass_en+life_husk_en	MJ, total biomass energy available based on biomass yield and energy content over life of plantation
urea_tot_lele	mat_urea_app*tree_density*fert_app_num* life_cycle_yr*plantation_tot/1000	kg urea as N required under Lele IOC fertilizer scenario

Table A-3. India Electricity Generation Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Indian Electricity Generated	1	kWh	
Avoided Products			
Resources			
Materials/Fuels			
Electricity/Heat			
Electricity, hard coal, at power plant/UCTE S	elec_gen_coal	kWh	Fraction of a kWh generated by coal
Electricity, natural gas, at power plant/UCTE S	elec_gen_ng	kWh	Fraction of a kWh generated by natural gas
Electricity hydropower in UCPTE S	elec_gen_hydro	kWh	Fraction of a kWh generated by hydro (based on European average)
Electricity, nuclear, at power plant/UCTE S	elec_gen_nuclea	kWh	Fraction of a kWh generated by nuclear power
Electricity, at wind power plant/RER S	elec_gen_renew/2	kWh	Fraction of a kWh generated by wind power (fraction of renewable energy by technology not specified, assuming 50% of renewable wind, 50% solar)
Electricity, production mix photovoltaic, at plant/U.S. S	elec_gen_renew/2	kWh	Fraction of a kWh generated by photovoltaics (fraction of renewable energy by technology not specified, assuming 50% of renewable wind, 50% solar)
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-4. Indian Electricity Delivered Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Indian Electricity Delivered	1	kWh	
Avoided products			
Resources			
Materials/fuels			
Electricity/heat			
Indian Electricity Generated	1/(1-elec_TD_loss)	kWh	Amount of electricity required to be generated in order to deliver 1 kWh to the user on average
Infra electricity LV use UCPTE S	1	kWh	Inclusion of impacts from transmission and distribution infrastructure for low voltage (LV) electricity delivery
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-5. Jatropha Seedling for Planting Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Jatropha Seedling for Planting	1	p	
Avoided products			
Resources			
Materials/fuels			
Polyethylene, LLDPE, granulate, at plant/RER S	poly_eth_bag	g	
Electricity/Heat			
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-6. Jatropha Plantation, Planted, India Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Jatropha Plantation, Planted Ha, India	1	ha	
Avoided Products			
Resources			
Materials/Fuels			
Jatropha Seedling for Planting	seedling_plant	p	
Urea, as N, at regional storehouse/RER S	seedling_plant*plant_urea/2.17/1000	kg	Urea required to plant one hectare
Single superphosphate, as P2O5, at regional storehouse/RER S	seedling_plant*plant_SSP/4.76/1000	kg	Single super phosphate required to plant one hectare
Potassium chloride, as K2O, at regional storehouse/RER S	seedling_plant*plant_MOP/1.67/1000	kg	Potassium chloride as potassium used to substitute for muriate of potash
Poultry manure, dried, at regional storehouse/CH S	seedling_plant*plant_manure	kg	Manure may be processed in the Indian context less than this module indicates
Irrigating/ha/CH S	1	ha	
Tillage, ploughing/CH S	1	ha	Used to represent energy required to plough the field to clear prior to planting. Individual holes dug and planted using manpower. Fertilizer applied by hand to each hole in initial establishment
Electricity/Heat			
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-7. Jatropha Seeds Harvested from Plantation Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Jatropha Seeds Harvested from Plantation	seed_yield_hect*plantation_tot* harvest_per_yr*life_cycle_yr/1000	tonne	Seeds harvested over 20 yr lifetime
Avoided Products			
Indian Electricity Generated	life_biomass_el	kWh	Indian electricity offset by combusting Jatropha biomass for electricity generation
Resources			
Materials/Fuels			
Fertilising, by broadcaster/CH S	plantation_tot*fert_app_num*life_cycle_yr	Ha	Energy required to distribute fertilizer to entire plantation given number of times per year for entire life cycle
Irrigating/m3/CH S	plantation_tot*irr_years*req_irrigation	m3	Energy required to distribute irrigation water to entire plantation given number of times per year for entire life cycle
Jatropha Plantation, Planted Ha, India	plantation_tot	Ha	Number of planted hectares required for the plantation.
Urea, as N, at regional storehouse/RER S	Fert_app_num/2*fert_switch* (N_fert_req*plantation_tot*life_cycle_yr* tree_density/reinhardt_dens)	kg	Amount of fertilizer required for plantation lifetime
Potassium chloride, as K2O, at regional storehouse/RER S	Fert_app_num/2*fert_switch* (K2O_fert_req*plantation_tot*life_cycle_yr* tree_density/reinhardt_dens)	kg	Amount of fertilizer required for plantation lifetime
Single superphosphate, as P2O5, at regional storehouse/RER S	Fert_app_num/2*fert_switch* (P2O5_fert_req*plantation_tot* life_cycle_yr*tree_density/reinhardt_dens)	kg	Amount of fertilizer required for plantation lifetime
Diesel, at regional storage/RER S	diesel_fuel_cul*plantation_tot* life_cycle_yr*spec_grav_dies	kg	Amount of diesel combusted for plantation operations over plantation lifetime
Indian Electricity Delivered	plantation_elec*life_cycle_yr* plantation_tot/10000	kWh	Amount of electricity consumed over plantation lifetime
Electricity/Heat			
Emissions to Air			
Dinitrogen monoxide	N_2O_volatized	kg	N_2O released over plantation lifetime owing to N fertilizer application
Emissions to Water			
Emissions to Soil			

Table A-8. Jatropha Oil, at Extraction Facility, India Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Jatropha Oil	oil_recov_eff	tonne	
Jatropha Seed Cake	1-oil_recov_eff	tonne	
Avoided Products			
Urea, as N, at regional storehouse/RER S	(1-oil_recov_eff)*seed_cake_rep* seed_cake_N	tonne	Avoided urea fertilizer production due to the generation and use of Jatropha seed cake
Single superphosphate, as P2O5, at regional storehouse/RER S	(1-oil_recov_eff)*seed_cake_rep* seed_cake_P	tonne	Avoided single super phosphate production due to the generation and use of Jatropha seed cake
Potassium nitrate, as K2O, at regional storehouse/RER S	(1-oil_recov_eff)*seed_cake_rep* seed_cake_K	tonne	Avoided potassium nitrate production due to the generation and use of Jatropha seed cake
Resources			
Materials/Fuels			
Jatropha Seeds Harvested from Plantation	1	tonne	
Hexane, at plant/RER S	solvent_hexane	kg	
Oil mill/CH/I S	jatoil_plnt_pce*oil_recov_eff	p	Fraction of oil extraction plant infrastructure allocated to Jatropha oil produced in this module
Electricity/Heat			
Steam, for chemical processes, at plant/RER S	solvent_steam	kg	
Indian Electricity Delivered	solvent_elec	kWh	
Tap water, at user/RER S	solvent_water	tonne	Water quality requirements not specified, assumes that tap water is adequate for this process
Transport, lorry 3.5-16t, fleet average/RER S	seed_tran_dist	tkm	Transport of seeds to facility
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-9. Biodiesel Production, Base-catalyzed Transesterification, India, at Plant Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Biodiesel	1	tonne	Biodiesel output
Avoided Products			
Glycerine	glyc_yield*jatoil_required	tonne	Avoided synthetic glycerine production based on anticipated glycerine yield from biodiesel production
Resources			
Materials/Fuels			
Methanol, at regional storage/CH S	transest_meth	kg	Methanol module includes transport distance
Sulphuric acid, liquid, at plant/RER S	transest_minacd	kg	Transportation distance for sulfuric acid is unknown. Composition of mineral acid required is unknown. Sulfuric acid is currently assumed in this analysis
Potassium hydroxide, at regional storage/RER S	transest_KOH	kg	Potassium hydroxide module includes transport distance
Jatropha Oil	jatoil_required	tonne	Amount of jatropha oil required to produce 1 ton biodiesel
Vegetable oil esterification plant/CH/I S	bio_plant_piece	p	Fraction of biodiesel transesterification plant infrastructure impacts attributed to each tonne produced
Electricity/Heat			
Indian Electricity Delivered	transest_elect	kWh	Energy data is per tonne of biodiesel generated at a 100,000 MT per year biodiesel facility
Steam, for chemical processes, at plant/RER S	transest_steam	kg	In absence of specific Indian steam data, generic steam production for use in chemical processes in Europe is used. Amount of steam is specific to the Indian transesterification plant
Transport, lorry 3.5-16t, fleet average/RER S	solvent_trans*jatoil_required	tkm	
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-10. Biodiesel Blending, India, at Processing Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Blended biodiesel	1	tonne	
Avoided Products			
Resources			
Materials/Fuels			
Biodiesel	biodiesel_blend	tonne	
Diesel, at rail yard, India	1-biodiesel_blend	tonne	
Transport, freight, rail/RER S	biodiesel_dist*biodiesel_blend	tkm	Rail transport assumed for biodiesel from biodiesel transesterification plant to blending facility
Electricity/Heat			
Indian Electricity Delivered	bio_blend_elec*1000	kWh	Electricity required to blend diesel with biodiesel
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-11. Indian Freight Train Operation, Biodiesel Blend Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Indian Freight Train Transport, Blended Biodiesel	1000	tkm	
Avoided Products			
Resources			
Materials/fuels			
Blended biodiesel	loco_bio_fuel	kg	
Electricity/Heat			
Emissions to Air			
Carbon dioxide	locomotive_CO_2*loco_bio_fuel	kg	CO_2 emissions from just the diesel portion of the blend
Emissions to Water			
Emissions to Soil			

Table A-12. Crude Oil at Indian Coastal Terminal Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Crude Oil, Indian Mix	1	tonne	
Avoided Products			
Resources			
Materials/Fuels			
Crude oil, at production onshore/RME S	crude_mid_east	tonne	Represents foreign oil extraction from the Middle East
Crude oil, at production/NG S	crude_Nigeria	tonne	Represents foreign oil extraction from the Niger delta of Nigeria. India's foreign oil primarily comes from the Middle East and Nigeria.
Crude oil, at production offshore/GB S	crude_bombay	tonne	Domestic oil production is assumed to occur in India's largest oil field, Bombay High and be transported to the coastal terminal to be combined with the foreign crude via oil tanker. United Kingdom (GB) production is used as proxy for Indian offshore production.
Transport, transoceanic tanker/OCE S	crude_ocean_trn	tkm	Average shipping distance for foreign and domestic oil weighted by the proportion of each
Electricity/Heat			
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-13. Diesel at Railyard Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Diesel, at rail yard, India	1	tonne	
Avoided Products			
Resources			
Materials/Fuels			
Diesel, at regional storage/Ecoinvent->India S	1	tonne	Represents refining of crude oil to diesel and transport to rail yard for combustion in a locomotive
Electricity/Heat			
Emissions to Air			
Emissions to Water			
Emissions to Soil			

Table A-14. Indian Freight Train Transport, Diesel Custom Module

Module Flows (drawn from Ecoinvent 2.0 or other custom modules)	Input Value or Variable	Units	Comments
Products			
Indian Freight Train Transport, Diesel	1000	tkm	
Avoided Products			
Resources			
Materials/Fuels			
Diesel, at rail yard, India	loco_dies_fuel	kg	Amount of diesel used in locomotive when train exclusively using diesel
Electricity/Heat			
Emissions to Air			
Carbon dioxide	locomotive_CO_2*loco_dies_fuel	kg	
Emissions to Water			
Emissions to Soil			

Appendix B – Sensitivity Analysis Scenario Details

Table B-1 details the parameter values used to generate the sensitivity scenarios evaluated in Tables 20-22.

Table B-1. Sensitivity Analysis Scenario Details

Sensitivity Scenario Number	Parameter Category Tested	Parameter Evaluated	Units	Base Case Value	Sensitivity Scenario A	Sensitivity Scenario B
1	**Rainfall**	Plantation rainfall	mm/year	1,385	0	--
2	**Irrigation**	Years required for irrigation	Years	3	20	--
3	**N_2O Volatization Rate**	Nitrous oxide release	g N_2O per g N in fertilizer	0.01	0.003	0.04
4	**Plantation Electricity Consumption**	Plantation electricity	MWh per year for 50,000 hectare plantation	12,000	6,000	0
5	**Tree Planting Density**	Tree density	Trees per hectare	2,500	1,667	1,100

Sensitivity Scenario Number	Parameter Category Tested	Parameter Evaluated	Units	Base Case Value	Sensitivity Scenario A	Sensitivity Scenario B
6	**Biodiesel Efficiency Compared to Diesel**	Biodiesel efficiency	Biodiesel fuel consumption per diesel fuel consumption	1	1.02	1.05
7	**Diesel Fuel Consumption Requirement**	Diesel fuel consumption	Liters per 1000 GTK	4.38	2.63	8.76
8	**Fertilizer Use**	Fertilizer application	Applications per year	2	0	4
9	**Seed Oil Content**	Oil content of Jatropha seed	Mass oil per mass total seed	0.35	0.4	0.25
10	**Dry Seed Yield**	Jatropha seed yield	kg sun dried seeds per ha-yr	2,382	4,446	1,413
11	**Oil Extraction Efficiency from Seeds**	Extraction efficiency	Mass percent	0.91	0.99	0.95
12	**Glycerine Production Offset**	Glycerine yield	Mass fraction	0.08	0	--

Sensitivity Scenario Number	Parameter Category Tested	Parameter Evaluated	Units	Base Case Value	Sensitivity Scenario A	Sensitivity Scenario B
13	**Seed Cake Offset**	Seed cake replacement	kg of NPK fertilizer (40:20:10) replaced by 1 kg of Jatropha seed cake	0.15	0	--
14	**Biomass Offsets**	Biomass Yield, Year 1, Year 2, Mature; Seed husk yield	kg biomass per tree; kg sun dried husks per ha-yr	2.5, 4.5, 8.5; 1,429	0, 0, 0; 0	--
15	**All Offsets**	Combines the glycerine production offset, seed cake offset, and biomass offsets into one sensitivity scenario run (all used or none used)				

Appendix C – Best- and Worst-Case Scenario Details

Table C-1 reports the parameters used to create the best and worst case scenarios tested in the sensitivity analysis. Note that these parameters are not necessarily internally consistent but are designed to represent the range of each individual parameter.
See Table A-1 for more detailed descriptions of each parameter.

Table C-1. Parameter Values Used To Model Best- and Worst-Case Sensitivity Scenarios

Parameter Description	Input Parameter	Units	Base Case Value	Best Case Value	Worst Case Value
Annual plantation rainfall	annual_rain	mm / yr	1,385	2,500	0
Years of irrigation required	irr_years	Years	3	0	20
Nitrous oxide volatilization rate from nitrogen fertilizer	N_2O_release	g N_2O / g N fertilizer	0.01	0.003	0.04
Number of fertilizer applications / year	fert_app_num	Applications / year	2	0	4
Jatropha seed oil content	oil_content	Mass fraction	0.35	0.4	0.25
Total Jatropha seed yield	seed_yield_tot	kg sun dried seeds per ha-yr	2,382	4,436	1,418
Jatropha seed yield per tree	seed_yield_tree	kg sun dried seeds per tree	1.5	2.8	0.89
Jatropha oil extraction efficiency	solv_extract_n	Mass fraction	0.91	0.99	0.91
Jatropha seedling survival rate	seed_survive	Fractional survival rate	0.8	1	0.4
Tree density	tree_density	Trees / hectare	2,500	2,500	1,100
Nitrogen fertilizer required	N_fert_req	kg / ha-yr	81	48	141
P_2O_5 fertilizer required	P_2O_5_fert_req	kg / ha-yr	31	19	56
K_2O fertilizer required	K_2O_fert_req	kg / ha-yr	89	53	139
Diesel fuel for plantation operation	diesel_fuel_cul	L / ha-yr	86	55	141

Parameter Description	Input Parameter	Units	Base Case Value	Best Case Value	Worst Case Value
Jatropha seed husk yield	seed_husk_yield	kg sun dried husk / ha-yr	1,429	2,136	0
Biomass harvested from Jatropha trees in year 1	yr_1_biomass	kg biomass / tree	2.5	3	0
Biomass harvested from Jatropha trees in year 2	yr_2_biomass	kg biomass / tree	4.5	5	0
Biomass harvested from Jatropha trees from year 3 onward	mature_biomass	kg biomass / tree	8.5	10	0
Transportation distance of Jatropha seeds from plantation to oil extraction facility	seed_tran_dist	km	50	0	100
Jatropha oil extraction required electricity	solvent_elec	kWh / tonne seed	55	27.5	110
Jatropha oil extraction required hexane	solvent_hexane	kg hexane / tonne seed	4	2	8
Jatropha oil extraction required steam	solvent_steam	kg steam / tonne seed	280	140	560
Jatropha oil extraction required water	solvent_water	m^3 / tonne seed	12	6	24
Transport distance for biodiesel from production facility to fueling	biodiesel_dist	km	25	0	50
Biodiesel production efficiency	transest_eff	Fractional conversion efficiency	0.95	0.99	0.95
Biodiesel production electricity required	transest_elect	kWh / tonne biodiesel	36	18	72
Biodiesel production steam required	transest_steam	kg / tonne biodiesel	660	330	1,320
Biodiesel production KOH required	transest_KOH	kg / tonne biodiesel	18	9	36
Biodiesel production methanol required	transest_meth	kg / tonne biodiesel	110	55	220
Biodiesel production glycerine yield	glyc_yield	Mass fraction	0.079	0.1	0

Parameter Description	Input Parameter	Units	Base Case Value	Best Case Value	Worst Case Value
Amount of NPK fertilizer offset by Jatropha seed cake	seed_cake_rep	kg NPK (40:20:10) fertilizer replaced by 1 kg seed cake	0.15	0.15	0
Fuel consumption increase for use of biodiesel blends	biodiesel_eff	Fractional fuel consumption increase	1	1	1.05
Plantation electricity consumption per 10,000 hectares	plantation_elec	kWh / yr for a 10,000 hectare plantation	2,431,620	0	4,863,240
Diesel fuel consumption in locomotives	diesel_fuel_con	Liters / 1,000 gross tonne kilometer	4.38	2.63	8.76

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With India's transportation sector relying heavily on imported petroleum-based fuels, the Planning Commission of India and the Indian government recommended the increased use of blended biodiesel in transportation fleets, identifying Jatropha as a potentially important biomass feedstock. The Indian Oil Corporation and Indian Railways are collaborating to increase the use of biodiesel blends in Indian locomotives with blends of up to B20, aiming to reduce GHG emissions and decrease petroleum consumption. To help evaluate the potential for Jatropha-based biodiesel in achieving sustainability and energy security goals, this study examines the life cycle, net GHG emission, net energy ratio, and petroleum displacement impacts of integrating Jatropha-based biodiesel into locomotive operations in India. In addition, this study identifies the parameters that have the greatest impact on the sustainability of the system.

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