An environmental, financial and economic analysis of introducing biodiesel to locomotives: An Indian Railways case study

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Declaration of Authorship

The candidate confirms that the work submitted is her own work, except where work which has formed part of a jointly authored publication has been included. The contribution of the candidate and other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Two-thirds of the work contained in Chapter 6, and sections 2.2 and 2.4.6 is based on the following publication

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As the lead author, the candidate gathered the information and wrote the journal paper. The remaining authors provided supervision, guidance, and corrections to the manuscript.

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Abstract

There are concerns about the increasing rate of global warming with the main cause being the combustion of fossil fuels. The transport sector is the second largest user of fossil fuels after electricity generation and power. The demand for fossil fuels is ever-increasing and this is not sustainable. Not only is it contributing to global warming through the emission of Greenhouse Gases (GHG), but also through the emitting of pollutants that are affecting our health. There is a strong link between energy use and economic growth. Emerging economies such as India and China are experiencing high levels of economic growth and therefore using increasing levels of fossil fuels. India has recognised that continuing to use fossil fuels at these increasing rates is unsustainable. As with many countries, India has committed to using fewer fossil fuels, and this includes Indian Railways. Indian Railways is exploring alternatives to using diesel. This includes the use of biodiesel. At present they are using biodiesel which has been produced from imported Malaysian palm stearin. It may, however, be more beneficial to use a feedstock that has been cultivated in India, such as jatropha. Environmental, financial, and economic analyses can be used to estimate the differences between them. Another alternative that India is pursuing is the electrification of the network. This thesis along with other studies shows that there are huge benefits to electrification both environmentally and economically. However, when infrastructure costs are included for electric traction this shifts the viability from electric traction to biodiesel. The density of traffic on the network affects the feasibility of electric traction, making it more economical than biodiesel even when infrastructure costs are included. Therefore, electric traction does have many benefits compared to diesel and biodiesel, but infrastructure costs are high and hence electric traction may be appropriate for certain parts of the network i.e. routes with a higher density of traffic.

CONTENTS

Nomenclature

ADB	Asian Development Bank
ALCO	American Locomotive Company
B…	% of diesel blended with biodiesel e.g. B10
CBA	Cost Benefit Analysis
CH_4	Methane
CJO	Crude jatropha oil
cm^3	Centimetre cubed
CN	Cetane Number
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPO	Crude palm oil
CV	Calorific Value
EFB	Empty fruit branches
EIA	Environmental Impact Assessment
EROI	Energy Return on Investment
EU	European Union
EUR	Euro
EV	Electric vehicle
FFA	Free Fatty Acid
FFB	Fresh fruit bunches
G	Gram
GHG	Greenhouse Gas
GWP	Global Warming Potential
ha	Hectare
HC	Hydrocarbon
INR	Indian Rupees
J	Jatropha
K	Potassium

kg	Kilogram
km	Kilometre
kWh	Kilowatt hour
L	Litre
LCA	Life Cycle Analysis
LPG	Liquified petroleum gas
MCDM	Multi-criteria decision making
mb/d	Million barrels per day
MJ	Mega joule
mm^2	Millimetre squared
N	Nitrogen
NOx	Nitrous oxides
N_2O	Nitrogen dioxide
OECD	Organisation for Economic Co-operation and Development
P	Phosphate
pkm	Passenger kilometre
PM_{10}	Particulate matter less than 10 micrometres
$PM_{2.5}$	Particulate matter less than 2.5 micrometres
PS	Palm stearin
RDSO	Research Design and Standards Organisation
Rs	Rupee
S	Second
SOBT	Southern Online Biotechnologies
SOx	Sulphur oxides
T	Tonne (metric)
US	United States
USA	United States of America
USD	United States dollar
WTP	Well-to-Pump
WTW	Well-to-Wheel
yr	Year

Chapter 1: Introduction

This chapter sets out the reasoning behind the objectives of the thesis. The background explains the current situation that the transport sector faces fuels. This focuses on the problems which are caused by using fossil fuels and highlights several alternatives. The focus is narrowed to examine energy use in India and more specifically assessing its transport system and fuels. Indian Railways is still a key component in India's transport network; therefore, the introduction narrows further to assess statistics associated with Indian Railways including the demand across the network. Once the objectives have been established, the structure of the thesis is then outlined.

1.1 WHAT IS THE PROBLEM WITH THE CURRENT FUEL WE USE?

The transport sector is the largest user of liquid petroleum fuel in the world. It accounted for 95.4 million barrels per day (mb/d) of crude oil in 2016. This figure is estimated to increase to 111.1 mb/d by 2040 (OPEC, 2017). While liquid petroleum products have advantages over other fuels for transport, such as higher energy content (Guo et al., 2015), there are serious questions over their longer-term sustainability. In 2015, the transport sector accounted for 23% of all carbon emissions (International Energy Agency, 2017); this exacerbates global warming concerns as well as other concerns, such as the impact that the combustion of fossil fuels has on health.

1.1.1 Climate Change

In transport greenhouse gases (GHGs) include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are being released into the atmosphere (Birley, 2010). Often the effects of GHGs on the ecosystem cannot be seen in the short term. It will take time to realise the true consequences. However, meteorological implications are starting to influence seasons such as more severe winters and summers (Agarwal, 2007). These weather conditions affect countries in different ways (Stern et al., 2006). For example, in the poorest countries, most of the population do not have the means to protect themselves against rising ocean levels caused by the warming of the waters and melting ice caps; this could lead to an increased probability of flooding and potentially result in the loss of homes, crops, and lives. Whereas other countries may be more susceptible to drought, which would dry up crops and could cause famine across nations. Developed countries face a different kind of disaster; financial. While they have the means to protect their shores and lands, there is still an increased risk of natural disasters and freak weather. This would result in the insurance industry increasing their premiums to cover this extra risk, affecting both people and businesses. Climate change will worsen unless steps are taken to help reduce mankind's contribution to rising CO_2 levels (Matthews et al., 2017, Kächele et al., 2019).

1.1.2 Health Impacts

There is an increased international concern for deteriorating health through the quality of the air (Sydbom et al., 2001). Countries are facing two main issues.

1. The first is that there is a migration from rural areas to urban (Gong et al., 2012).
2. The second is that the world population is growing.

With people in urban areas likely to have more disposable income and general population growth, there will likely be an increase in private vehicle ownership. Consequently, with more vehicles on the road, combusting fossil fuels in engines will worsen air quality further.

Within the past twenty years there has been an increase in mortalities due to asthma, chronic bronchitis, respiratory infection, and heart disease, all of which are not solely related to genetic changes, but changes in the level of air quality (Sydbom et al., 2001, Cox et al., 2018).

1.1.3 Depleting resources

Reserves of fossil fuels are limited (Agarwal, 2007). Unless there are unexpected discoveries of reserves, the limitation of fossil fuels is unlikely to change (Black et al., 2010). Over time, it has become increasingly geographically difficult to mine fossil fuels. This requires not only more financial investment, but also more energy as seen in Figure 1-1. As a business investment, the initial investment should be as small as possible with the largest conceivable return; this concept is called Energy Return on Investment (EROI). Crude oil is one product, but it can have different EROI values. Some oil is very easy to extract, such as Saudi Crude in Saudi Arabia with an EROI value of 40 as seen in Figure 1-1. Not much energy needs to be input into the extraction process meaning the net energy of input (extraction) and output (how much energy we can use in the crude oil) is much higher. Ultra-deep crude oil is much more difficult to extract (higher energy input), but the energy output may be like that of Saudi Crude. However, the net energy of energy for Ultra-deep is smaller, in Figure 1-1 it has an EROI level of 8.

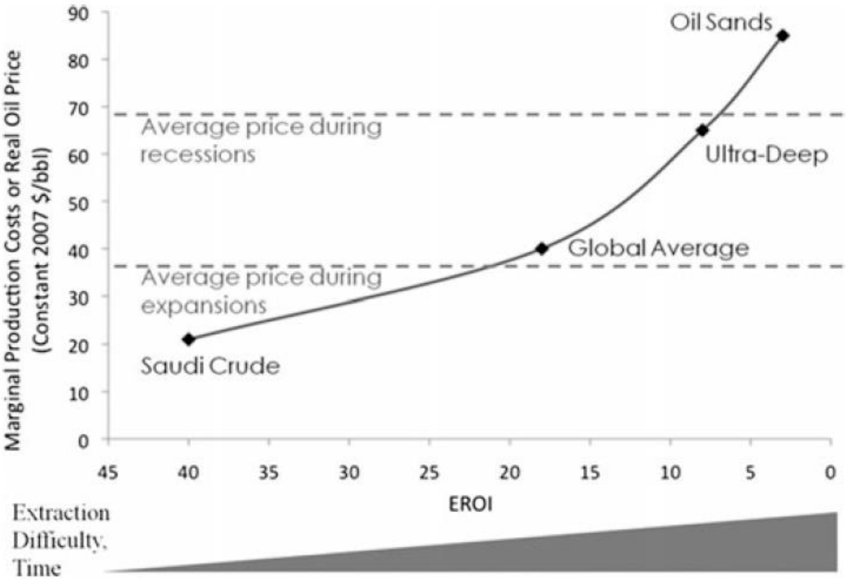

Figure 1-1: Relationship between Oil Production Costs and EROI from a Variety of Sources

Source: Murphy and Hall, 2011

The energy efficiency decreases as seen by a decreasing EROI, which correlates with marginal production costs, i.e. the cost of adding one more unit to the production schedule, of the real oil price as seen in Figure 1-1. As the production costs increase the EROI decreases, which will impact downstream factors such as fuel prices and trade balances, should the producer aim to maintain profit margins.

1.1.4 Cost

A basic economic principle is that when the supply of a good decreases the price will rise. Unexpected events, shocks, and uncertainty to the economy may lead to a shift in the supply curve and have an impact on the price; examples of this between 1988 and 2015 are shown in Figure 1-2.

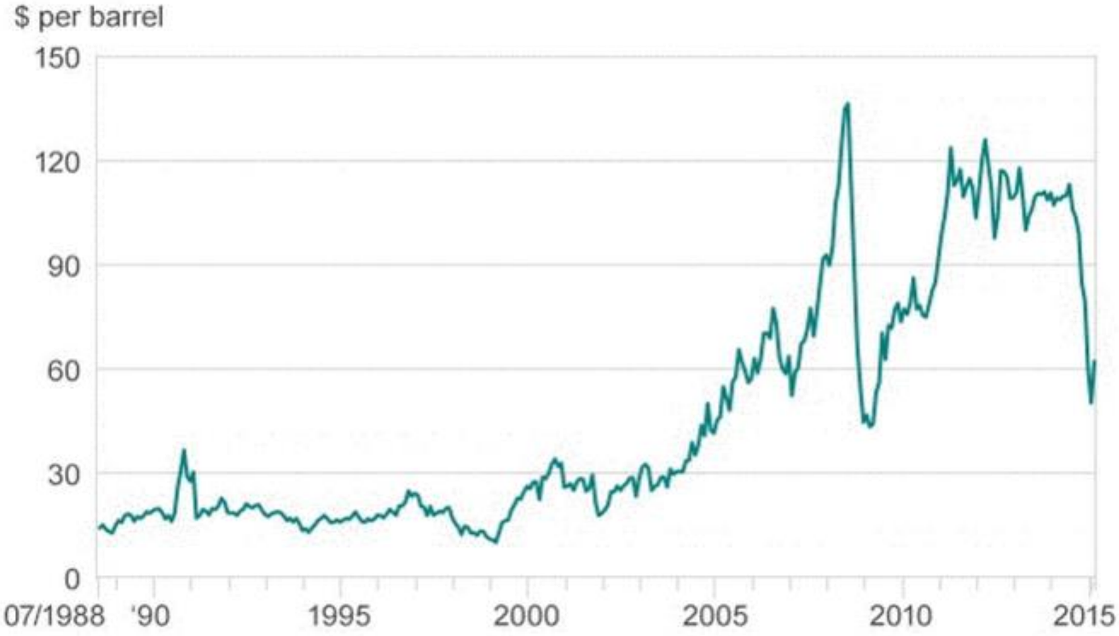

Figure 1-2: Oil prices 1988-2015

Source: Anderson, 2015

Since approximately 2004 the cost of oil has been steadily increasing except with large decreases between 2008 and 2009, and 2014 and 2015. The first decrease was due to the global financial crash; with regards to the second dip, there is uncertainty as to why this happened, but there has been speculation. Some explanations include links to an increase in US shale oil production and shifting environmental policies that had an impact on demand prospects (Stocker et al., 2018). With a decreasing EROI level, the practicality of crude oil compared to alternatives will wear thin, and it is likely that eventually, crude oil due will be less affordable due to the energy balance production cost. However, it is noted that in some cases, such as electricity generation, renewables are cheaper than fossil fuels (Safwat Kabel and Bassim, 2020, Kalair et al., 2021). At present fossil fuels are still the cheapest source of energy in transport (Barreto, 2018).

1.2 ALTERNATIVES TO USING FOSSIL FUELS

It is important to reduce the number of fossil fuels used in the transport sector (Kächele et al., 2019) because as mentioned in section 1.1 in 2015, the transport sector accounted for 23% of all carbon emissions (International Energy Agency, 2017). There are different options to reduce carbon emissions for transport; for example, switching to public transport, increasing the efficiency of vehicles, and reducing the carbon intensity of fuels. Large reductions in emissions, however, will likely require reducing the carbon intensity of fuel (Yin et al., 2015, Zhao et al., 2016). Possible options include alternate energy carriers such as electricity or biofuels. Of these, biofuels have received significant attention from researchers and policymakers for several reasons (Azad et al., 2015, Kim and Isma'il, 2014):

1. Energy security in a country can be improved because of the large choice of feedstock available (Papong et al., 2010);
2. A biofuel's lifecycle emissions are lower than crude oil-based fuels if harvested efficiently (De Souza et al., 2010, Eshton et al., 2013);
3. Biofuels are renewable (Ong et al., 2011);
4. They can promote economic development in rural areas (Akbar et al., 2009, Altenburg et al., 2009);
5. Other environmental effects such as air pollution and oil spills can be reduced; and
6. The energy content in biofuels such as biodiesel is not too dissimilar to that of liquid petroleum fuels, making them nearly similar replacements.

In 2018 renewable energy accounted for 3.7% of transport fuel demand. Biofuels made up 93% of the renewable energy with biodiesel and bioethanol dominating the market (International Energy Agency, 2019).

Biodiesel is used in diesel engines and is produced from high oil content crops such as sunflowers and rapeseed, waste vegetable oils such as cooking oil and animal fats (Ong et al., 2011, Akbar et al., 2009, Silalertruksa et al., 2012).

Bioethanol is the most favoured bio-alcohol and is used in a spark-ignition (SI) engine. It is produced from a variety of sugar and starch feedstocks including, sugarcane, corn, wheat, and sugar beet (Demirbas, 2009, Black et al., 2010). One country that is exploring the use of biofuels in the transport sector is India.

1.3 INDIA'S ENERGY USE IN THE TRANSPORT SECTOR

In India, the electricity generation, heat, and other energy sectors dominate the energy consumption of the country and have a share of 46.2% of the total energy consumption. This is followed by the transport sector which consumes 22.7% (International Environmental Agency (IEA), 2014). Coupled with economic expansion these sectors are set to continue to grow. Within the transport sector, from 1970 to 2010, passenger km (pkm) have increased from 289 billion to 6,966 billion pkm. A modal shift is seen during the same period. In 1970 there was a split of 41% and 59% for travel by rail and road respectively. In 2010 rail held an 11% share of the passenger market and road an 88% share (Dhar and Shukla, 2015).

A similar shift can be seen for freight. Demand has increased from 194 billion tonnes km (tkm) to 1,570 billion tkm from 1970 to 2010. The rail sector had a 66% share in 1970 and then decreased to 41% by 2010. The road transport sector held 34% of the market in 1970 and then increased to 59% by 2010 (Dhar and Shukla, 2015). These shares are not the same split for CO_2 levels with the road sector having a 72.6% contribution to overall transport emission levels and rail 3.3% input in 2011 (International Environmental Agency (IEA), 2014). This could indicate that energy on the railways is less intensive than on roads which highlights the importance of the railway network.

Even though the proportion of transport by rail is decreasing the network is still referred to as "the lifeline of India". It is one of the busiest railways in the world with over one million employees, over one trillion passenger kilometres per year, just under one billion net tonnes km and nearly 11,000 locomotives in operation (Indian Railways, 2014). The increase in the number of passengers can be seen in Figure 1-3.

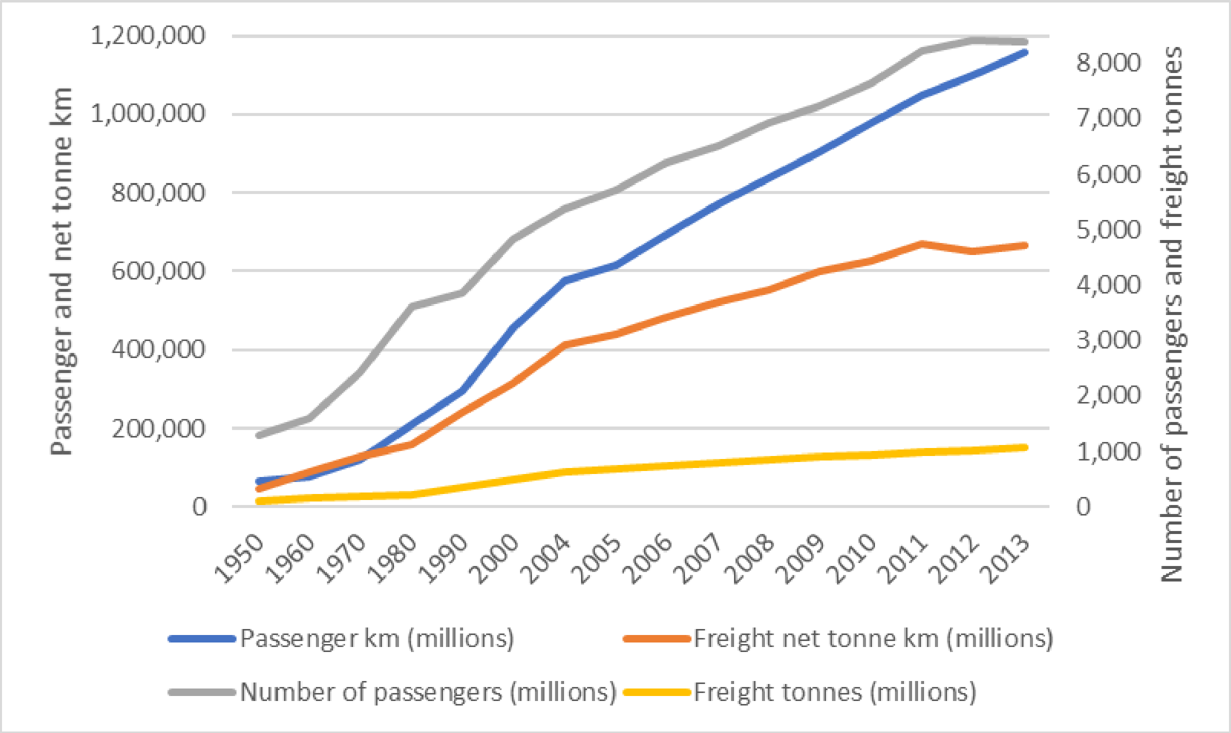

Figure 1-3: Statistical Summary of Indian Railways 1950-2014

Source: adapted from Indian Railways, 2014

The number of passengers increased between 1950 and 2014; from 1,284 million in 1950 to 8,397 million in 2014 which is a 554% increase. However, this is smaller compared to the passenger km which had an increase of 1,642% from 66.5 billion km in 1950 to 1,147.1 billion km in 2014.

Freight tonnes follows a similar trend to passenger km in that between 1950 and 2014 the increase is steady going from 93 million tonnes to 1,058 million tonnes which is a 1,039% increase. Net tonne km of freight once more follows a similar pattern. From 1950 to 2014 it increases from 44,117 million net tonne km to 666,728 million net tonne km, which is a 1,411% increase.

Through the continuous growth of transport, an increase in energy demand is inevitable. Diesel and electricity demand for rail has been increasing. From 2000 to 2014 diesel demand has grown from 1.9 million kilolitres to 2.8 million kilolitres (Indian Railways, 2014).

Indian Railways uses a combination of diesel and electric locomotives, but investigations are ongoing about introducing biofuel into its fleet. They are interested in biofuels because of the benefits explained in section 1.2.

1.3.1 Indian Railways use of biodiesel

The Indian government has implemented targets and policies to encourage the uptake of biodiesel. However, the policies are primarily aimed at road transport. It is in this area where most of the literature focuses on. However, Indian Railways has explored the use of biodiesel in its locomotives to provide energy security to the country; reduce the use of fossil fuels and consequently save on foreign exchange; and because it is perceived as environmentally friendly (RDSO, 2010). The feedstocks used to produce biodiesel must be non-edible (Blanchard et al., 2015, Shinoj et al., 2011). Some examples which have been tested in the engines include fish oil, jatropha, Pongamia, and palm stearin (RDSO, 2009, RDSO, 2010, RDSO, 2008). Biodiesel can only be used in locomotives if the feedstock and company producing the biodiesel have been approved. Palm stearin has been approved feedstock as has biodiesel producer Southern Online Bio-Technologies (SOBT).

Palm stearin is a by-product of the production of crude palm oil. The main reason for choosing this feedstock over other sources is the cost. However, this cost is based on the market value price of biodiesel produced from palm stearin; this cost does not take into consideration the economic cost which can include externalities such as GHGs and pollutants. Therefore, it is important to conduct economic viability tests to understand the effects of using such fuel on the Indian economy.

Palm stearin is imported from Malaysia. By using this feedstock India is not promoting a domestic market for growing feedstocks to be used in the production of biodiesel. There could be wider benefits for using a feedstock cultivated in India, such as reduced travel of the feedstock and an increase in rural job opportunities.

The Indian government has promoted the growth of jatropha in India for the past decade through various policies and programmes. The reasons for choosing this feedstock are that it is a shrub. The shrub is hardy, and drought and disease resistant.

It can also be grown on wasteland, which eliminates the competition for agricultural land. There have been some studies that have examined the supply chain of producing biodiesel from jatropha (Gmünder et al., 2012, Achten et al., 2010, Ajayebi et al., 2013, Akbar et al., 2009, Ariza-Montobbio and Lele, 2010, Arvidsson et al., 2011). Even though this research has mainly been focused on the use of jatropha-based biodiesel in the road sector, there is some research on the rail sector using jatropha-based biodiesel (Whitaker and Heath, 2009, Whitaker and Heath, 2010). Further to these studies, jatropha biodiesel has been compared to other feedstocks including palm oil, which have highlighted several differences along the supply chain (Ajayebi et al., 2013, Hou et al., 2011, Lam et al., 2009a, Nazir and Setyaningsih, 2010).

1.4 THE OBJECTIVES OF THIS THESIS

The Indian government has recognised the need to diversify its transport fuel. The continuous demand for transport using fossil fuels is no longer sustainable for a variety of reasons, including energy security and health impacts. Therefore, this thesis has the following objectives to identify whether Indian Railways should switch to using biodiesel from diesel:

1) Assess the environmental, financial, and economic feasibility of using biodiesel produced from palm stearin at different blend levels compared to diesel.
2) Analyse the differences between biodiesel produced from an imported feedstock (palm stearin) and a feedstock that is grown in India.
3) Establish the viability of using biodiesel instead of electric traction.
4) Determine the key lessons that can be learned from the introduction of biodiesel to the road sector and whether they can be applied to rail transport and Indian Railways.

The objectives will be answered through a case study. The case study is explained in more detail in the below chapters.

1.5 THE STRUCTURE OF THE THESIS

The thesis has five chapters excluding the introduction, conclusion, and references. Chapter two is a literature review and analyses the different stages of the production of diesel, biodiesel, and electricity. As well as giving an overview from this perspective, it also explores the financial and economic literature on diesel, biodiesel, and the use of electricity in the transport sector. The third chapter explains the method that will be used to address objectives one, two, and three as outlined in section 1.4. It explains the software and modelling techniques used and the reasoning behind them. It also explains the data inputs and outputs to be used during the analysis. Chapter four analyses biodiesel produced from palm stearin with different concentrations of biodiesel, biodiesel produced from jatropha, and diesel. Emissions along the supply chain are compared. This is followed by a financial analysis and lastly by an economic assessment. Chapter five is a comparison of diesel and palm stearin-based biodiesel and electric traction. This is analysed from a GHG, pollutant, financial, and economic perspective. Chapter six takes a wider look at the biodiesel industry and how it can be introduced to the market. This chapter analyses the literature and countries that have attempted to introduce biodiesel to their transport systems and analyses lessons that can be learned. These lessons are assessed on whether they are useful and relevant for the rail sector. This chapter extends this analysis further by also applying these lessons directly to Indian Railways. The thesis concludes with a chapter that summarises each of the chapters and links them back to the objectives outlined in this introduction. The conclusion also discusses and acknowledges the limitations of the thesis and potential areas for future work.

2 Literature Review

2.1 INTRODUCTION

Biodiesel is one alternative to diesel to address emissions from the transport sector. (Demirbas, 2000, Demirbaş, 2001, Şensöz et al., 2000). There has been an increasing amount of literature comparing diesel and biodiesel. There are often differences in the literature regarding the environmental and economic feasibility of biodiesel. This is mainly due to the different feedstock used. Alongside this, electric traction is also seen as a cleaner alternative to the use of fossil fuels. There is an increasing amount of literature showing that electric traction is the future for cleaner travel.

This chapter considers the literature surrounding the following aspects of biodiesel and electric traction:

- The environmental side uses a life cycle analysis (LCA). A further explanation of an LCA can be found in section 2.4.1.
- The inputs along the supply chain and some of the concerns with this.
- An analysis of the costs of using biodiesel and electric traction alongside the cost of externalities. Further to this, there is an analysis of the different methods to assess and compare the fuels financially and economically. This also includes an exploration into the externalities which will be included in the economic analysis.

2.2 DIFFERENT TYPES OF BIOFUELS

The use of biofuels has received increasing attention from environmental groups and governments as they are viable alternatives to fossil-based fuels. As previously mentioned in section 1.2, there are two main types of biofuel: biodiesel and bio alcohol. There are many different feedstocks (i.e. raw materials) that can be used to produce each of the biofuels. The feedstocks can be split into categories, commonly known as generations. The new generations are more advanced than their predecessors.

First generation biodiesel is plant-based oil crops such as corn, rapeseed, and sunflower. These crops can be used in one of two pathways, as food or for energy e.g. biodiesel. This is one of the most significant drawbacks of using 1st generation feedstocks; the “food vs. fuel” debate (Tomei and Helliwell, 2016, Fradj et al., 2016, Paschalidou et al., 2016, ETIP, 2019).

Second generation feedstocks, also known as a sustainable generation (Azad et al., 2016), eliminate the problem of whether crops should be used for food or fuel. Second generation biodiesel is produced from feedstocks such as waste or energy crops. This generation is advantageous for many reasons including not competing with food directly and their higher energy yields when compared to 1st generation biodiesel (Sims et al., 2008). There is more contention around energy crops than waste because they often compete for arable land which would otherwise be used to produce food.

Finally, there is third generation feedstock that is primarily produced from algae (Alam et al., 2015). Algae is more advanced and sustainable than previous generations because it can produce 20 to 400 times more biodiesel than other feedstocks on an area basis. However, this feedstock has not dominated the market because monetary implications hinder business creation (Saroya and Bansal, 2018).

The variety of feedstocks has widened. Figure 2-1 shows the growth in worldwide biodiesel and bioethanol production in 2006 and 2016. During this period bioethanol experienced roughly a 140% increase, whereas biodiesel experienced a 300% increase. The increased demand for bioethanol has mainly been driven by the Americas. The geographical areas pursuing a biodiesel route are primarily Europe and Eurasia. Future biodiesel growth is forecast to be around 3% over the next five years. This growth is expected to come mainly from Latin American and non-OECD Asian countries. The forecast for the European Union (EU) and the United States (US) is lower (International Energy Agency (IEA), 2018). Even with a high increase in biodiesel production, biodiesel is still lagging behind bioethanol.

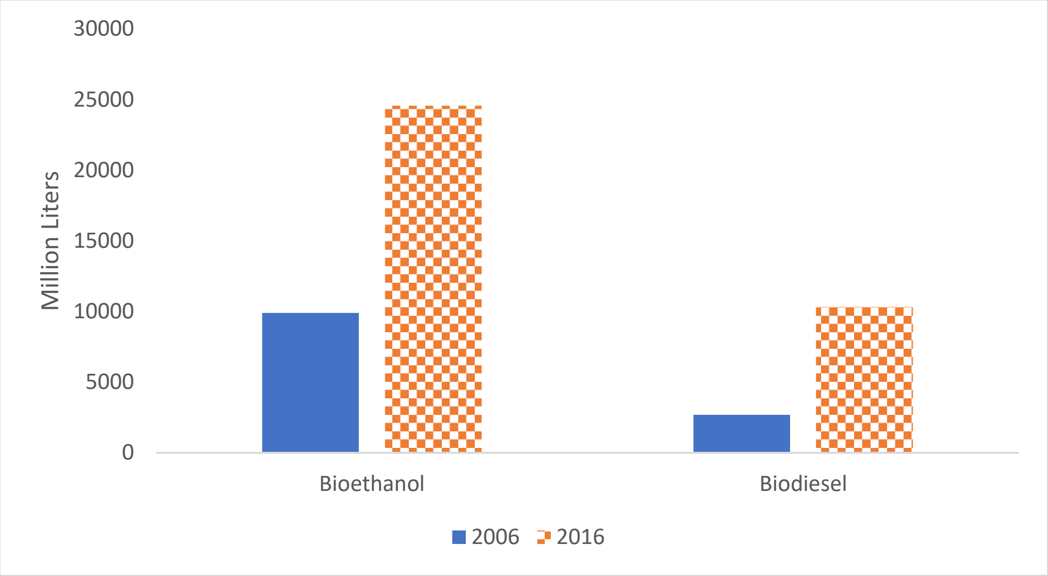

Figure 2-1: World biodiesel and bioethanol production in 2006 and 2016

Source: adapted from BP Global, no date.

Diesel dominates the rail sector, unlike the road sector where both diesel and petrol are available. The equivalent biofuel for diesel is biodiesel and the equivalent biofuel for petrol is bioethanol due to their similar physical and chemical properties. Although, bioethanol is not the focus of this thesis there may be lessons that can be learned from the bioethanol industry despite the fact it is not a direct substitute for diesel.

2.3 PHYSICAL AND CHEMICAL PROPERTIES OF DIESEL AND BIODIESEL

Biodiesel is attractive for its environmental benefits (Bhatia et al., 1998, Nagai and Seko, 2000, Sang, 2003, Zhenyi et al., 2004, Demirbaş, 2003, Giannelos et al., 2002). However, one of the concerns is that because of the different feedstocks, biodiesel can vary in chemical and physical properties compared to diesel.

Table 2-1: A comparison of physical properties and costs of diesel with different feedstocks used to produce biodiesel

	Feedstock	Kinematic viscosity (mm^2/s, at 40 ^oC)	Density (g/cm^3 at 21^oC)	Cetane number	Flash Point (^oC)	Pour Point (^oC)	Calorific Value (MJ/kg)
	Diesel	2.0-4.5[1,2,4,5,6,7]	0.820-0.860[1,2,5,6,7]	46-58[1,4,5,6,7]	55-76[1,4,5,6]	-25- -16[1,2,4,5,6]	42-43.8[1,2,5]
Edible Seeds	**Soybean**	3.97-4.5[1,2,3,4,6,7]	0.884-0.885[1,2,3,6,7]	45-50.9[1,3,4,6]	69-178[2,3,4,6,7]	-12.2 – 1[1,2,,4,6,7]	33.5-69[1,2,3,4]
	Palm Oil	4.28-5.7[1,2,3,4,7,8]	0.860-0.900[1,2,3,7,8]	57.3-62[1,3,4,8]	<100-182[1,2,4,7]	12-15[2,7]	33.5-39.8[1,3,4,8]
	Sunflower	4.03-4.60[1,3,4,6,7]	0.860-0.884[1,3,6,7]	49[1,3,4,6]	157-183[1,4,6,7]	-15-1[1,4,6,7]	33.5[1,3,4]
	Rapeseed	4.43-4.83[2,3,6]	0.882[2,3,6]	52.9-54.4[3,6]	155-183[2,3,6]	-12- -9.4[2,4,6]	37[2]
	Peanut	4.9[1,3,4]	0.883[1,3]	54[1,3,4]	176[1,3,4]	-6.7[1,4]	33.6[1,3,4]

Non-edible Seeds	**Jatropha**	4.8-4.84[2,3,5]	0.879-0.880[3,5]	51.6[5]	135-161.85[2,3,5]	-6.25-2[2,,5]	37.2-39.23[2,3,5]
	Pongamia pinnata	4.8[2]			150[2]		36.5[2]
	Castor	15.25[3]	0.899-0.960[2,3]		260[2]	-32[2]	39.5[2]
	Rubber seed	5.81[2]	0.874[2]		130[2]		
Waste	**Vegetable /cooking oil**	4.52-5.3[3,5]	0.882-0.897[3,5]	54[5]	195.85[5]	-11.15[5]	(H) 42.65[5]
	Animal Fat (tallow)	4.82-5.0[3,6]	0.874-0.877[3,6]	58.8[6]	96-150[1,4,6]	9[1,4,6]	8.0[3]

Sources: [1] Barnwal and Sharma, 2005 [2]Gui et al., 2008 [3]Karmakar et al., 2010 [4]Singh and Singh, 2010 [5]Balat, 2011 [6]Canakci and Sanli, 2008 [7]Alptekin and Canakci, 2009 [8]Benjumea et al., 2008

2.3.1 Kinematic viscosity

Kinematic viscosity is affected by the chain length of the fatty ester. Raw vegetable oils have very high kinetic viscosity levels which if injected directly into a diesel engine would cause blockages and extensive damage (Demirbas, 2008). This is why vegetable oils need to be taken through the transesterification process (Knothe and Steidley, 2005). Diesel has a viscosity of 2.0-4.5mm^2/s at 40^{o}C which is lower than all the feedstocks. As seen in Table 2-1 the closest is soya bean with a range of 39.7-4.5 mm^2/s. Soya bean could be considered as the most suitable substitute for diesel, but some of the other feedstocks have a smaller minimum than soya bean's maximum. For example, palm oil and sunflower have a minimum of 4.28 and 4.03 mm^2/s respectively whereas soya bean's maximum is 4.5 mm^2/s. The worst feedstock to use is castor with a value of 15.25 mm^2/s. Most of the feedstocks are between 4.0 and 5.0 mm^2/s.

2.3.2 Density (g/cm^3 at 21^{o}C)

The density directly affects the engine performance characteristics and is defined as the mass of the object divided by its volume (Alptekin and Canakci, 2009). In this instance, diesel has a density of 0.82-0.86 g/cm^3 at 21^{o}C which is lower than all the feedstocks. They have a range of 0.86-0.96 g/cm^3. Sunflower has the closest density to diesel with the lowest value at 0.86 g/cm^3 and castor has the highest at 0.96 g/cm^3.

2.3.3 Cetane number

A higher cetane number is desired for quicker combustion because it lowers the risk of knocking (random explosions of unburned fuel), which can cause damage to the engine. The exact cetane number of the diesel would depend on the hydrocarbons and can range from 46-58. The feedstock's CN ranges from 45-62. Soya bean has the lowest CN at 45 and palm has the highest at 62. Even the minimum CN for palm oil (57) is higher than all other feedstocks except animal fat which is 58.6. Therefore, palm oil or animal fat would be the most suitable alternative to mix with or replace diesel.

2.3.4 Flash Point (°C)

The flashpoint is related to the safety of storing and transporting the fuel. It is the lowest temperature at which the vapours of the fuel can ignite. The higher the flash point the safer the fuel. Diesel has a flashpoint ranging from 55-76°C. The feedstocks have a range of 69-260°C with soya bean having the lowest at 69°C and castor having the highest at 260°C.

2.3.5 Pour Point (°C)

The point at which the fuel transforms into a semi-solid state and loses its flow is known as the pour point. This can be a setback for countries with colder climates during all or part of the year. A lower pour point is desirable because the fuel can be used in countries and seasons when the temperature is much lower. The pour point for diesel ranges from -25 to -16 °C. For biodiesel, there is a large variation with the different feedstocks ranging from -32 to 15 °C. Soya bean and sunflower alone have large ranges of -12.2 to -1 °C and -15-1 °C respectively. This does cause concern for countries that experience a colder climate for part or the entire year. -12.2 °C may cause no problems throughout wintertime but -1 °C may do.

2.3.6 Calorific Value (MJ/kg)

The calorific value (CV) is the energy that is stored in the fuel. Alternatively, it is the amount of heat released during combustion and two values can be used here:

1) Higher heating value (HHV): this is the gross value which includes the condensation of the vapour produced during combustion; and
2) Lower heating value (LHV): this is the net value where the heat of vaporisation is not included.

Diesel has a CV variation of 42-43.8 MJ/kg. The feedstock varies from 33.5-69 MJ/kg. Soya bean, palm oil, and sunflower all have values at the lowest end of the range. Soya bean is also at the highest end of the range. It could be questioned about soya beans 69 MJ/kg because it appears to be the only extreme. Excluding this value and vegetable oil, the range would be 33.5-39.8 MJ/kg.

2.4 THE LIFECYCLE ANALYSIS OF PRODUCING BIODIESEL

2.4.1 A definition of a life cycle analysis

A life cycle analysis (LCA) is a tool that assesses the environmental impact of a product's life (Finnveden and Moberg, 2005). The analysis can be conducted throughout all or part of a product's life. For example, biofuel produced from a crop:

1. The LCA could begin at the cultivation stage i.e. ploughing the land, planting the crop, etc.
2. The crop is then harvested.
3. It is transported.
4. It is produced into a biofuel.
5. This biofuel is further transported to a filling station.
6. The final stage is the biofuel being combusted.

This process is known as cradle to grave or, more commonly in transport examples as Well to Wheel (WTW). It is also possible to only include parts of the product's life cycle such as Well to Pump (WTP). In this case, the LCA would include the earlier stages of producing the biofuel but not the combustion stage i.e. stage 6 above. The decision of how far the LCA should be taken is down to the purpose of the analysis.

LCAs have been around for several decades. It is often used to support the development of policy and performance-based regulation, in particular bioenergy (McManus et al., 2015, Giuntoli et al., 2018). Life cycle analyses, which examine the amount of carbon produced, have been established worldwide and form a key component in determining bioenergy based policies in many larger economies including the UK, EU, and US (McManus et al., 2015).

There have been concerns about LCA models including credibility, transparency, and communication. Uncertainties have developed because of the complexities associated with an LCA which in turn could affect their credibility (McManus et al., 2015). This is closely linked to transparency. It is rational to assume that the studies that appear to be very similar (i.e. producing biodiesel from soya beans) should yield similar GHG emission results. However, this is not always the case and there are often large differences in results (Hennecke et al., 2013). Small differences in inputs or calculation methods are examples of factors that can drive differing results. Hennecke et al. (2013) showed that it was possible to enhance GHG savings by 20-35% by selecting more favourable tools in models. There have been attempts to help overcome this issue. For example, the Renewable Transport Fuel Obligation (RTFO) in the UK issues guidelines on how GHG emissions should be calculated for biofuels. It is difficult to compare assessment methods due to differences in interpretation of terminologies, such as waste definitions and co-products' system boundaries (Whitaker et al., 2010). Therefore, it is very difficult to make direct comparisons between studies.

Even though there are uncertainties about LCAs, it is still a recognised tool to determine the environmental impact of a product's life. There are few if at all any alternatives.

To demonstrate the complications of an LCA and understand the best way to use them, it is possible to compare the same feedstock from different assessments. In subsequent sections, the literature reviewed is either an analysis of jatropha or palm oil/ stearin. The literature either reviews the feedstock as a standalone or is a direct comparison.

2.4.2 Comparison of cultivation inputs for jatropha and palm stearin

Jatropha and palm oil do share some common features during the cultivation stage (e.g. the use of similar fertilisers). They often use fossil fuels to help in the cultivation stage, which in turn would likely have a negative environmental impact.

Table 2-2: Comparison of cultivation conditions for jatropha and palm stearin

Stage of production	Parameter	Jatropha	Palm Stearin
Cultivation	Seeds/ha	2000 litres/ha/yr [1] 2 tonnes seeds/ha/yr[2]	130-140 trees/ha[6] 16.5 tons of FFB ha/yr[7]

		1250 plants/ha[3] 0.4-12 tonne/ha/yr[4] 8 tonne/seeds/ha[5]	2.5-3.8 tons/tree/yr 18-20 tonnes FFB/ha/yr[4] 21. tonnes FFB/ha
	Harvesting	4 months old[5]	Can harvest 2.5-3 years after[5,8]
	Land type used	Grown on degraded and wasteland[3,9,10] Rough land[5]	Using peatland and forests causing GHGs[4] Uses forests[4] Prime forests[5]
	Fertilisers	N, P and K are used as fertilisers [2,3,4]	N, P, and K are used as fertilsers[4,6]
	Age	Jatropha can be harvestable for 50 years [2]	Maximum yield between 10-15 years[6] At age 20 the plants reduce to 60% of maximum[6] Last 25 years then too high for safe harvest[4,6,7,8,10] Reach 15m in height[4]

	Emissions	Negative mitigation because of fossil fuels used[3]	
	Environmental impact		Deforestation leading to the extinction of animals[4]

Sources: [1]Akbar et al., 2009 [2]Ghosh et al., 2007 [3]Eshton et al., 2013 [4]Lam et al., 2009a [5]Siregar et al., 2015 [6]Achten et al., 2010 [7]Kittithammavong et al., 2014 [8]Pleanjai et al., 2007 [9]Arvidsson et al., 2011 [10]Ong et al., 2012

In the cultivation stage, there is more reliability for the yield of palm stearin due to the smaller gap in tonnes of fresh fruit branches (FFB) produced; 2.5-3.8 tonnes FFB/hectare whereas jatropha can produce from 0.4-12 tonnes seeds/ha. This range produces levels of uncertainty and thus consequences:

1) Assuming the lower end for jatropha, a lower yield means that more land and energy are needed to produce the amount to meet the desired production target (Siregar et al., 2015).
2) Due to these differences in yields, less land is required to produce 1 tonne of biodiesel when using palm oil; around 0.28 ha compared with 0.61 ha for jatropha (Lam et al., 2009a). Consequently, due to the need for less land and a higher yield of palm oil, emissions from soil are lower compared to jatropha. If, however, the land was compared like for like, the Global Warming Potential (GWP) for palm oil would be greater compared with jatropha because of the ammonia and nitrogen leaked from the soil (Arvidsson et al., 2011).

Siregar et al. (2015) disagree with Arvidsson et al. (2011) over how palm produces the most emissions. They argue that it is not from soil leakage but the preparation of the land before seedlings are planted. Weeds are more common with palm oil crops and therefore herbicide must be used to prepare the land to prevent the growth of weeds.

The number of bushels and trees varies per ha with around 1,250 bushels/ha for jatropha and 130-140 trees/ha for palm. This may not be relevant for oil extraction because the same quantity of oil could be obtained from 130 palm trees and 1,250 jatropha bushels. However, the amount may be relevant for the initial costs; more bushels may mean a higher cost. Even though there is uncertainty about jatropha yield, literature has indicated that there are more advantages for jatropha than for palm in the cultivation stage:

1) Jatropha seeds can be harvested after 4 months, compared to 2.5 years for palm. This shows that jatropha could recover its costs more quickly.
2) Jatropha can be grown on wasteland which is not suitable to grow food crops. Palm is often grown on deforested land destroying wildlife habitats and contributing to an increase in emissions.
3) Jatropha can be replaced every 50 years whereas palm is often replaced every 25 years. Palm can be harvested with maximum yield when it is 10-15 years old and only harvests 60% of this at around 20 years old. At 25 years old the plant is often too tall to safely harvest so it is replaced. Even though jatropha can be replaced every 50 years there is little data on the productivity of the yield over this period.

The literature examined can be divided into two categories:

1) Papers that examine the LCA of palm or jatropha-based biodiesel.
2) Papers that directly compare the LCA of palm and jatropha-based biodiesel.

Different literature focuses on different parameters. A focus on different parameters could result in different outcomes. The age and maximum efficiency of fruit/seeds produced are examined more thoroughly in the literature that focuses on only one of the feedstocks. This particular focus is more commonly seen in literature that concentrates on palm (Achten et al., 2010, Kittithammavong et al., 2014, Pleanjai et al., 2007). Some of the comparisons also draw attention to the age of the plants (Ong et al., 2011, Lam et al., 2009a), but do not do so for jatropha with only (Ghosh et al., 2007) mentioning the age of jatropha. Few papers identify the land used when analysing the feedstock at an individual level.

For both jatropha and palm stearin, the comparison papers are more optimistic about the yield of the crops (Lam et al., 2009a) indicating that yield could be between 18-20 tonnes FFB/ha/yr whereas (Kittithammavong et al., 2014), who only examined palm oil, estimated a yield of 16.5 tonne FFB/ha/yr. For jatropha, Ghosh et al. (2007), like Kittihammavong, have downgraded their yield estimate to 2 tonnes seeds/ha/yr compared to Lam et al. (2009a) and Siregar et al. (2015) who estimate a yield of up to 12 tonnes seeds/ha/yr.

2.4.3 Comparison of the oil extraction stage inputs for jatropha and palm stearin

Lam et al. (2009a) state that palm oil has the highest yield of 3.74 tonnes/ha/year compared with a yield of 1.72 tonne ha/year for jatropha. This difference was also found by Arvidsson et al. (2011) with 4.22 tonnes/ha for palm oil and 1.15 tonnes/ha for jatropha.

Table 2-3: Comparison of oil extraction conditions for jatropha and palm stearin

Stage of production	Parameter	Jatropha	Palm Stearin
Oil extraction	Efficiency	28-30% of oil can be extracted from the whole seeds[1] 1 tonne of seeds produce 200kg of oil- 20%[2] 75-80% efficiency when using a screw press, manual press 60-65% efficiency[3] 1150 kg oil/ha[7] 30-50% oil by weight[9]	20% oil[3] 198.8 kg palm oil/tonne FFB[3] 4220kg oil/ha when palm and kernel included[7] 4-5 tonnes oil/ha[9]

	Waste	Press cake used as fertiliser or digested into biogas[3]	Fibres, nuts, and shells burned in a boiler[5,7,8,10] 23% as EFB 14% as fibre and 8% as shells[3]
	Separation		Stearin and Olein need to be separated (33 and 67% respectively)[5] Palm stearin is 0.29kg/kgCPO[6]

Sources: [1]Ghosh et al., 2007 [2]Eshton et al., 2013 [3]Lam et al., 2009a [4]Siregar et al., 2015 [5]Achten et al., 2010 [6]Kittithammavong et al., 2014 [7]Pleanjai et al., 2007 [8]Arvidsson et al., 2011 [9]Ong et al., 2012 [10]Silalertruksa et al., 2012

The next stage is the oil extraction where like the cultivation stage, there are discrepancies in the oil extraction levels. This could be dependent on the machinery used during the extraction process with a manual press having 60-65% efficiency and a screw press having 75-80% efficiency. The extraction of palm oil produces 4-5 tonnes of crude palm oil/ha from 21 tonnes of FFB with a 20% oil extraction rate. From the same size of land around 4 times as much oil can be produced from palm trees compared to jatropha.

From the production of each, waste is inevitable; the difference is how the waste is used. Palm oil has waste that includes shells and seed cake which can either be burned in boilers; or used as animal feed. The jatropha process produces waste that cannot be used as animal feed as it is poisonous; it could be incinerated but is often not (Arvidsson et al., 2011).

Once the oil has been extracted there is crude palm oil (CPO) and crude jatropha oil (CJO). However, it is not palm oil that India is using to power locomotives, but palm stearin. This is a by-product of palm oil where 0.29kg of palm stearin is produced from every kg of CPO (Kittithammavong et al., 2014).

The extraction of oil from the crops requires different machinery and processes. There is a contradiction in the literature over the amount of energy needed for each of the processes. Siregar et al. (2015) believe that the energy required to process palm oil is greater than jatropha because of the extra materials needed for the palm press; jatropha only needs electricity and diesel to extract the oil. However, Arvidsson et al. (2011) state that the processes are more complex than explained by Siregar et al. (2015):

Palm oil: Sterilise the fruits → strip the fruits from the branches → press the fruit to release the liquids

Jatropha oil: dried → shells are cracked to release the seeds → the seeds are deshelled → the seeds are pressed to release the oil → filter the oil to rid the impurities

After the oil extraction stage and before transesterification, esterification is discussed in some literature- an extra stage to reduce the Free Fatty Acid (FFA) content. There is little information on esterification, but it has been indicated that jatropha needs esterification, but palm oil does not. The use of esterification could make a difference in terms of energy consumed, emissions released, and overall cost. Siregar et al. (2015) believe that esterification is needed for jatropha because of its FFA and therefore requires more energy. This would lead to increased emissions during the biodiesel production for jatropha resulting in a GWP of 897.77 kgCO$_2$e compared to a GWP of 602.12 kgCO$_2$e for palm oil. This is disputed by Ong et al. (2011) who state that esterification is needed for both palm oil and jatropha because they have higher than desirable FFA levels (< 1%). This would lead to a change in levels of emissions during the biodiesel production stage.

Once again the literature focussing on one feedstock are more pessimistic than that which compares feedstocks; the amount of oil extracted from jatropha seeds varies from 20-30% (one feedstock focus) (Eshton et al., 2013, Ghosh et al., 2007), whereas Ong et al. (2011) are more optimistic with the extraction of 30-50% of oil from the seeds (more than one feedstock).

Waste is a large part of oil extraction and only Lam et al. (2009a) address this issue with jatropha but more so for palm. Jatropha waste often is not utilised, but the seed cake could be used as fertiliser or digested into biogas. For the waste to be useful other processes or new equipment may have to be introduced, such as an anaerobic digester to produce biogas. This makes it is easier to throw it away, and hence why it does not appear often in the literature. The nuts, fibres, and shells can be used in the boiler and little processing must take place. This could reduce the overall cost of the process because other fuels for the boiler are not needed and is of interest to manufacturers and financers.

2.4.4 Comparison of the transesterification stage inputs for jatropha and palm stearin

Table 2-4: Comparison of transesterification conditions for jatropha and palm stearin

Stage of production		Parameter	Jatropha	Palm Stearin
Biodiesel production		Efficiency	95-96% efficiency in producing biodiesel from jatropha oil[1] 90 minutes for reaction[2] 91% efficiency[3] 1 tonne of biodiesel requires 0.61 ha/yr[2]	Take around 90 minutes for the stearin to be transeserfied[2,4] 8 hours per batch[5] 1 ton is produced from 1.14 tons of crude palm oil /6-7 tonnes of FFB[5] 5.56-6.13 ton FFB/ ton CPO[6] 95% coversion[2]

				1 tonne of biodiesel requires 0.28 ha/yr[2] 92% efficiency[3]

Sources: [1]Ghosh et al., 2007 [2]Lam et al., 2009a [3]Siregar et al., 2015 [4]Achten et al., 2010 [5]Pleanjai et al., 2007 [6]Silalertruksa et al., 2012

During transesterification, efficiency is similar for both jatropha and palm oil; between 92% and 96%. The process takes approximately 90 minutes. With a similar process for both feedstocks during this stage, it highlights the importance of earlier stages in the supply chain.

To produce 1 tonne of biodiesel from jatropha, 0.6 ha of land is required and for palm oil 0.28 ha. This indicates that less land is required to produce 1 tonne of biodiesel from palm oil, but as India is producing biodiesel from palm stearin more land is required as 0.29kg of palm stearin is produced from every kg of CPO. Therefore 0.82 ha of land is required to produce 1 tonne of biodiesel from palm stearin. This is 34% higher compared to palm oil and 0.22ha more than needed for jatropha.

Compared to the cultivation and oil extraction stages, the analysis of transesterification is more consistent in the literature. The main difference is the timing processes for palm stearin. The timings vary from 90 minutes to 8 hours. Both could be true, but it is difficult to determine because the conditions of each of the studies are not clearly defined.

2.4.5 Comparison of the combustion for jatropha and palm stearin

Table 2-5: Comparison of combustion conditions for jatropha and palm stearin

Stage of production	Parameter	Jatropha	Palm Stearin
End use	Price	Feedstock costs account for a large % of the total	About 69% of the cost comes from feedstock[4]

		production costs and final price[1] 72% of total production cost[2]	
	Energy content	1 tonne of diesel compared with 1.16t biodiesel[3] Flashpoint 160-170, cetane 55-58[2]	

Sources: [1]Akbar et al., 2009 [2]Ghosh et al., 2007 [3]Eshton et al., 2013 [4]Silalertruksa et al., 2012

The cost of the final product heavily relies on the feedstock price. Jatropha has a higher percentage at 72% compared to 69% for palm oil. Using biodiesel affects the engine mechanics and this differs further depending on the feedstock. The fuel consumption is lower for both jatropha and palm oil compared to diesel. There is also more corrosion and wear of the engine when using biodiesel (Ong et al., 2011).

There is inconsistency in the literature about overall LCA emissions and energy use when comparing biodiesel produced from palm oil and jatropha. Arvidsson et al. (2011) and Lam et al. (2009a) state that CO_2 savings are higher for palm oil than jatropha. When methane is recycled during the process GWP is once again lowest for palm. The other side of the argument is that CO_2 levels reduce by 63.61% and 37.83% for jatropha and palm oil respectively compared to diesel (Siregar et al., 2015). Palm oil can have 66% higher environmental damage (including human health, ecosystem quality, and resources) when compared to jatropha (Nazir and Setyaningsih, 2010).

Along the supply chain, at various stages, there are differing and complementary opinions and values. It is widely regarded that cultivation contributes to a high proportion of GHGs (Arvidsson et al., 2011, Siregar et al., 2015, Lam et al., 2009a, Nazir and Setyaningsih, 2010). Results vary from 37.77% to 60% for jatropha and

50.66% to 60% for palm oil as proportions of the whole LCA. This is based on emissions from the soil preparing the ground for seedlings (more so for palm oil) (Arvidsson et al., 2011) and also the fertiliser used. However, Siregar et al. (2015) and Nazir and Setyaningsih (2010) disagree. They believe that the biodiesel production stage has a higher percentage of GWP; 52.86% for the production stage and only 46.66% for the cultivation stage (Siregar et al., 2015). Nazir and Setyaningsih (2010) distinguish this difference of opinion further by stating that oil extraction for palm has the highest contribution to emissions followed by cultivation and then biodiesel production. These differing options highlight that it is difficult to compare LCA like for like.

2.4.6 Emissions from a life cycle analysis of producing biodiesel when compared to diesel

The use of biodiesel can potentially help reduce GHGs and pollutants. Generally, the higher the blend the larger the reduction. There have been numerous studies that have investigated the difference in emissions compared to diesel and this can be seen in Table 2-6.

Table 2-6: Emission level differences for biodiesel produced from different feedstocks along the supply chain when compared to diesel

Emission	% Difference when compared to diesel
CO_2	-72 to 1.1[2,3,4,5]
PM	-20 to 10.3 [3,4,5,6,7,8,9]
HC	-55.6 to -19[1,3,4,5,6,7,8,9]
CO	-50.6 to 17.6[1,3,4,5,6,7,8,9]
NOx	-11.8 to 15[1,3,4,5,6,7,8,9]

Sources: [1]Tan et al., 2012 [2]Whitaker and Heath, 2010 [3]Schumacher et al., 1996 [4]Peterson et al., 1996 [5]Chang et al., 1996 [6]Osborne et al., 2011 [7]Su et al., 2005 [8]Fritz, 2004 [9]Sze et al., 2007

CO_2 has a range of 72% reduction to a 1.1% increase. A large reduction is often due to carbon sequestration by using biomass as a feedstock. During the cultivation, production, and combustion stages of biodiesel carbon dioxide is emitted through the combustion of fossil fuels and biodiesel. This carbon dioxide is then recycled back into the cultivation stage i.e. the growth of plants. However, some studies (Czyrnek-Delêtre et al., 2016) show that it is possible to have an increase in CO_2 if direct and indirect land use change is included. This is quite a contentious area and the full extent of land use change is unclear let alone putting a value on it.

There is often an increase in NOx levels with the use of biodiesel. In this review, there is a range of values; from a reduction of 11.8% to a 15% increase. The increase is because of the higher oxygen in the fuel compared to diesel. There have been attempts to reduce NOx emissions by improving the cetane number. These tests did not result in much improvement and proved to be expensive (Szybist et al., 2005). Also, there have been attempts to help reduce NOx by up to 15% by lowering the levels of oxygen in the system. However, once again this is expensive and with biodiesel already being more expensive than diesel, this is not prudent to use at present. Other studies have seen that it is possible to reduce NOx emissions through modifications in the engine (Mofijur et al., 2012, Peterson et al., 1996, McDonald et al., 1995) because NOx appears to be the emission that is most sensitive to driving conditions. Other possible solutions for reducing NOx emissions include changing the initial chemical composition of the feedstock (Szybist et al., 2005). There are significantly more studies that show an increase, but it is difficult to ascertain exactly how NOx emissions are measured and that is a possible reason why there is a range of levels, both positive and negative (Szybist et al., 2005, Yusuf et al., 2011).

Hydrocarbons (HC) are the only emissions where there is a higher level of certainty on reductions with a range of 19- 55.6% compared to diesel.

2.4.6.1 Emission levels of different blends

Biodiesel can be mixed at different concentrations with diesel. This is called a blend and is often shown as B10 or B20 for example. B10 means that 10% of the fuel is biodiesel, B20 means that 20% of the fuel is biodiesel. There are concerns that B80 or higher potentially damages the engine and causes other engineering problems (Shahid and Jamal, 2008, Mofijur et al., 2012).

Different blends also result in different emission levels. Tests have shown that B100 has the largest decrease in levels and B20 has a smaller reduction. B20 made from soya beans has a reduction in PM, HC, and CO (10.1%, 21.1%, and 11% respectively), whereas NOx emissions increase by 2% when compared to B0 (Markel et al., 2018). Regardless of the feedstock used, there is a reduction in HC, CO, PM, and SO_2. When using B100, many researchers believe that NOx increases by up to 14% compared to B0 (Basha et al., 2009, Wang et al., 2000, Pradeep and Sharma, 2007, Chang et al., 1996, Schumacher et al., 1996). When increasing the concentration of biodiesel in the fuel, emissions and brake specific fuel consumption (bsfc) tend to increase in an almost linear manner (Environmental Protection Agency, 2003, Lapuerta et al., 2008). However, this is not necessarily true for all emissions. Particulate matter is more contentious with disagreement in the literature. Lapuerta et al. (2008) stated that a higher percentage reduction in PM for B25 compared to B50, B75, and B100. On the other hand, some authors conclude that there is a linear reduction with different concentration levels of biodiesel (Graboski and McCormick, 1998, Graboski et al., 2003).

2.4.6.2 Emission levels in locomotives

Emission levels for locomotives are different from road vehicles. Tests have been carried out that show an increase of NOx, HC, and CO when the locomotive is in an idle state when using B20 (Prueksakorn et al., 2010). However, as the blend increases in biodiesel concentration, the emissions show a larger change. At B20 overall emission levels are seen to reduce by 1-7% (Fritz, 2004, McCormick, 2003, Sze et al., 2007) and in a B100 blend emission level, they are seen to reduce by 10-30% in comparison to conventional diesel. HC and CO both showed a reduction; B20 with reductions of 21% and 17% and B100 with reductions of 24% and 34% respectively. However, there are debates about the higher reduction of HC and PM for the B20 blend with some believing that this should be much less (Fritz, 2004).

Studies have shown that most emissions decrease when biodiesel replaces diesel, completely or partially. The large variance in values is for several reasons:

1) The type of feedstock used. Each feedstock has diverse chemical structures and physical properties and will, therefore, react differently when burned or combusted. This difference can lead to different levels of emissions.
2) The blend used. While diesel and biodiesel have similar chemical and physical properties, they are not the same. Therefore, as the concentration of biodiesel changes so will the properties of the fuel. This will consequently add to the range of emissions.
3) The test conditions and facilities may differ. The emissions presented in Table 2-6 are from a range of feedstocks. For example, the faster the fuel combusts and the lower the ignition delay time, the lower the emissions will be, including hydrocarbons and NOx (Lakshminarayanan and Aghav, 2010). This ignition can vary depending on the conditions, such as temperature, and equipment used.

2.4.6.3 Global Warming Potential (GWP)

In transport, GHGs consist of three gases: carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Rather than assessing these gases individually, they are often combined to create CO_2 equivalent, also known as Global Warming Potential (GWP). GWP is "an index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period, such as 100 years" (US Energy Information Administration, no date). These ratios are as follows:

Table 2-7: Global Warming Potential ratios

Gas	20 years	100 years
Carbon dioxide	1	1

Methane	84	21
Nitrous Oxide	264	310

Source: Pachauri et al., 2014

Table 2-7 shows the global warming potential for CO_2, N_2O, and CH_4. CO_2 is 1 because it is the baseline. The ratios show the impact it has on global warming compared to CO_2. For example, if 1 tonne (t) of methane is released into the atmosphere this is 84 tCO_2eq over 20 years. In this thesis 100 years is used, but "for most metrics, global cost differences are small under scenarios of global participation and cost-minimizing mitigation pathways, but implications for some individual countries and sectors could be more significant." (IPCC, 2014)

2.5 COST OF PRODUCING BIODIESEL COMPARED TO PRODUCING DIESEL

2.5.1 Costs of producing biodiesel

In the 1990s when the use of biodiesel was increasing it was more expensive than diesel. Biodiesel produced from oil seeds or animal fats ranged from US $0.3-0.69/l whereas diesel in the US was priced at US $0.18/l and between US $ 0.2-0.24/l in European countries (Bender, 1999). It has also been shown that economies of scale affect the cost of producing biodiesel (Booth et al., 2005). For example, (Bender, 1999) showed that a plant producing 12 million litres of biodiesel a year from animal fats had an operating cost of US $0.09/l whereas a plant producing 115 million litres operated at a cost of US $0.07/l. Another of the main contributing factors to the cost of producing biodiesel is the feedstock cost which can range from 70-95% of the total.

More recent literature suggests that the cost of producing biodiesel is like nearly 20 years ago. Biodiesel is still perceived as more expensive, but there have been some breakthroughs where this has been overcome. Živković et al. (2017) conducted a cost comparison between different feedstocks, whereby 20 different literature sources were used. Several different variables were included such as the process type i.e. batch or continuous production, the plant capacity, and the feedstock. The end production cost ranges from US $0.17 to 2.30/l. Waste materials such as used cooking oil are the cheapest feedstocks to use and made cheaper again if the waste is processed in a plant with a larger capacity. Used cooking oil with a plant size of 7,260 tonnes/year has a biodiesel cost of US $0.58/l whereas a plant with a capacity of 36,036 tonnes/year has a biodiesel cost of US $0.5084/l. Similar economies of scale can be seen for soya oil with capacities of 8,000, 30,000, and 100,000 tonnes/year at US $ 0.733, 0.615, and 0.576/l respectively. What this study does not do is state a baseline figure for a diesel counterpart for comparison. However, it does suggest that biodiesel is around 1.5 times the cost of diesel.

Three primary factors can affect the overall production costs and consequently the price of biodiesel.

1) Technological advancement. For example, this has been seen in Brazil and the US for their production of bioethanol. Daugaard et al. (2015) applied the Stanford-B model and showed that biofuel cost had the potential to decrease by 55-75% on the base case estimates. The same study showed that it was more optimal to invest in strategies and technologies to increase the learning rate compared to investing in advanced biofuels.
2) Economies of scale (as demonstrated above) are present during the biodiesel production stage i.e. the larger the facility the larger the benefits (Bender, 1999). This study analysed three facilities with capacities to produce 2, 12, and 155 million litres per year and total costs estimated at 0.44, 0.37, and $0.32/l respectively.
3) The cost of the overall feedstock. This can range from 70-95% of the total production costs. The large range is due to several influencing factors including the type of feedstock, the country of origin of the feedstock, the plant capacity and whether they are experiencing economies of scale; the yield of the feedstock and finally whether any taxes or subsidies are applied to the feedstock (Živković et al., 2017, Chen et al., 2018, Madani et al., 2017, Patel et al., 2017, Lam et al., 2009b, Shen et al., 2018)

The literature has been forthcoming in stating that biodiesel is more expensive than diesel regardless of whether it is pure biodiesel or a blend; “the cost of biodiesel after blending with diesel will reduce as the cost of biodiesel becomes less significant in blended form," (Cheng, 2009)(p.420). This means that as the proportion of biodiesel in the blend increases so does the overall cost of the fuel. In the USA, B100 cost $3.76 per gallon in June 2006 whereas B20 totalled $2.98 per gallon at the same time (Shurland et al., 2014).

2.6 THE USE OF ELECTRICITY IN TRANSPORT

Another alternative to the use of fossil fuels is the use of electric transport. While there are emissions along the entire supply chain, a large proportion of the emissions come from the direct combustion of the fuel (Agrawal et al., 2014, Spath et al., 1999). There are discrepancies in the transport of coal concerning the amount of energy used, and emissions produced. Some say it contributes to only a small percentage (Odeh and Cockerill, 2008), whereas others believe it to be much larger at around 40-60% of the total supply chain (Spath et al., 1999, Hondo, 2005). This depends on the amount of coal transported and the mode used. Like the feedstock of biodiesel, coal has different forms and properties. This can influence emissions when combusted. For example, "substituting lignite (brown coal) for bituminous coal increases total LCAs by 20.2%" (Odeh and Cockerill, 2008). Coal is, however, not the only source for producing electricity.

2.6.1 A comparison of conventional and renewable electricity generation systems

Electricity is conventionally produced from fossil fuels including coal, natural gas, and oil. Nuclear often falls into this category as well. There is a range of alternative sources which can also produce electricity including wind, solar and hydro. The alternative sources emit lower GHGs. This can be seen in Table 2-8.

Table 2-8: Comparisons of LCAs of the conventional generation with renewable electricity generation sources

Conventional system			Renewable systems	
System	g-CO_2/kWh		System	g-CO_2/kWh

Coal Fired	975.3		Wind	9.7-123.7
Oil Fired	742.1		Solar PV	53.4-250
Gas Fired	607.6		Biomass	35-178
Nuclear	24.2		Solar Thermal	13.6-202
			Hydro	3.7-237

Source: Bhat and Prakash, 2009

Table 2-8 shows the comparison of CO_2 emitted from an LCA when using conventional and renewable systems to generate electricity. Excluding nuclear, the conventional systems produce between 607.6 and 975.3 g-CO_2/kWh compared with the renewable systems which have a range of 3.7-250 g-CO_2/kWh. Even the highest level of emissions from the renewables- solar PV- is less than the lowest value of the conventional system- gas fired. While nuclear is on the lower end of the scale for both conventional and renewable systems at 24.2 g-CO_2/kWh there are other environmental concerns such as the disposal of radioactive materials. For wind, there is a large variation of emissions: 9.7-123.7 g-CO_2/kWh. This depends on the location and the size of the turbine. Schleisner (2000) states that land based wind farms tend to have higher emissions and Jungbluth et al. (2005) demonstrated that offshore turbines have higher emissions. PV systems have a range of 53.4-250 g-CO_2/kWh, and this depends on the materials and the construction (Schaefer and Hagedorn, 1992, Prakash and Bansal, 1995, Alsema, 2000).

2.6.2 Electricity generation in India

The electricity generated in India is primarily for the consumption of the residential, commercial, agricultural, and industrial sectors. Rail traction consumes a minute proportion in comparison at around 2.3%. Electricity supply has had a growth rate of 15% each year, but power shortages are still likely due to excess demand (Bose and Shukla, 1999, Moallemi et al., 2017). The Indian government has recognised this as a growing concern. Electricity in India is primarily generated from burning fossil fuels. In 2016 there was a push to commission new coal power plants to meet the growing demand. Once these are completed and with the addition of renewables producing electricity, by 2030 electricity generation should be exceeding the country's future demand (Shearer et al., 2017). Consequently, India is likely to exceed its committed CO_2 emission levels. This is a concern as CO_2 has been increasing in recent years. In 2005 electricity emissions intensity was 901 gCO_2/kWh and grew to 926 gCO_2/kWh in 2012. This is more than the global average as calculated for the same years; these were 542 and 533 gCO_2/kWh respectively (International Energy Agency (IEA), 2015). There has been speculation that Carbon Capture Storage (CCS) may be able to help with the increasing emission levels, but presently it has not been included in any of the proposed power plants, mainly due to the expense. It is the Indian government's view that by 2030 57% of electricity will be generated from non-fossil fuels according to the (Ministry of Power, 2016); however, in 2016 only 28% was produced from non-fossil fuels (Shearer et al., 2017).

2.6.3 The external costs of generating electricity

External costs occur when a cost is imposed on a third party during the consumption or production of a good or service by another party (European_Commission, 2014). Examples include pollution produced by a power plant affecting the surrounding neighbourhood's health. Zhang et al. (2007) investigated the external costs of electricity generated in China up to the year 2030. The study included pollutants SO_2, NO_x, PM_{10}, and GHG gas CO_2 resulting in external costs of 3,680.42, 2,438.25, 2,624.59, and 50 US$/t respectively.

Mahapatra et al. (2012) monetised the human health and environmental damages caused by the generation of electricity with a range of 1.6-5.8 € per kWh depending on the feedstock used; gas being the lower and coal being the higher values.

Georgakellos (2012) examined the external costs associated with electricity generation in Greece from a life cycle perspective. The marginal external cost of in euros/MWh resulted in lignite fired power generation being the most expensive at 24.30 followed by oil fuel at 16.04 and natural gas at 9.42. Costs can vary greatly depending mainly on the electricity mix (Sánchez et al., 2013, Sánchez et al., 2012).

2.6.4 Electric vehicles (EV)

The electricity mix is important for determining the overall environmental effects of using electric vehicles (Faria et al., 2013, Woo et al., 2017). If a coal power plant is scheduled to be built and the electricity demand continues to rise (also due to a rise in electric cars) there is a possibility that the GHGs will be higher in 30 years than the present day. Only low-carbon electricity will help reduce GHGs with electric cars (Samaras and Meisterling, 2008). On the other hand, GHG emissions are seen to decrease by 3-36% when switching from petroleum-based vehicles even if coal is the main source of electricity; although to have a larger impact a cleaner energy mix is needed (Ou et al., 2010).

While the electricity mix plays a key role in the environmental effects of using EVs, it is not the only influence. The driving cycle and the technology used also play a role. Lajunen and Lipman (2016) examined Finland and California's use of EVs and modelled them separately due to the different driving cycles. They explained that this reason alone makes it difficult to compare results and findings to other studies and countries.

There are two main types of EVs (this excludes hybrids):

1) Battery powered: the vehicle is plugged into the electrical grid and the battery is charged. It is unplugged then driven around until it needs to be recharged.
2) Constant charging: the vehicle is attached to infrastructure (usually wires above) that delivers a constant flow of electricity to the vehicle. Locomotives are more commonly known for using this method.

Electric vehicles used on the road are primarily battery-powered. Literature shows that there are environmental benefits to using electric vehicles compared to other sources of fuels such as biodiesel or LPG. Not only do electric vehicles produce zero tailpipe emissions, but they also produce fewer GHGs and pollutants than hybrids, LPG, and gasoline even when the production and distribution of electricity are included (Boureima et al., 2009, Sánchez et al., 2013).

2.6.5 Monetary costs of using electricity as a power source

From an operational perspective using electricity is a more cost-effective way of powering vehicles. Cooney et al. (2013) observed that switching to electric buses could save $160,000 in operational costs over 12 years. This, however, was not enough to cover the capital costs of $300,000. During the time of this study, diesel was priced at $3.9/gallon. However, were it to drop to $2.8/gallon then diesel would be more effective to operate compared to electricity which was priced at $0.11/kWh (Cooney et al., 2013). This demonstrates that electric vehicles become less feasible when capital costs are taken into consideration.

2.7 COMPARISON OF ECONOMIC ASSESSMENT METHODS

2.7.1 A Cost Benefit Analysis (CBA)

A CBA is a recognised appraisal technique, which is used by decision makers - primarily governmental bodies (Annema et al., 2015). It is used throughout the world (Munger, 2000, Nickel et al., 2009, Valentin et al., 2009, Beria et al., 2011). Many government bodies use this method to assess whether a project is economically viable including those in the Netherlands, the UK, Germany, Austria, Spain (Cascajo, 2005), the US, and Canada (Jones et al., 2014); as well the OECD (Little and Mirrlees, 1969), the UN (United Nations Industrial Development, 1972, Mishan and Quah, 2007) and the World Bank (Squire et al., 1975). In EU countries a CBA and an Environmental Impact Assessment (EIA) are required before a project can begin (European_Commission, 2014).

A CBA uses a common measurement (money) which makes the information comparable. It informs a policy maker with everything they would need to know about a project (Williams, 2008). It gives policy makers objective information and informs them of how social welfare will possibly change due to influencing factors including healthcare and environmental changes. A CBA is a way to help control political action and help regulation become more transparent. A CBA attempts to give an objective analysis of a project by using the information and data of those directly affected.

As mentioned above it is often a requirement to include an environmental assessment as well as a CBA during decision making. In recent years LCAs have been used as the environmental analysis for a project, specifically fuels (Borrion et al., 2012, Larson, 2006, Manik and Halog, 2013, Quinn and Davis, 2015, Shonnard et al., 2015, Von Blottnitz and Curran, 2007, Wiloso et al., 2012, Osorio-Tejada et al., 2017). It is possible to apply monetary values to the results to help identify or compare the possible economic benefits of using different fuels.

To give another angle to the decision a life-cycle sustainability assessment could be carried out (LCSA), although this method has not been applied to any published case studies. The method is comprised of three elements; an LCA, a social life-cycle assessment (SLCA), and a life cycle costing (LCC) (Andrews, 2009, Heijungs et al., 2010, Kloepffer, 2008, Weidema, 2006). As well as including an environmental and cost assessment, a social element is also encompassed. This is to offer policy makers more realistic and comprehensive trade off options (Life Cycle Initiative, 2020).

Even though a CBA is widely used it has been heavily criticised for several reasons; the result is not decisive and trade-offs cannot easily be seen (Annema et al., 2015). When estimating the long-term cost of a project it can be miscalculated by a significant amount (Skamris and Flyvbjerg, 1997, Flyvbjerg, 2007, Maher and McGoey-Smith, 2006, Rasouli and Timmermans, 2012). This miscalculation can happen because of several reasons:

1) It is difficult to get an accurate projection because there are many complex factors to consider (Saha et al., 1988).
2) There are high levels of uncertainties with external costs (Hill et al., 2009, Niemeyer and Spash, 2001, Diakoulaki and Karangelis, 2007).
3) The environmental impact of the construction of facilities is often not calculated and included (Lee Jr, 2002, Edgerton, 2009).
4) The CBA can be distorted for several reasons (Vejchodská, 2015).

While work has been conducted to help address some of these issues, refinements are still needed in these areas (Jones et al., 2014). Some alternatives can be used (different techniques in terms of methods and focus), yet a CBA is still a requirement for government projects.

2.7.2 Multi-criteria decision making (MCDM)

A common alternative to CBA is a multi-criteria decision making method, which considers the differing opinions of stakeholders and then represents them through weights. The analysis can consider the social, economic, and environmental impacts, whereby weights are placed on each indicator. The weights are not necessarily monetary terms, but scores or rankings (Beria et al., 2011).

Some of the advantages which have been concluded from the literature include:

1) Its ability to handle different data sets; quantitative and qualitative (Mendoza and Martins, 2006, Løken, 2007).
2) The broad range of techniques enables MCDM to be applied to multiple and conflicting problems (Mendoza and Martins, 2006, Pohekar and Ramachandran, 2004, Diakoulaki and Karangelis, 2007, Løken, 2007, Wang et al., 2009).
3) It provides a better understanding of the features which are involved in the decision through realistic scenarios instead of using a stance of maximising benefits and minimising costs (Pohekar and Ramachandran, 2004).
4) This method has been widely used and is increasing in popularity (Pohekar and Ramachandran, 2004, Diakoulaki and Karangelis, 2007); successful examples include solar energy projects (Golabi et al., 1981), energy policy making decisions (Jones et al., 1990) and EIAs (McDaniels, 1996)

While there are obvious advantages there are also clear disadvantages and some of these appear like those of a CBA:

1) Due to the different techniques involved with MCDM, it can be difficult to choose the most appropriate approach and this can have a significant effect on the overall judgement (Hobbs and Horn, 1997).
2) As weights are often applied by the stakeholder or those with expert knowledge in the field of the projects these could be subjective and

consequently, the result can be biased towards their preferences and opinions (Diakoulaki and Karangelis, 2007, Wang et al., 2009).

3) Each of the different techniques within MCDM has its positives and negatives (Løken, 2007) and a one size fits all approach cannot be applied.

MCDM and a CBA could be considered as competing techniques, but there have been several attempts in the literature to combine them so that they work with one another. The idea of this is to use the advantages of both methods.

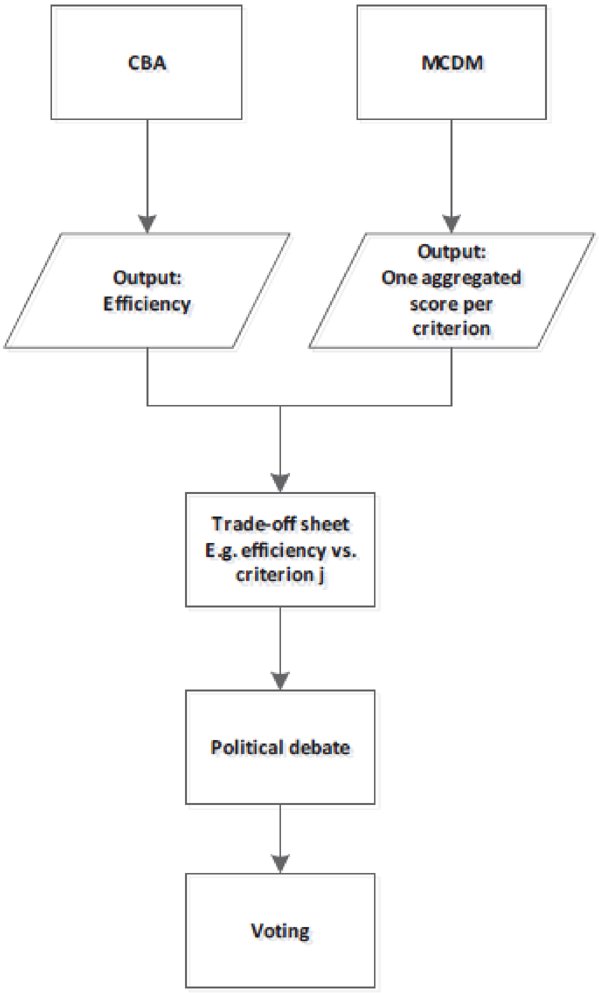

Figure 2-2: An example of how CBA and multi-criteria decision maker methods can be used together

Source: Annema et al., 2015

Figure 2-2 shows one example of how a CBA and multi-criteria decision maker method could be used in conjunction with one another. CBA provides the efficiency criterion and MCDM provides other criteria such as an environmental impact assessment. At this level, none of the criteria is weighted. The next level is comparing all the criteria and weighting them. It is possible to examine trade-offs. It is noted that this trade off approach is a rough idea and would need further research before it could be considered a useful tool.

A real-world example shows that a CBA was conducted to evaluate architecture methods, but this depended heavily on the stakeholders' empirical knowledge. This was difficult to reflect in the CBA. Therefore, the multi-criteria decision maker method was used in combination with CBA to assess which architecture method would produce the highest return. By combining the two methods the knowledge of experts was reflected and it minimised any abnormalities that would have been produced otherwise (Lee et al., 2009). This method enabled those with expert knowledge to place weightings within the CBA, which would otherwise likely have been over or underestimated.

2.7.3 Externalities associated with transport and measures to correct them

When assessing a project, the financial cost is important. What may not be included in the assessment are externalities. For example, when using diesel, the purchase price will be shown in the financial accounts. However, what is not accounted for are emissions during the combustion of the fuel. The variety of emissions can either be detrimental to the environment (GHGs) or human health (pollutants). The creation of negative externalities that are not accounted for leads to market failure (Phaneuf and Requate, 2016). To reconcile these effects, it is possible to apply instruments such as Pigouvian taxes. However, to apply the correct levy, the externality must first be valued. This can be achieved through a variety of methods (Cherry et al., 2017).

Some typical external costs that can lead to market failure if not accounted for are described by Macharis et al. (2010) including:

1) Accident levels

2) Noise pollution
3) Air pollution
4) Climate change
5) Congestion

Externalities do not have a market value, but there are methods to estimate the cost of an externality:

1) Stated preference
   This method reveals a consumer's purchasing habits. Consumers are given hypothetical choices in a scenario and asked to choose. This indicates their preference.
2) Revealed preference
   This method also reveals a consumer's purchasing habits but in conjunction with their budget constraint. An example of this preference is hedonic pricing. This is a comparison of two scenarios when only one aspect changes. A common example is the value of pollution through house prices. Two housing estates have the same characteristics and surroundings except one is next to a power station. The hedonic pricing is the difference in house prices. This difference is the cost of pollution.

There have been several contributions towards the field of establishing external costs for road transport (Newbery, 1988, Jansson, 1994, Maddison et al., 1996, BICKEL et al., 1997, McCubbin and Delucchi, 1999, Sengupta and Mandal, 2005, European Commision, 2019). There are still challenges and uncertainties when forecasting costs (Hill et al., 2009, European_Commission, 2014); it is easy to under- and overestimate the externality values. This is partly due to not having the most up to date information such as real-world emissions; this is then not reflected in the relevant databases. Nevertheless, some databases such as COPERT and TREMOD are considered reliable data sources (European Commision, 2019). Some countries such as India do not have such data (at least not in the public domain) and often borrow values from other countries.

2.7.4 Shadow pricing

A shadow price is a factor that is applied to market values to reflect their true/economic value. This is also called economic accounting prices. It is used to adjust market prices that do not truly reflect the value of the input. In developing countries, the foreign exchange rate is often distorted because the scarcity value of the exchange rate is not reflected effectively. This can lead to import costs being artificially low whilst demand remains high (Adler, 1987). Shadow pricing uses conversion factors to show the true relationship between trade and prices (European_Commission, 2014).

Emerging economies are more likely to have greater distortions because of informal markets such as begging, shoe shining, or cleaning a vehicle windscreen when stopped at a red light (Adler, 1987 p.11). Other contributing factors that lead to greater distortions include “rapid inflation, government controls, over valuation of domestic currency, imperfect market conditions including underemployment of labour.” (Adler, 1987, p.11). Shadow pricing is difficult to apply due to the large amount of data required.

2.7.4.1 Foreign exchange

The cost of imports is often seen as low while demand remains high. This is due to the currency being used misrepresented in its scarcity. Tariffs and quotas are used to balance this misinterpretation. Shadow prices are needed for each input that leads to a distortion; however, this is not practical and often a group factor is applied instead. Adler (1987) recommends using a rate of 1.75 to calculate the economic value of the foreign exchange. This should apply not only on items that were bought from abroad but also on items that were manufactured locally but where the raw materials are imported. For example, diesel produced in India where crude oil has been imported. It is noted that this value is outdated. There appears to be a lack of literature in this area and in studies on imports such as feedstocks to produce biodiesel.

2.7.4.2 Labour and wages

The real cost of labour can be distorted for several reasons:

1) Wage law: when a minimum wage is enforced this could be above or below the real cost of labour depending on the value. Unless the real cost of labour is equal to the minimum wage then distortion will always exist when minimum wage laws are present.
2) Where a market has high levels of unemployment or underemployment there may be differences between the real wage to the worker and those hiring the worker i.e. the worker and the real cost of labour (Bank of England, 1984).

Shadow pricing of labour is difficult to determine due to the constant movement of workers. Seasonal work, which usually consists of unskilled labour, is the most difficult to evaluate. The busiest time in the agriculture sector is the beginning and end of a growing season. Workers are needed to sow and prepare the land at the beginning and at the end to harvest the crop. In-between unemployment is high. At times these labourers will seek work elsewhere, often in the construction industry. In construction, projects are estimated to last for a certain period, but if the project extends then labourers may not go back to the agriculture sector. This leads to a disruption in assessing the labour situation in an area. Labour situations are difficult to determine at a country level due to the uneven distribution of labour and unemployment. In one area there could be a labour shortage and in another no shortage. This is a common problem in unskilled labour due to a lack of mobility. Unskilled labour wages in many emerging economies could be up to 50% lower than the real wage cost due to the reasons above. Shadow pricing of wages should be used with caution and are only necessary where the proportion between skilled and unskilled workers is high, due to the likelihood that wages may be distorted. More often than not shadow wages can be omitted (Adler, 1987).

2.7.4.3 Natural resources

The prices of natural resources used in the manufacturing of a product can often be misleading. While these prices are market derived, they do not represent the cost to the economy. For example, water has a market value, but the cost of environmental damage is not included in the price. Contributions to environmental damage include “production of natural resources, the dilution, and detoxification of wastes, provision of hospitable climate and biodiversity” (Richmond et al., 2007, p.1). By not including the sourcing of natural resources (i.e. mining for coal) or cleaning the waste after use into the price, environmental degradation is inevitable, and thus economic efficiency is compromised.

2.7.5 Nominal or real prices and costs

When conducting a financial or economic analysis two types of costs, prices, and discount rates can be used; nominal or real. Nominal prices are current values; the money paid for something at the time. Real are adjusted according to inflation and deflation. This presents purchasing power in that it shows the number of goods and services that can be bought in the present. It is important to define which is being used in an analysis. In this investigation, costs are used from different sources and consequently different years. This presents inconsistency within the data. If the costs were to be used at face value, then this would be using nominal data. However, using real costs is more advantageous because of the consistency it brings to the model. The year to which the values are adjusted is 2018 as this is the latest year where full inflation data is available.

2.7.6 Comparing externality values of different modes of transport

By applying a “one size fits all” approach to modes of transport there may be wrong signalling to the market and then the market failure still exists. According to the International Union of Railways (2019, rail produces fewer external costs when compared to the road sector. Even within the rail category, there are differences between electric traction and diesel. Diesel traction produces € 34.1 per 100 pkm whereas electric traction has average external costs of € 12 per 100 pkm. The main differences are between air pollution and climate change which are less and absent (respectively) for electric traction.

The EU’s latest handbook (European Commision, 2019) which determines externalities shows a similar pattern in that rail has a lower average external cost than road transport. For example, for air pollution, a diesel car costs € 1.18/pkm whereas a diesel train costs € 0.8/pkm. An electric passenger train is even lower at € 0.01/pkm. This handbook also has a comparison of biodiesel in the bus section whereby the most modern bus (Euro VI) emits fewer pollutants for biodiesel than diesel. A similar scenario is also seen for GHGs; a car running on diesel has a value for climate change of € 1.12/pkm whereas a diesel train has a value of € 0.34/pkm. The Well-to-Tank portrays a different image. The Well-to-Tank analysis includes the production stages up to the point at which the fuel is produced. This analysis shows electric traction has higher average costs than diesel for trains and cars: € 0.8, 0.11, and 0.37/pkm respectively.

2.7.7 Life cycle cost analysis

A life cycle cost analysis (LCCA) considers the economic and environmental impact through the lifetime of a service or good (Belarbi et al., 2016). This is a particularly useful method when considering the building of facilities such as the structure of the building and the different pieces of equipment needed. It can help identify differences in pathways when producing similar goods such as the optimal chemicals or equipment to use when producing biodiesel (Wu et al., 2019). Studies and examples of using LCCA are seen more commonly in the construction industry, there are few if at all any which directly links to biofuels. However, if a new biofuel facility needed to be built then the results of this method could provide valuable insights e.g. when including the environmental impact of building a new biofuel refinery to what is already available i.e. using diesel, is it worth it?

Instead of an LCCA for biofuels, it is more common to use a techno-economic assessment (Wright et al., 2010). It is more useful to understand the technologies that enable a more efficient process rather than building the plant.

2.8 SUMMARY

The literature shows that there is a considerable amount of evidence on the environmental effects of using biodiesel compared to diesel. Biodiesel is perceived as beneficial for helping to mitigate climate change because of the reabsorption of CO_2 into the biomass.

The main obstacle to adopting biodiesel to the wider market is the production cost. The cost of the feedstocks plays a large part in the overall production cost of biodiesel and consequently the price for the end user. What this price does not include is the externalities associated with the production of biodiesel and diesel. It is only with the inclusion of these that the true economic cost can be analysed.

Most literature on biodiesel is about road vehicles and there is little evidence relating to rail or other modes of transport. Therefore, this literature review has shown two main gaps:

1) Negative externalities are often not considered when assessing whether biodiesel should be used as an alternative fuel to diesel. This is important when addressing the wider economic impacts.
2) Most of the literature is associated with road transport but rail is just as important, especially in countries such as India. To maximise the mitigation of climate change, all modes of transport need to be addressed.

The next section will address the method which will be used in the modelling thereafter.

3 Methodologies

3.1 INTRODUCTION

This chapter discusses the methods used for analysing and comparing different fuels.

1) Different blends of biodiesel produced from imported palm stearin ;
2) Biodiesel produced from jatropha cultivated in India;
3) Diesel; and
4) Electric traction.

The analysis will consist of three areas: environmental, financial, and economic. Each section of this chapter will state the software used (if applicable), inputs, and reasoning behind each decision.

3.2 THE CASE STUDY CHOSEN

3.2.1 Geographical location

Indian Railways is electrifying more of its rail network each year. It aims to electrify the entire network (The Economic Times, 2019). There is a question of whether this is the best approach when trying to find alternatives to using diesel. To help understand the answer to this question part of this thesis is comparing biodiesel to electric traction to conclude which is the most viable option.

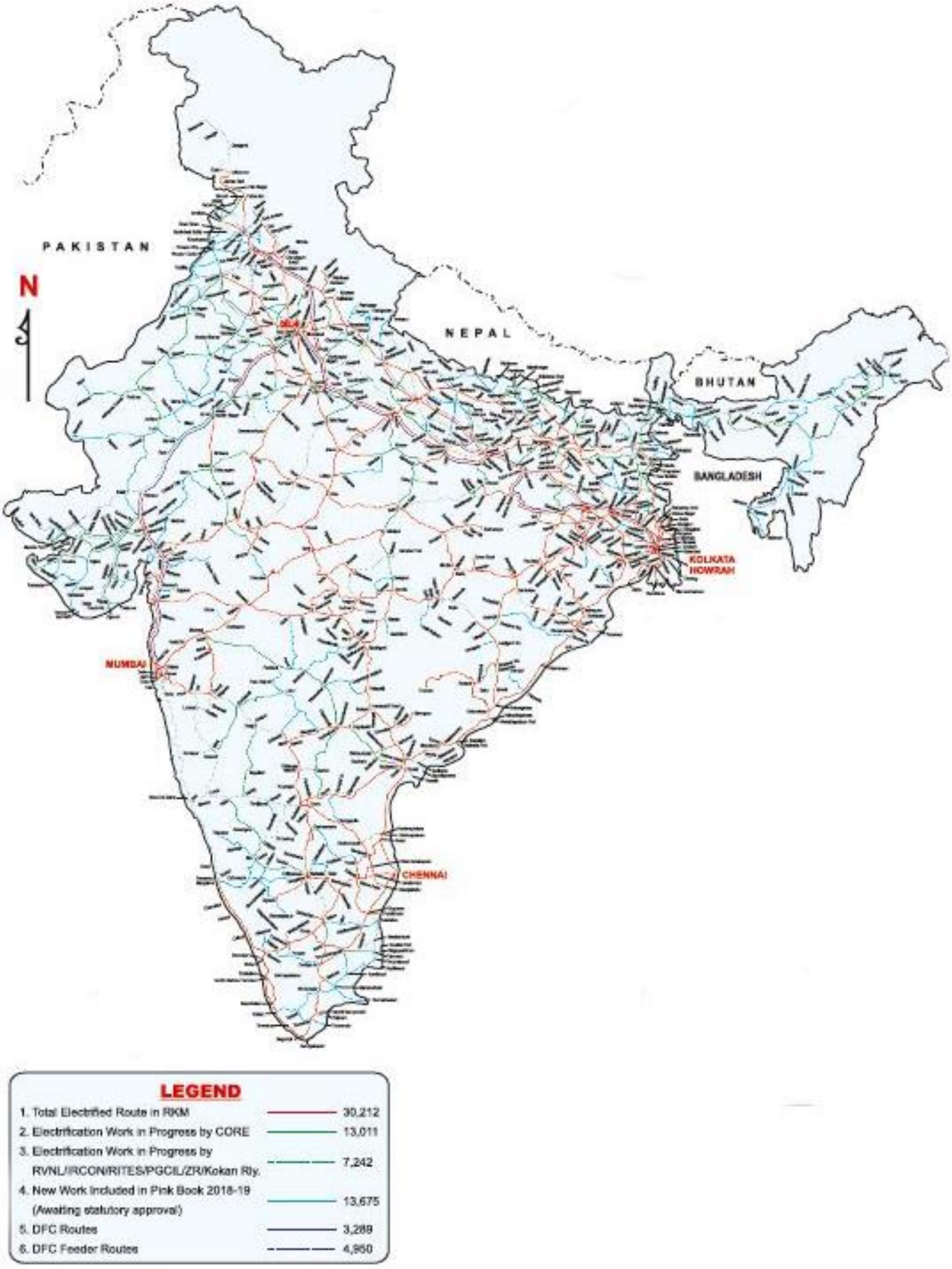

Figure 3-1: Railway Electrification on Indian Railways network

Source: Indian Railways, 2018

Figure 3-1 shows a map of potential railway lines to be electrified in India. The red lines show routes that have already been electrified; the solid green line and dotted green lines show those that are under construction. The blue lines show lines that are waiting to be approved for electrification.

Electrifying lines first started in the 1940s and have been steadily increasing over the years.

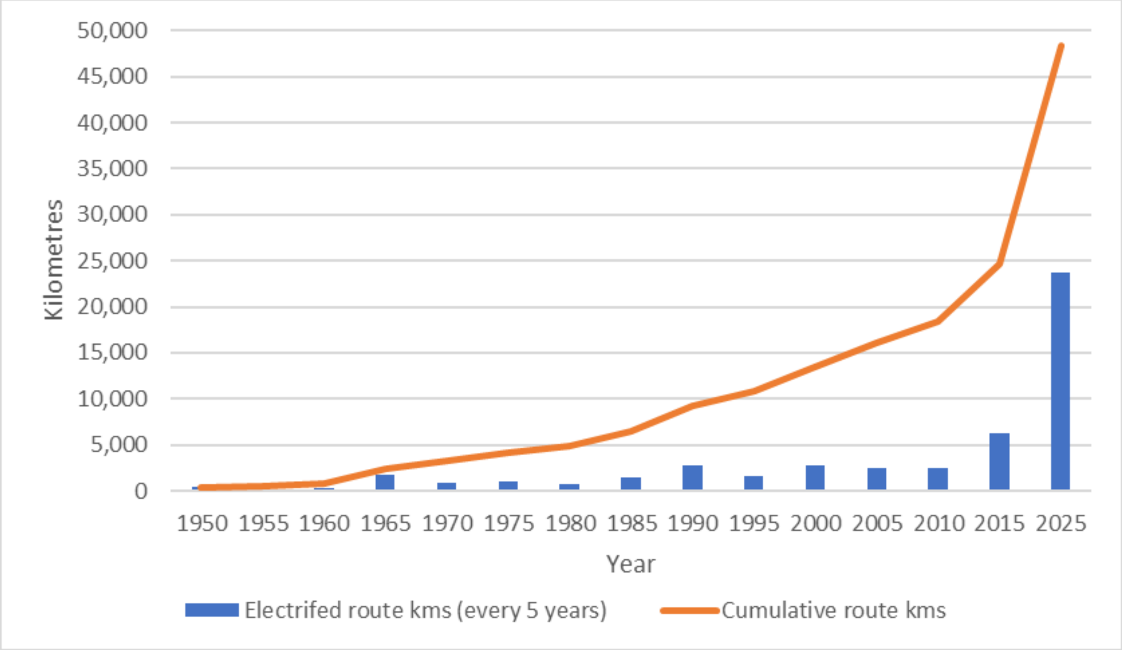

Figure 3-2: The growth of electrified railway traction in India from 1947 to 2025

Sources: adapted from Indian Railways, 2017, Indian Railways, 2020 and Nag, 2020

Figure 3-2 shows the growth of electrified railway traction in India. Even though there has been continuous growth the level of growth during each period has varied. However, from 1985 onwards there was a higher level of electrification during each period. This is due to economic reforms such as import liberalisation that resulted in more easily available capital. Most electricity in India is generated from coal, of which it has large reserves. If it had used this to make electricity rather than importing crude oil to make diesel for use in locomotives, it would have made a positive contribution to India’s balance of trade. However, today there are concerns about the emissions being produced in thermal power stations. Therefore, it is important to assess alternatives such as biodiesel that could be used on the lines which may be electrified.

The case study to be used in this thesis could be either a specific line or section or the entire network. It was decided that a specific line would be used for the following reasons:

1) This thesis is considering the alternatives to diesel, biodiesel, and electric traction. Some routes on the network are already electrified. As a result, these are eliminated from the consideration of which line to choose as a case study.
2) Certain geographical areas in India would not be suitable for using biodiesel. Biodiesel has an estimated pour point (the temperature at which the fuel transitions into a semi-solid state) of -12 to 15°C (Barnwal and Sharma, 2005, Gui et al., 2008, Singh and Singh, 2010, Balat, 2011, Alptekin and Canakci, 2009, Canakci and Sanli, 2008) depending on the feedstock used. Therefore, it is important to use biodiesel where the temperature does not drop below the higher value.
3) It was considered that a comparison of lines in different states would offer insight into optimal locations of using biodiesel or electricity. This was partially based on each state having a different split of sources for electricity i.e. some states have more renewables than others. However, Indian Railways advised that the railways use the national grid average for calculations, so such comparisons would offer little insight.
4) This thesis is comparing alternatives to diesel. This should remain the focus and so looking at multiple lines with different fuels would offer little extra information on deciding which is the most viable.

In the south of India on the east coast, several lines have not been electrified. One is Karaikal Port to Erode Junction line with a distance of 291km.

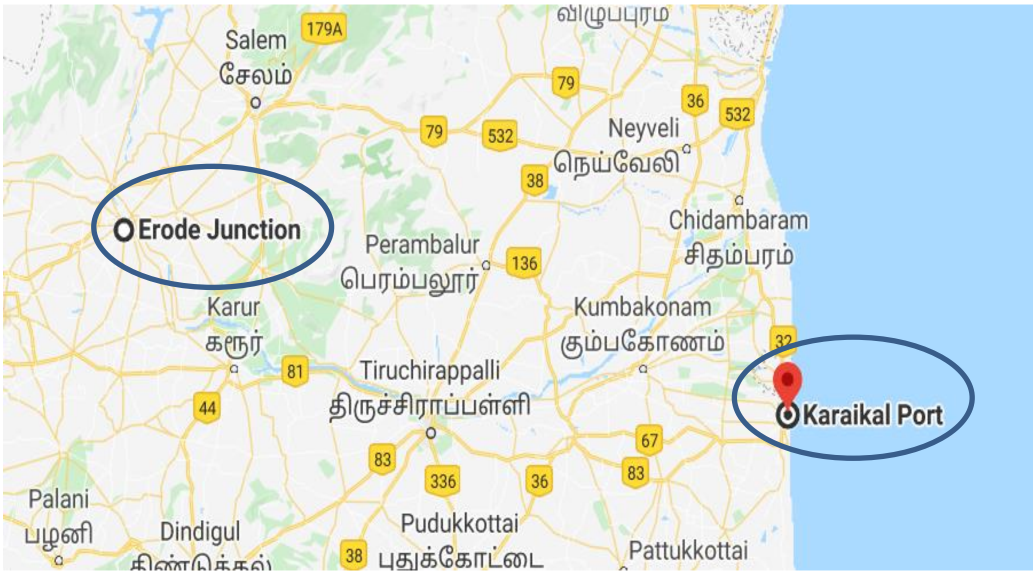

Figure 3-3: Map showing the case study route – Karaikal Port to Erode Junction

Source: Google Maps, no date

The route passes through one state and one zonal railway authority; Tamil Nadu, which is in the south of India and under the jurisdiction of Southern Railways. This line also suits the criteria for biodiesel because it is in the south of India where temperatures average 28 ^{o}C (ClimaTemps, 2015).

3.2.2 The choice of feedstocks when using biodiesel

It has already been noted that different feedstocks to produce biodiesel are compared. These are palm stearin and jatropha. These feedstocks were chosen for specific reasons.

3.2.2.1 Palm Stearin

Indian Railways has tested other feedstocks such as used fish oil as mentioned in 1.3.1. However, it advised that palm stearin should be used as a feedstock. This feedstock, as well as the others, meets India’s criterion of not being an edible crop or seed – palm stearin is a waste product of producing palm oil. It is an approved feedstock to be used by Indian Railways. The primary reason for this is that it is the most cost-competitive to diesel compared to the other feedstocks as discussed with Indian Railway officials.

3.2.2.2 Jatropha

Out of the feedstocks that Indian Railways tested jatropha was the only one that was cultivated in India, all others were imported. Through the explanation in 3.2.2.1 jatropha was not an approved feedstock because of the cost. However, there may be additional benefits to using a feedstock grown in India such as reduced transportation and an increase in jobs through the creation of a domestic market. Other feedstocks could be grown in India and used to produce biodiesel, but Indian Railways already has some experience in using jatropha as a feedstock for biodiesel, not in rail but for the road sector. More explanation on this can be seen in 6.5.2. The Indian government can learn from existing research relating to jatropha. Therefore, using jatropha is a realistic and viable feedstock producing biodiesel to be used by Indian Railways.

3.3 ENVIRONMENTAL LIFE CYCLE ANALYSIS (LCA)

3.3.1 Reasons for choosing an LCA

A background explanation of an LCA is given in 2.4.1. There are few alternatives to using an LCA method. One of the virtues of an LCA is that because it is so versatile it can be adapted to meet the user's needs. This, however, comes with its drawbacks as explained in 2.4.1 including concerns about credibility and transparency. By building one's own LCA for each of the feedstocks, the concerns are subdued because the inputs can be more easily controlled.

Using an LCA is appropriate to use in this thesis because it can be adapted to meet the needs of the desired outcome using the functional unit, system boundary, etc. and can be used to compare the different fuels. Further details are in section 3.3.2.

3.3.2 Life cycle analysis specifics

This thesis analyses four fuels and power sources, therefore it is necessary to have this many LCAs; diesel, biodiesel produced from imported Malaysian palm stearin, biodiesel production from Indian grown jatropha, and electric traction. The LCA measures the output of the locomotive travelling a return journey of the chosen route. This is known as the functional unit. An LCA also needs a system boundary. A system boundary is the supply chain showing the inputs and outputs needed to achieve the functional unit (Pelletier et al., 2019). There is no set method for determining the boundary so it is often difficult to interpret other LCAs unless they are very clearly defined (Li et al., 2014). This thesis has a Well-to Wheel approach. This gives an analysis of the main contributing factors including the production and use of the fuel.

3.3.3 The output of the LCAs - emissions

The purpose is to examine the environmental effect of using alternatives to diesel. With climate change and people's health at risk from combusting fossil fuels; GHGs and pollutants are the output analysed in this thesis. GHGs directly contribute to global warming – these are global emissions. Pollutants, unlike GHGs, do not affect the earth's temperature, but people's health – these are local emissions. Over time they can cause health problems such as allergies, respiratory problems such as asthma and bronchial hyperreactivity; cardiovascular diseases, and cancer; in particular, lung cancer (Krzyżanowski et al., 2005). According to the World Health Organisation (WHO), road traffic is the largest contributor to pollutants produced from the transport sector; however, this does not mean that other modes of transport are insignificant (Krzyżanowski et al., 2005). It is important to reduce in all areas.

Until recently nitrogen oxides (NO_x) and carbon monoxide (CO) were labelled as two of the most harmful pollutants. More recently, particulate matter (PM) has also attracted attention with findings suggesting that it is dangerous to human health. PM is not only directly released through the tailpipe but is also formed in the atmosphere from already existent pollutants such as NO_x and sulphur oxides (SO_x). Therefore, the pollutants that will be assessed when introducing biodiesel to locomotives are:

- CO
- NOx
- SOx
- PM_{10}
- $PM_{2.5}$

It is noted that these pollutants are produced along the entire supply chain of the life cycle analysis. However, because they are local emissions they will only be counted when they are emitted in India.

Indian Railways has opted to use a 5% blend and therefore proportions of diesel and biodiesel are needed to represent the proportion of emissions. This is calculated using the below equation (1).

$$B5\ blend = (biodiesel\ total * 0.05) + (diesel\ total * 0.95) \quad (1)$$

The baseline is an analysis of emissions including B5, B100, and B0. However, more blends are included for biodiesel produced from palm stearin compared to diesel.

3.3.4 Spatial, functional, and temporal aspects of the LCA

To get the output inputs are needed. When deciding the scope of the inputs different components need to be cogitated. For example, the inclusion of spatial or temporal awareness.

It is becoming more common to include spatial awareness in LCAs. It gives further understanding and evidence from an environmental perspective of the effects that bioenergy can have on, for example, land use change or how far a piece of land is from a water source (Chaplin-Kramer et al., 2017). The LCA can be integrated with the Geographical Information System (GIS) to help this understanding (Hiloidhari et al., 2017). This thesis has followed literature suggestions and Indian Railways' advice on the logistics of fuels. These include:

- The biodiesel production facility is based in Karnataka (a facility that already produces biodiesel for Indian Railways)
- The cultivation site of jatropha is around 50km from the biodiesel production facility
- Optimal location of jatropha cultivation sites
- The crude oil is imported from Nigeria
- The transportation of the fuels and feedstock e.g. tanker, pipelines

The life cycle of bioenergy could be affected by temporal means such as the impact of perennial crops and non-productive years (Raschio et al., 2018). LCAs can be adapted to include such effects. Palm stearin is a by-product so it is not purposely grown to be made into biodiesel so spatial and functional aspects are not taken into consideration.

As jatropha would be a crop purposely grown in India on locations that are not already established to cultivate then it could potentially be an important aspect to include. However, this largely depends on the land which is being used (Bailis and Baka, 2010). However, when converting wasteland or abandoned agricultural land to establish a jatropha plantation there are no significant adverse negative effects such as releasing additional carbon into the atmosphere (Firdaus and Husni, 2012, Kgathi et al., 2017).

3.3.5 Software

The software used is GREET as developed by Argonne Laboratories in the US. This is a key piece of software for estimating upstream emissions (Ogden et al., 2004). This software is used by Indian Railways and boasts many other credible aspects. These include having a large default database of input and output values and the ability to tailor an LCA supply chain to the needs of the study by using the default values as well as inputting one’s own data. This LCA piece of software is specifically designed for transport.

Currently in GREET, having a locomotive as a vehicle is not an option; therefore, a compression ignition vehicle was selected, and consumption and emission levels were added. This information comes from RDSO/Indian Railways. The specifics of the engine are explained in section 3.4.

3.3.6 Diesel Life Cycle Analysis

The overall output of the LCA is described in 3.3.3. It also explains that not all emissions are counted at every stage. By breaking down the LCA at each stage it is possible to analyse emissions at each stage (where relevant). The inputs and outputs for each stage of the LCA are outlined in Figure 3-4 Each input is linked to a value. The values are primarily taken from GREET’s database, due to there being very little in the literature. Those inputs highlighted in red use default pathways. The specific ones used in GREET are given in Table 3-1.

Due to this thesis also looking at electric traction a separate LCA was created for the electricity generated and used to power an electric locomotive. This electricity LCA is used in the diesel LCA where electricity is an input.

The diesel input used in the fractional distillation stage has the A diesel input was looped back from the total diesel LCA.

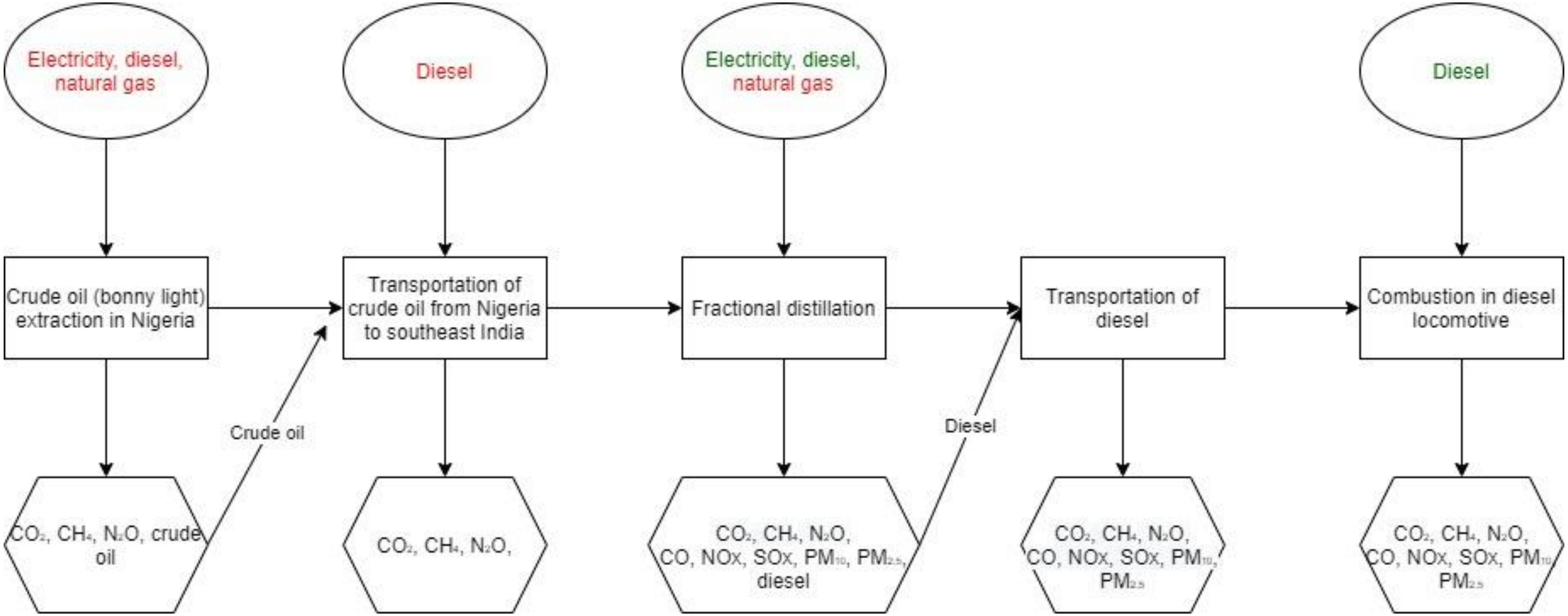

Figure 3-4: Life cycle analysis of diesel used in locomotives in India

Source: author’s own

(red = GREET default LCA; green = author’s own LCA)

Time in India aided the understanding of the supply chain of diesel. For example, Indian Railways advised that Bonny Light crude oil was used, which is imported from Nigeria. Therefore the ‘Well’ of this LCA is in Nigeria.

Pollutants affect people’s health and as the focus is on India’s economy, pollutants produced in Nigeria are not accounted for in this model. However, GHGs lead to global warming therefore GHGs at each stage of the supply chain are counted in the model. There is debate on whether GHGs should be included at these stages at all, due to the international trade of CO_2. The GHGs are being produced by Nigeria and not India so it raises the question of whether India should be accepting these emissions into their GHG inventory, but as this is an international emission it should be included. To add further reasoning, the demand for crude oil from India motivates oil extraction in Nigeria. If the demand were not there, then the emissions would not be there either, therefore it is included in this model. For the further stages of fractional distillation, transportation of diesel, and combustion in the engine all GHGs and pollutants are included.

3.3.6.1 Data used for the diesel LCA

There are limited resources in the public domain that provide a breakdown of input and output values for diesel production; therefore, default data in GREET is used for diesel production. The data had to be scaled to obtain the functional unit. Whilst it is difficult to compare the input data with other literature it is possible to check with the results of other published work to ensure quality, reliable data is used for the LCA.

Values used to attain the functional unit are found in Table 3-1. Full details are given in appendix 8.

Table 3-1: Inputs to LCA to produce 1 tonne diesel

Diesel	Value	Unit	Note
Oil extraction			
Data used from GREET (diesel produced from US refineries)			Scaled up to meet functional unit
Transportation			
Distance	16,108.7	km	Ocean tanker (fuel is the default in GREET)
	1302	km	Pipeline (fuel is the default in GREET)
Fractional distillation			
Crude oil	4,562	kg	This is the amount needed to produce 1,000kg of diesel
Electricity	220	kWh	Electricity is a pathway used for electric traction
Water	1182.2	kg	
Unfinished oil	4.0625	MMBtu	Data used from GREET (diesel produced from US refineries)
Natural Gas	46.8609	MMBtu	

Transportation			
Distance	100	km	HGV (fuel is the default value in GREET and assume 30% urban environment)

During work in India, it was advised to build an LCA where the crude oil is imported from Nigeria (Bonny Light crude oil) and transported to the southeast coast of India. The final product i.e. diesel is transported through pipelines.

3.3.7 Life Cycle Analysis of Biodiesel produced from Imported Malaysian palm stearin

The life cycle analysis for biodiesel produced from palm stearin is like the diesel LCA and can be seen in Figure 3-4 The source and pathways of diesel, natural gas, and electricity have already been explained in 3.3.6. Default pathways already in GREET are used for fertilisers, water, methanol, and sodium hydroxide.

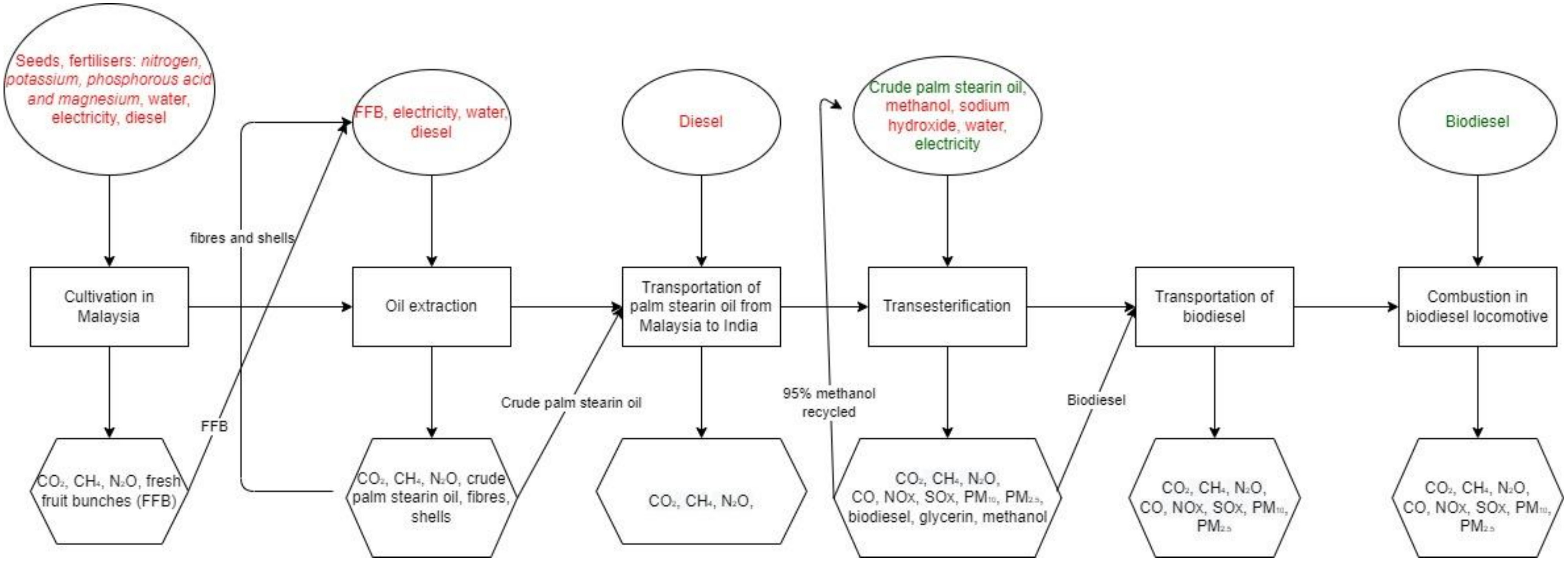

Figure 3-5: Life cycle analysis of biodiesel produced from palm stearin used in locomotives in India

Source: author’s own

(red = GREET default LCA; green = author’s own LCA)

Southern Online BioTechnologies (SOBT) is a biodiesel production company that meets the criteria to provide Indian Railways with biodiesel (Indian Railways, 2015). The LCA of the cultivation stage through to oil extraction is completed in Malaysia. The crude palm stearin is then transported to India from Malaysia.

It is common for fibres and shells to be used as fuel for the furnaces used during the oil extractions stage. This is assumed in this thesis and these wastes are recycled back into the GREET model and emissions adjusted accordingly.

One of the inputs during transesterification is methanol which SOBT recovers at a 95% level and then recycles to be reused. This is incorporated into the GREET model.

Glycerine is a by-product during the transesterification stage. This has a market value and is therefore included as additional income to biodiesel.

Once the biodiesel has been produced it is transported Karaikal Port, the origin of the route being used in this model.

3.3.7.1 Data used for the biodiesel produced from palm stearin LCA

When cultivating palm, palm stearin is not the desired product, it is palm oil. Palm stearin could be classed as different outputs, for example, a co-product or a waste. Palm stearin meets the criteria for India to use it as a feedstock for producing biodiesel. For this thesis, it is a co-product because there are other uses for it, such as using it in the chemical or cosmetic industry. In LCAs it is common to allocate a proportion of the emissions to other outputs other than the main product. What is meant by allocating is that the output of producing a product, e.g. emissions, can be split between, products, and co-products in different ways such as through energy, mass, or cost. Doing so ensures appropriate weighting is given. There are different methods for determining allocation, most used are by mass, energy, or cost. Literature favours mass or energy (Ekvall and Finnveden, 2001, Renewable Transport Fuel Obligation, 2008) but there is also economic/cost allocation. Each method has its limitations, although energy appears to be the most favourable (Yan and Boies, 2013, Gnansounou et al., 2009). This method allocates any emissions associated with their intensity within the LCA. In this thesis emissions only associated with palm stearin would be counted towards the output.

A market-based system argues that it is more transparent and subjects industry to take ownership of the GHG emissions. However, market prices are often subject to fluctuate depending on demand and supply but also future prices of the products can lead to levels of uncertainty, which could affect business and investment decisions (Wang et al., 2011).

Noting the importance of allocation this is applied for palm stearin because this is not the main product when cultivating palm and should only have the associated emissions applied. It has been estimated that palm stearin should be allocated approximately 21.5% of energy (Papong et al., 2010).

Another factor to consider is whether more palm stearin is required to produce enough oil to transestify into biodiesel. For every tonne of palm oil produced, there is 290kg of palm stearin produced (Papong et al., 2010). This indicates that to have enough palm stearin to produce one tonne of diesel a little over three times the amount (3.45) is required compared to palm oil.

Taking this into account the following steps were taken to determine the inputs for the palm stearin model:

1) Due to there being multiple values for each of the inputs from different sources an average is taken and then adjusted to fit the functional unit of the LCA; full details can be found in appendices 1-3.
2) To allow for the additional palm stearin needed the values from step 1 above have a factor of 3.45 applied to them (0.29kg palm stearin/tonne palm oil)
3) As palm stearin is a waste it should only account for a proportion of the total out of emissions. As mentioned above it has been estimated that 21.5% of energy should be given to palm stearin.

The final values that have been used in the model are found in Table 3-2 below.

Table 3-2: Inputs used in LCA for biodiesel produced from palm stearin

Biodiesel (from palm stearin)	**Value**	**Unit**	**Note**
Cultivation			
Seeds	291.48	kg	Literature (21.5% energy is not applied as this is needed to get enough FFB)
Nitrogen	52.07	kg	Nitrogen mix pathway in GREET
Potassium	97.93	kg	Mix pathway in GREET
Phosphoric acid	18.56	kg	Mix pathway in GREET
Magnesium	11.12	kg	Mix pathway in GREET
Water	926.72	M^3	Primary source
Diesel	1.83	kg	Pathway diesel produced from US refineries
Oil extraction			
Fresh fruit branches	16683.36	Kg	Literature (21.5% energy is not applied as this is an absolute needed to get enough palm stearin oil)
Electricity	57.42	kWh	Pathway mix for the US
Diesel	9.17	l	Pathway diesel produced from US refineries
Water	2.47	M^3	Primary source

Shell	250.93	kg	Literature
Fibre	794.26	kg	Literature
Transportation			
Distance	3,675	km	Rail 50km (fuel is the default in GREET) Ocean tanker 3,076km (fuel is the default in GREET) Rail 549km (5% urban share) (fuel is the default in GREET)
Transesterification			
Crude palm stearin	1170	kg	Literature
Methanol	178.37	Kg	Methanol pathway from GREET
Sodium hydroxide	7.83	kg	Sodium hydroxide pathway from GREET
Electricity	186	Kg	Electricity is a value used for electric traction
Water	211.96	M^3	Primary resource
Glycerine (output)	423	kg	literature
Transportation			
Distance	1000	km	Pipeline

When allocating the energy content to the palm stearin portion of the supply chain this is only applicable to the cultivation and oil extraction stages. This is because by the transesterification stage all wastes, co-products, and products have been separated and can be treated as a standalone without the need for further consideration.

3.3.8 Biodiesel produced from Indian Grown Jatropha life cycle analysis

Jatropha is cultivated in India, however, there are optimal locations to do this not only for botanical reasons but also for transportation reasons. Transporting the feedstock is an added cost to the overall cost and therefore the end price.

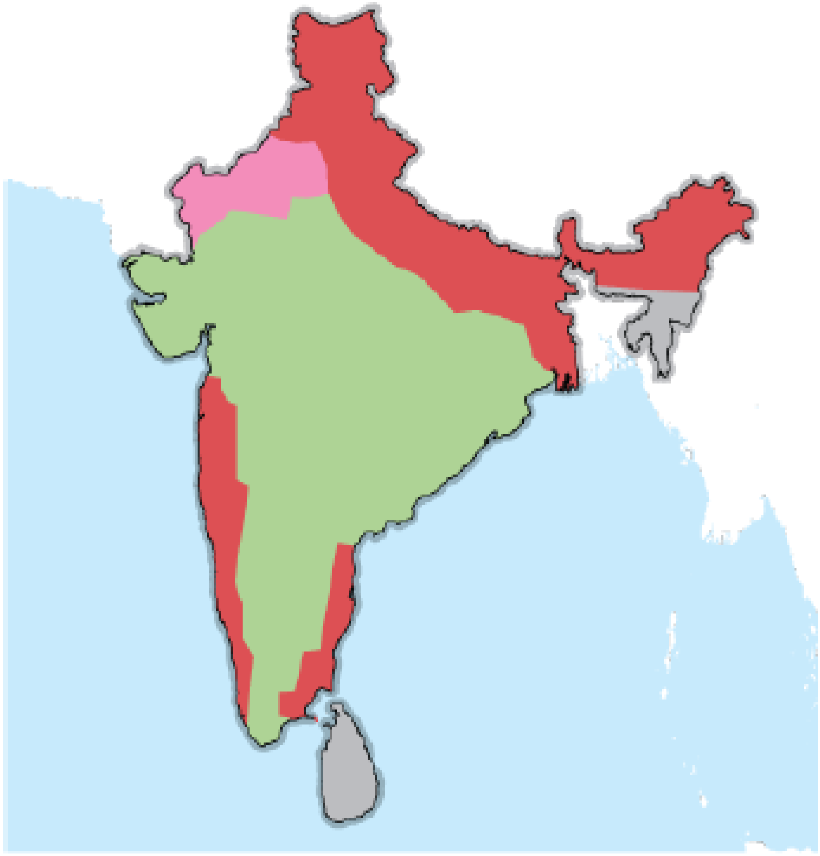

Figure 3-6: Jatropha cultivation zones

Source: Whitaker and Heath, 2010

The green area shows the optimal location to grow jatropha. The red zones show fertile land, which is unlikely to be used to grow jatropha due to favouring agriculture for food. The pink is desert where it would not be possible to grow jatropha due to poor growing conditions. As the production plant is based in Hyderabad, the fields where the jatropha is grown should be within reasonable proximity to the production facilities. Some authors estimate that a 50km distance is reasonable to assume (Ajayebi et al., 2013, Hou et al., 2011).

Jatropha is a crop that has been championed across India due to it being able to grow on India’s vast wastelands rather than precious agricultural lands. It has many properties that are described in 1.3.1. The main reason jatropha has been chosen as a comparator to palm stearin-based biodiesel is that it meets India’s criterion of not being an edible crop. It supports India’s plight to pursue an energy security agenda by not relying on imported energy and increases the generation of jobs and incomes through being able to grow jatropha on wasteland (Sharma, 2019, Garg et al., 2011).

Similar inputs were used for biodiesel produced from jatropha as for palm stearin.

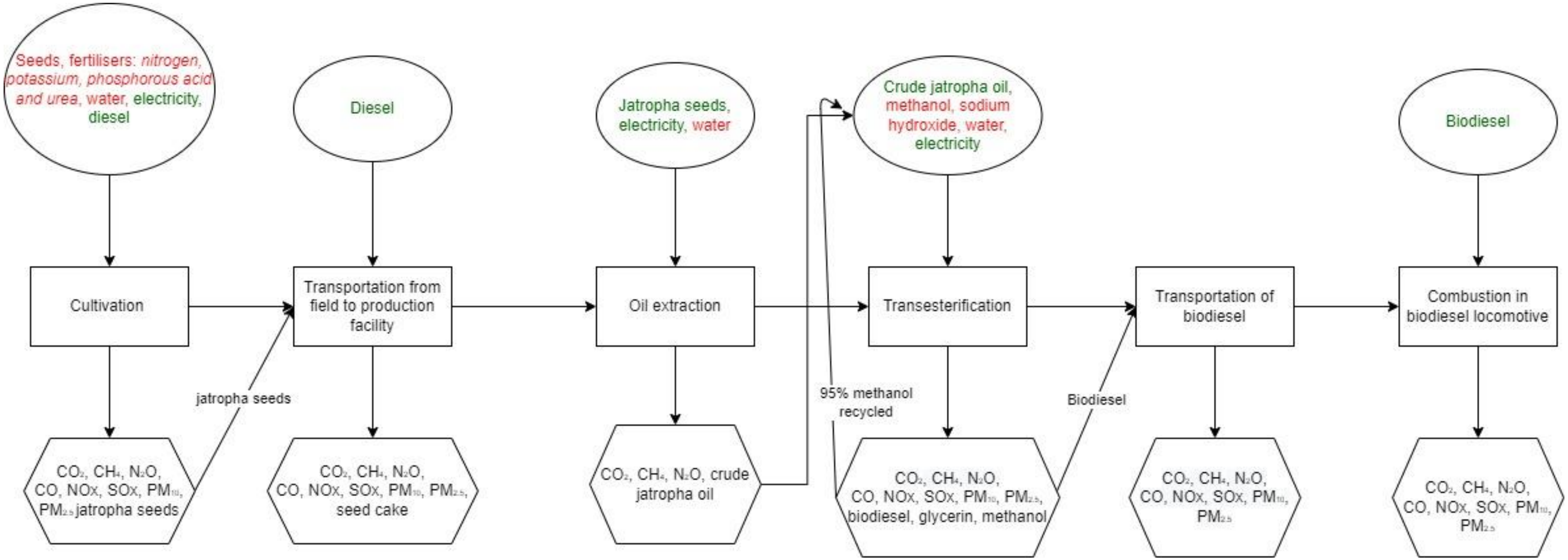

Figure 3-7: Life cycle analysis of biodiesel produced from jatropha in used in locomotives in India

Source: author’s own

(red = GREET default LCA ; green = author’s own LCA)

Unlike diesel and biodiesel produced from palm stearin, this LCA includes all pollutants and emissions along the supply chain. As jatropha is produced into biodiesel by SOBT, like palm stearin, conditions are the same, such as temperatures, catalysts, and time.

From the oil extraction stage, seed cake is a co-product and can be used as a fertiliser or used as a feedstock to produce biogas. However, as stated in section 2.4.3, this is often not utilised. Therefore, to be in keeping with the literature and real-world practice, in this thesis the seed cake is not recycled.

As mentioned above, biodiesel produced from palm stearin glycerine is a by-product during the transesterification stage. This has a market value and is therefore included as additional income to biodiesel.

3.3.8.1 Data used for the biodiesel produced from jatropha LCA

Data is sourced primarily from academic papers or government documents. The difficulty in using different sources is that each author may use their functional unit and data. Therefore, it is necessary to adjust the data to suit the functional unit. Full details are found in appendices 4-6 and a summary of values used is seen in Table 3-3 below.

The input values as already mentioned come from primarily the literature. However, in GREET it is possible to link to input values through an existing pathway. This was an important factor to include because it considers the energy and emissions needed to produce that product. For example, sodium hydroxide input value was obtained from the literature, this was inserted into the GREET software and then linked to a pathway. A pathway is an LCA that accounts for inputs and outputs – GREET has an inbuilt database of many pathways.

Table 3-3: Inputs used in LCA for biodiesel produced from jatropha

Biodiesel (from jatropha)	Value	Unit	Note
Cultivation			
Seeds	3866.35	Kg	Literature
Nitrogen	107	Kg	Nitrogen mix pathway in GREET
Potassium	92.7	Kg	Mix pathway in GREET
Phosphorous acid	84.3	Kg	Mix pathway in GREET
Urea	159.8	kg	Mix pathway in GREET
Water	254	M^3	Primary source
Diesel	50.2	kg	Diesel pathway (author's own)
Transportation			
Distance	50	km	Rail (fuel is the default value in GREET and assume 5% urban environment)
Oil extraction			
Seeds	3.58	Tonnes	Literature Previous pathway in GREET
Electricity	227.5	kWh	Electricity is a pathway used for electric traction
Steam	1082	kg	Natural gas pathway in GREET

Hexane	14	kg	Liquified petroleum gas from crude oil pathway in GREET
Water	42	M^3	Primary resource
Seed cake (output)			Literature
Transesterification			
Jatropha oil	1162.95	kg	Literature Previous pathway in GREET
Methanol	112.63	kg	Methanol pathway from GREET
Sodium hydroxide	48	kg	Pathway from GREET
Electricity	38	kWh	Electricity is a pathway used for electric traction
Water	48	M^3	Primary resource
Glycerine (output)			Literature
Transportation			
Distance	1000	km	Pipeline

3.3.9 Electric Traction life cycle analysis

The electric traction LCA is most like the LCA of biodiesel produced from jatropha because all stages of the cycle are completed in India. Therefore, pollutants and GHGs are counted at each stage along the supply chain.

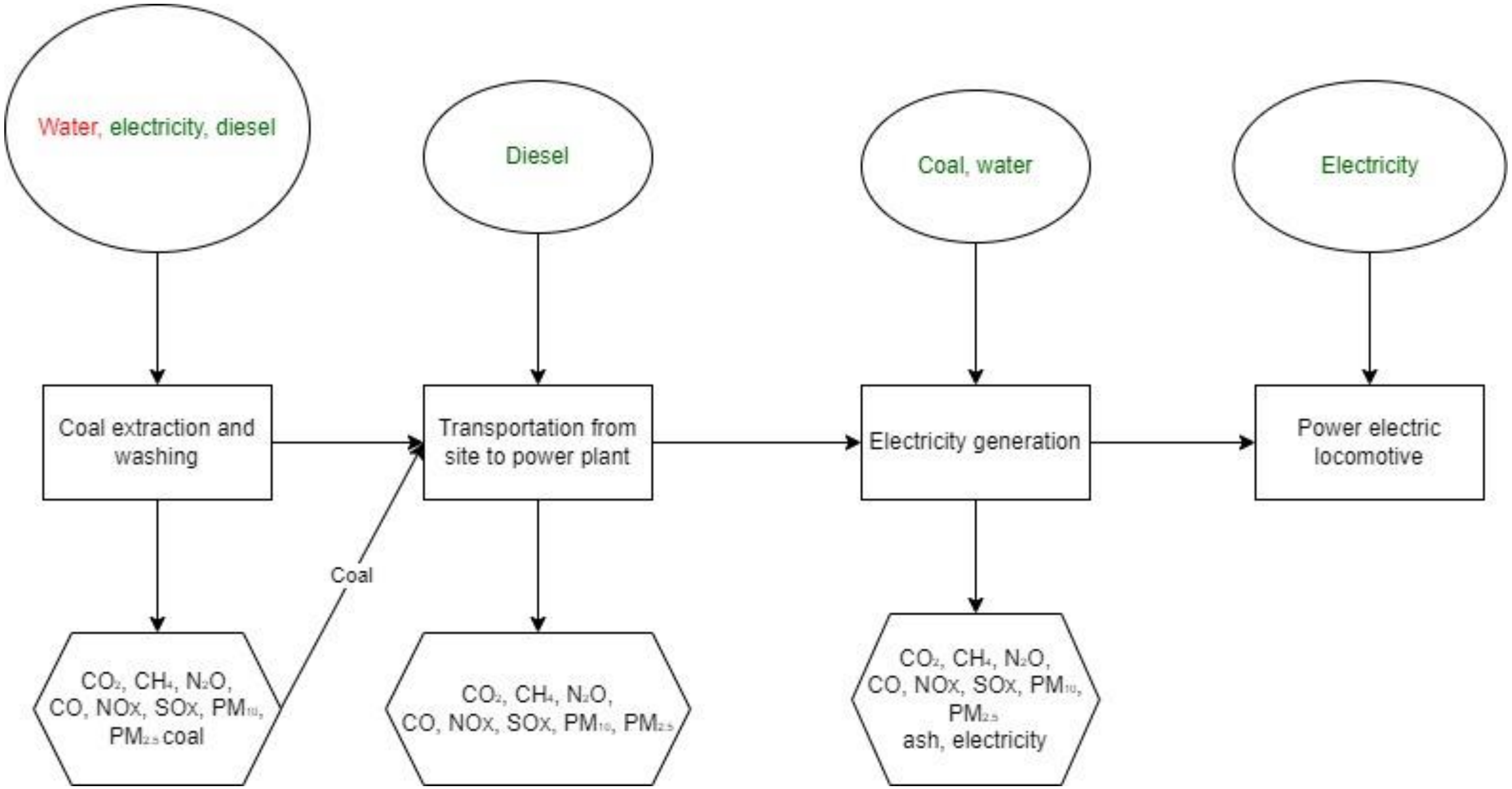

Figure 3-8: Electric traction LCA with inputs and outs along the supply chain

Source: author's own

(red = GREET default LCA; green = author's own LCA)

The LCA is being created for the supply chain of electricity generated through the combustion of coal. It is recognised that coal is not the only source of electricity in India as seen in Figure 3-9.

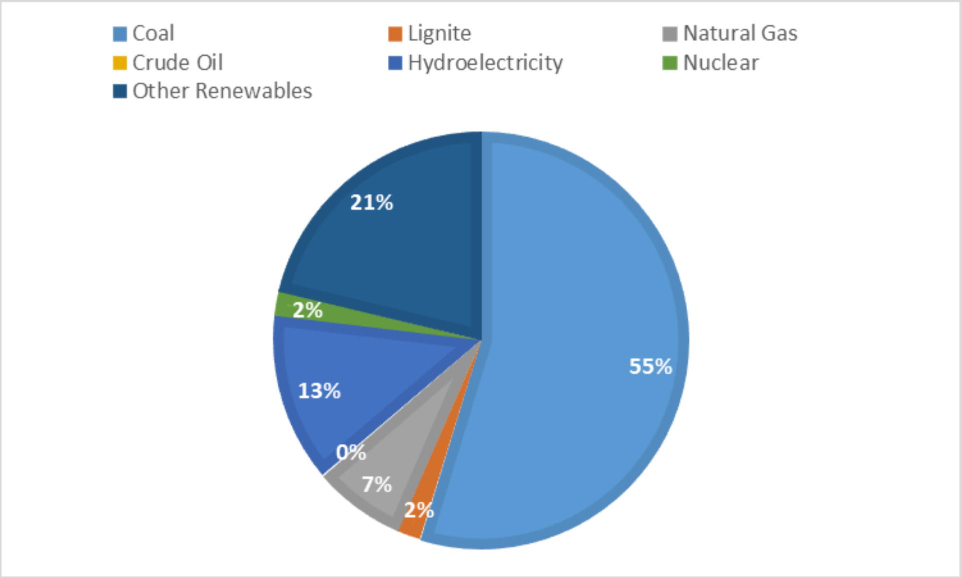

Figure 3-9: India’s electricity mix as of March 2019

Source: Ministry of Power, 2019

The electricity mix is important regarding environmental, financial, and economic sustainability. Therefore, the electricity mix in India is the most up to date available in published works. The LCA is designed only to incorporate coal into the mix. However, the other sources are included, but only in the overall output. The supply chain for coal has been designed to reflect the process i.e. mining the coal in India and transporting it to the power stations in India. The other sources for electricity generation are in the base system for GREET and these values are used in the model.

There is a loss of electricity during transmission mainly caused by line heating. In 2010 the IEA estimated that in developed countries losses were between 5.1 to 7.7%, whereas in emerging economies it ranged from 11.6 to 20.7% in the same year (ETSAP, 2014). The EIA estimated this is around 5% (EIA, 2019) but the World Bank estimated that the loss varies in different countries. (The World Bank, 2018). India had a loss range of between 16 and 20% except during the early 2000s when it rose sharply to 28% before dropping to a little under 20%. It is important to incorporate the transmission loss into the LCA; this is done during the electricity generation stage. If there is a loss, then more electricity is needed to compensate. Therefore 18% more electricity is produced to incorporate this loss. 18% loss is being used because this is the average loss in India across the years excluding the abnormal peak in the early 2000s.

3.3.9.1 Data used for an electric traction LCA

The data used for creating the electric traction LCA took a different approach to the other LCA mentioned above. The LCA for electricity generation from coal was already available on the GREET database, however, it was set up as an inbuilt system where it was not possible to add in own data without rebuilding the system. This was an option, but the data needed to rebuild it was limited. By using the database already in GREET the model was closer to real-world parameters and inputs.

Values used in the LCA for electric traction are given in Table 3-4 below.

Table 3-4: Inputs used in LCA for electric traction

Electric traction	Value	Unit	Note
Coal extraction and washing			
GREET database – coal average			
Transportation			
Distance	100	km	Rail (default value for the fuel input and assuming travel through 7% urban area)
Electricity generation			
GREET database –electricity generated from coal powering a steam turbine			

Coal only accounts for approximately 55% of the total electricity. This leaves 45% of electricity which is generated differently. Figure 3-10 shows how the other 45% is accounted for.

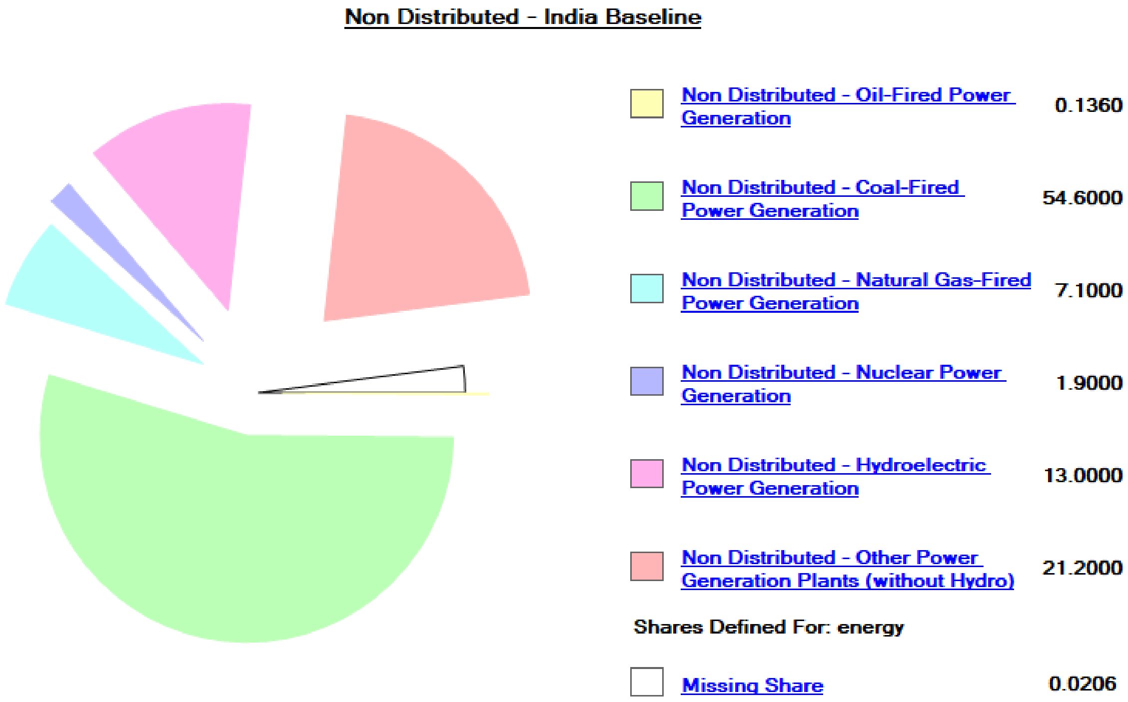

Figure 3-10: GREET electricity split for India - data are taken from Figure 3-9 and put into GREET software

As mentioned previously in GREET it is possible to use pathways already built into the software. This is what is used for the other sources of electricity. These pathways are listed in Figure 3-10.

3.4 ENGINE AND CALCULATIONS USED FOR THE LCA

GREET did not have the option to select a locomotive as a vehicle, therefore an alternative engine was chosen. Details of the engine outputs of the locomotive are given below. These were inputted into GREET.

Table 3-5: Indian locomotive's engine outputs for an ALCO 3100 HP

ALCO 3100 HP	
Consumption (kg/hr)	143
Calorific Value (MJ/kg)	44
NOx (gm/bhp-hr)	15
THC (gm/bhp-hr)	0.3
CO (gm/bhp-hr)	1.3
PM (gm/bhp-hr)	0.1

Source: from IR, during a trip to India

Table 3-5 estimates how much fuel is needed for the journey and the combustion emissions. The data was obtained through a visit to Indian Railway's Research Design and Standards Organisation (RDSO) in Lucknow, India in 2016.

Average emission factors are determined by sampling the amount of time spent at each notch during a locomotive journey. A notch is like a gearbox used in a car (Johnson et al., 2013). There is a specific factor linked to each notch and the average is weighted through the amount of time spent in each notch, also known as the duty cycle The duty cycle can vary depending on the make of the locomotive (Gould and Niemeier, 2009). Table 3-6 shows the duty cycle that has been used to calculate the average emission factor as used in Table 3-5.

Table 3-6: Percentage of time spent in each notch of an Indian locomotive (duty cycle)

Notch	%	Fuel consumption in kg/hr	% time spent at each notch *fuel consumption at each notch
Idle	49	25	12.25
1st	6	32	1.92
2nd	7	67	4.69
3rd	5	119	5.95
4th	4	178	7.12
5th	7	248	17.36
6th	5	311	15.55
7th	5	396	19.8
8th	12	487	58.44

Source: from IR, during a trip to India

The locomotive spends 49% of its journey in idle mode followed by being at the 8th notch 12% of the time. The same rationale and duty cycle are applied to fuel consumption.

The following equation (2) calculates the amount of fuel in litres needed to run the journey selected. It is assumed that the locomotive is travelling at an average speed of 50 mph as recommended by Indian Railways.

$$litres\ needed\ to\ travel\ 291km^{1} = \frac{(time\ to\ complete\ journey\ (hrs) * fuel\ consumption\ (\frac{kg}{hr}))}{density\ of\ fuel\ (\frac{\mathrm{g}}{cm^3})} \quad (2)$$

The densities of the fuel are averages taken from table 2-1; 0.86. 0.88 and 0.8795 g/cm^3 for diesel and biodiesel produced from palm and jatropha respectively. This thesis also assumes that biodiesel has a lower energy content compared to diesel, 11% and 12% for jatropha and palm stearin, respectively (Koh and Ghazi, 2011, Yunus et al., 2013a).

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[1] 291km is one single journey from Karaikal Port to Erode Junction

For electric traction, under the same circumstances, the following formula (3) was used:

$$Kw\ needed\ to\ travel\ 291km^{2} = \frac{(time\ for\ single\ journey\ (hrs) * locmotive\ wattage(\frac{kW}{hr}))}{locomotive\ consumption\ (\frac{kW}{km})} \quad (3)$$

It is assumed that the locomotive consumption rate is 5kW/km which was advised by Indian Railways to use.

This equation calculates the inputs needed to meet the assumptions made about the analysis. For both calculations, once the input of fuel has been calculated it is multiplied out by two (for a return journey), 365 (journey runs every day in a year) and 35 (the lifetime of the project).

3.4.1 Davis Equation

Average fuel consumption was obtained from Indian Railways which incorporates the driving cycle of the engine. Different terrain, locomotives and geographical locations could result in a different fuel consumption and thus emission output. To include such factors to estimate fuel consumption is important, however, as the case study focuses on one route the fuel consumption would not differ between biodiesel and diesel as the conditions are the same except for the fuel itself and needing more biodiesel due to it having a lower energy content. Needing extra fuel would also not influence the weight due to the fuel tanks being the same size (using the same locomotive), the difference is that the locomotive using biodiesel would need to fill up more often.

However, one of the fuel comparisons includes the use of a different locomotive when using electric traction. The main difference would be the weight of the locomotives, but these are not too dissimilar (IRFCA, 2010).

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[2] 291km is one single journey from Karaikal Port to Erode Junction

This thesis compares fuels where the driving conditions are kept the same for each fuel. Were the study to compare different routes for part or all of India then using the Davis equation to calculate fuel consumption has benefits. This equation evaluates rolling resistance (Günay et al., 2020) and can be affected by several factors including the weight of the engine or rolling stock on the braking resistance. However, as already mentioned for this thesis using the Davis equation is not necessary.

3.5 FINANCIAL ANALYSIS

A financial analysis assesses the cost to the individual rather than the economy. In this thesis, the individual is Indian Railways. This is the cost that will appear in accounts and is the cash flow. The prices and costs are all market derived. As Indian Railways is only interested in the prices during the end use, this will be the only stage from the supply chain that will be used. The input values include the prices of fuel and the maintenance of the locomotives.

A discount rate needs to be applied. This is needed because it discounts future prices/costs to the present value (Snell, 2011). This analysis has four discount rates that are obtained from two sources. The first, third and fourth (5%, 10% and 15%) are from ADB (2011) as they have conducted a feasibility study of comparing two different feedstocks to produce biodiesel. The second (7.75%) is the discount rate used by India (International Monetary Fund, 2017). The values being used are:

- 5%
- 7.75%
- 10%
- 15%

3.5.1 Inputs to the financial analysis for biodiesel

Indian Railways pays the same price for biodiesel as it does for diesel. The value used in this thesis is explained in 3.5.3 Therefore, the cost of fuel that Indian Railways pays will not change. The difference in this financial analysis is the amount of fuel needed because of the energy content. Another aspect that is accounted for is the maintenance of the locomotives with the differing biodiesel blend levels. Up to B20, no extra maintenance is required, therefore only B50 and B100 will have additional costs added (Greater London Authority, 2015). The maintenance value is outlined in appendix 7 and has been adjusted to 2018 levels through applying inflation levels which are outlined in appendix 12. The thesis states that extra maintenance is required, however, there is no literature (or at least not in the public domain) that gives a value for what the additional cost would be for this maintenance. After consulting with Indian Railways, it was deemed reasonable to increase maintenance costs by 10% for B50 and 15% for B10. This is to accommodate more frequent oil and filter changes.

3.5.2 Inputs to the financial analysis for electric traction

At present, the route selected cannot accommodate electric trains. Therefore, the infrastructure needs to be included in the overall costs. For the first four years, only infrastructure costs will count towards the electric traction financial cost. It is assumed that the locomotives fuelled by B5 (palm stearin) will continue to run during this duration.

3.5.3 Input to the financial analysis for diesel

The price of diesel used in this thesis is Rs 74.19/l which is adjusted for inflation (from 2014 prices). This is the price that is used for the financial analysis. Obtaining the breakdown of costs for diesel is difficult because the data is not in the public domain. However, the Railway Board (2014) has broken down the costs of using diesel as seen in Table 3-7.

Table 3-7: Breakdown of the diesel price for rail

	Diesel price for Rail (RS per litre unless stated)
Crude Oil Price with transport	Rs 4930 per barrel
Crude Oil	**31**
Entry tax, refinery processing, landing costs & other operational costs with margins	4.07 (-45% for entry tax)
OMC margin, transportation, freight costs	2.87
Cumulative total: (crude oil + refining cost)	**37.94**
Excise duty + road cess charged by the central government	15.33
Cumulative total: (crude oil + refining cost + government taxes)	**53.27**
VAT (this varies from state to state) assumed here as 16.75%	8.92
Final total paid	**62.19**

Source: adapted from Railway Board, 2014

In 2014 India was importing crude oil at Rs 4,930 per barrel. It cost Rs 4.07/l to process the crude oil into diesel. Other costs such as transportation and taxes are added resulting in India paying Rs 62.10/l in 2014, which is equivalent to Rs 74.19/l.

3.6 ECONOMIC ANALYSIS

The economic analysis follows the same format as the financial analysis, including the same discount rates. The main difference between the financial and economic analysis is that non-monetary values are included i.e., the cost of GHGs and pollutants

3.6.1 Reasons for choosing the economic analysis method

The purpose of this thesis and analysis is to demonstrate the environmental, financial, and economic feasibility of choosing biodiesel compared to diesel and electric traction. Several methods could potentially be used for the economic analysis, but the method used is a cost-effectiveness model. Reasons for choosing this method and not others are outlined below:

1) This thesis is to establish whether using biodiesel is a viable option or not for Indian Railways. MCDM involves weights based on the direction of the government e.g., environmental, social, or economic. Without direct input, it is difficult to use this method. Time in India did not extend this far and contacts were not available to establish weights.
2) It is not necessary to use LCCA or techno-economic analysis because the construction of biodiesel production facilities is not included in this analysis. There is already enough capacity for the case study up to B100.
3) A modified CBA is most appropriate. It is modified because there are no benefits, such as time, to be accounted for. Therefore, the cost-effectiveness is used for the economic analysis. This is suitable for all fuels which are included in the analysis due to its common unit of money.

3.6.2 The monetary costs for the economic analysis

The difference in an economic analysis compared to a financial is that import costs will be absent of all taxes and shadow prices applied i.e. foreign exchange rate shadow price. This represents the true cost to the country of importing the item. Like the LCA not all stages of the supply chain have the same level of input and output.

3.6.2.1 Biodiesel and diesel inputs

As biodiesel and diesel have their feedstocks imported it is not necessary to include cultivation or oil extraction costs because this is reflected in the import cost. Therefore Table 3-8 has N/A at certain stages of the supply chain.

Table 3-8: Inputs for the economic analysis of diesel

Diesel	**Value**	**Unit**	**Note**
Oil extraction			
N/A	N/A		
Transportation			
N/A	N/A		
Fractional distillation			
Cost of crude oil	33.43	Rs/kg	
Electricity	5.65	Rs/kWh	
Natural gas	216.37	Rs/MMBtu	The cost increases by 0.62% each year. This is in line with past data.
Water	131.98	Rs/m^3	
Maintenance	435,610,000	Rs/year	
End use			
Maintenance	15.28	Rs/km	

Table 3-9: Inputs for the economic analysis of biodiesel produced from palm stearin

Biodiesel (from palm stearin)	Value	Unit	Note
Cultivation			
N/A	N/A		
Transportation			
N/A	N/A		
Oil Extraction			
N/A	N/A		
Transesterification			
Crude palm stearin oil	37,181	Rs/tonne	
Water	131.98	Rs/m^3	
Electricity	5.65	Rs/kWh	
Methanol	17,092.82	Rs/tonne	This increases by 0.04% each year. This is in line with recent data.
Sodium hydroxide	14,763.13	Rs/tonne	
Glycerine (sell this as a by-product)	21.4	Rs/kg	
Maintenance	10,744,817.9	Rs/year	Maintenance costs are a constant through the lifetime of the project

End use			
Maintenance	15.28	Rs/km	

Fewer monetary input costs are needed for palm stearin because it is imported from Malaysia. The cultivation and oil extraction costs are reflected in the import cost. Once the palm stearin has been imported it follows a similar supply chain to that of jatropha. It was not possible to source Indian prices for all inputs in the year 2018, so prices from other countries and years were used. They were adjusted for inflation and used a PPP exchange rate to exchange into INR.

Jatropha is the only feedstock that is not imported. It is cultivated in India. Therefore, all stages along the supply chain need monetary values. This includes the initial setup stage such as ploughing the land and planting the jatropha plants. The values used in the modelling are in Table 3-10 and fuller details of these values are in appendix 9.

Along the supply chain care must be taken not to double count. If a price were applied to the jatropha fruit used during the oil extraction stage, then this would already be included in the cultivation stage because the cost has already been established.

Table 3-10: Inputs for the economic analysis of biodiesel produced from jatropha

Biodiesel (from jatropha)	**Value**	**Unit**	**Note**
Cultivation			
Planting, maintaining and harvesting	784,090.5 to 167,059.39	Rs/year	Cultivation costs vary year on year depending on the level of work needed e.g., higher initially at the beginning due to costs

			relating to ploughing and sowing seeds
Transportation			
Transportation cost	0.61	RS/km	
Oil Extraction			
Water	131.98	Rs/m^3	
Electricity	5.65	Rs/kWh	
Diesel	45.47	Rs/litre	
Transesterification			
Crude palm stearin oil	37,181	Rs/tonne	
Water	131.98	Rs/m^3	
Electricity	5.65	Rs/kWh	
Methanol	17,092.82	Rs/tonne	This increases by 0.04% each year. This is in line with recent data.
Sodium hydroxide	14,763.13	Rs/tonne	
Glycerine (sell this as a by-product)	21.4	Rs/kg	
Oil cake (sell this as a by-product)	2.44	Rs/kg	

Maintenance	10,744,817.9	Rs/year	Maintenance costs are a constant through the lifetime of the project
End use			
Maintenance	15.28	Rs/km	

When the blend increases production costs will increase but likely at a decreasing rate. The production of the fuel needs to be scaled to reflect economies of scale. There is limited literature on this scaling. This scaling is based on (Goldemberg et al., 2004) analysis of Brazil's bioethanol programme. This shows the relationship between cost and the production of ethanol over 25 years. Factors are taken based on the relationship between the cost and production levels. These factors are applied to the blends based on their proportions and can be seen below:

Table 3-11: Factors to scale the production of biodiesel to meet new demand for increased concentration in blends

(1) US$/m^3	**(2) Cumulative ethanol production (thousand m^3)**	**(3) Brazil scale**	**(4) Factor for scaling**
690	5,000	0.1380	1
640	5,000	0.1280	B10 = 0.0696
610	13,000	0.0469	
555	20,000	0.0278	B20 = 0.0278
550	26,000	0.0212	
570	37,000	0.0154	

420	45,000	0.0093	B50 = 0.00856
450	60,000	0.0075	
400	72,000	0.0056	
425	80,000	0.0053	
300	90,000	0.0033	B100 = 0.00305
305	108,000	0.0028	

Source: adapted from Goldemberg et al., 2004

1) US\$/m^3 (column 1)
    a. This is the cost of the fuels
2) Cumulative ethanol production (thousand m^3) (column 2)
    a. The amount of ethanol being produced in Brazil.
3) Brazil scale (column 3)
    a. This is the ratio of cost and production.
    b. Brazil scale = cost/volume.
    c. As the volume increases, so does the cost but this is at a decreasing rate.
4) Factor for scaling (column 4)
    a. This value represents the factor that needs to be applied to the model to show the economies of scale as production increases.
    b. B5 is represented by the value 1. The volume being produced is 5,000 thousand m^3 (seen in column 2) – no factors are applied when the minimum amount of biodiesel is being produced.
    c. B10 is the next blend being used. This is double B5 and should be 10,000 thousand m^3, however, there are 5,000 and 13,000 in the table (column 2), therefore the factor should be between 0.1280 and 0.0469 (seen in column 3).
    d. A weighted average is taken of the two Brazil scales

$$5{,}000 + 13{,}000 = 18000$$

$$\frac{5{,}000}{18{,}000} = 0.28\ and\ \frac{13{,}000}{18{,}000} = 0.72$$

$$(0.128 * 0.28) + (0.0469 * 0.72) = \mathbf{0.0696}$$

e. This factor is applied to the biodiesel production stage, but only the monetary value.

The cultivation, oil extraction, and transport of the oil only have GHG values included. These do not need to have a factor included as there is a linear correlation between blend and emission levels (Graboski and McCormick, 1998, Graboski et al., 2003, Environmental Protection Agency, 2003, Lapuerta et al., 2008). The economic analysis excludes taxes and subsidies.

3.6.2.2 Comparison of biodiesel, diesel, and electric traction

Electric traction has a different supply chain compared to biodiesel and diesel as there are not as many stages. However, there is an additional stage of infrastructure. At present, the infrastructure to allow electric trains on this route does not exist and is therefore accounted for. Table 3-12 shows the costs used for modelling electric traction with full details of these costs in appendix 10.

Table 3-12: Input cost variables for the economic analysis of comparing electric traction and B5

Electric traction	Value	Unit	Note
Construction			
Infrastructure	35,000,000	Rs	
Electric locomotive	265,537,500	Rs	
Extraction of coal			
Transportation cost	0.61	RS/km	
Water	131.98	Rs/m^3	

Electricity	5.65	Rs/kWh	
Diesel	45.47	Rs/litre	
Transportation of coal			
Transportation cost	0.8	Rs/km	
Electricity generation			
Water	131.98	Rs/m^3	
Maintenance	850,127	Rs/year	Maintenance costs are a constant through the lifetime of the project
End use			
Maintenance	6.2	Rs/km	
Cost of additional electricity needed	3.39	kWh	Solar and wind power

No stage along the supply chain for electric traction involves importation. Therefore, all inputs need monetary values.

As mentioned above electric traction infrastructure costs are needed for the first four years of the analysis, so the same assumption as for the financial analysis is applied to the economic analysis.

The model has been designed to accommodate that 100% of the electricity is produced from coal, due to no GHGs or pollutants being emitted when solar or wind power is generating electricity. However, in reality, this is not the case and therefore the costs at each of the stages will be weighted so that 55% of the cost is present in the final economic model. 55% is being used because this is how much electricity is being produced from coal.

3.6.3 The non-monetary costs for the economic analysis

3.6.3.1 Shadow pricing

It has been discussed that shadow pricing can be applied to models to compensate for the distortion. The shadow price of foreign exchange is recognised as a fundamental tool in a CBA.

The development of the shadow price of foreign exchange has produced voluminous levels of literature (Dusansky et al., 2000). The literature also focuses on the modelling to determine the foreign exchange rather than calculating values (Beyer, 1975). Beyer (1975) has estimated the shadow prices of foreign exchange for India with a range of Rs 9.8 to 12 per dollar. This range could be narrowed using other methods, but this is time consuming and requires significantly more data. It is recognised that this value is out of date and there is literature that states how to conduct the modelling, but it requires much more data than can be obtained for this thesis.

The Asian Development Bank has completed some more recent work on shadow pricing in India (Asian Development Bank, 2004), and whilst it is still old it is more recent than Adler (1987) and Beyer (1975). Table 2 in the document has a range of values of the standard conversion factor for India. This is the inverse of a shadow exchange rate, so this would imply a foreign exchange premium for India in the range of 10-25%.

A shadow price for foreign exchange is not used in the main modelling because of a lack of recent data. It would be possible to apply inflation to the values from 1975, but they would bear no relevance to today. The shadow price was calculated when India's economy was much more stringent. By the 1970s India was known worldwide for having a heavily protected and regulated economy. During the 1970 and 80s some steps were taken to liberalise the market, but more extensive steps were taken during the 1990s which resulted in, for example, fewer restrictions on imports (Kotwal et al., 2011).

Even though the Asian Development Bank has more recent estimates these are still likely to be out of date so are not used in the main modelling. However, to understand the importance of foreign exchange shadow pricing it is accounted for in the sensitivity analysis.

Shadow pricing should be applied to labour for the cultivation of jatropha, but it is not possible in this case. The main reason for this is the lack of specific data on labour costs. The costs for the cultivation of jatropha are generalised into categories such as ploughing, planting, harvesting, etc. and labour costs are incorporated into these costs; therefore, it is not possible to assess the labour numbers during the cultivation stage in the main modelling as well as in the sensitivity analysis.

3.6.3.2 Externality prices

Monetary values are applied to GHGs and pollutants. The monetary values are taken from the EU External Costs handbook. The values are given in euros, but they are exchanged into rupees.

Table 3-13: External costs for GHGs and pollutants in the transport sector

	Value (2016 prices)		**Value in Rs (2018 adjusted)**	
CO_2	Short term (up to 2030)	Long term (up to 2060)	Short term (up to 2030)	Long term (up to 2060)
	€100/tonne	€269/tonne	Rs 8073.32/tonne	Rs 21,717.23/tonne
CH_4[3]	Short term (up to 2030)	Long term (up to 2060)	Short term (up to 2030)	Long term (up to 2060)
	€100/kg CO_2 eq	€269/kg CO_2 eq	Rs 8073.32/kg CO_2 eq	Rs 21,717.23/kg CO_2 eq
N_20[3]	Short term (up to 2030)	Long term (up to 2060)	Short term (up to 2030)	Long term (up to 2060)
	€100/kg CO_2 eq	€269/kg CO_2 eq	Rs 8073.32/kg CO_2 eq	Rs 21,717.23/kg CO_2 eq
NO_x	City	Rural	City	Rural
	€21.3/kg	€12.6/kg	Rs 1,719.62/kg	Rs 1,017.24/kg

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[3] This will be converted to CO_2e according to GWP

SO$_x$	€10.9/kg		Rs 879.99/kg	
PM$_{10}$	€22.3/kg		Rs 1,800.35/kg	
PM$_{2.5}$	City	Rural	City	Rural
	€123/kg	€70/kg	Rs 9,930.18/kg	Rs 5,651.32/kg

Source: adapted from European Commision, 2019

The external costs are sourced from the EU's external costs handbook (European Commision, 2019). The costs were developed by the New Energy Externalities Development for Sustainability (NEEDS) (Ott et al., 2008). Before 2019's update, the model for external costs was last updated in 2009. It has been updated by reassessing some key areas which may have changed and ultimately change the overall value of the GHG pollutant. These include the background concentration level, knowledge about impacts from pollution and valuation framework. The values used in this thesis represent an average of the EU 28.

The external costs are combined values for road, railway, and inland waterway transport. These values are from 2016 and would need to be index linked to bring them to the 2018 level required in this thesis.

In Table 3-13 $CO_{2,}$ N_2O, and CH_4 have the same values because they are valued as CO_2 equivalent by applying GWP to the GHGs. The CO cost is difficult to estimate as there is limited literature on this value, so has been excluded from this thesis. Each cost was adjusted to 2018 values and then exchanged into INR through a PPP exchange rate; these rates are outlined in appendix 11.

As seen in Table 3-13 some emissions have more than one value. GHG value increases in future years. This is applied to the model in the form of an average increase per year to reach the upper value: this is an increase of 3.5% per year. There is no indication in the literature that forecasts have been published regarding future costs of pollutants. The value of pollutants is dependent on population density. It is split into three categories: rural, city and metropolis. During the combustion stage, the costs for pollutants are split between 70% rural and 30% city. This is based on an assessment of the route. All other stages of the supply chain have the city price applied.

3.7 BASE CASE ASSUMPTIONS

1) For this thesis, GHG emissions from biodiesel at the combustion stage are assumed to be zero, due to carbon sequestration during the feedstock cultivation stage.

   However, GHGs are produced at other stages along the supply chain such as the production of biodiesel because fossil fuels are used during these stages; for example, electricity is used during the transesterification stage and is primarily produced from coal. Therefore, these emissions need to be accounted for.
2) No sulphur is emitted during the combustion of biodiesel because there is none in the final product (Ajala et al., 2015, Sharma and Murugan, 2015).
3) The cultivation stage for biodiesel produced from palm stearin is assessed from a palm oil perspective. Palm stearin is a co-product of producing palm oil and cannot be obtained without growing palm oil. As a result, there is approximately 200kg of palm stearin per tonne of palm oil produced. This piece of data is taken into consideration when estimating the GHGs for the cultivation stage of palm oil.
4) During the production of biodiesel, it is assumed that 95% of methanol is recycled (Mu et al., 2016). This is normal practice in the transesterification stage and has been confirmed by research and producers, including SOBT who provide biodiesel to Indian Railways.
5) It is assumed that a jatropha plantation is 50 km from the production facility.
6) The frequency of locomotives on the network is taken from timetables provided by Indian Railways.
7) Freight is not analysed in this thesis. There is a high level of uncertainty about the density of freight on the network and this information is not in the public domain.
8) The terrain of the rail journey is assumed to be flat. The amount of fuel consumed can be affected by the terrain; more fuel is required if the terrain is uphill or rough whereas less is needed if the journey is smooth, flat, or downhill. It is difficult to determine the exact nature of the terrain and thus

the fuel consumption. However, from an assessment of maps of the area, it appears reasonably flat, therefore there is no adjustment to fuel consumption.

9) The construction costs for building the biodiesel and diesel production facilities are not included. This is due to facilities already existing and being able to meet the demand for the biodiesel needed. Indian Railways has strict criteria on who it will buy biodiesel from and one of the companies produces enough biodiesel that any extra demand from the railways would be insignificant to their production. However, if more or all routes were to use biodiesel then this view would need to change. The analysis would then have to incorporate a biodiesel facility.
10) Initial cultivation costs for growing jatropha are included. A large enough jatropha plantation does not exist to meet demand; therefore, there would be an extra capital investment to set this up.

3.8 SUMMARY

This chapter has explained the method of the environmental, financial, and economic analyses. It explained the software and models used and the reasoning behind them. The inputs and outputs for biodiesel, diesel, and electric traction are demonstrated with explanations of how they must be adjusted for 2018 Indian prices. Assumptions have had to be made because of the lack of data for some of the fuels, such as the LCA inputs for diesel. The method of analysing the fuels is as consistent as possible to enable a comparison of them on a more equal basis.

The next chapter compares the different variants of biodiesel and diesel. This consists of imported Malaysian palm stearin-based biodiesel in a range of blends; biodiesel from jatropha grown in India and diesel. Each is analysed and compared from an environmental, financial and economic perspective.

4 A comparison of biodiesel produced from palm stearin at different blends, jatropha, and diesel

4.1 INTRODUCTION

This chapter compares biodiesel produced from palm stearin at different blends, jatropha, and diesel. The palm stearin is imported from Malaysia and is a feedstock that has been approved by Indian Railways. Jatropha is grown in India approximately 50km from the production facility. Crude oil is imported from Nigeria and is fractionally distilled in India. Each fuel is compared with one another examining differences in emissions, financial viability, and economic feasibility.

4.2 LIFE CYCLE ANALYSIS RESULTS AND DISCUSSION

For ease of reading of the emission analysis graphs, the following grouping of categories are used for the different stages along the supply chain and explained in Table 4-1.

Table 4-1: Grouping stages for LCA analysis

Categories of graphs	Diesel	Palm stearin	Jatropha
Extraction	Crude Oil Extraction	Cultivation	Cultivation
Feedstock transportation	Crude Oil	N/A	Jatropha seeds
Oil extraction	N/A	Oil extraction	Oil Extraction
Production	Fractional Distillation	Transesterification	Transesterification
Fuels transportation	Fuel Transportation	Fuel Transportation	Fuel Transportation
Combustion	Combustion	Combustion	Combustion

4.2.1 Greenhouse Gases

In this analysis, GHGs are included as an output at all stages of the supply chain. In this section firstly GHGs are analysed separately and secondly analysed as CO_2eq.

4.2.1.1 Carbon dioxide

Literature has shown that biodiesel emits less net CO_2 than diesel (Whitaker et al., 2010, Schumacher et al., 1996, Peterson et al., 1996, Chang et al., 1996, Thompson et al., 2018, Santamaría and Azqueta, 2015). This can be seen in Figure 4-1.

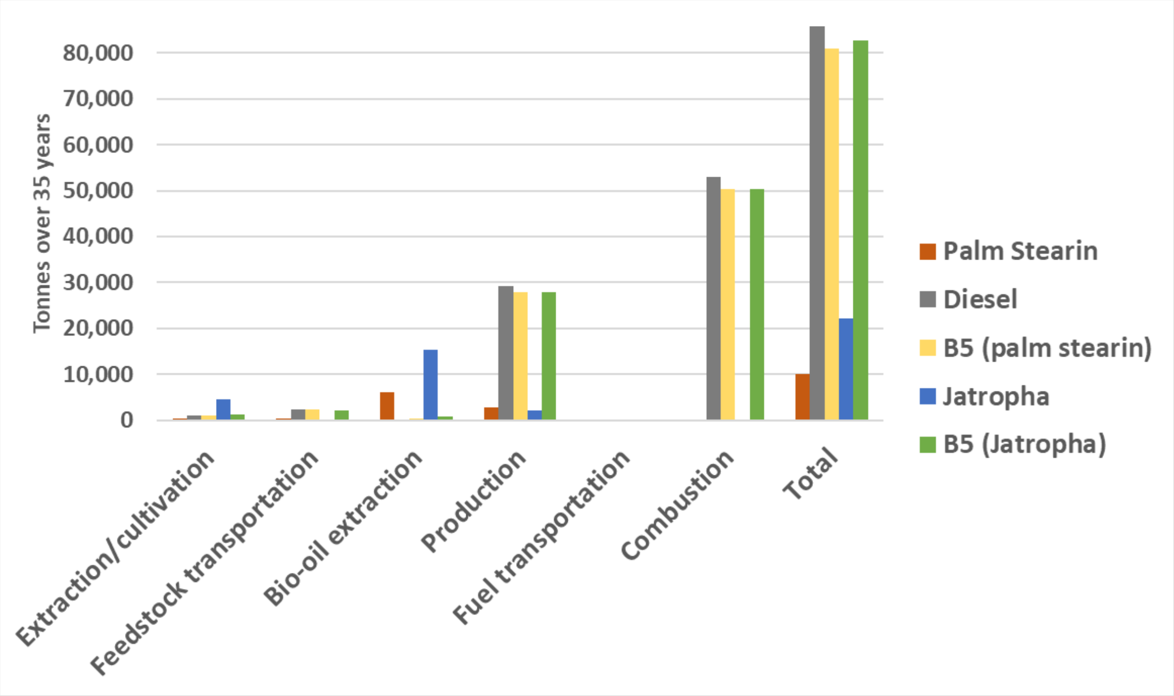

Figure 4-1: CO_2 emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

Diesel emits a total of just under 86,000 tonnes of CO_2. 62% of the total is emitted during the combustion stage - approximately 2.5 kgCO_2/l. Indian Railways has reported a similar value of 2.651 kgCO_2/litre (India GHG Program, 2015). Fractional distillation is the stage with the second highest level emitting 34% of the total.

In total B100 from palm stearin emits just under 76,000 tonnes less CO_2 compared to B0. During combustion, B100 emits CO_2 into the atmosphere but it is absorbed back into the supply chain (Gupta and Gaur, 2019) – hence zero during the combustion stage. This reasoning is why biodiesel is known as being carbon neutral. However, biofuel is not carbon-neutral because of the other stages emitting CO_2 e.g. transportation (Eshton et al., 2013). They published a study that investigated the life cycle of biodiesel produced from jatropha in Tanzania. In total, the LCA emitted 3,608 CO_2 eq. emissions (kgt^{-1}) and 2,760 were absorbed back into the process at the cultivation stage. This highlights the importance of conducting an LCA and not just focus on tailpipe emissions. A further example of this is seen in this thesis. The oil extraction stage for palm stearin emits the most CO_2 with a share of 62%, this is followed by the transesterification stage accounting for 28% of the total CO_2 emissions.

Biodiesel produced from jatropha emits just over 22,000 tonnes of CO_2 in total of which 69% is from the oil extraction stage. Unlike biodiesel produced from palm stearin the second-largest share of CO_2 emissions is from the cultivation stage having 21% of the total. There is a 74% reduction in the total CO_2 emissions for jatropha compared to diesel. This reduction falls within the range that was extracted from literature as seen in Table 2-1.

In total B100 produced from palm stearin emits approximately 12,000 tonnes less of CO_2 compared to B100 produced from jatropha with the biggest difference in the oil extraction stage. There are two reasons for this:

1) The process to extract the oil is much lengthier for jatropha and palm stearin compared to diesel. Therefore more energy is needed resulting in higher emissions.
2) The waste materials from producing palm oil are recycled and burned, thus reducing the need for external energy (Lam et al., 2009a). The recycling of waste, including shells, takes place during the oil extraction stage.

During the transesterification stage, the use of palm stearin emits more CO_2 compared to using jatropha. This is linked to the inputs. Biodiesel produced from palm stearin requires more electricity, methanol, and sodium hydroxide than biodiesel produced from jatropha as can be seen in appendices 3 to 6. The inputs differ because of the chemical structures of the feedstocks. For example, more methanol and sodium hydroxide is needed for palm stearin oil because it has a higher fatty acid (FFA) content than jatropha (Zahan and Kano, 2018). It is noted that this study refers to palm oil, but palm stearin has a higher fatty acid content than palm oil (Cardoso et al., 2014). The methanol and sodium hydroxide catalysts are needed to create the reactions between ions to produce glycerine and to react with the FFA to form fatty acid methyl ester (FAME). FAME is the biodiesel proportion (Dutton, 2018). The blends for both palm stearin and jatropha are not too dissimilar to diesel.

4.2.1.2 Methane

CO_2 is one of three GHGs that are included in this thesis. The second GHG is CH_4. The results of CH_4 being emitted along the supply chain are demonstrated in Figure 4-2.

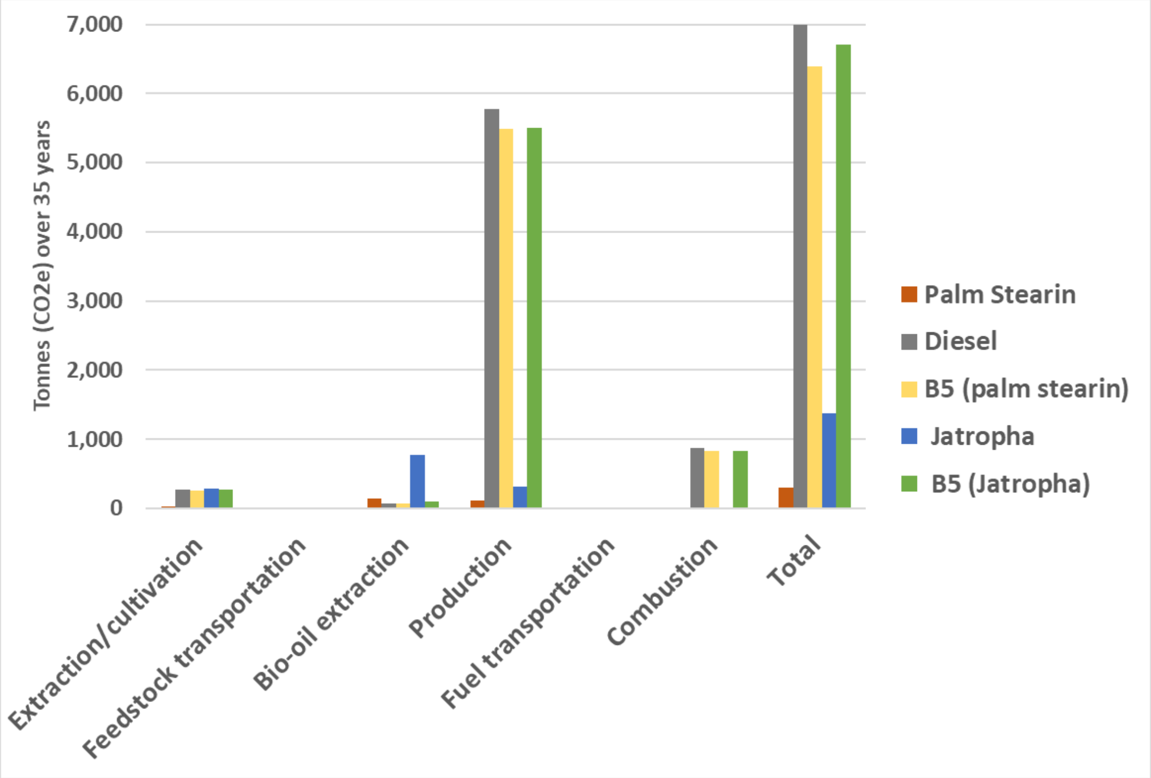

Figure 4-2: CH_4 emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

Diesel produces the most methane over the supply chain with the highest proportion of emissions coming from the fractional distillation stage. Natural gas is the most common fuel used in fractionally distilling crude oil, because of its energy efficiency and its lower emissions produced when combusted (Bhat and Prakash, 2009). When natural gas is being harvested methane is released into the atmosphere when drilling the ground (Howarth et al., 2011), which contributes to the overall methane emission. Methane is not only released when natural gas is extracted but also during the extraction of crude oil and coal.

CH_4 for jatropha is 78% higher than palm stearin. When using jatropha as a feedstock 56% of the total comes from the oil extraction stage. This is due to the use of fossil fuels, the extraction of fossil fuels, and the decomposition of organic matter (Arvidsson et al., 2011, Sumiani and Sune, 2007). To extract oil from jatropha 227 kWh of electricity is needed when producing one tonne of biodiesel compared to 57 kWh for palm oil (when the allocation of energy is taken into account). Electricity in India is primarily generated from coal and therefore to extract fossil fuels methane is inevitably going to be released.

4.2.1.3 Nitrous oxide

The third GHG emission is N_2O. The results of N_2O being emitted along the supply chain are demonstrated in Figure 4-3.

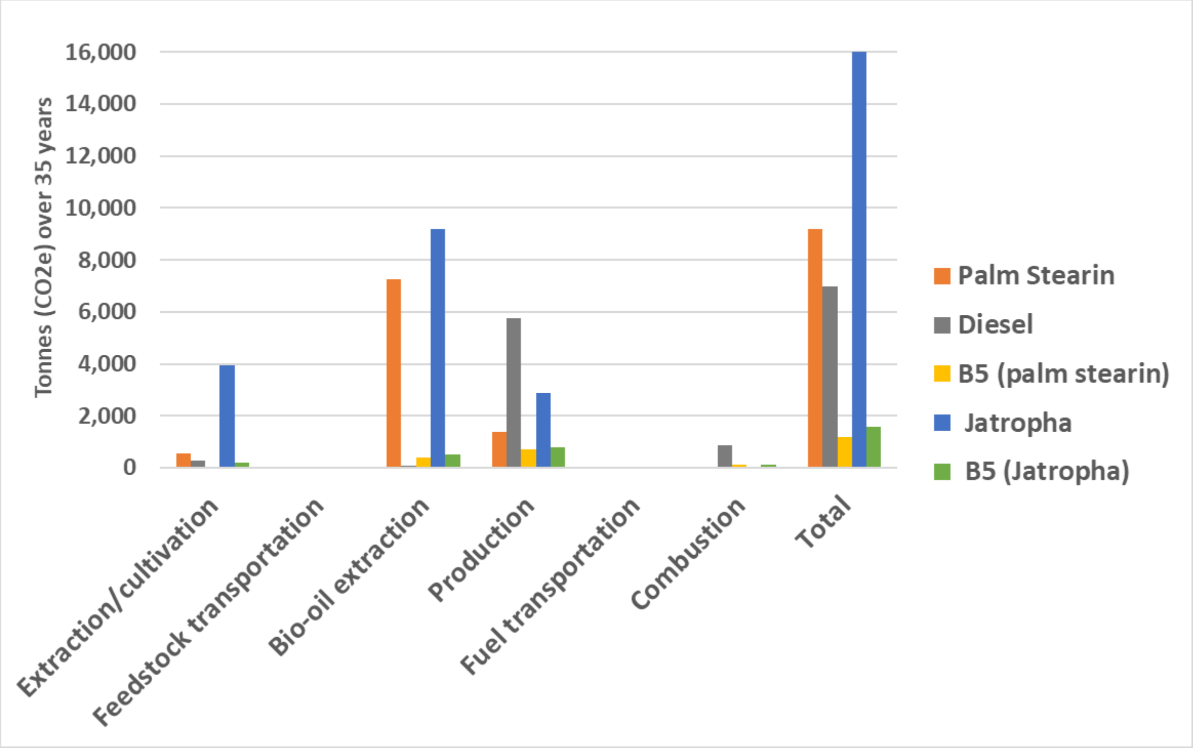

Figure 4-3: N_20 emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

Biodiesel produced from jatropha is the highest contributor to N_2O followed by palm stearin-based biodiesel. These results show that the highest levels of N_2O are from the oil extraction stage accounting for 79% for palm stearin and 57% for jatropha. The second highest emitting stage is cultivation for jatropha and transesterification for palm stearin. However, some literature suggests that the majority of N_2O is emitted during the cultivation stage because of nitrogen N fertiliser being used (Silalertruksa et al., 2012, Siregar et al., 2015, Arvidsson et al., 2011). As mentioned in the literature review it is widely regarded that cultivation contributes to a high proportion of GHGs (Arvidsson et al., 2011, Siregar et al., 2015, Lam et al., 2009a, Nazir and Setyaningsih, 2010). Results vary from 37.77% to 60% for jatropha and 50.66% to 60% for palm oil as proportions of the whole LCA. This is based on emissions from the soil preparing the ground for seedlings (more so for palm oil) (Arvidsson et al., 2011) and also the fertiliser used. However, Siregar et al. (2015) and Nazir and Setyaningsih (2010) disagree. They believe that the biodiesel production stage has a higher percentage of GWP; 52.86% for the production stage and only 46.66% for the cultivation stage (Siregar et al., 2015).

Combined reasoning can explain why these results disagree with the literature:

1) These results show that the higher levels of N_2O are in the cultivation stage are likely from excess nitrogen in the fertiliser. NH_3 is present in the fertiliser which reacts with oxygen to produce N_2O which then volatilises. The N_2O is then lost by volatilisation (Lam et al., 2009a).
2) During the oil extraction stage for palm stearin wastes such as cake and fibres tend to be reused in the boilers to replace fossil fuels (Saswattecha et al., 2015). These wastes also contain nitrogen and when combusted the nitrogen is released into the atmosphere (Eshton et al., 2013). Miura and Kanno (1997) saw an increase in N_2O emission when rice straw was burned. The emission factors between studies can vary greatly depending on the moisture content of the biomass, combustion conditions, and the density in which the biomass is stored (Romasanta et al., 2017).
3) Crutzen et al. (2016) explain that the oil itself has high nitrogen content (due to the fruits/seeds absorbing the nitrogen through the fertiliser application). This nitrogen is likely to be released when the oil is extracted which would explain why this stage emits higher N_2O.
4) Through indirect N_2O emissions van Wijnen et al. (2015) explain that these emissions can be associated with the wastewater that has contacted the n-

fertiliser rich soil during oil extraction. They have estimated that emissions may increase by 25-45% when indirect emissions are included.

4.2.1.4 Global Warming Potential

Applying GWP to GHGs is essential for giving a true perspective of an environmental assessment (Pachauri et al., 2014). Tables 4-2 and 4-3 show the differences in share proportions between GHGs which have had GWP values applied and GHGs which have not.

Table 4-2: Breakdown of GWP unadjusted proportions (based on mass)

Total GHGs with GWP unadjusted % Breakdown	Palm Stearin	Jatropha	Diesel
CO_2	99.56	99.47	99.61
CH_4	0.14	0.29	0.39
N_2O	0.30	0.23	0.00

When the emissions are unadjusted N_2O and CH_4 become insignificant accounting for less than 0.4% towards total GHGs for biodiesel produced from palm stearin and jatropha.

Table 4-3: Breakdown and total of GWP adjusted of GHG emissions (tCO_2e)

Total GHGs with GWP	Palm Stearin (tCO_2e)	Jatropha (tCO_2e)	Diesel (tCO_2e)
CO_2	9,982	22,234	85,858
CH_4	296	1,380	6,988
N_2O	9,174	16,008	812
Total	19,452	39,623	93,659

Table 4-4: Breakdown of GWP adjusted proportions (based on mass)

Total GHGs with GWP Adjusted % Breakdown	Palm Stearin	Jatropha	Diesel
CO_2	51.32	56.12	91.67
CH_4	1.52	3.48	7.46
N_2O	47.16	40.40	0.87

As seen in Table 4-3 diesel emits the most GHG emissions over the life cycle with a total of 93,659 tCO_2e compared to palm stearin and jatropha-based biodiesel which emits

19,452 tCO_2e and 39,623 tCO_2e, respectively. Table 4-2 shows that CO_2 accounts for 99.56% of total emissions, however when GHGs have GWP factors it changes the split between emissions This is only between two of the GHGs; CO_2 and N_2O. For example, palm stearin has a split of 51.32% for CO_2 and 47.16% for N_2O as seen in Table 4-4: Breakdown of GWP adjusted proportions (based on mass).

Most notably N_2O, in this thesis, has a range of 40-48% whereas Whitaker and Heath (2009)'s study has an N_2O value of 18%. Assessing N_2O emissions is challenging due firstly to the lack of studies that analyse the emissions and secondly to the numerous approaches. Bessou et al. (2013) examined 39 LCAs of perennial cropping systems and only eight presented adequate details on the methods used when including key emissions. These studies varied in detail and results making a comparison difficult.

4.2.2 Pollutants

Pollutants are local emissions that are only included in the supply chain when that stage is taking place in India.

4.2.2.1 Carbon monoxide

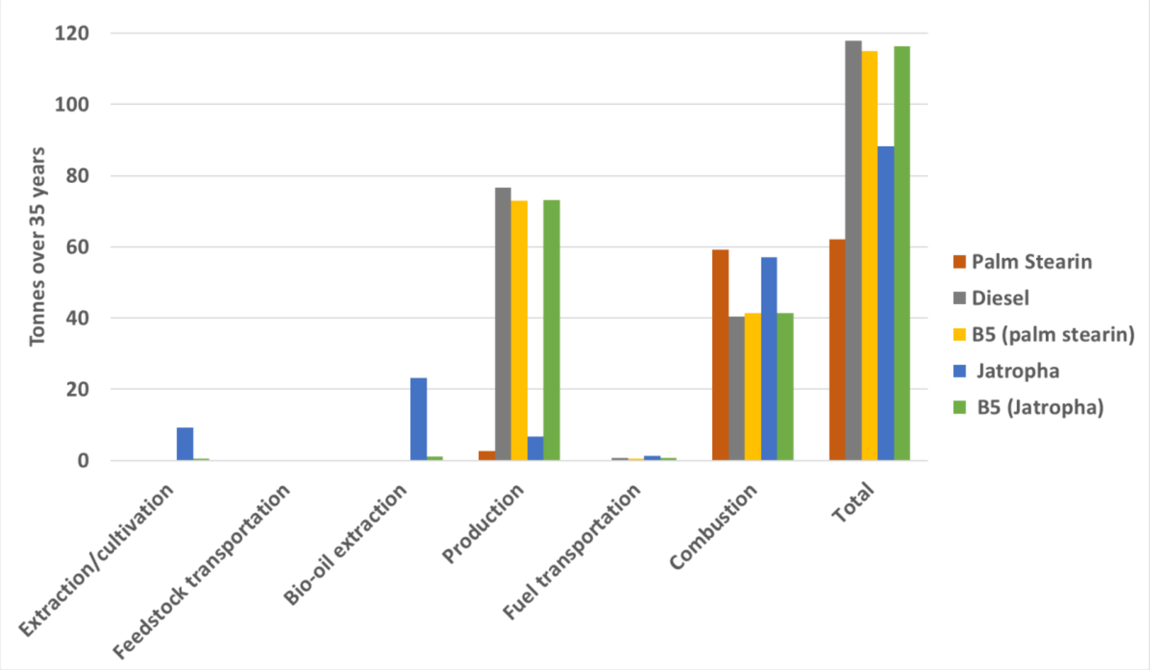

Figure 4-4: CO emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

A lack of oxygen can lead to incomplete combustion whereby poisonous CO is produced. Diesel emits the most carbon monoxide, 118 tonnes - 34% from the fractional distillation, and 65% from combustion. B5 palm stearin emits 115 tonnes of CO over its lifetime, which is 3 tonnes less than B0. B5 jatropha emits 116 tonnes. Overall, for B100 jatropha and palm stearin, there is a 25% and a 47% reduction, respectively, of CO compared to conventional diesel. Tan et al. (2012) estimated reductions between 15% and 23.1% depending on a variety of parameters. Peterson et al. (1996) reported a 50.6% decrease in CO levels of biodiesel produced from rapeseed oil compared to conventional diesel. With a 50% blend CO is reduced by an estimated 25.3% (Chang et al., 1996).

Indian Railways has tested Pongamia, waste fish oil, and waste mahua oil. Results showed that there is a 14% increase, 81% decrease, and a 10% decrease respectively in CO emissions compared to conventional diesel (RDSO, 2009, RDSO, 2010, RDSO, 2008). Indian Railways offers little explanation for the large variance in CO levels. However, other literature offers an insight into these differences such as:

1) **The temperature in the combustion chamber**

   When the temperature is lower in the combustion chamber few oxidation reactions take place. This leads to incomplete combustion (Omidvarborna et al., 2016, Agudelo et al., 2016).

2) **The driving cycle**

   Emissions can be affected by the way the vehicle is driven. For example, Armas et al. (2014) explained that during their investigation CO levels were very low during idle and low-velocity conditions, but increased dramatically during acceleration.

3) **The composition of the fuel**

   Chemical structures can affect carbon monoxide emissions, more specifically the double bonds in the chain lengths. Longer chains make it more difficult to oxidize and therefore have complete combustion (Pinzi et al., 2013).

4.2.2.2 Nitrous oxides

The next pollutant to be compared is NOx shown in Figure 4-5.

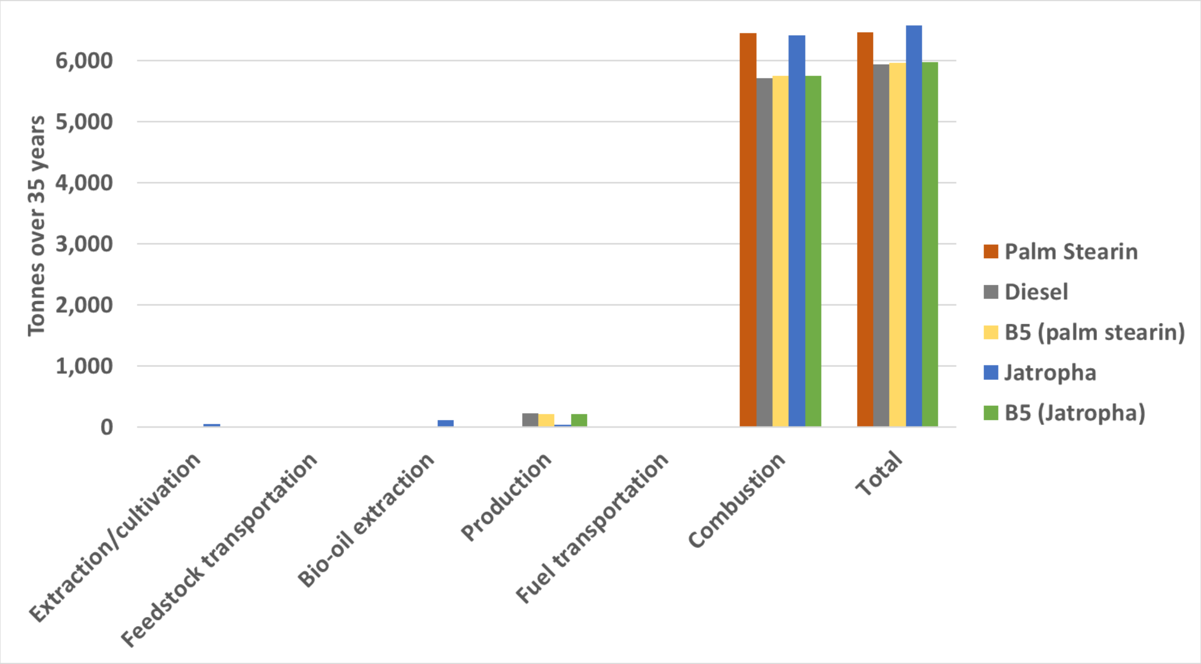

Figure 4-5: NOx emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

NOx are formed from reactions between nitrogen, oxygen, and heat. The higher the oxygen content and heat levels the larger the NOx (Yunus et al., 2013b). Regardless of the feedstock, biodiesel has a larger content of oxygen than diesel (Abed et al., 2019, Fazal et al., 2010, Devarajan et al., 2018) and consequently B5 and B100 emit higher NOx over the entire supply chain, primarily at the combustion stage. B0 emits 150 tonnes with 77% linked to the combustion stage. B100 palm stearin emits 99.88% of its total NOx during the combustion stage.

Jatropha based biodiesel emits 109 tonnes more NOx compared to palm stearin biodiesel. However, during the combustion stage jatropha releases 40 tonnes less NOx than palm stearin. The overall NOx emissions for jatropha are higher than palm stearin because there is the inclusion of pollutants in the early stages of the supply chain for jatropha.

Increased NOx from biodiesel compared to diesel is seen in the literature. Findings from Tan et al. (2012) showed a 13.9% increase for B100 and a 1.02% increase for B5. Yunus et al. (2013b) had similar results showing that diesel has fewer NOx emissions compared to biodiesel.

Australian Automobile Association (2018) found that lab-based testing and modelling can often be underestimated. It reported that 91% of their tested vehicles are were above the regulated limit for NOx gas when comparing the real world to lab-based results.

4.2.2.3 *Sulphur Oxides*

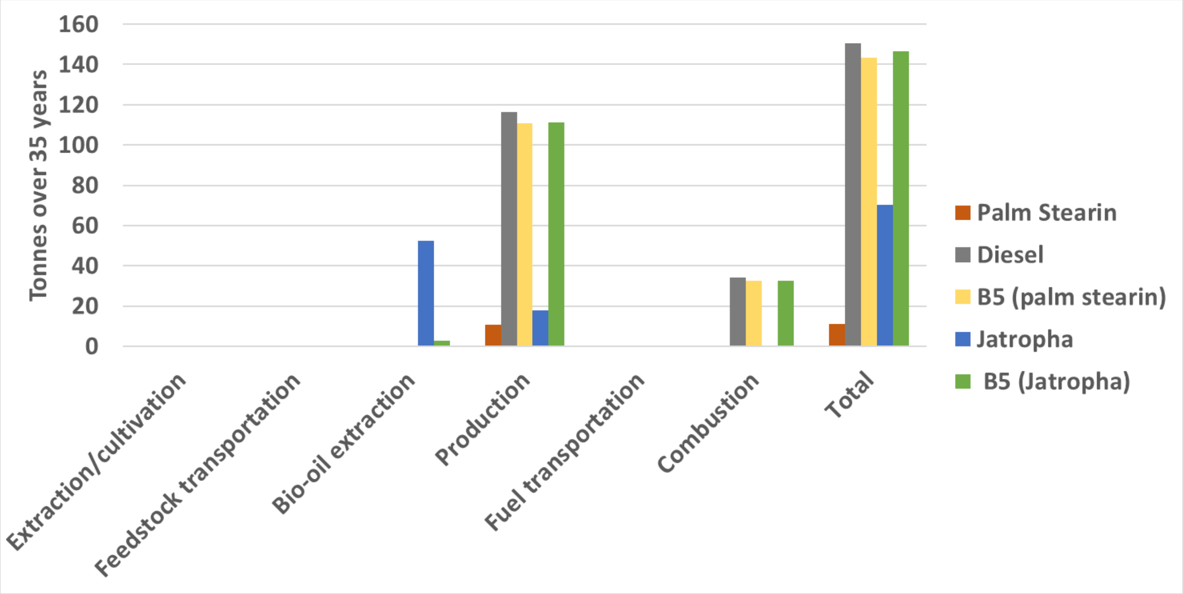

Figure 4-6: SOx emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

Like NOx, SOx are emitted with the presence of oxygen, heat, and sulphur instead of nitrogen. Diesel is the biggest emitter of SOx with 150 tonnes. Both B5 jatropha and B5 palm stearin release fewer SOx. This decrease is supported by the literature including Nazir and Setyaningsih (2010) and Antolın et al. (2002) who stated that there is a decrease in SOx as well as other pollutants.

Fractional distillation is the biggest emitter at one single stage along the supply chain at 116.2 tonnes accounting for 77% of the total. The transesterification stage is the biggest emitter for palm stearin and the second for jatropha based biodiesel. This is likely caused by the production of steam, the use of electricity, and the consumption of methanol (through the life cycle of producing methanol) and natural gas (Tsoutsos et al., 2010, Ceuterick and Spirinckx, 1997), where the upstream environmental effects are accounted for.

4.2.2.4 Particulate matter (2.5 and 10 micrograms)

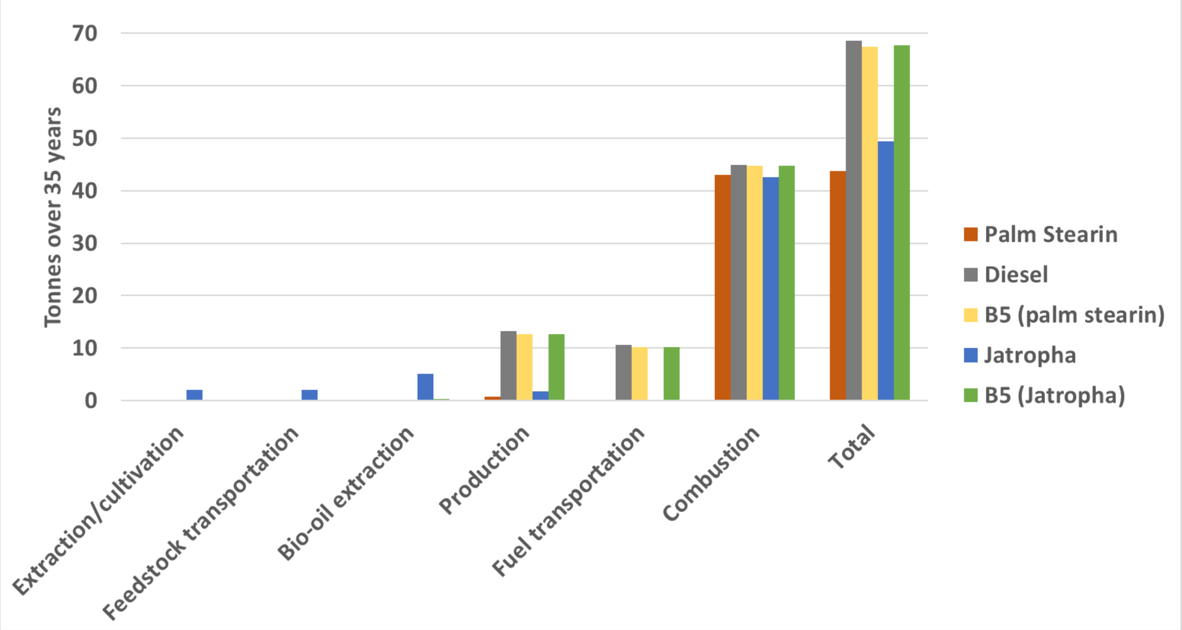

Figure 4-7: PM_{10} emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

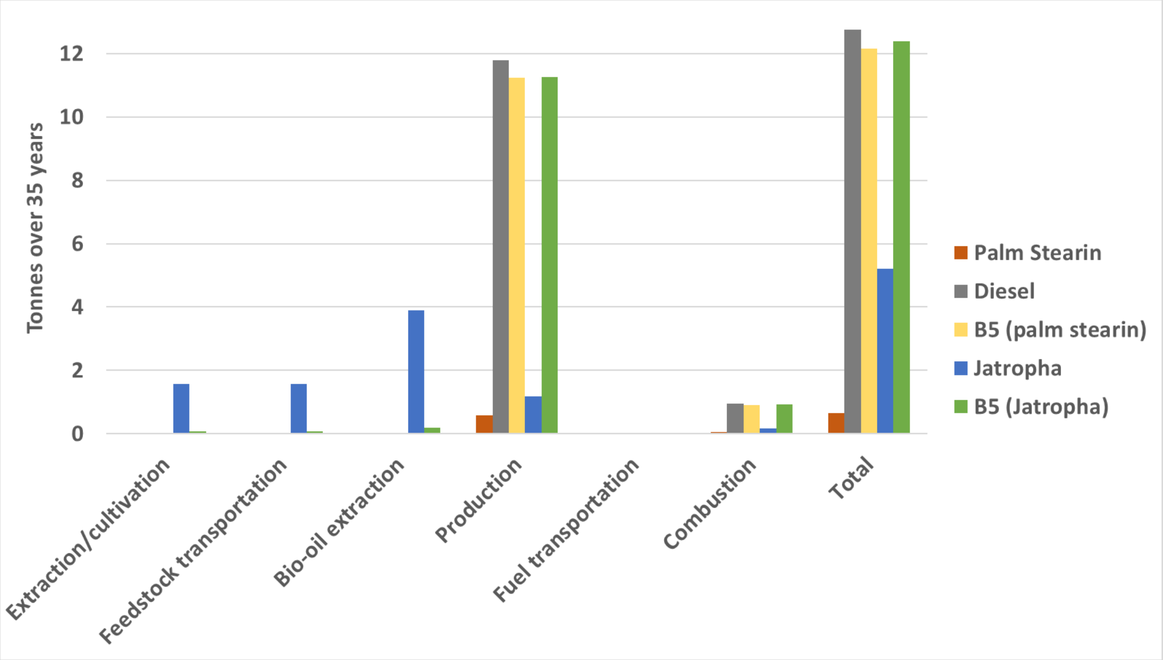

Figure 4-8: $PM_{2.5}$ emissions from the LCA for biodiesel produced from jatropha, palm stearin and diesel

Particulate matter can be either primary or secondary.

1. Primary components consist of sodium chloride, elemental carbon, trace metal, and mineral components.

2. Secondary components include sulphate, nitrate, and water. Organic carbon falls into both categories (DEFRA, 2005).

Particulate matter is given a number based on the size of the particles.

$PM_{2.5}$ is considered more harmful than PM_{10} because the particles can pass through the body's protective system and settle in the lungs more easily, leading to respiratory problems (Planning Commission, 2003).

Diesel emits 69 tonnes of PM_{10}, B100 jatropha and B100 palm stearin emit 28% and 36% less respectively compared to diesel.

The fractional distillation stage is the largest emitter of $PM_{2.5}$ for diesel at 11.8 tonnes. The pattern for $PM_{2.5}$ is very similar to PM_{10} but in smaller quantities. This however does not mean that $PM_{2.5}$ is not as important as PM_{10}. $PM_{2.5,}$ as already explained, is considered more harmful because the smaller particulates can enter the body more easily causing harm to the respiratory system for example.

High reductions in PM have been noted in the literature. Ghosh et al. (2007) estimated an 80% reduction for B20. Planning Commission (2003) reported reductions between 25-50% when biodiesel is used compared to conventional diesel, although the blend is not clearly defined.

4.3 FINANCIAL APPRAISAL

In this thesis, the locomotives are travelling the same distance with the same conditions applied regardless of the fuel being used, and according to Greater London Authority (2015), Barnitt et al. (2006) and Barnitt et al. (2008) the maintenance costs will not change when using a low blend. Also, Indian Railways purchases biodiesel at the same price they would pay for diesel. This is fixed at the beginning of the financial year. The only variable for financial analysis is the volume of fuel. This is due to the energy content of the fuels. On average there is approximately 12% less energy in bioenergy compared to diesel (Yunus et al., 2013a, Rahman et al., 2010). With jatropha having a higher energy content than palm oil, this would be reflected in the volume needed to power the locomotive. These factors influence the final price that Indian Railways would pay.

Table 4-5: Financial Cost-Effectiveness (million Rs) with varying discount rates for palm stearin based biodiesel at different blends, jatropha biodiesel compared to diesel

Cost-Effectiveness (million Rs) with varying discount rates							
Discount Rate	Diesel (B0)	Biodiesel (J B5)	Difference	Biodiesel (PS B5)	Difference	Biodiesel (PS B10)	Difference
5%	1,611.1	1,624.9	-13.8	1,626.0	-14.8	1,640.8	-29.7
7.75%	1,570.0	1,583.4	-13.4	1,584.5	-14.5	1,423.5	-25.9
10%	1,537.9	1,551.0	-13.1	1,552.1	-14.2	1,566.2	-28.3
15%	1,471.0	1,483.6	-12.6	1,484.6	-13.6	1,498.1	-27.1

Cost-Effectiveness (million Rs) with varying discount rates							
Discount Rate	Diesel (B0)	Biodiesel (PS B20)	Difference	Biodiesel (PS B50)	Difference	Biodiesel (PS B100)	Difference
5%	1,611.1	1,670.5	-59.4	1,765.0	-153.9	1,924.3	-313.2
7.75%	1,570.0	1,627.9	-57.9	1,720.0	-149.9	1,875.2	-305.2
10%	1,537.9	1,594.6	-56.7	1,684.8	-146.9	1,836.8	-298.9
15%	1,471.0	1,525.3	-54.2	1,611.5	-140.5	1,757.0	-285.9

Biodiesel, both jatropha and palm stearin-based, is more expensive than diesel at all discount levels. B5 from jatropha is Rs 13.8 million more expensive to use and B5 from palm stearin is Rs 14.8 million more expensive at a 5% discount rate. As the discount rate increases, the financial feasibility of using biodiesel becomes more viable. For example, there is an increase in feasibility for B5 from jatropha when comparing a 5% discount rate with 15% with a difference of Rs 5.2 million.

The cost of crude oil and consequently diesel will likely increase in the long term due to supply decreasing because it is non-renewable and not easily replaced, but even with models which claim to be robust, it is difficult to forecast with certainty future crude oil prices (Baumeister and Kilian, 2016, Zhang et al., 2018). However, the present price of diesel would need to increase by close to 35% for biodiesel to become competitive with diesel.

As the blend increases so does the overall cost. Biodiesel is more expensive to buy, not because of the cost but because of the energy content which is less than diesel. From B5 to B20 the increase is linear because the only increase is the amount of fuel needed. For example, the difference with B10 at a 10% discount rate is double that of B20 (Rs 56.7 million and Rs 28.3 million respectively). This is relevant for all the discount levels. This equal proportion changes when B50 is introduced because of the increase in maintenance costs. Therefore, the cost of using biodiesel becomes more expensive at an increasing rate with higher blends. This analysis is in line with the literature that B100 is more expensive than lower blends. In the US B100 cost $3.76 per gallon in June 2006 whereas B20 totalled $2.98 per gallon at the same time (Shurland et al., 2014).

However, the way India has structured its pricing policy with biodiesel producers means that on an Rs/litre basis biodiesel is cheaper.

Table 4-6: Rs/l for different biodiesel blends produced from palm stearin

	B0	B5	B10	B20	B50	B100
Price of fuel (Rs/l)	74.19	74.19	74.19	74.19	74.19	74.19
Maintenance (Rs/litre)	5.34	5.29	5.24	5.14	5.35	5.13
Total	79.53	79.48	79.43	79.33	79.54	79.32

On an Rs/litre basis, B100 is the cheapest because the marginal cost of maintaining the locomotives decreases. The amount of fuel needed increases with an increase in the concentration of biodiesel (due to biodiesel having a lower energy content compared to diesel), but the maintenance costs remain stationary. B50 is the most expensive fuel because of the extra maintenance needed on the locomotives. However, as seen in table 4-5 overall biodiesel is not the cheaper option because of extra volumes needed when using biodiesel.

4.4 ECONOMIC APPRAISAL

The economic appraisal is the cost-effectiveness of diesel and biodiesel produced from jatropha grown in India and palm stearin imported from Malaysia. The appraisal considers monetary and non-monetary costs. Taxes and subsidies are absent.

4.4.1 A comparison of biodiesel produced from palm stearin to diesel

Diesel is often perceived as being the "cheaper" fuel, to a certain extent, this is true. This was demonstrated in the financial section of this work, however economically it is more expensive. A deeper analysis of the inputs can explain why diesel is not "cheaper" than biodiesel.

Table 4-7: Economic Cost-Effectiveness (million Rs) with varying discount rates for biodiesel produced from palm stearin compared to diesel

	Cost-Effectiveness (million Rs) with varying discount rates											
	5%			7.75%			10%			15%		
	Diesel (B0)	Biodiesel (B5)	Difference	Diesel (B0)	Biodiesel (B5)	Difference	Diesel (B0)	Biodiesel (B5)	Difference	Diesel (B0)	Biodiesel (B5)	Difference
Base Case	3,999.2	3,983.3	15.9	3,897.1	3,881.7	15.5	3,817.4	3,802.3	15.1	3,651.4	3,636.9	14.5
20% biodiesel production cost increase	3,999.2	3,988.8	10.4	3,897.1	3,887.0	10.1	3,817.4	3,807.5	9.9	3,651.4	3,641.9	9.5
15% diesel production cost decrease	3,847.9	3,839.6	8.3	3,749.7	3,741.6	8.1	3,673.0	3,665.0	7.9	3,513.3	3,505.7	7.6
20% diesel production cost decrease	3,797.8	3,792.0	5.8	3,700.9	3,695.2	5.6	3,625.2	3,619.7	5.5	3,467.6	3,462.3	5.3
40% diesel production cost decrease	3,597.7	3,601.9	-4.2	3,505.8	3,509.9	-4.1	3,434.1	3,438.2	-4.0	3,284.8	3,288.7	-3.8

Across all discount rates, B5 is more viable compared to B0. B5 at a 5% discount level has a cost of Rs 3,983 million which is Rs 15.9 million less than B0, whereas at a 15% discount level there is a Rs 14.5 million difference between B0 and B5. At a higher discount level, biodiesel becomes less economically viable.

Even if biodiesel production costs were to increase B5 would remain more economically feasible than B0, by Rs 10.4 million. This biodiesel production cost only refers to monetary inputs so thus the environmental costs would remain constant.

However, the sensitivities of producing diesel are greater compared to biodiesel. For example, a 20% decrease in diesel production costs would mean that B5 is still more feasible than B0 but less than a 20% increase in biodiesel production costs. A decrease in diesel production costs results in B5 being more economically feasible than B5 by Rs 5.8 million. Were diesel production costs to decrease by 40% then B5 would no longer be economically feasible. This is true at all discount levels.

There is a consensus that biodiesel is more expensive compared to diesel. However, there is some literature supporting the conclusion that biodiesel is cheaper than diesel. What is unclear is whether the literature is portraying an economic or financial cost. Dorado et al. (2006) reported that diesel was around 0.82-0.86 euro/kg and biodiesel was between 0.41 and 0.66 euro/kg depending on the feedstock. The results in this thesis are not directly comparable because Dorado et al. (2006) also included indirect costs such as insurance and storage and it is uncertain whether taxes are included in this analysis, however it indicates that biodiesel can be cheaper to use than diesel.

An aspect that is unclear in the economic analysis is the share between monetary and non-monetary costs. This can be done through the breakdown of the economic costs at each stage of the LCA. This is seen in Figure 4-9.

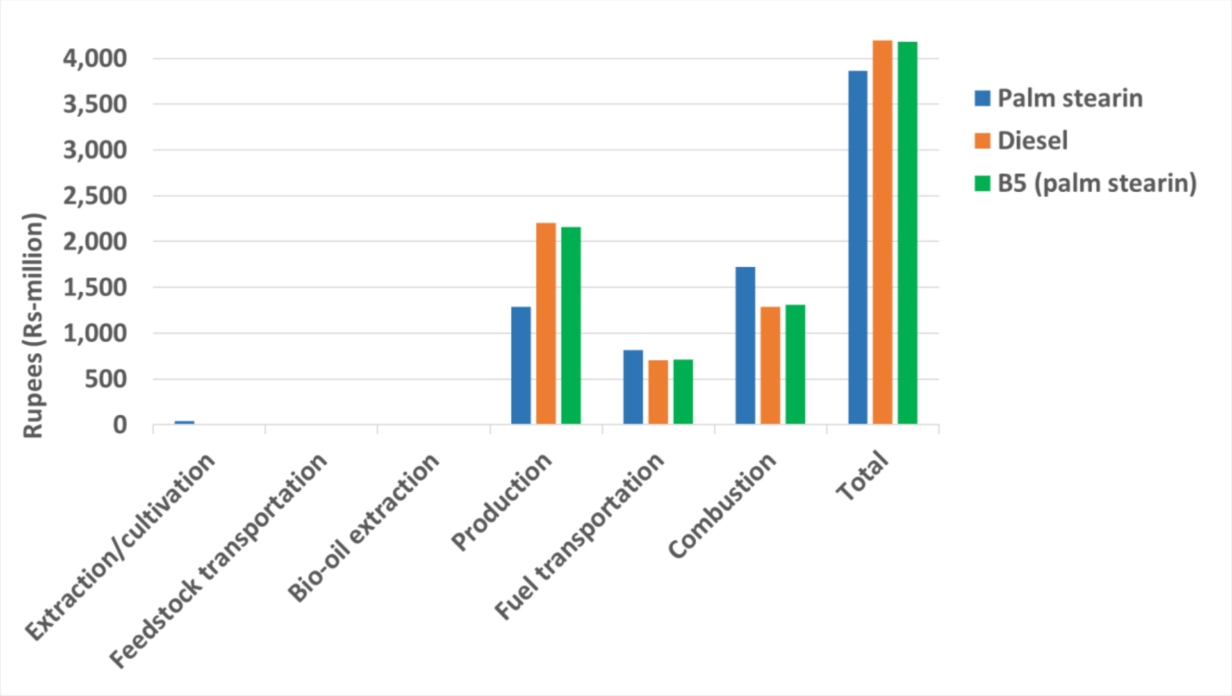

Figure 4-9: Economic Analysis comparing B100 palm stearin, diesel, and B5 palm stearin

B100 is the most economical fuel to use, but only one stage of the supply chain is smaller than B0 – the fuel production stage all others are greater than B0. B5 is more economically feasible than B0 in total. This is the transesterification/fractional distillation stage Rs 1,290 million and Rs 2,203 million for B100 and B0 respectively. For B0 the fractional distillation stage has a share of nearly 52% of the total economic value compared to the second-largest share of 31% which is the combustion of diesel. This is a similar pattern but opposite for B100, but with a more even split between the stages; 33% of the total for transesterification, and a 44% share for the combustion of fuel.

4.4.1.1 Monetary costs

From figure 4-9 it is unclear whether this is associated with monetary or non-monetary costs. This is discussed in Figure 4-10.

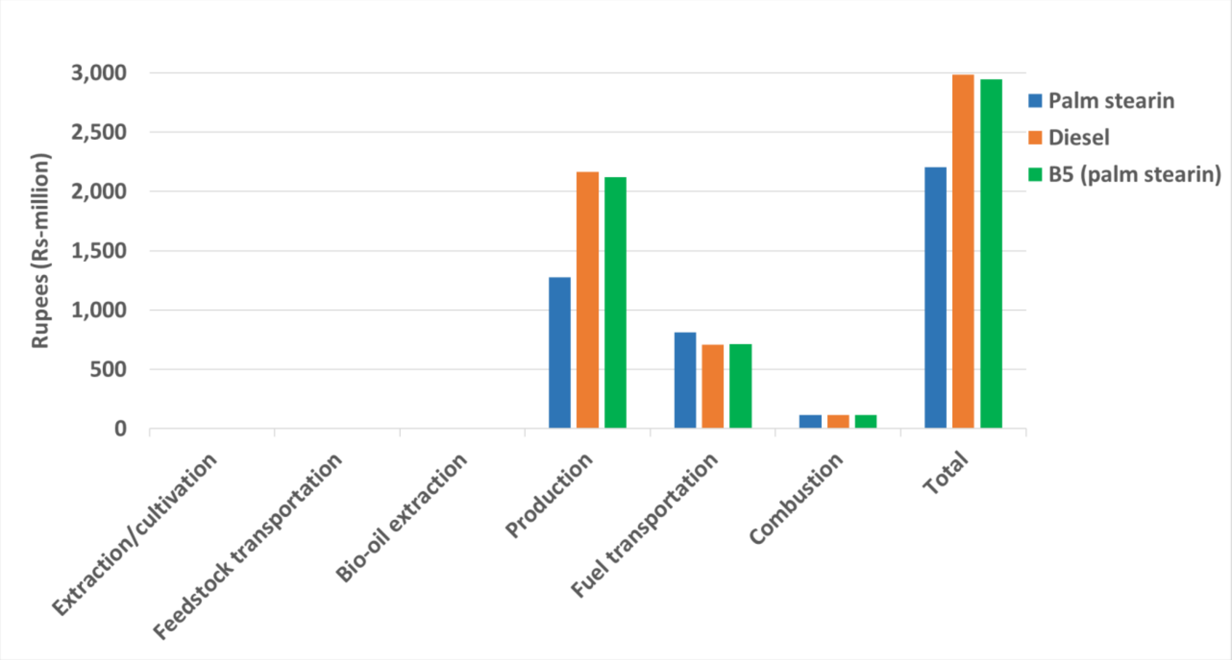

Figure 4-10: Monetary Values comparing B100 palm stearin, diesel, and B5 palm stearin

There are no monetary costs for the first three stages to produce biodiesel and diesel because the monetary costs are reflected in the imported cost of the feedstock. The largest share of monetary value total is from producing biodiesel and diesel 57.9% and 72% respectively resulting in an 80% share for B5 at this stage.

In the financial analysis, biodiesel is more expensive than diesel. In the economic analysis, diesel is more expensive than biodiesel. The main difference between the two assessments is that taxes and subsidies have been removed for economic analysis. This raises the question of the extent of distortion in the market. If subsidies were removed from diesel then diesel would be more expensive financially and thus biodiesel would likely become more competitive.

To help understand the extent that subsidies contribute to the end price of diesel the fractional distillation stage is broken down into individual inputs. During the fractional distillation, the importation of crude oil and natural gas are the largest monetary contributory factors.

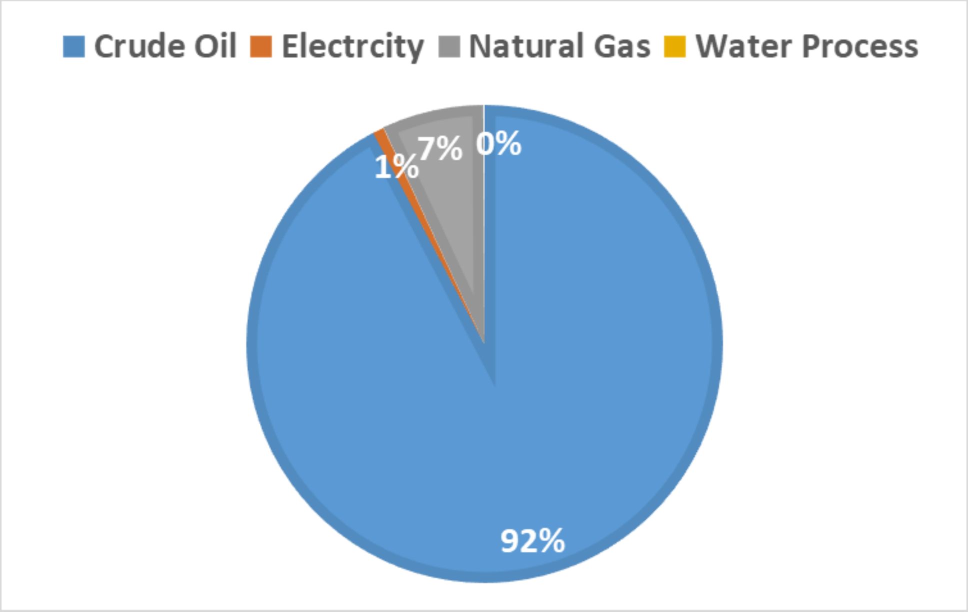

Figure 4-11: Breakdown of diesel production costs

The cost of crude oil contributes to 92% and natural gas 7% of the total monetary production costs of diesel. Both of these inputs receive subsidies (Jain, 2018, Acharya and Sadath, 2017). This causes a knock-on effect in the biodiesel market. For example, natural gas receives subsidies at some stage along its supply chain, which indirectly makes natural gas cheaper in the end. This cheaper natural gas can be sold, in this instance into producing biodiesel. This is where the knock-on effect of the distorted natural gas price affects other markets and thus making them also distorted.

In this instance, it is, however, difficult to put a value on the subsidies and the knock-on effect because of a lack of data in the public domain. Some reports and studies, such as those conducted by Charles et al. (2013) and the International Institute for Sustainable Development (2017) have attempted to estimate India's fossil fuel subsidies but admit that it is difficult due to the lack of openness - 38 subsidies were provided for the oil and gas industry, but 12 of these are unquantifiable because it is closed data. 5.4 % of the subsidies are directly injected into the industries, but most are through measures such as tax breaks. For many years these subsidies were being supplied to the end-user/consumer, but such incentives have now been removed. However, the industry is still receiving subsidies, which leads to the conclusion most of the subsidies for oil are going to producers. Subsidies will likely increase if the oil price increases (ETEnergyWorld, 2018, The Economic Times, 2017). This, as mentioned above, cannot be estimated due to insufficient information in the public domain (International Institute for Sustainable Development, 2017, Charles et al., 2013).

Often it is the argument that subsidies are there to help lower-income households for services or goods they may not be able to afford otherwise. There have been estimates made as to the extreme of how much India is spending on fossil fuel subsidies and how subsidies are not as effective as thought to be. del Granado et al. (2012) found that low-income households receive a small share of the benefits from subsidies. This has been backed up by the Asian Development Bank (2016) which concluded that "less than 50% of subsidy savings were necessary to fully compensate households for the direct and indirect impacts of increased prices" (p.33). Were subsidies to be removed prices would likely rise. This increase would likely be paid for by households. The Asian Development Bank (2016) concluded that it is cheaper to give the value of the subsidy directly to the household as compensation for the rise.

4.4.1.2 Non-monetary costs

The monetary cost is not the only contributory factor to the overall economic cost. The other is from an environmental perspective. The environmental emissions have already been discussed, but for these to contribute towards the economic assessment monetary values must be applied.

The monetary cost is one-half of the economic costs the other is the environmental cost. This can be found in Figure 4-12.

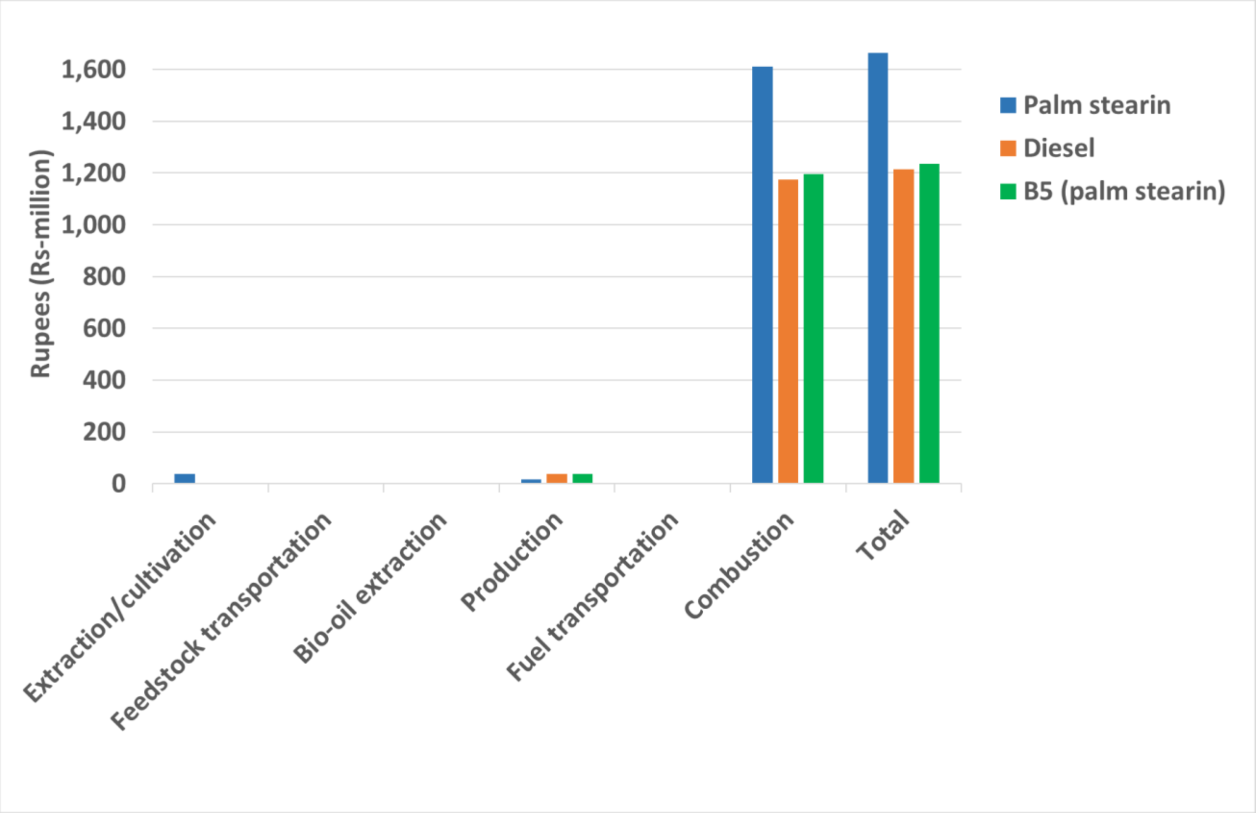

Figure 4-12: Environmental Non-Monetary Values comparing B100 palm stearin, diesel, and B5 palm stearin

B100 and therefore B5 are more expensive than diesel by Rs 451 million and Rs 23 million, respectively. The combustion stage has the largest non-monetary share for both B100 and B0 at around 98% each.

GHGs are absorbed back into the life cycle, but other emissions are not. NOx emissions are higher for biodiesel compared to diesel and have a higher monetary weighting compared to the other emissions. Exposure to this emission over a long period can have a significant negative impact on the respiratory system or lead to premature death (European Environment Agency, 2017, World Health Organization, 2000).

The second highest environmental cost along the supply chain is the transesterification for biodiesel and fractional distillation for diesel with diesel having the higher. This is consistent with the environmental analysis with diesel having more of a negative effect on the environment than biodiesel.

During transesterification and fractional distillation, fossil fuels are combusted in the process to produce biodiesel and diesel, respectively. Natural gas is the primary source of the emissions at this stage for diesel, but for palm stearin it is electricity. Even though natural gas is cleaner than coal on a g-CO$_2$/kWh basis as seen in Table 2-8, temperatures to break down hydrocarbons are higher for crude oil. For palm stearin, it is around 90^{o}C, but for crude oil, it is between 176-357^{o}C to fractionally distil diesel (Mancio et al., 2018). Even though the environmental cost of palm stearin is more than diesel, the overall economic outcome still shows that switching to B5 is beneficial to the Indian economy.

A common element that palm stearin-based biodiesel and diesel have in common is that the feedstock (palm stearin and crude oil respectively) are both imported. There are few alternatives to importing crude oil due to only being able to extract the oil where the reserves are. One of the benefits that biofuels in general have over their fossil fuel equivalent is the large variety of raw materials available.

4.4.1.3 Economic Analysis for Different Blends

The economic analysis consists of prices that are without taxes or subsidies and externality costs.

Table 4-8: Economic Cost-Effectiveness (million Rs) with various discount rates for different biodiesel blends compared to diesel

Cost-Effectiveness (million Rs) with varying discount rates						
	5%			7.75%		
	Diesel (B0)	Blend	Diff.	Diesel (B0)	Blend	Diff.
B5	3,999.2	3,983.3	15.9	3,897.1	3,881.7	15.5
B10	3,999.2	3,957.2	42.0	3,897.1	3,856.2	40.9
B20	3,999.2	3,914.8	84.4	3,897.1	3,814.9	82.2
B50	3,999.2	3,793.2	206.0	3,897.1	3,696.4	200.7
B100	3,999.2	3,602.1	397.1	3,897.1	3,510.2	386.9

	10%			15%		
	Diesel (B0)	Blend	Diff.	Diesel (B0)	Blend	Diff.
B5	3,817.4	3,802.3	15.1	3,651.4	3,636.9	14.5
B10	3,817.4	3,777.3	40.0	3,651.4	3,613.1	38.3
B20	3,817.4	3,736.8	80.6	3,651.4	3,574.4	77.1
B50	3,817.4	3,620.8	196.6	3,651.4	3,463.3	188.1
B100	3,817.4	3,438.4	379.0	3,651.4	3,288.9	362.5

This analysis is taken on the assumption that the extra demand for biodiesel would be met through the existing production facilities. At all blend levels and discount rates, biodiesel is more economically viable than diesel. With B5 at 5% being Rs 15.9 million more viable than B0 and B100 being Rs 397.1 million more viable.

As mentioned in section 4.4.1 subsidies distort the market. Table 4-9 shows the difference between the financial and economic costs for different blends.

Table 4-9: A comparison of Rs/l for the financial and economic cost-effectiveness

	B0	**B5**	**B10**	**B20**	**B50**	**B100**
Financial Cost	79.5	79.5	79.4	79.3	79.5	79.3
Economic Cost	188.0	185.4	182.4	177.05	162.3	141.41

The cost to the economy is much greater than the financial implication for Indian Railways including B0. For B0 approximately 71% of the economic cost is linked to the monetary costs and the other 29% to non–monetary i.e., environmental. The monetary cost for B0 is Rs 133.5/l. ThereforeB0 is receiving approximately 54 Rs/l (difference between financial and monetary cost) in subsidies across the supply chain through a variety of measures including injection of cash flow, tax incentives, tax relief, and an absence of shadow pricing.

The difference between the financial cost and monetary cost for palm stearin is much smaller which means that biodiesel – using palm stearin as a feedstock in this instance - receives fewer subsidies than B0. For B100 when it is produced from imported palm stearin the economic cost is made up of 57% monetary costs and 43% environmental costs. B100 is receiving Rs 1.3/l (difference between financial and monetary cost) in subsidies across the supply chain through a variety of measures including injection of cash flow, tax incentives, tax relief, and an absence of shadow pricing. To make biodiesel competitive from a financial perspective the Indian government would need to consider redistributing subsides from fossil fuels to renewable fuels.

4.4.2 A comparison of biodiesel produced from jatropha to diesel and biodiesel produced from palm stearin

Palm stearin is imported from Malaysia. An alternative feedstock may be one that is cultivated in India. This thesis uses jatropha for the reasons given in 3.2.2.2.

Table 4-10: Economic Cost-Effectiveness (million Rs) with varying discount rates for biodiesel produced from jatropha compared to diesel and biodiesel produced from palm stearin

	Cost-Effectiveness (million Rs) with varying discount rates					
	5%			7.75%		
	Diesel (B0)	Biodiesel (B5)	Difference	Diesel (B0)	Biodiesel (B5)	Difference
B5 Jatropha	3,999.2	4,020.8	-21.6	3,897.1	3,918.1	-21.0
B5 Palm stearin	3,999.2	3,983.3	15.9	3,897.1	3,881.7	15.5
15% diesel production cost increase	4,148.1	4,162.2	-14.1	4,042.2	4,056.0	-13.8
20% diesel production cost increase	4,198.1	4,209.8	-11.6	4,091.0	4,102.3	-11.3
40% diesel production cost increase	4,398.3	4,399.9	-1.6	4,286.0	4,287.6	-1.6

	10%			15%		
	Diesel (B0)	Biodiesel (B5)	Difference	Diesel (B0)	Biodiesel (B5)	Difference
B5 Jatropha	3,817.4	3,838.0	-20.6	3,651.4	3,671.1	-19.7
B5 Palm stearin	3,817.4	3,802.3	15.1	3,651.4	3,636.9	14.5
15% diesel production cost increase	3,959.5	3,973.0	-13.5	3,787.4	3,800.3	-12.9
20% diesel production cost increase	4,007.3	4,018.4	-11.1	3,833.1	3,843.7	-10.6
40% diesel production cost increase	4,198.4	4,199.9	-1.5	4,015.8	4,017.3	-1.5

Biodiesel produced from jatropha is not more economically feasible than diesel or biodiesel produced from palm stearin. This is also true for all other discount rates. Were diesel costs to increase then the difference between B5 jatropha and B0 would increase making B5 even more economically viable. At 40% diesel production cost increase B5 is almost at break even with diesel with B5 being Rs 1.6 million more expensive than B0.

As with palm stearin-based biodiesel, the economic assessment can be analysed from each stage along the supply chain from a monetary and non-monetary perspective.

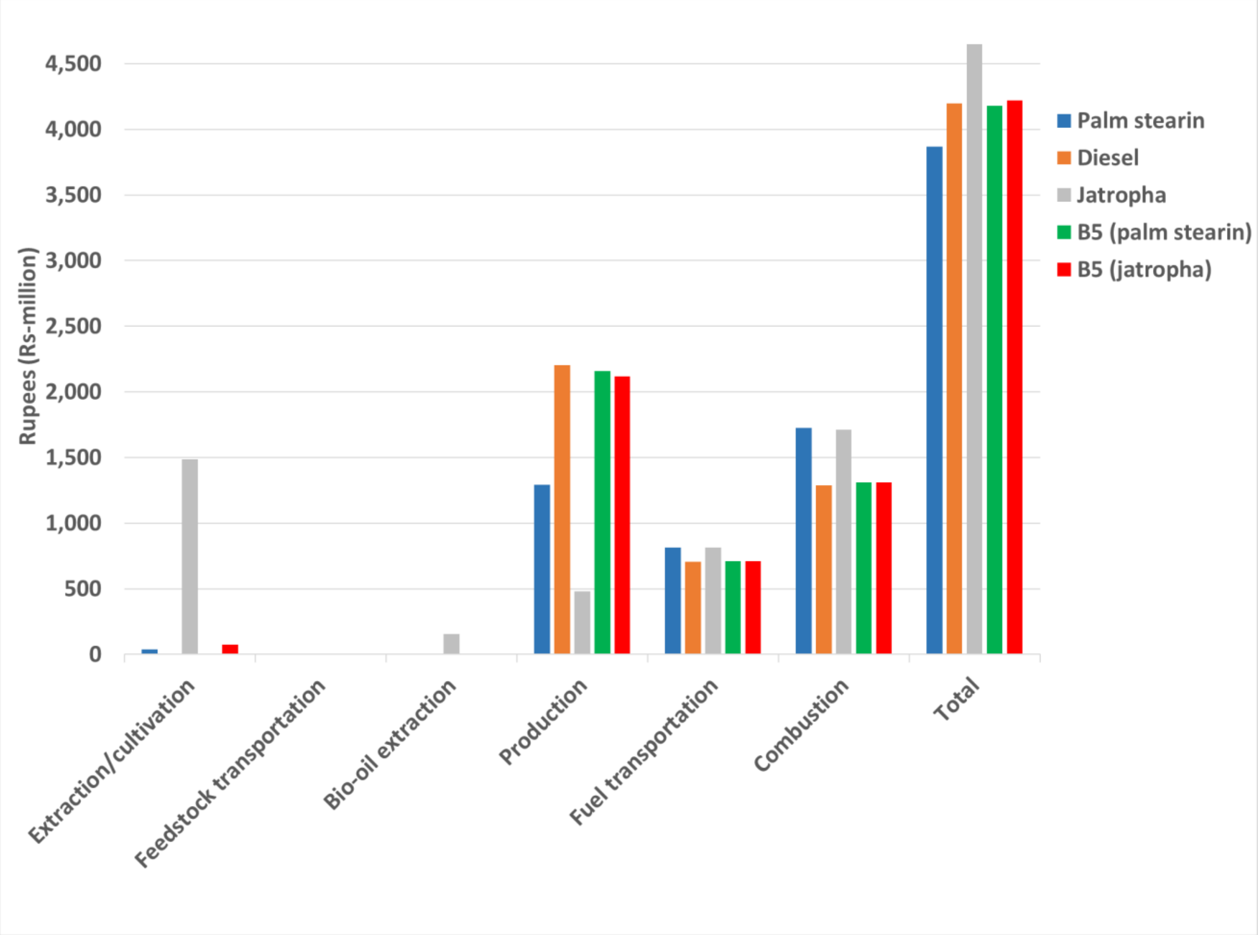

Figure 4-13: Economic Analysis comparing B100 palm stearin, B100 jatropha, diesel, B5 palm stearin, and B5 jatropha

B5 jatropha is less economically viable than B0. B100 jatropha costs Rs 4,600 million and B0 costs Rs 4,200. The combustion stage is the largest single contributor to the overall economic cost of Rs 1,700 million for jatropha-based biodiesel. Jatropha-based biodiesel is less cost-effective overall compared to palm stearin-based biodiesel. At this part of the analysis, it is difficult to determine why there is a difference between B100 and B0. Breaking the economic analysis down into monetary and non-monetary may help accomplish this. Firstly, the monetary value is demonstrated in Figure 4-14.

4.4.2.1 Monetary costs

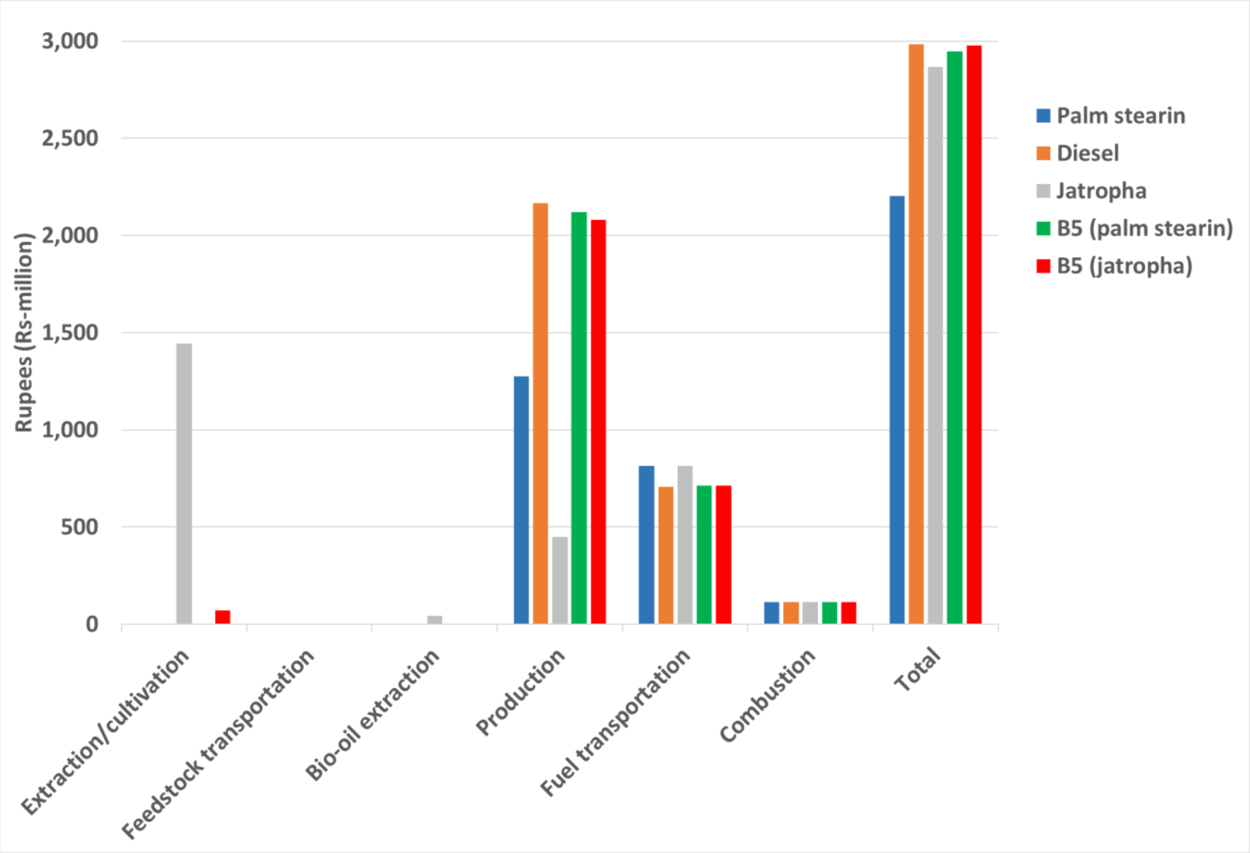

Figure 4-14: Monetary Values comparing B100 palm stearin, B100 jatropha, diesel, B5 palm stearin, and B5 jatropha

There is a difference of Rs 120 million and Rs 663 million in total between B100 jatropha with B0 and B100 palm stearin respectively with jatropha-based B100 being more expensive than palm stearin based biodiesel less than biodiesel. The highest monetary cost for B100 jatropha is the cultivation stage. It is assumed that jatropha plantations do not exist therefore the initial ploughing stages are needing to be accounted for. Cultivating jatropha is labour intensive so labour costs are high. The transesterification cost is higher for biodiesel produced from palm stearin than jatropha. The process for each of the fuels is different, therefore are elements that could lead to palm stearin-based biodiesel being more expensive during transesterification.

1) Palm stearin has a high melting point (Kim-Tiu et al., 2014). There is a need to have warm pipes and machinery to avoid the feedstock solidifying or crystallising. To do this heated water flows continuously through the pipes. Water needs to be heated in a boiler. To heat the boiler, it needs to be burning waste products, using electricity, or combusting fossil fuels, this will have an additional cost.
2) For jatropha-based biodiesel 41% of the transesterification, the cost is linked to the feedstock as seen in Figure 4-15. As mentioned previously jatropha is still an under-researched feedstock and therefore there is uncertainty about the yield and reliability of the crop. Because of this, the cost of producing biodiesel from jatropha is more uncertain.

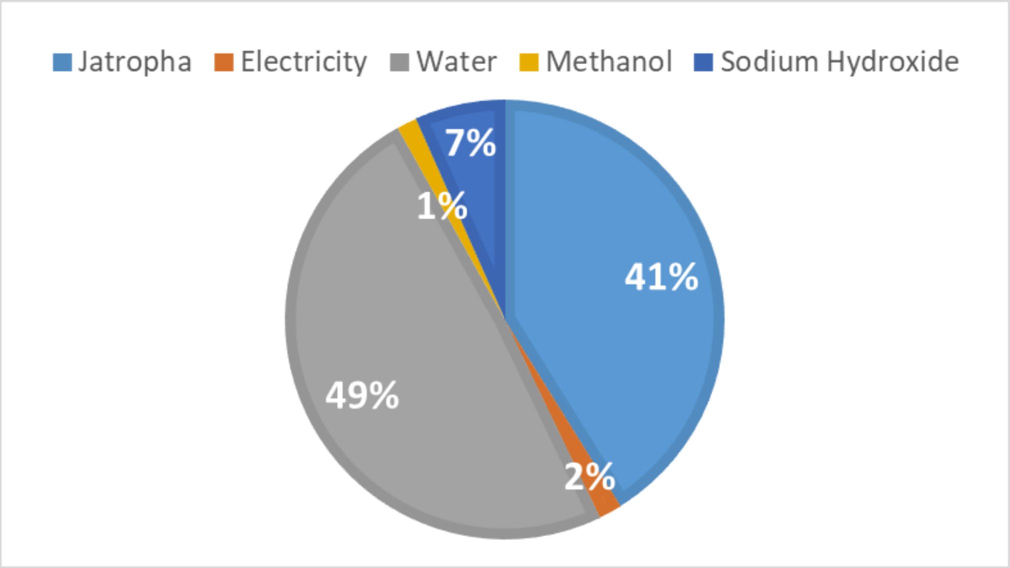

Figure 4-15: Transesterification monetary split for biodiesel produced from jatropha

As previously mentioned in 2.4.5 and 2.5.1 the feedstock is often the largest cost toward producing biodiesel. However, the feedstock is not the largest monetary factor of the production cost here. Here there are no taxes or subsidies. Were they to be applied then it is likely that results would show similar finds to in the literature. This estimation can be seen in Figure 4-16.

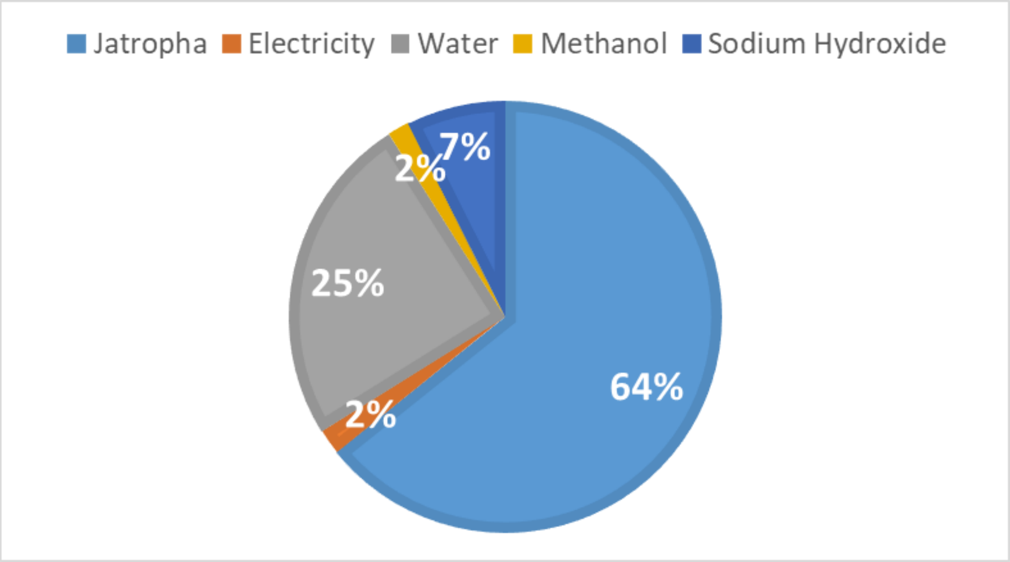

Figure 4-16: Transesterification monetary split for biodiesel produced from jatropha (tax on feedstock included)

With the same taxes applied to jatropha as palm stearin (seen in appendix 7) the proportional split changes so that the raw materials were 64% of the total cost. This is similar, although a little less, to the literature as explained in 2.4.5 and 2.5.1.

There is limited literature that not only examines the economic value of producing and using biodiesel but also little that compares both palm oil/stearin and jatropha-based biodiesel in the same analysis. This thesis also differs from other such comparisons because it also compares between a feedstock that is cultivated in India and one which is imported from Malaysia.

The environmental cost also has a share which can be seen in Figure 4-17.

4.4.2.2 Non-monetary costs

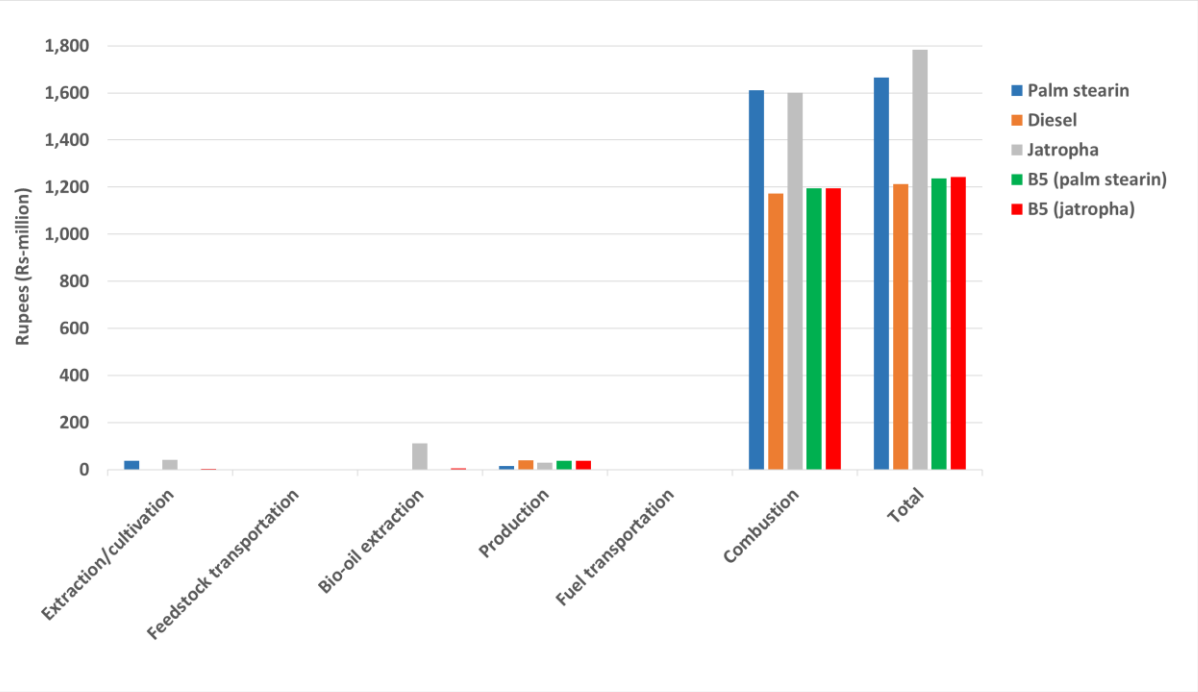

Figure 4-17: Environmental Non-Monetary Values comparing B100 palm stearin, B100 jatropha, diesel, B5 palm stearin, and B5 jatropha

Overall, the environmental costs are higher for biodiesel produced from jatropha and consequentially B5 compared to B0. The largest portion of this cost is linked to the combustion stage. At the combustion stage, B100 jatropha is Rs 570 million more expensive than B0. This is not abnormal as it is common that biodiesel has higher levels of some emissions during combustion, NOx in particular due to biodiesel having a higher oxygen level than diesel. As well as producing higher levels of NOx, it also is an expensive emission thusly contributing a higher proportion to the combustion stage.

The main difference in the analysis of jatropha and diesel is the inclusion of different emissions. Diesel only has the inclusion of GHGs, whereas jatropha has the inclusion of not only GHGs but also pollutants. The emissions from the cultivation stage are often associated with the fertilisers used as is frequently referenced in the literature (Whitaker and Heath, 2009, Eshton et al., 2013, Lam et al., 2009a, Siregar et al., 2015).

The extraction of jatropha oil is the second highest contributor to the environmental cost. It is also important to note there is no diesel cost at this stage due to the supply chain having one less stage.

Overall jatropha-based biodiesel and B5 have higher environmental costs compared to B0. When this value is combined with the monetary values then jatropha-based biodiesel is less economically beneficial for India.

4.5 SENSITIVITY ANALYSIS

A sensitivity analysis can highlight uncertainty and influencing factors with a model. Often best- and worst-case scenarios are used to indicate the different outcomes.

4.5.1 Method

There are two main types of sensitivity analysis: local and global. A local sensitivity analysis tests parameters individually while maintaining others. This can simplify the model by eliminating input parameters that are deemed insignificant. A global analysis takes into account all parameters at once (Chaudhry et al., 2021). This thesis uses a local sensitivity analysis to determine which variables are sensitive and have the potential to change the outcome of the model.

It is possible to run a sensitivity simulation in several ways. The first is to show the best- and worst-case scenarios. The second is to use a Monte Carlo method, which is a numeric concept assisting with probabilistic models. It is often used when the data is vast and influenced by randomness (Mavaddat et al., 2020). The sensitivity analysis in this thesis uses a maximum and minimum range when estimating the values. There is not a vast amount of data to analyse and the method chosen helps identify any potential variables which could affect the model. As this is the aim of this sensitivity analysis using a probabilistic model is not necessary.

4.5.1.1 Variables

Each parameter is tested for one of two reasons; either they may significantly influence the model, or the values are uncertain. However, as pointed out by Hackney and De Neufville (2001) changes in assumptions and values along the supply chain do not often change the overall conclusion of the results.

Imported biodiesel

It has been noted that the feedstock price has a considerable effect on the end price of biodiesel. Palm oil is one of the cheapest feedstocks to produce biodiesel. Malaysia is the second-largest producer and exporter of palm oil in the world with a 40% global share. However, Malaysia was not for many years a large producer of biodiesel, but with the help of government subsidies, the number of production facilities has grown in recent years (Nomanbhay et al., 2018).

The amount of biodiesel that Malaysia is exporting is increasing. In 2016 they exported 94.29 million litres, then in 2017, they exported 267 million litres (USDA Foreign Agricultural Service, 2019, USDA Foreign Agricultural Service, 2019). Of these exports, a portion was imported by India. This raises the question of whether Indian Railways should be importing its biodiesel directly from Malaysia. This may make economic sense if it was more viable, but a barrier to directly importing biodiesel is that India limits the amount of biodiesel being imported.

However, it is still worth testing this variable. It is difficult to compare the cost of importing biodiesel directly and the cost of producing it directly. This is because there is limited data on imported biodiesel. Data available includes the cost of the feedstock. As stated in the literature feedstock costs account for an average of 69% of the total cost of producing biodiesel as seen in Table 2-5. This value can be used to calculate the total cost of biodiesel, and this is the method used in the sensitivity analysis.

An alternative to doing this is extracting the monetary costs from the transesterification stage and subtracting that total value from the model. However, this would not show the representation of biodiesel being produced in another country as the baseline is modelled on a production plant based in India. Palm stearin is being imported at 37,181 Rs/tonne. This represents 69% of the total cost according to the literature so it is possible to calculate the cost of biodiesel for this sensitivity analysis.

Table 4-11: Workings to calculate the cost of imported biodiesel

Value	Unit	Notes
37,181.05	Rs/tonne	
37.18	Rs/kg	Divided by 1000
53.89	Rs/kg	total biodiesel cost calculated using the 69% to find 100%
48.50	Rs/litre	Using 0.9 as the conversion – mass to volume
727,808.54	litres/year	Litres needed for one year
35,296,546.42	Rs/year	Indian Railways would pay this amount per year for the routes specified in the case study (price of biodiesel is the same as diesel)

This value replaces the monetary cost of transesterification, and one monetary value is used, and this is the importation cost of biodiesel. Also, pollutants emitted during this stage are taken out of the model due to these being local emissions and no longer being generated in India they are not needed.

Palm stearin feedstock cost

The feedstock cost is one of the largest contributing factors to the overall cost of producing biodiesel. This would lead us to assume that it would be sensitive and could potentially change the outcome of the model (Ong et al., 2012). Ong et al. (2012) showed that the feedstock cost has the biggest impact on their model, however, combined inputs such as oil conversion yield and operating costs can offset the significance of feedstock costs.

It is difficult to forecast the cost of feedstock in the future, but it is possible to look at what has happened in the past. This indicates price variations. If the price of palm oil is taken from 2020 it is possible to look at the peak and trough of the price for the past 10 years. This gives a range on how to model the sensitivity analysis.

Recently palm oil has been trading at 2,483 Malaysian Ringgit (MYT) (Trading Economics, 2020). The currency is irrelevant because it is the percentages that are of interest. In the last 10 years, the price has reached 4000 MYT which is a 61% difference, and 1,781 MYT which is a 28.3% difference. This gives a good indication of the range of feedstock cost, and these are the percentages that are used in this sensitivity analysis to show the maximum and minimum cost impact.

The baseline used in the model is: **33,017.4 Rs/tonne**

Maximum increase with a 61% difference is: **53,189.53 Rs/tonne**

Maximum decrease with a 28.3% difference is: **23,682.64 Rs/tonne**

The increase and decrease values replace the baseline value that is used in the model.

Cultivation costs of jatropha

Like palm oil/palm stearin, according to the literature, the jatropha feedstock is one of the most expensive inputs to producing biodiesel. In the economic analysis, this depends on whether taxes are included.

The cost of cultivating jatropha in India varies year on year because of different needs. For example, in the first year, the ground needs to be ploughed and the bushels need to be planted, in subsequent years fertiliser needs to be applied with intermittent years requiring more work.

The cultivation of jatropha in the baseline model is an average of several models. With this data, it is possible to test both ends of the input values. These values are calculated by taking the baseline and replacing it with a maximum and minimum value. However, due to different values being applied to each year a percentage factor is applied to adjust the value to reflect the increased or decreased cost of cultivating jatropha in India.

The baseline used in the model in the first year is: Rs **23,371.75**

Maximum cost is: **Rs 32,000. This is a 37% increase**.

Minimum cost is: **Rs 17,759. This is a 24% decrease.**

Inclusion of shadow prices

As mentioned in 2.7.4 shadow prices can help reduce price distortions. It is difficult to include labour shadow prices due to not having the available data. However, it is possible to include a shadow price on the foreign exchange of imports. Two values are applied the first is 25%. This value is sourced from an Indian Planning commission document (Planning Commision, 2014). The second is from the Asian Development Bank (Asian Development Bank, 2004). The ADB offers a range of shadow prices which is between 10-20% additional costs on the imported price. For this sensitivity analysis, a 10% value is used to give a broad range.

The shadow prices are applied only to materials that are imported. These are:

- Crude oil
- Palm stearin

Inclusion of biodiesel production plant costs

This thesis assumes that there is enough capacity from biodiesel production plants to meet the demand of the case study. However, in some instances, this may not be the case. Therefore, the sensitivity analysis has included three levels of production plant costs to be included in the modelling. Production plant costs can vary depending on the feedstock and size of the plants; therefore, a range is being presented.

The maintenance of the plant is included in the baseline which is a percentage of 2.5% (Riayatsyah et al., 2017) of the total cost to build the plant which is Rs 429,792,716. This value can be scaled up to accommodate increased blends.

4.5.2 Results of the sensitivity analysis

Table 4-12: Sensitivity analysis of B5-B100 palm stearin and B5 jatropha when compared to B0

Parameter	Description	B5 (J)	B5 (PS)	B10 (PS)	B20 (PS)	B50 (PS)	B100 (PS)
Base Case at 5% discount rate	N/A	-21.6	15.9	42	84.4	206	397.1
Imported biodiesel (produced from palm stearin)	Baseline of importing	N/A	56.7	113.5	84.4	206	371.1
Palm stearin feedstock cost	Increase	N/A	-4.5	-8.6	-17.1	-42.8	-85.5
	Decrease	N/A	33	76.2	158	395.4	790.9
Cultivation costs of jatropha	Increase	-44.8	N/A	N/A	N/A	N/A	N/A
	Decrease	-4.9	N/A	N/A	N/A	N/A	N/A
Shadow Pricing (Shadow prices applied to crude oil and palm stearin)	25%	17	42.7	85.4	170.7	421.4	824.8
	10%	-6.1	26.6	53.2	106.4	260.5	503.1
Construction cost of plant	Included	N/A	-6.2	-18.5	-58.8	-181.8	-381.2

Overall, only a few of the variable changes in this sensitivity analysis alter the outcome of the analysis. These include:

1) The increase in palm stearin feedstock cost.
2) The inclusion of a higher shadow price resulting in biodiesel produced jatropha becoming economically feasible compared to B0; and
3) When the construction costs of the plant facility are included.

This is in line with the literature, which states that the sensitivity often does not change the outcome (Hackney and De Neufville, 2001). In this instance, B5 palm stearin is still the most economical.

Importing biodiesel produced from palm stearin directly is more economical than importing palm stearin and producing biodiesel. So, if India wanted to use the most cost-effective biodiesel in its locomotives it should import biodiesel directly. However, by importing biodiesel directly India would no longer be supporting the local economy through the creation of jobs in the biodiesel production sector. Also, this option is difficult in India as it is limiting the amount of biodiesel being imported.

As mentioned above, the literature states that feedstock is one of the largest contributing factors to the overall cost of biodiesel. As the feedstock cost increases, B5 becomes less economically viable with the baseline at Rs 15.9 million and the new value at Rs -4.5 million. This shows that the overall outcome is sensitive to the feedstock price.

The cultivation costs are included for biodiesel produced from jatropha but are uncertain hence why it is prudent to do a sensitivity analysis on them. Even with lower cultivation costs, it is not more viable than palm stearin or diesel at Rs -4.9 million

In the baseline, there is Rs 37.5 million between B5 jatropha and B5 palm stearin. When shadow prices are applied, this is reduced to Rs 25.7 million at a 25% rate and Rs 32.7 million at a 10% rate. For the higher shadow price biodiesel produced from jatropha becomes more economical compared to diesel. This shows the importance of including shadow pricing to eliminate market distortions. However, it is still more economical to import palm stearin than cultivate jatropha in India.

The modelling assumes that there is enough capacity in India to produce the required amount of biodiesel from palm stearin, hence, why the construction costs have not been included. However, were the blend to increase or more routes were to use biodiesel then it is possible that biodiesel production facilities will need to be built. At any blend level when the construction costs are included it is no longer economically feasible to use biodiesel from palm stearin. However, were the government to pursue using biodiesel then using palm stearin would still be better than using jatropha-based biodiesel.

4.6 SUMMARY

In summary, the use of biodiesel in locomotives boasts many advantages compared to diesel. GHGs are lower for biodiesel even when CH_4 and N_20 are included and GWP is included. As with the existing literature, most of the pollutants are lower for biodiesel except for NOx where there is an increase primarily from the combustion stage. Were the locomotives' routes going through highly populated areas then this could have a profound effect on the population's health in that area. This is where the government would need to assess their reason and justification for using biodiesel. This assessment, however, would not be supported through the financial analysis due to biodiesel being more expensive than diesel because of the lower energy density for biodiesel. Although when analysing from a per litre basis, it is financially viable.

Economically only biodiesel produced from palm stearin is a feasible alternative to diesel. This is not necessarily because it is "cheaper" to produce biodiesel but more that diesel is "expensive" to produce with the absence of subsidies. The model is sensitive to certain parameters including the palm stearin feedstock price, inclusion of constructing a biodiesel facility, and the inclusion of shadow prices. From the results, it is recommended that biodiesel produced from palm stearin should replace diesel. However, it would only be beneficial if subsidies were removed from fossil fuels.

In the next chapter, this baseline (palm stearin B5) will be built upon by comparing this to electric traction.

5 Analysis of biodiesel and electric traction

5.1 INTRODUCTION

As well as biofuels being a possible alternative to using diesel in locomotives to reduce emissions on the railways, electric traction is another option. Similar to the biodiesel LCA each stage along the supply chain to use electric locomotives uses different energy intensities and emits different levels of emissions depending on location, feedstock, and size of the power plant amongst other parameters.

To produce the electricity needed to power the electric locomotive GHG emissions can vary between 584-1129 g eqCO_2/kWh depending on these factors (Koornneef et al., 2008, Agrawal et al., 2014). Several studies have conducted an LCA to examine the environmental effects of using coal and natural gas to generate electricity (Phumpradab et al., 2009, Odeh and Cockerill, 2008, Walvekar and Gurjar, 2013, Spath et al., 1999).

This chapter firstly analyses the environmental effects of using electric traction. This is compared to diesel and B5, where biodiesel is being produced from palm stearin. Secondly, there is a financial comparison. Lastly, an economic appraisal is conducted.

5.2 ENVIRONMENTAL RESULTS AND DISCUSSION

Like section 4.2.1 GHGs have been split into CO_2, NOx, and CH_4. A comparison of CO_2 is seen in Figure 5-1.

5.2.1 Greenhouse Gases

5.2.1.1 Carbon dioxide

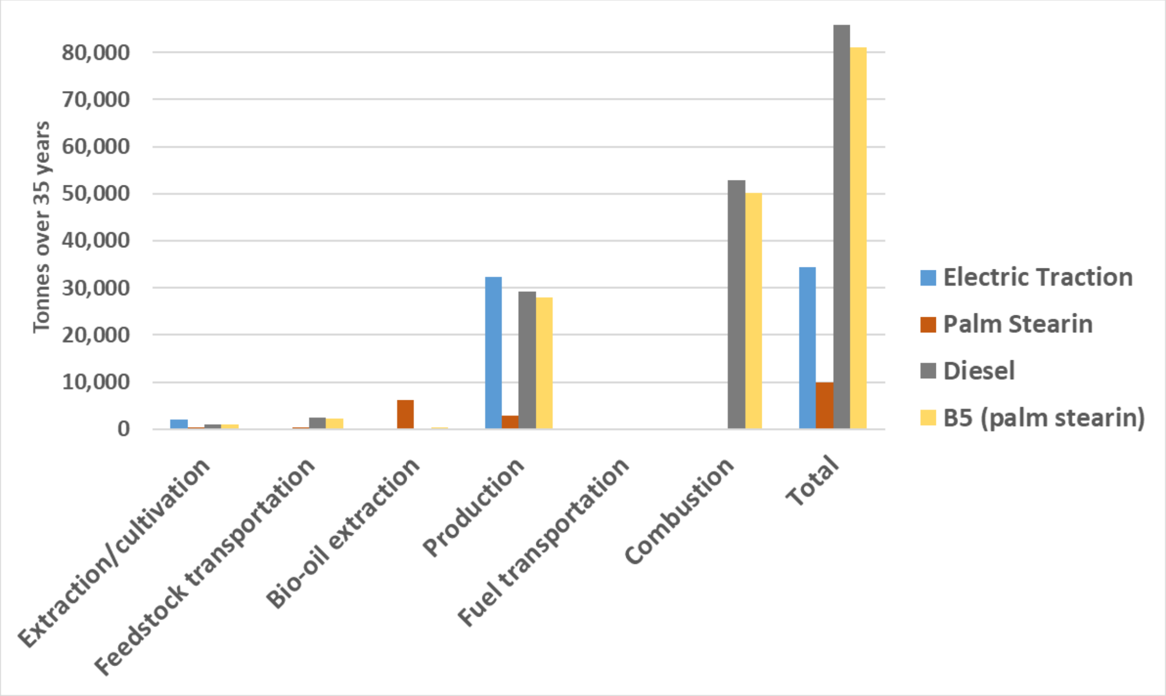

Figure 5-1: CO_2 emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

Electric traction emits just over 34,000 tonnes of CO_2 over the lifetime of the study. This is approximately 1.95kg/kWh. This value could vary depending on the efficiency of the power plant, the type of coal used for combustion, whether measures/technology are in place to mitigate emissions, the size of the thermal plant, and the location e.g., in a developed or emerging economy. Taking this into account within the literature CO_2 level can range from 0.91 - 1.17kg/kWh (Parliamentary Office of Science & Technology, 2011, Wingas, no date, Mittal et al., 2012, Parliamentary Office of Science & Technology, 2011). The value in this study is not so unreasonable as the range is based on developed countries; emerging markets such as India could be different due to their high economic growth and higher use of fossil fuels.

The primary source of emissions is from the generation of electricity and accounts for 94% of the total. This is due to the high carbon content of the coal. Different types of coal have different levels of carbon, for example, lignite contains around 60% carbon and anthracite around 80% (Munawer, 2018). The amount of oxygen in coal also matters. If there is a higher oxygen level, then the coal has a lower heating value;

this is due to the oxygen being already bound to the coal. This partially oxidises the carbon leading to a decreased ability to release heat (Hong and Slatick, 1994).

Electric traction emits more CO_2 than B100, but less than B5 and B0. This shows the importance of assessing the blend of the fuel, because if CO_2 were the only concern, then it would be more beneficial to use B100 instead of electric traction.

5.2.1.2 Methane

Alongside CO_2, CH_4 is another GHG analysed. This analysis can be seen in Figure 5-2.

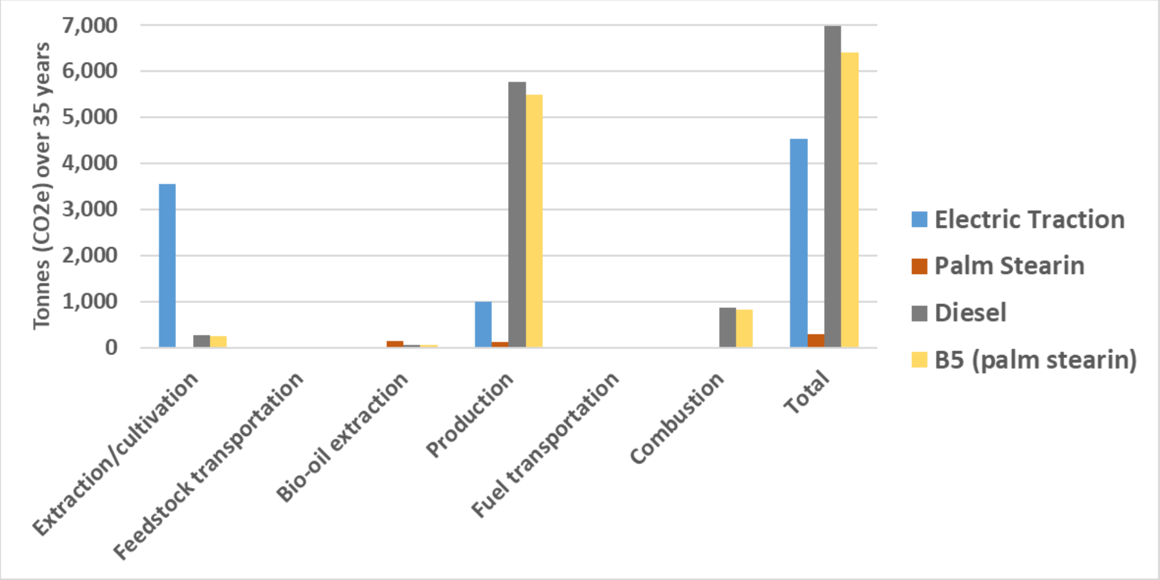

Figure 5-2: CH_4 emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

For electric traction a total of just over 4,500 tonnes CO_2eq of CH_4 is emitted over the lifetime of the project with the majority coming from electricity generation; this accounts for 73.6% of the total CH_4 emitted.

Coal mining accounts for 78% of the total CH_4 emissions emitted; however, this can vary greatly. CH_4 upstream emissions can account for anywhere between 7 and 70% of the total GHGs (CIRAIG, 2016, Mallapragada et al., 2018). This is largely dependent on the type of coal mine and the geographical location. When the coal mine is mainly underground it is primarily methane that is emitted compared to CO_2 and N_20. When the coal mine is 50% open cast, methane becomes the minority; and finally when the coal mine is open cast there is minimal CH_4 (CIRAIG, 2016). In total 0.026

kgCO$_2$eq/kWh of CH$_4$ is emitted into the atmosphere across the supply chain, but 0.020 kgCO$_2$eq/kWh for the coal mining stage of the supply chain. This is lower than mentioned in the literature 0.036 kgCO$_2$eq/kWh (Mallapragada et al., 2018). This could be for several reasons mainly based on the assumptions of the study including:

- The geographical location;
- The type of coal mine;
- The method of hollowing out the coal mine;
- The equipment used; and
- Whether methane gas is flared or not.

An important note to remember is that electricity generated from coal only plays a proportion of the electricity needed, so the electricity mix is important.

5.2.1.3 Nitrous oxide

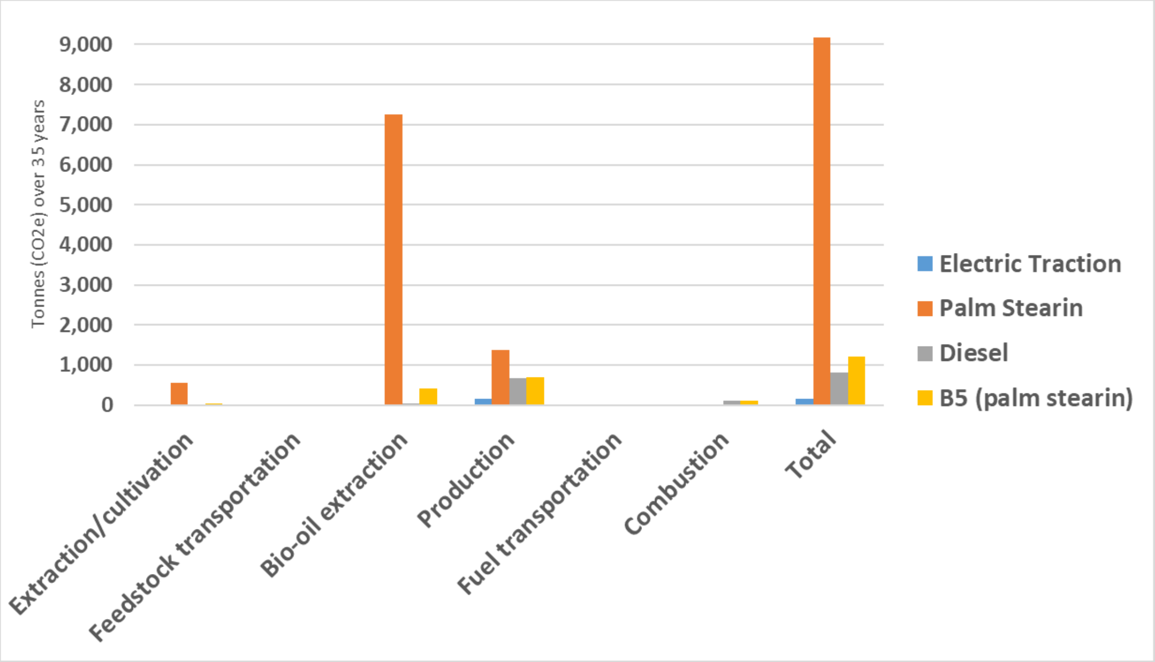

Figure 5-3: N$_2$O emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

For electric traction, N$_2$0 is the least contributory GHG and accounts for 0.4% as a proportion of all GHGs. Around 160 tonnes CO$_2$eq is emitted, with it being less than both B100 and diesel.

There is little literature in this area because it is such a small contributory factor to global GHGs. However, it is known that nitrous oxides primarily come from the agricultural sector followed by the energy sector (69.6% and 19.6% respectively of total nitrous oxides released into the atmosphere). The energy is made up of mobile combustion (vehicles) and stationary combustion (electricity generation, but predominately coal thermal plants); whereby vehicles hold a share of around two-thirds of nitrous oxide and electricity generation the remaining third in the energy category (Energy Information Administration, 2011). This partly explains the large differences between locomotives that are run on electricity, biodiesel, and diesel.

5.2.2 Pollutants

5.2.2.1 Carbon monoxide

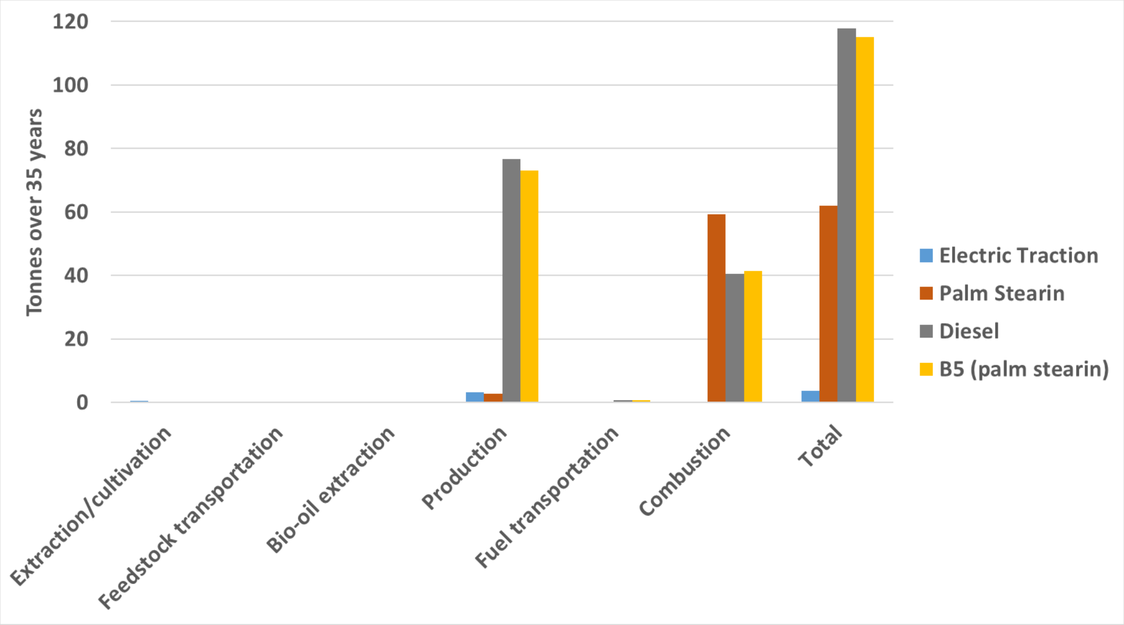

Figure 5-4: CO emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

Around 3.5 tonnes of CO are produced over the lifetime of the project for electric traction which is approximately 0.2 g/kWh. This is primarily from the electricity generation stage. Carbon monoxide is produced when there are not enough oxygen molecules to produce CO_2. In this thesis there is a higher proportion of CO_2 produced compared to other studies; therefore, it is fair to assume that CO emissions are minimal during this life cycle analysis. Also, few studies directly calculate CO. This is likely due to the small amount emitted compared to other pollutants. Nevertheless, it is still a harmful gas that can lead to illness, especially to those who are local to the source of the emission. CO from electric traction is significantly less than diesel and biodiesel.

5.2.2.2 *Nitrous Oxides*

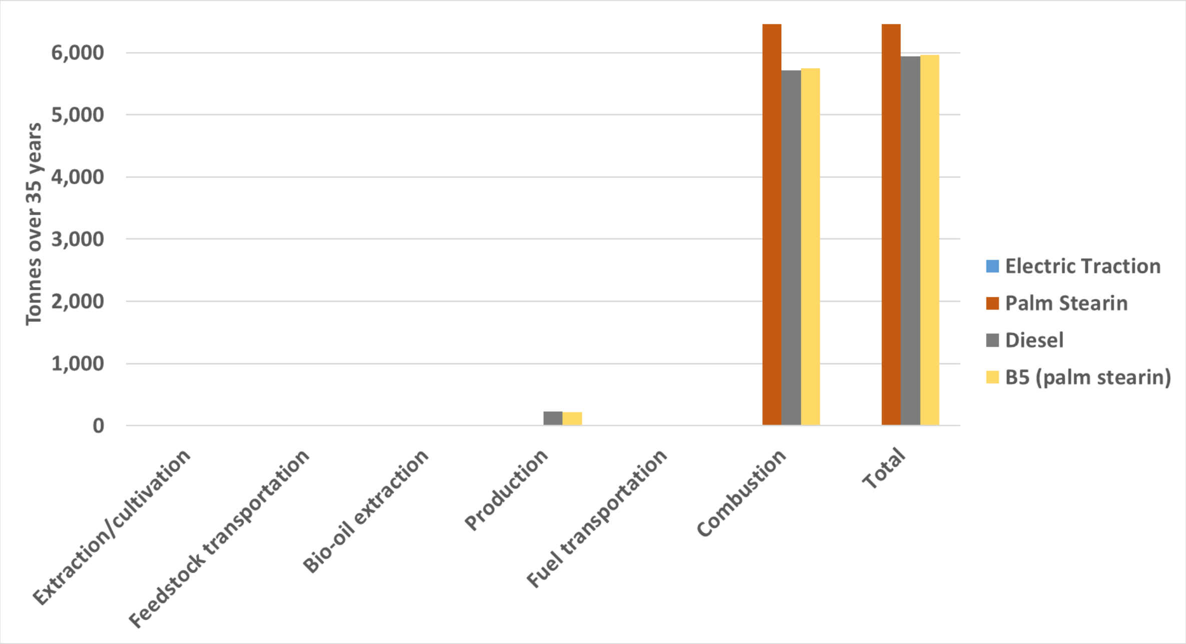

Figure 5-5: NOx emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

Around 527 tonnes of NO_x are produced during the lifetime of the project with 89.8% of this emitted during the electricity generation stage. Emissions can vary from 1.54-7 g/kWh (Mittal et al., 2012, Chakraborty et al., 2008, Chowdhury et al., 2004). In this thesis, the value is 1.1 g/kWh. NOx emissions are considerably less than B100, B5, and B0. Were NOx the only concern then electric traction would be the preferred choice.

5.2.2.3 *Sulphur Oxides*

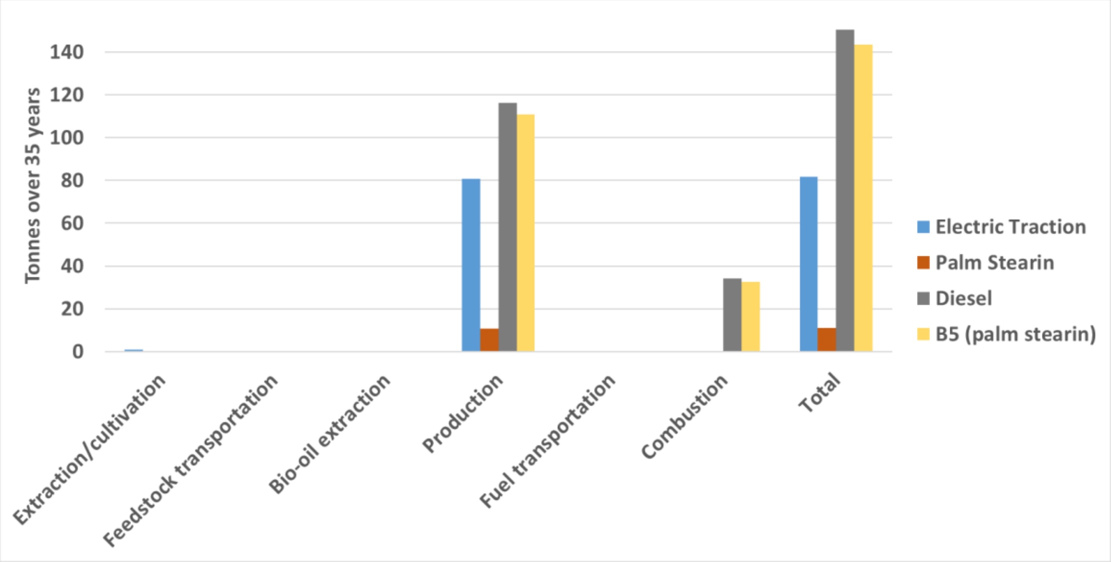

Figure 5-6: SOx emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

Around 82 tonnes of SOx are released during the life of the project with the highest proportion coming from the electricity generation stage at 99.%. SOx is formed through the sulphur in coal and oxidises during combustion. This releases a range of sulphur pollutants including sulphur dioxide (SO_2), sulphur trioxide (SO_3), and sulphuric acid (H_2SO_4) not only into the air but also into the water.

SO_2 is a poisonous gas that can lead to wheezing, coughing, and a reduction in lung function (Munawer, 2018). Once in the respiratory system, it reacts with the mucus lining and forms SO_3 which is the cause of many diseases and illnesses (Pourgholami et al., 2005, Hussain et al., 2013, Hussain et al., 2016). SOx typically can have a range of 2.7-15.99 g/kWh, which is largely dependent on the fuel type and the size of the thermal plant (Chakraborty et al., 2008, Chowdhury et al., 2004, Garg et al., 2006). H_2SO_4 is the main cause of acid rain and can damage buildings (Munawer, 2018). This thesis has a value of 4.6 g/kWh.

5.2.2.4 Particulate Matter

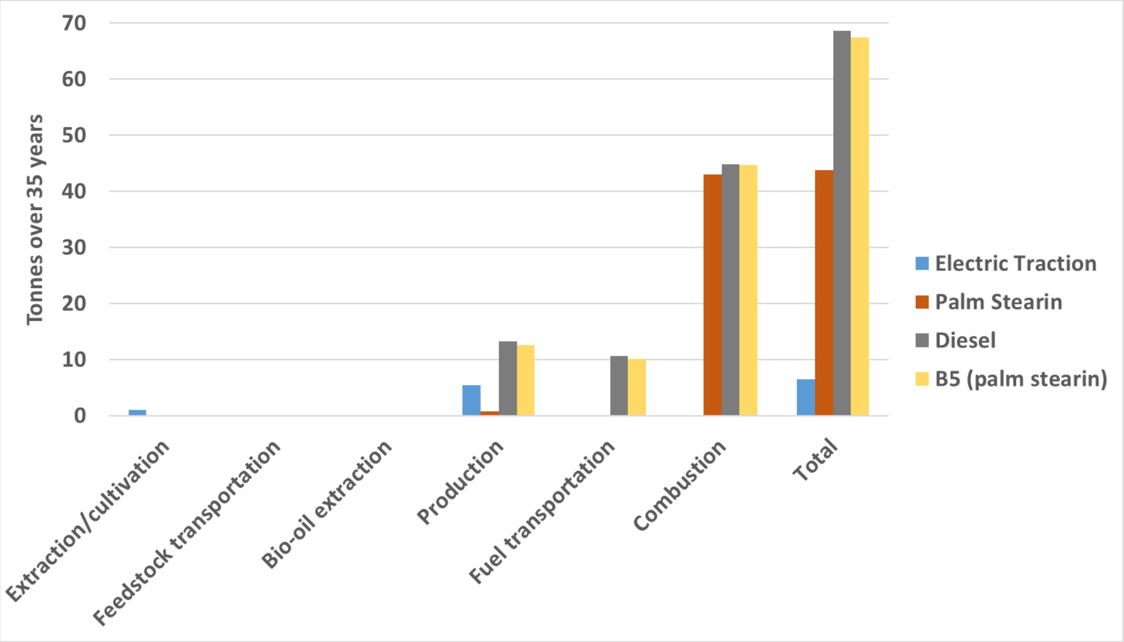

Figure 5-7: PM_{10} emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

Particulate matter is a particle that can be absorbed into the respiratory system and contribute to causing certain illnesses such as heart disease and some forms of cancer (Clancy et al., 2002, Chen et al., 2004, Pope et al., 1995, Miller et al., 2007).

Compared to B100, B5, and B0, electric traction is much cleaner by producing 9 tonnes of PM_{10} over the lifetime of the project; alternatives emit 44, 67, and 69 tonnes (B100, B5, and B0 respectively). Electric traction's PM_{10} is equivalent to 0.37 g/kWh, which is not too dissimilar to the literature which has a range of 0.023 to 1.180g/kWh. The higher end of this range appears to be abnormal compared to other values. The range would be reduced to 0.023 to 0.65 g/kWh were it to be removed (Xu et al., 2017, Von Blottnitz, 2006).

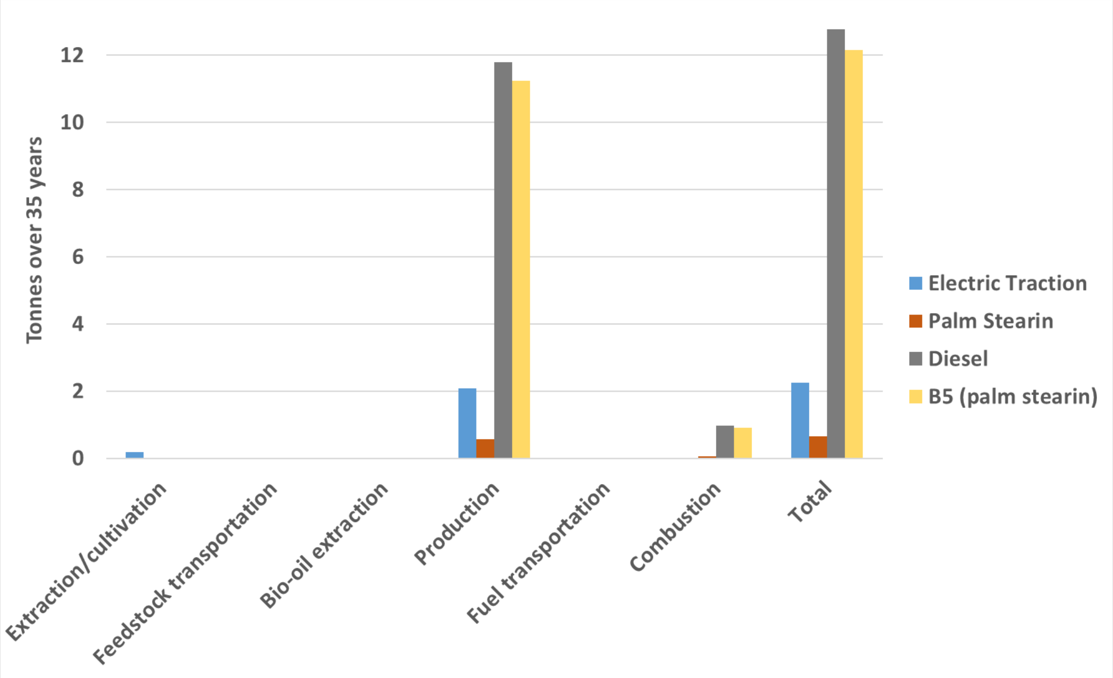

Figure 5-8: $PM_{2.5}$ emission comparing B100 palm stearin, diesel, B5 palm stearin, and electric traction

Around 2.3 tonnes of $PM_{2.5}$ is emitted using electric traction. This is less than diesel and B5, but more than B100. In this thesis, approximately 0.13 g/kWh is emitted with a range of 0.22 to 0.5g/kWh being recorded in the literature (Xu et al., 2017). Differences in emissions could be for several reasons such as the inclusion of waste in the emissions. For example, the impact of including ash content and the decontamination efficiency of removing particles from the results. The ash produced from burning coal can contain a high proportion of particulate matter (Clancy et al., 2002, Chen et al., 2004, Pope et al., 1995, Miller et al., 2007).

$PM_{2.5}$ has a similar effect to that of PM_{10} but is considered more harmful because the particles are smaller and can enter the body more easily. It has been highlighted that in 2011 there were 20 million asthma cases in India from exposure to $PM_{2.5}$ which cost the government between Rs 16,000 crore[4] and Rs 23,000 crore (Guttikunda et al., 2015).

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[4] 1 crore = 10,000,000 (10 million)

5.3 FINANCIAL RESULTS AND DISCUSSION

With nearly 20% of Indian Railway’s total costs stemming from fuel costs, they are keen to reduce these operational costs. This financial section contains the operational costs of using electric traction or B5 across varying discount levels. It also considers the inclusion and exclusion of infrastructure costs for electric traction.

Table 5-1: Financial Cost-Effectiveness (million Rs) with varying discount rates for electric traction and B5

	Cost-Effectiveness (million Rs) with varying discount rates				
	5%			7.75%	
	Electric Traction	Biodiesel (B5)	Difference	Electric Traction	Biodiesel (B5)
Base Case (with infrastructure costs)	11,266.47	1,625.98	9,640.48	10,978.92	1,584.49
Base Case (without infrastructure costs)	141.21	1,625.98	-1,484.77	137.61	1,584.49
10% electricity price decrease	11,260.65	1,625.98	9,634.66	10,973.25	1,584.49
20% electricity price decrease	11,254.82	1,625.98	9,628.84	10,967.58	1,584.49
50% electricity price decrease	11,237.36	1,625.98	9,611.38	10,950.56	1,584.49

	10%		15%	
	Electric Traction	Biodiesel (B5)	Electric Traction	Biodiesel (B5)
Base Case (with infrastructure costs)	10,754.36	1,552.08	10,286.77	1,484.59
Base Case (without infrastructure costs)	134.79	1,552.08	128.93	1,484.59
10% electricity price decrease	10,748.80	1,552.08	10,281.46	1,484.59
20% electricity price decrease	10,743.24	1,552.08	10,276.14	1,484.59
50% electricity price decrease	10,726.57	1,552.08	10,260.20	1,484.59

Excluding infrastructure costs, electric traction is more financially viable than B5 by approximately Rs 1,485 million compared to B5. This is the same across all discount levels. Were infrastructure included in the analysis then electric traction becomes financially unviable and favours B5 by Rs 9,640.48 million. It makes little difference to the outcome with decreases in operational costs for electric traction when infrastructure is included.

However, electric traction can provide other advantages compared to combustion engines such as being able to travel faster (acceleration speed), are cheaper to operate, and could increase employment mainly through the construction stage (Cabinet Committee on Economic Affairs, 2018). These are some of the benefits that India hopes to gain by electrifying its rail network.

5.4 ECONOMIC RESULTS AND DISCUSSION

An economic analysis shows the cost to the economy. This is an important aspect to include when potentially investing in a new project. An economic analysis eliminates distortion from the market through the absence of taxes and subsidies. This economic analysis also includes the environmental cost to each of the fuels.

Table 5-2: Economic Cost-Effectiveness (million Rs) with varying discount rates for electric traction and B5

	Cost-Effectiveness (million Rs) with varying discount rates				
	5%			7.75%	
	Electric Traction	B5	Difference	Electric Traction	B5
Base Case (with infrastructure costs)	11,508.24	3,983.31	7,524.93	11,214.53	3,881.65
Base Case (without infrastructure costs)	382.99	3,983.31	-3,600.33	373.21	3,881.65
10% decrease of electricity generation cost	11,495.73	3,983.31	7,512.42	11,202.34	3,881.65
20% decrease of electricity generation cost	11,483.22	3,983.31	7,499.91	11,190.15	3,881.65
50% decrease of electricity generation cost	11,445.69	3,983.31	7,462.38	11,153.57	3,881.65

	10%		15%	
	Electric Traction	B5	Electric Traction	B5
Base Case (with infrastructure costs)	10,985.14	3,802.25	10,507.53	3,636.94
Base Case (without infrastructure costs)	365.58	3,802.25	349.68	3,636.94
10% decrease of electricity generation cost	10,973.20	3,802.25	10,496.10	3,636.94
20% decrease of electricity generation cost	10,961.26	3,802.25	10,484.68	3,636.94
50% decrease of electricity generation cost	10,925.43	3,802.25	10,450.41	3,636.94

The overall pattern of this analysis is like that of the financial analysis when comparing electric traction and B5. Without the infrastructure in the analysis electric traction is the most viable option by Rs 7,524.93 million over 35 years at a 5% discount level. With infrastructure included, electric traction becomes financially unfeasible by Rs 3,600.33 million. There is a difference of Rs 2,115.56 million between the economic and financial analysis of electric traction (inclusive of infrastructure costs). This could be stem from two factors: firstly, the difference in the absence of taxes and subsidies, and secondly, the inclusion of environmental costs.

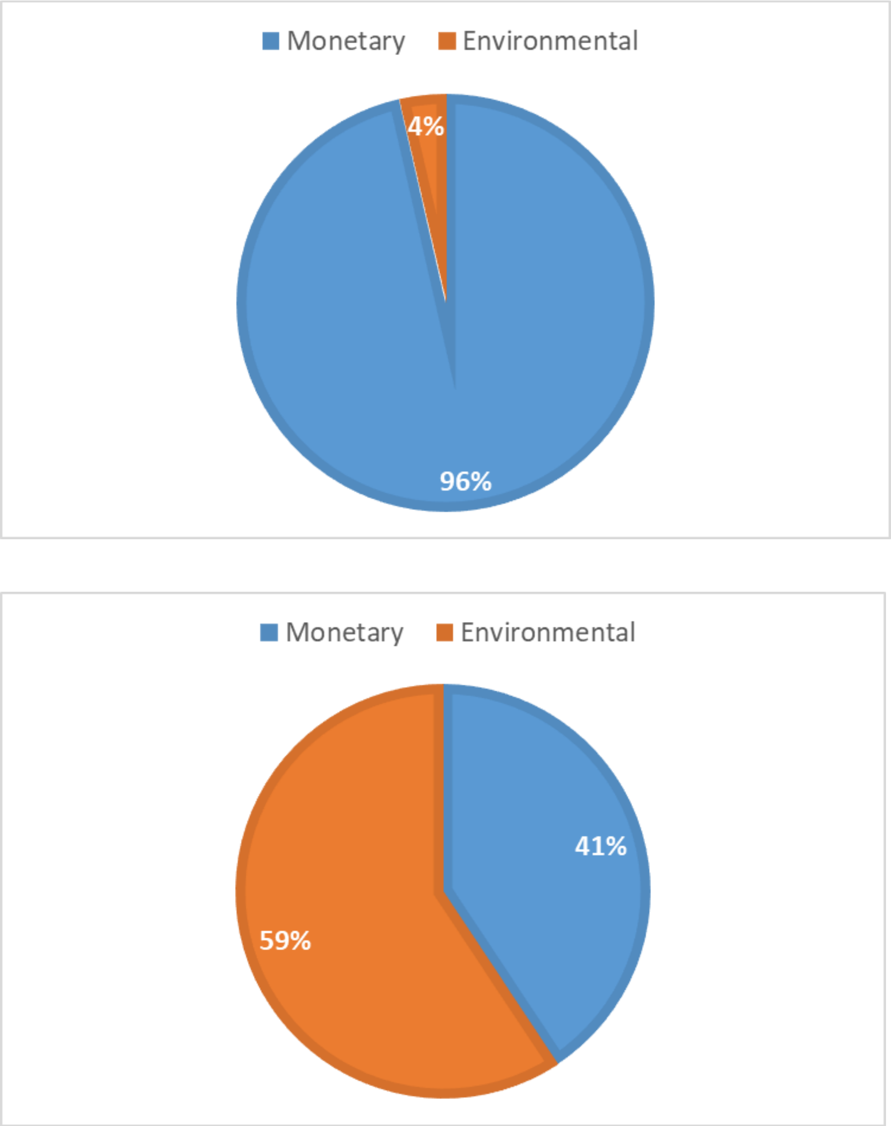

Figure 5-9: Percentage breakdown of the monetary and environmental costs for electric traction (infrastructure included and excluded, respectively - a comparison)

When the infrastructure of electric traction is included, the non-monetary (i.e., environmental) contribution to the overall project is at 4%. The weighting of the monetary value is far greater at 96%. This is primarily due to the initial stages of construction. When the analysis is absent of this value, the environmental cost impact is greater than the monetary value at 59%.

Whilst all three analyses show that there are potentially greater benefits in switching to electric traction, there are some real concerns. For example, this analysis assumes that the network can supply the extra demand needed. However, there is already a shortage in India of electricity with demand exceeding supply. In 2017/18 there was a deficit of 8,567 MU. To compensate for this deficit, India must import electricity from other countries such as Bhutan (Tiewsoh et al., 2019). This deficit is slowly decreasing; for example, in 2009/10 it was nearly 10 times what it is today (Ministry of Power, 2019). This is likely due to the expanding electricity supply. This will likely be primarily from renewables due to the government's ambition to become a country that produces lower-emission electricity. In 2016/17 thermal energy increased by 7.7 gigawatts and renewables added 15.7 GW to the national grid (Institute for Energy Economics and Financial Analysis (IEEFA), 2017).

The deficit of electricity causes problems for the industry. It is estimated that such shortages can lead to a business's revenue and product surplus decreasing between 5 and 10% (Allcott et al., 2016).

There is a drive to increase electricity for households. Roughly 20% of the population was without electricity in 2012 (Bhattacharyya et al., 2017), the government has an ongoing rural electrification program with the aim to provide electricity to all households. Some of the benefits of electrifying households include improved education, income, and health (Tiewsoh et al., 2019).

Travel, especially by rail, is essential in everyday life and fuel contributes to a large proportion of Indian Railways' expenses. This thesis has shown that there are many benefits to using electric traction and that it is a feasible alternative to diesel. Electric traction has many advantages from an environmental and operational cost perspective. However, infrastructure costs are high, which is the most significant barrier for electric traction. As discussed above, there is a shortage of electricity, and this is only going to increase with the rural electrification program. There are economic benefits to this program. However, with a deficit in electricity supply, there is an opportunity cost over which area should have priority. There are multiple alternatives to diesel including biodiesel and electric traction.

5.5 SENSITIVITY ANALYSIS

This sensitivity analysis examines two variables. First is the density of the traffic on the route. The second is the electricity mix of the grid. Similar to the sensitivity above this is a local sensitivity where only one variable changes each time.

Increasing density of traffic on the route

The case study chosen for this thesis was partly based on whether routes were to be electrified. These routes likely had a higher density of traffic compared to others. However, when examining the density, it was only possible to get an estimate for passenger services. This resulted in the model being built around one return passenger journey per day. It was not possible to estimate the level of freight services on this route. To understand the effect of a traffic variable this has been included in the sensitivity analysis. The baseline of the model is one return journey. In the sensitivity analysis, this is increased to five return journeys.

Table 5-3: Increasing traffic density to compare electric traction and B5 (infrastructure costs included)

Scenario Name	Electric traction	B5	Difference
Base rate: 1 return journey	11,516.98	3,983.31	7,533.66
2 return journeys	11,614.85	6,047.26	5,567.59
3 return journeys	11,721.45	8,111.21	3,610.25

4 return journeys	11,828.06	10,175.15	1,652.91
5 return journeys	11,934.66	12,239.10	-304.43

Estimated calculations show that only when 5 return journeys are completed each day does electric traction become economically viable competed to B5 when initial infrastructure is included. The economic analysis shows that with the inclusion of infrastructure costs electric traction is not a viable option. At present this model accounts for one return journey. If more traffic were on the same route, then electric traction could become the more favoured option because of the low operating costs.

Different electricity inputs

Most literature explains that electric vehicles (in general and not just rail) would likely only become environmentally viable if the electricity is generated from renewables as mentioned in section 2.6. Therefore, this is the focus of the sensitivity analysis for electric traction. At present 55% of electricity is generated through thermal combustion i.e., burning of coal. This is reduced to 20% and increased to 80% and 100%. Both infrastructure scenarios are included.

Table 5-4: Different electricity mixes for the of electricity on the railways

Scenario Name	Description	
Base Case at 5% discount rate	Infrastructure included	7,524.9
	Infrastructure excluded	-3,531.8
20%	Infrastructure included	7,302.8
	Infrastructure excluded	-3,753.9
80%	Infrastructure included	7,683.6
	Infrastructure excluded	-3,373.2

100%	Infrastructure included	7,810.5
	Infrastructure excluded	-3,246.3

Different levels of fossil fuel usage do not affect the overall outcome of the economic analysis for either when infrastructure is included or excluded. There is a difference of Rs 507.7 million between 20% fossil fuel use and 100% for when infrastructure is both included and excluded. What this study does not represent are the extra benefits of using more renewable energy:

1) Coal is primarily transported by rail (Kamboj and Tongia, 2018) and there is a high density of freight traffic on the railways causing delays and lengthened journeys. Reducing the amount of coal used would likely reduce congestion on the networks. Accompanied by electric locomotives being able to carry heavier loads, reducing coal would only be beneficial to the network, Indian Railways' finances, and India's economy.
2) To meet the demand for increased renewable energy, investment would be needed in the industry. This would encompass building new solar farms, wind farms, and hydroelectric facilities. This would boost employment through the manufacturing of the facilities and then the running and maintenance of them (Cartelle Barros et al., 2017).
3) Switching to more renewable energy would contribute to India's national and international targets of reducing GHGs. India has pledged to reduce its GHGs by 33-35% of its gross domestic product by 2030 based on 2005 levels of which it is on track to do (PBL Netherlands Environmental Assessment Agency, 2012, National Research Development Corporation, 2020)
4) There is a concern with the rise in coal demand and the rate at which coal is being burned (Varadham, 2019, Sengupta, 2018). Therefore, switching to alternative sources of electricity generation would ease these burdens.

There are several concerns and barriers to switching to renewable energy:

1) Building new facilities such as solar and wind farms; nuclear, and hydro stations would take time. Depending on funds, labour, and materials available it is unclear how long it would take to install such facilities.
2) Renewables can be unreliable. For example, in parts of India, there are droughts (Agha, 2019). Hydropower plants cannot run efficiently if water is not available. This rationale also applies to solar and wind. To always meet demand, supply should exceed demand; therefore, if one area of electricity generation is unable to function efficiently there is not a deficit in the supply. However, this could have implications for the price of electricity as oversupply will likely drive the price down.
3) There may be large cost implications. Gambhir et al. (2013) published a report that explains India's CO_2 emissions pathway to 2050. This would primarily be a switch to alternative fuels. The cost would be between 1.2 and 2.4% of India's projected GDP in 2050 (between US$200 and 400 billion per annum). These values depend on the severity and type of measures taken:
    - The 1st scenario i.e., the cheaper one. Electricity is generated from nuclear, renewables, and CCS with thermal power (fossil and biomass). The industry would need to change its technology i.e., changing from coal to gas. In the residential sector, their source of fuel would have to switch from using coal or biomass to using electricity.
    - The 2nd scenario would consist of more wind and solar to compensate for the lack of biomass and CCS. There is a certain level of uncertainty associated with the latter especially in the technology.
4) By moving away from coal to alternatives coal thermal plants may likely be closed (unless switching to biomass with/without CCS) and therefore jobs lost. With new low-carbon energy facilities being constructed; some workers may switch to work elsewhere. This may require retraining, which would likely be at further expense.

5.6 SUMMARY

Electric traction has more financial and economic benefits when compared to B5. Infrastructure is the biggest monetary cost for electric traction, but with higher load rates, better efficiency, and speeds there are many more benefits than mentioned in this thesis.

India aims to electrify all the networks, but it may be more prudent to use a mixture of electric traction on busier routes and biodiesel on other ones. The electricity network would then face less strain in meeting the new demand and there would also be less competition for businesses and households.

The next chapter takes a wider look at the biodiesel sector. It assesses the literature on-road transport sector use of biofuels and determines the key lessons which can be learned. It will then examine and analyse whether these lessons could be applied to the rail sector, and, to India’s rail network.

6 Lessons learned from the road sector and applied to the rail sector

6.1 INTRODUCTION

While all modes of transport have some potential for using biofuel, the primary user has so far been the road transport sector (Ong et al., 2011). Other modes have received much less attention but could be equally important, especially in the particular context of specific countries: For example, in a country like India, where the rail sector is often referred to as a lifeline and is responsible for transporting 15% of passengers and 30% of freight (Iimi et al., 2017). The sector is still dominated by diesel and electricity. However, the rail sector could also benefit from the same advantages of biofuels, as in the road sector, and it is, therefore, important for the rail sector to learn lessons from the successes and failures in using biofuels in the road transport sector.

This chapter will therefore address two issues:

1) The rail sector has an advantage over the road sector in that lessons can be learned from not only the biodiesel industry but also the bioethanol industry. If this information can be harnessed, analyzed, and applied to rail, then it could help a smoother introduction of biodiesel to the rail sector.

2) Using biodiesel in India is a viable option both financially (in certain scenarios) and economically. Introducing biodiesel to the rail network is not as easy as buying the fuel and replacing or blending it with diesel. Other factors need to be taken into consideration. Many of these factors will likely have already been experienced by the road sector and therefore Indian Railways can learn from this.

6.2 METHOD

To capture multiple perspectives of the lessons learned, a PESTLE framework is followed in this study. PESTLE is a decision-making technique that analyses the political, environmental, social, technological, legal, and economic aspects of a new project. This method was used instead of SWOT (Strengths Weaknesses, Opportunities, and Threats) because it is focused on the issues that are of interest to policymakers and developers (Zalengera et al., 2014). PESTLE highlights the categories that need to be considered when introducing new concepts within, for example, the renewable energy sector. It has been used in the UK to assess the risk involved in the tidal industry (Kolios and Read, 2013). In Malawi, PESTLE was used when investigating the development of renewable energy (Zalengera et al., 2014).

The results from the PESTLE analysis will be discussed on how and if they could be applied to the rail. The opposite also needs to be considered; the lessons that cannot be used in rail and why it is not possible. This section will also highlight what the rail industry needs to consider that is not necessarily applicable to the road sector.

Finally, these lessons will be learned from India’s perspective. Each country and economy are structured differently and not all lessons will likely be applicable, or some will be more valid than others.

6.3 THE LESSONS LEARNED FROM ROAD TRANSPORT

6.3.1 Regulating the Introduction of Biodiesel

Policies, the political system, and regulating enforcement (laws) cannot be easily separated so they have been combined in this section. Policies play a key role when introducing biodiesel to transport and legislation help implement them. Introducing biodiesel policies is complex because of the multiple stages of the supply chain and would likely need specific policies applied at each stage, as well as an overarching policy framework (Basavaraj et al., 2012). The policy instruments used can include tax exemptions and mandates. However, setting the policies is not difficult, the challenge lies with understanding the consequences (De Gorter and Just, 2010).

6.3.1.1 Enforcing Tax Exemptions

Tax exemptions are where the consumer or producer of biodiesel receives a reduced or complete removal of tax when using or producing biodiesel. In 1999, Germany began its transition to alternative fuels through the introduction of an Eco-Tax to help reduce fossil fuel consumption. Further, 2002 biofuels were exempt from tax (International Energy Agency (IEA), 2012, Henke et al., 2005). Due to a combined Eco-Tax on crude oil-based fuels and tax exemptions on biodiesel at the pumps, the price of biodiesel fell below that of diesel (Wiesenthal et al., 2009). At the same time, the infrastructure of the biodiesel network helped ensure higher blends that could be used. This was achieved by the government demanding fuel stations to convert the pumps to handle up to 100% biodiesel (Bomb et al., 2007).

Figure 6-1 shows Germany's consumption of biodiesel between 1995 and 2015. There was a consistent increase in the consumption of biodiesel in Germany from 1995 to around 2010/2011. From 2002, there was a steep increase in consumption over the next five years. An existing tax exemption was slowly being replaced with a blending mandate from 2006 (International Institute for Sustainable Development, 2012) and was completely abolished in 2012, as indicated by the dashed line. A drop in consumption is seen in 2010 when the likely increased price of biodiesel is exceeding consumers’ willingness to pay. The tax exemption was replaced with fuel supplier mandates. In this instance, a mandate refers to a certain level of biofuel that fuel suppliers had to blend or sell. The mandate in Germany was that 5.75% of fuel suppliers’ sales had to be biodiesel (International Energy Agency (IEA), 2012). Despite the mandate in place, consumption was still decreasing. There was no legislation stating that the biodiesel had to be used in a domestic capacity, and since 2012, exports of biodiesel from Germany have been increasing (UNION ZUR FÖRDERUNG VON OEL- UND PROTEINPFLANZEN E.V. (UFOP), 2016). An alternative to giving tax incentives to consumers is to give them to the producers of biodiesel. This is the approach that the United States (US) took.

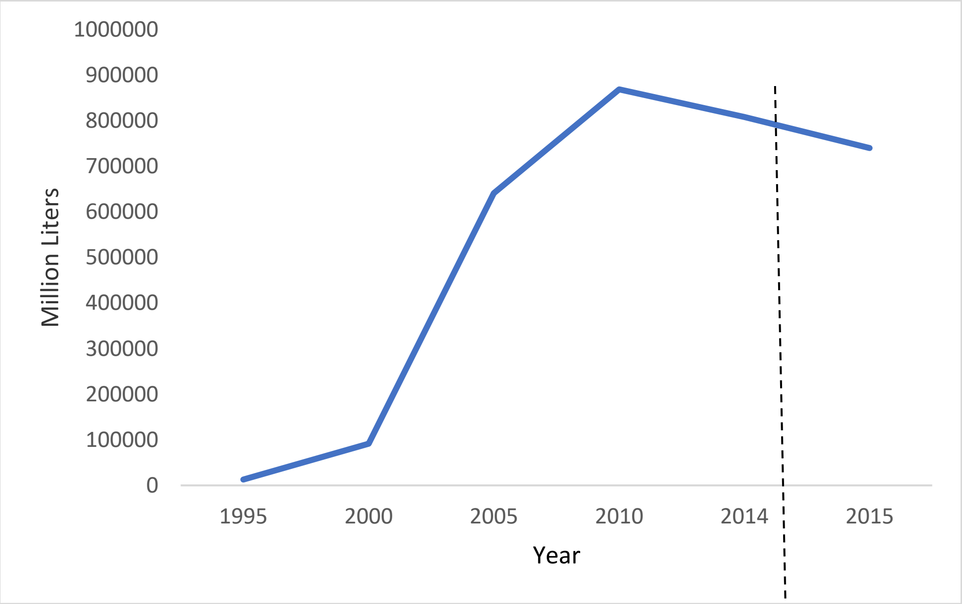

Figure 6-1: Consumption of biodiesel in Germany 1995–2015

Source: adapted from Statistica, 2018

Figure 6-2 shows the US' production and consumption of biodiesel between 2001 and 2017. Production began to increase more noticeably from 2005. During this time, tax relief was present for the production of biodiesel, and this encouraged production (Rusco, 2012). However, there were few incentives for consumers. Instead of selling to the domestic market, the US began exporting more biodiesel (Energy Information Administration, no date). The tax relief was abolished in 2016 and there was a slight decrease in production, as indicated by the dashed line. When the tax relief was abolished, there was no replacement or alternative introduced. From the evidence of production dropping when there is no tax relief present, the US was set to reinstate the tax relief in mid-2017 (Energy Information Administration, 2017).

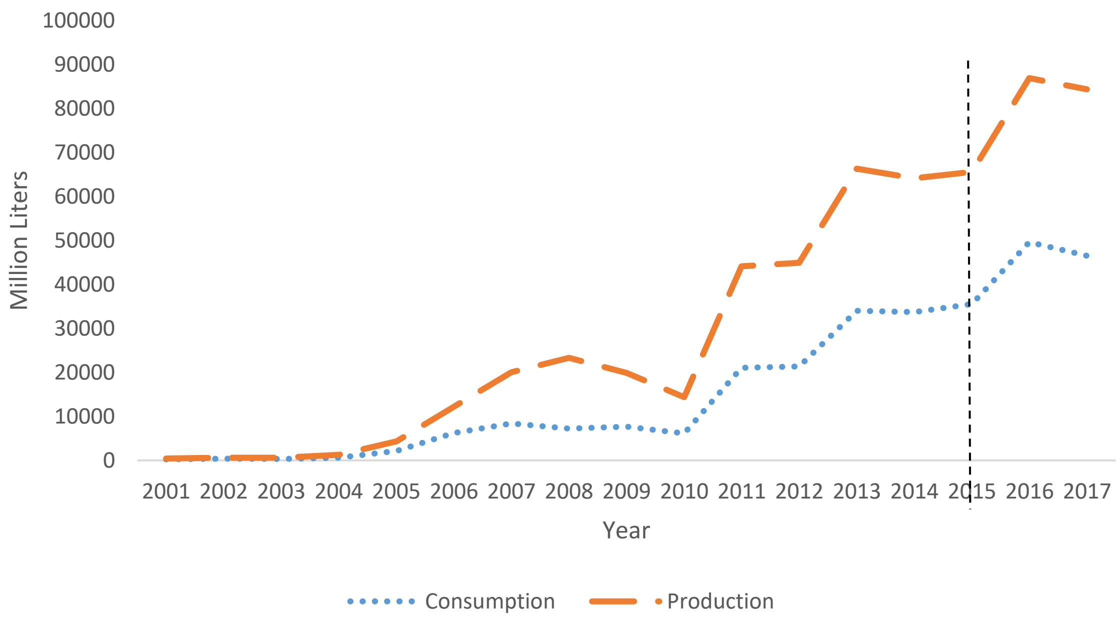

Figure 6-2: US Production and Consumption of Biodiesel between 2001–2017

Source: adapted from BP Global, no date

In Germany, the tax incentives were for the consumers, however, in the US, tax incentives were for the producers of biodiesel. When tax incentives were abolished for consumers in Germany, the demand for biodiesel decreased. When tax incentives were abolished for producers in the US, the supply of biodiesel decreased. This indicates that tax incentives influence the demand and supply of biodiesel. The consequences of using a tax exemption are dependent on other factors, such as whether the price of crude oil-based fuels is consistent. There is limited research in this area, especially with biodiesel, but some research has been conducted on the possible consequences of using bioethanol (De Gorter and Just, 2010)—this is explained in section 6.3.2.2.

6.3.1.2 Mandates Issued Due to Legislation

An alternative to using tax exemptions is to use a mandate. Malaysia used mandates to ensure the consumption of biodiesel. Before 2010, Malaysia's consumption of biodiesel was zero. It exported all its biodiesel. When the Government of Malaysia was originally setting the blend level, there was a debate on what it should be. A blend is any concentration of biodiesel mixed with diesel, e.g., 5% biodiesel with

95% diesel is called B5. Initially, a blend of 5% was established, but with high palm oil costs, the government would have to supply large subsidies to compensate for this (Chin, 2011). The 5% was reduced to 3%, but this was met with opposition because producing such a small amount would not be economically prudent. The government reverted to 5% but was delayed and only applied to certain regions. At the same time, pumps at petrol stations were adapted to handle higher blends (Lim and Teong, 2010). In 2015, after delays, B7 was introduced, and consumption started to increase very slowly. The government of Malaysia imposed a B10 mandate at the end of 2016, but there has been resistance from car manufacturers who claim that engine damage is inevitable if the blend goes above 7% (Chin, 2011).

In the US, there are federal policies that promote the use of biodiesel, but Minnesota was the first state to introduce compulsory biodiesel blending in 2002. In 2013, B10 was meant to be introduced but was delayed until 2014 because of a lack of blending infrastructure and inadequate regulatory measures. This shows that having ancillary policies supporting the technical side of introducing biodiesel is important for it to be successful. B10 is only applicable during the summer months because the fuel in the winter months causes solidifying problems. The mandate reverts to B5 during the winter months (Minnesota Department of Agriculture, no date).

6.3.1.3 The Importance of Legislation and Political Structure in Introducing Biodiesel to Road Transport

Policies have been further strengthened by legislation. For example, in Brazil, which is one of the most successful countries in the world in introducing biofuel, the Alcohol Programme was partly successful because of the laws and decreases that had been introduced at the beginning of 1975. This held industry accountable by law to the commitments of introducing bioethanol.

1) On November 14th, 1975 The National Alcohol Programme was established through parliament (Colares, 2008), which outlined the objectives and financing of the programme.

2) In the early 1990s, the ethanol program was under threat because of declining oil prices. People were reverting to using petrol as it was becoming cheaper once again. On October 28th, 1993, legislation was passed that stated a 22% ethanol blend was to be used across the country (Colares, 2008).

The effectiveness and ease of using policies and laws partly depend on the political structure of a country. For example, during the OPEC oil crisis, Brazil was under a military dictatorship. During this time, economic growth was made a priority (Nass et al., 2007). To meet the targets, President Geisel was prepared to further the country's debt through foreign loans—he was more liberal in allowing foreign investment compared with his predecessors (Flynn et al., 1989). This, in turn, would lead to Brazil being able to finance infrastructure projects. After reviewing what turned out to be implausible strategies such as further exploration for Brazilian oil because reserves were less than previously thought and nuclear where the time frame for implementation was too long, and therefore, biofuel was the favorable option to reduce the importation of oil (Hira and De Oliveira, 2009). For this project to succeed, this required tools that Brazil already had, including the ability to control oil prices because of the monopoly state-owned Petrobras, and Brazil was able to finance the project because of Geisel's liberal view of allowing foreign investment (Flynn et al., 1989).

Unlike Brazil, the EU consists of member states/countries and therefore have approached the introduction of biofuel in a different format. The EU issues targets and individual countries, then have the flexibility to meet the targets in an approach that is fitting to their resources (Ziolkowska et al., 2011). To achieve these targets, each member state has its own Energy Action Plan (European Commission, no date) with sections specific towards biofuels in general and not only biodiesel. Compared to Brazil, the EU appears to have more flexibility in its approach. Thus, even though it may be an option to use Brazil's approach to introducing biofuel, it may not be possible, because of the political structures within countries. Each country is different and will always have varying levels of success.

6.3.2 The Economics of Using Biodiesel

Policy instruments can influence the production and consumption of biodiesel in the transport sector, but this can result in a cost to the government, transport companies, the biodiesel industry, and consumers. It is essential to establish the costs before embarking on such a venture to assess whether the introduction of biodiesel to transport is beneficial in monetary terms.

6.3.2.1 The Costs of Using Tax Exemptions and Mandates

Tax incentives can result in a loss of revenue for the government. In 2005, Germany had a loss of €1.14 billion (US $1.3 billion) due to a reduction in fuel taxes on biodiesel. In total, the support for biofuels costs the EU around €3.7 billion (US $4.22 billion) per annum, split between bioethanol at €1.3 billion (US $1.48 billion) and biodiesel at €2.4 billion (US $2.74 billion) (Wiesenthal et al., 2009). The US has experienced similar results and it has been estimated that B20 could cost around US $0.68–0.9/L more for the producer than the cost of unblended diesel (Bozbas, 2008). To help compensate for these losses, foreign or private investment is often encouraged and promoted. As Malaysia emerged as a world player in biodiesel production, foreign investments have been injected into the industry. Yanmar, a Japanese diesel engine manufacturer, opened a biodiesel research facility. Additionally, Middle East Dubai Group invested US $49.5 million in Global Biodiesel, a Malaysian biodiesel producer (Lim and Teong, 2010). This shows that not all costs fall to the taxpayer or consumer.

When there is a loss of revenue for the government, funds may have to be reallocated or reduced in other areas of government spending; thus, the government faces an opportunity cost. To avoid the drop in expenditure in other areas of the economy, the government may have to consider measures such as a rise in taxes elsewhere. Politicians are often against raising taxes due to the possibility of voters turning against them. Governments need to assess the risk and sacrifice they are willing to make to introduce biodiesel.

When a mandate is issued, there will likely be an increase in the cost of the fuel, which will likely fall upon the fuel supplier. The fuel supplier has to decide on what to do with the extra costs, either to absorb them or pass them onto the consumers (Gheewala et al., 2013). Some variables could influence the decision on which option the fuel supplier would choose. However, more often than not, the consumer will usually bear the increased cost (Charles et al., 2013). If competitors absorb the costs, then other fuel suppliers who do not could be pushed out of the market. Governments could put price caps on fuels, so it is not possible to shift the cost to fuel supplier's customers. However, if the fuel supplier is a private company, the passing of the cost onto the consumer is more likely to maximize their profits.

6.3.2.2 The Price of Ethanol and Economies of Scale

In the long term, costs may reduce with the introduction of bulk production and the learning curve. A new project or venture can often have high initial costs through the possibility of using new technologies and producing a new product. With time, as the process and technology become more advanced and efficient, the marginal cost will reduce. This was experienced by Brazil. Brazil is a prime example of a nation that has demonstrated the interdependent links between policy, the market, and economics when trying to increase the use of biofuel (Gee and McMeekin, 2011). Using policies such as mandates, tax exemptions, and investment, along the bioethanol supply chain (Zapata and Nieuwenhuis, 2009), Brazilian bioethanol has become competitive against gasoline.

Figure 6-3 shows the production of ethanol in Brazil and the prices of Brazilian ethanol, international gasoline/petrol, and Brazilian gasoline from 1980–2005. In 1980, the price paid for Brazilian ethanol was more than double that of international gasoline, even though subsidies were being given to ethanol production. From 1990, subsidies were slowly removed as ethanol became more competitive with Brazilian gasoline. From 2002 to 2005, Brazilian produced bioethanol had a slow decreasing price, whereas international gasoline had a sharper increase in price—thus making ethanol cheaper than petrol by around US $0.22/L. During this time, all subsidies were removed from the production of ethanol making, and it is competitive with international gasoline without the need for government intervention. By 2005, bioethanol was 60%–70% of the price of international gasoline [48–50]. Brazil is a good example in that with a supportive structure and framework in place biodiesel can become successful. The price of ethanol is decreasing as ethanol production increases. This shows the link between the price of ethanol and the scale of production, i.e., the larger the production the lower the marginal cost.

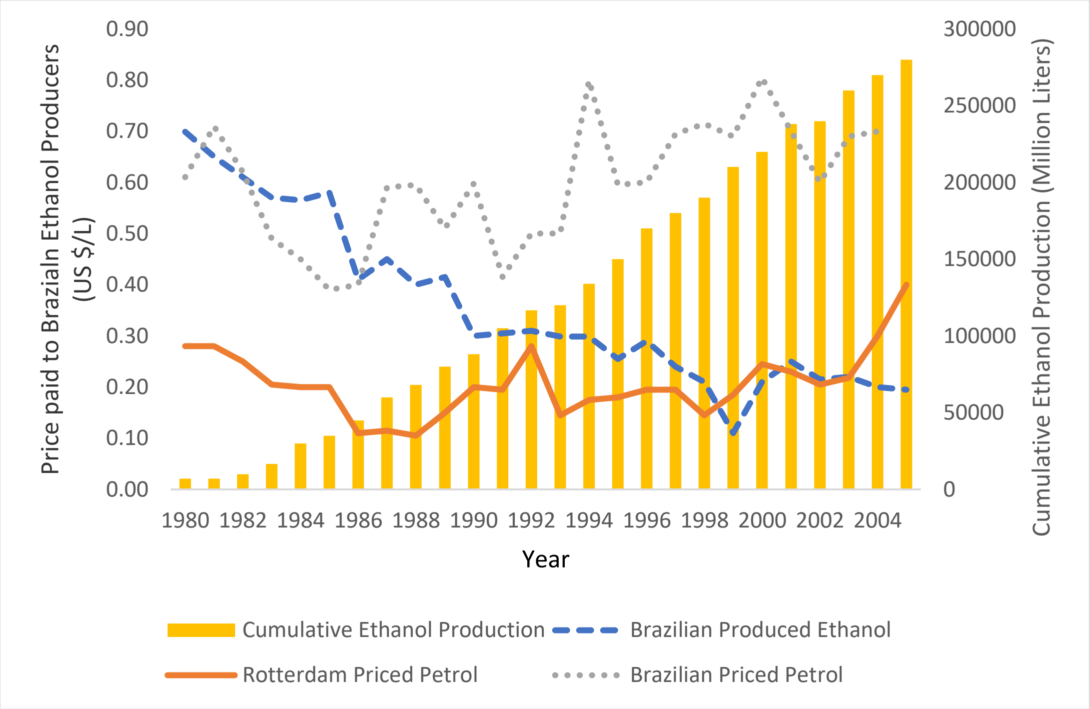

Figure 6-3: The production of ethanol in Brazil and the prices of Brazilian ethanol, international gasoline/petrol, and Brazilian petrol from 1980–2005

Source: adapted from Goldemberg et al., 2004

6.3.2.3 The Costs of Maintaining Vehicles using Biodiesel

Apart from the price of biodiesel for the consumer being often more expensive than diesel, other factors could also affect the costs to the consumer. Table 6-1 shows two studies of maintenance costs when using B20 in buses compared with diesel.

Even though the studies are independent of one another, the results could be considered as quite similar

.

Table 6-1: Comparison of fuel efficiency and maintenance costs from two bus studies investigating the use of biodiesel

Study	**Time Frame**	**Number of Buses**		**Km/L**		**Maintenance Cost (US $/km)**		**Bus Engine and System Maintenance Costs (US $/km)**		**% Overall Difference Compared to Diesel**
		Diesel	Biodiesel	Diesel	Biodiesel	Diesel	Biodiesel	Diesel	Biodiesel	
A Barnitt et al. (2006)	24 months	4	5	1.6	1.6	0.86	0.82	0.08	0.02	5.2% lower
B Barnitt et al. (2008)	12 months	7	8	1.3	1.2	0.91	0.91	0.08	0.12	0.32% higher

Sources: adapted from Barnitt et al., 2006 and Barnitt et al., 2008

Table 6-1 compares the fuel efficiency and maintenance costs from two separate bus studies. Fuel efficiency is approximately the same or slightly increased for biodiesel. There is little difference in the overall maintenance costs, but in study A, diesel was the more expensive because of the high costs for transmission repairs. The monthly running maintenance costs are higher for biodiesel. Study A reports a fourfold difference between biodiesel and diesel at US $0.08/km and biodiesel at US $0.02/km. Study B, however, shows that biodiesel is 50% more expensive than diesel. Overall, the bus maintenance costs are similar for diesel and biodiesel, but the engine and fuel maintenance costs are higher for biodiesel. However, when the blend increases to above 20%, it is recommended that fuel filters are changed more frequently, and when above 80%, manufacturers recommend an extra oil change per year (Greater London Authority, 2015). This shows that, when using biodiesel, consumers can expect little change in the costs of maintaining their vehicle if the blend is 20% or below.

6.3.2.4 The Cost of Feedstock

The choice of feedstock has an influence on the overall production cost of biodiesel and thus the price the consumer pays. Biodiesel production costs can be up to three times more than that of petroleum diesel (Gaeta-Bernardi and Parente, 2016).

Table 6-2 shows a comparison of diesel and biodiesel produced from a variety of feedstock. Biodiesel made from peanut butter oil is the most expensive at US $0.52/L, which is more than diesel. The feedstock derived from waste, in general, is the cheapest out of the feedstock, including diesel with tallow being US $0.36/L less than diesel, although this varies. This is positive because it eliminates the food versus fuel debate; the competition of land between feedstock grown for food or fuel. Edible feedstock has a large range, from the most expensive of US $0.52/L more expensive than diesel to the cheapest of soybean, which is US $0.05/L cheaper than diesel. The non-edible feedstock (jatropha) is more expensive than diesel at US $0.20/l. These are guidelines of biodiesel prices produced from various feedstock on the parameters mentioned above. Policy instruments, including tax exemptions, have been used to help reduce the price of biodiesel, but it is not successful for all. From 2004 to 2013, the US saw the cost of biodiesel produced from soybean and yellow grease increase in cost from US $0.56/L to US $0.62/L and US $0.31/L to US $0.34/L, respectively, based on a production of 909.2 million liters. The cost of producing petroleum during the same period varies from US $0.15/L to US $0.17/L (Bozbas, 2008). With these costs, biodiesel is not economically feasible from a monetary perspective. Were externality costs to be included in this estimate, then the opposite may be true, but research is limited in this specific area. When choosing to introduce biodiesel, the choice of feedstock is important because this will affect the costs and prices along the supply chain and the burden the government accepts from applying policy instruments such as tax exemptions.

Table 6-2: Comparison of diesel and biodiesel produced from a variety of feedstock

Feedstock	**Type of feedstock**	**Cost (US $/L)**	**Difference to Diesel (more to less expensive) (US $/L)**
Palm Oil	Edible	0.63–0.64[1, 2, 3]	0.0 to 0.06
Rapeseed	Edible	0.54–0.62[1, 3]	0.04 to −0.04
Tallow	Waste	0.22–0.63[2, 3]	0.06 to −0.36
Waste Oil	Waste	0.25–1.01[1, 2, 4, 5]	0.16 to −0.48
Soybean	Edible	0.53–0.57[1, 3, 5]	−0.01 to −0.05
Sunflower	Edible	0.54–0.62[6]	0.04 to −0.04
Peanut	Edible	1.1[1]	0.52
Diesel	Crude Oil	0.58[6]	N/A

Sources: [1]Balat, 2011 [2]Canakci and Sanli, 2008 [3]Gui et al., 2008 [4]Bozbas, 2008 [5]Karmee et al., 2015 [6]Barnwal and Sharma, 2005

6.3.3 Social Implications and Acceptance of Introducing Biodiesel to Transport

Social implications and acceptance of biodiesel are important because they can affect the overall welfare of a country. By demonstrating that welfare can be increased with the introduction of biodiesel, this may lead to social acceptance and thus support for current and future energy schemes. Over time, the introduction of the Brazilian Alcohol Program was welcomed by the people because it has enabled around 700,000 jobs to be created across the entire supply chain, mainly in rural areas (Coelho et al., 2006). While creating these jobs may initially be costly, in the long term, it would likely benefit the economy by having higher employment, higher wages, and a higher standard of living (Gheewala et al., 2013). For those not directly involved in the programme, it was important for the government to gain support from the people in the use of bioethanol. With this, they provided incentives such as Value Added Tax (VAT) reductions (Gaeta-Bernardi and Parente, 2016) to switch to ethanol-fueled cars. Other than Brazil, there is little information on how people are given incentives to choose biodiesel for their cars. The policies used can also influence social welfare. As mentioned previously with a mandate, for example, oil companies would have to provide a certain percentage of biofuels, which are usually more expensive. This extra cost could be passed on to the end user (Wiesenthal et al., 2009).

6.3.4 A Technological Perspective

While there is a lot of literature about how biodiesel affects engines, there are also several studies that have investigated the performance of biodiesel in locomotives. Areas include the effects on fuel consumption, different blend levels, and the materials in the engine.

6.3.4.1 Storage, Engine and Fuel Performance

The length of storage of biodiesel without affecting the use varies depending on the blend. B100 should be used within one year and requires regular monitoring, B20 can span longer and B5 can remain stable for the longest (Christensen and McCormick, 2014). Additionally, due to the increased density of B100 compared to lower blends, the risk of sediments settling to the bottom of the tank is higher, and therefore, proper mixing may be needed in the engine tank or fueling system before use. Biodiesel can be mixed by the fuel supplier before being dispatched to the consumer or it will be mixed while putting it into the tank. Biodiesel has a higher pour point temperature than diesel (Gui et al., 2008) and solidifies at a higher temperature, and therefore, cannot be used in winter months. Thus, biodiesel may not be feasible to use in countries with colder climates. As mentioned above, Minnesota only allowed the use of biodiesel in engines during the summer months, because of the physical properties of biodiesel.

The higher the blend, the lower the energy content, but the change is insignificant for B5 (SAE, 2014). Biodiesel is a good solvent and can dissolve varnish and gums, which, along with wax formed in lower temperatures, can cause the clogging of filters. There are also concerns that a blend higher than 80% biodiesel could potentially damage the engine and cause other engineering problems (Shahid and Jamal, 2008, Pramanik, 2003). When B100 is used, certain metals can be degraded such as bronze, tin, zinc, and lead, so should not be used in the engine (Pramanik, 2003). These problems have led to vehicle manufacturers, invalidating warranties when biodiesel is used. For example, France wanted to increase its compulsory blending from 7% to 8% but faced objections from automobile manufacturers, who state that the warranties on vehicles would become invalid if an 8% blend is used (Lane, 2016). Germany has been able to use B100 because the government and organizations that promote the use of biodiesel have worked closely with automobile manufacturers and have established the following conditions in which B100 can be used in certain vehicles (UNION ZUR FÖRDERUNG VON OEL- UND PROTEINPFLANZEN E.V. (UFOP), 2010, Gärtner and Reinhardt, 2005):

1) Fuel had to comply with DIN EN 14214 standards.
2) A certificate must accompany each supply of fuel ensuring that it meets the required conditions. Any additives added to the fuel must be included in the certificate.
3) Tanks must be emptied and cleaned when switching from summer to winter fuel.

1. When a warranty claim is issued the manufacturer must have proof of the fuel's origin.

These guidelines were established after rigorous tests, including different climate situations, usage, chemical observations, and mechanical contingencies.

6.3.4.2 Blending Diesel and Biodiesel

Biodiesel can be blended at refineries, which are already producing and supplying diesel. For low blends such as B7 used in the UK, there is no need to change the pumps at fuel stations. Some countries such as Brazil, Germany, and Malaysia converted their refueling station pumps for distributing pre-mixed high blend fuels. Apart from blending at refineries, it is possible to load biodiesel and diesel separately directly into the fuel tank. There are two methods for this:

1. Splash blending. This is widely available, but the least effective. First, the diesel is loaded into the tank followed by the biodiesel being pumped on top

2. In-line blending. Warm biodiesel is pumped into an already running stream of diesel as it is loaded into the tank. It is thoroughly mixed through the turbulent movement of the fuel (Archer Daniels Midland Company, no date, Scharffbillig and Clark, 2014). Even though this is the most efficient and reliable method, it is also more expensive than splash blending.

This shows that there are different methods to mix biodiesel and diesel so there is flexibility for a country or mode of transport to choose the method that is most beneficial for them.

6.3.5 Environmental Effects of Using Biodiesel in Automotive Vehicles

The use of biodiesel can help reduce Greenhouse Gases (GHGs) and pollutants (e.g., NOx and SOx), generally, the higher the blend, the larger the reduction. GHGs are important to observe because they contribute to global warming, which can lead to severe weather and rising sea levels. During the production and combustion of biodiesel, CO_2 is released, but it is absorbed by the crops (Lam et al., 2009a). To account for this absorption back into the supply chain, it is often assumed that CO_2 exhaust emissions are neutral. Pollutants can affect people's health, especially the respiratory system. A lot of research on emissions from biodiesel has been conducted and reported and this can be seen in Table 2-1.

6.4 A DISCUSSION ON THE TRANSITION TO BIODIESEL USED IN LOCOMOTIVES AND THE LESSONS LEARNED FROM THE ROAD SECTOR

Many influencing factors contribute to success or failure during a transition to biodiesel as an alternative fuel. By assessing the successes and failures, it is possible to establish the areas for further development and risk factors of introducing biodiesel to the rail sector. Table 6-3 is a summary of the lessons learned from the road transport sector. Each lesson is categorized in whether it was successful, unsuccessful, or partially successful. A brief explanation is given to describe this decision, and finally, the consequences of applying the lesson to the rail sector.

Table 6-3: A breakdown of the lessons learnt from the road sector and how they apply to rail.

Item	Success /Failure for road	Explanation of the lesson learnt from the road sector	Application to Rail
Policy, politics, and regulation			
Mandates	**+ –**	Mandates are a success or failure depending on whose perspective is being considered. Mandates ensure that biodiesel is used and there is no direct cost to the government. However, any increased costs to the fuel supplier will likely be passed onto the consumer.	Mandates will likely lead to an increased cost to rail users and freight companies.
Tax exemption	**+ –**	This may affect the budget of a country to finance introducing biodiesel.	Diesel used in the rail sector is often exempt from tax, so tax exemptions on biodiesel would likely not be a useful policy instrument.
Legislation	**+**	Laws can provide structure and a framework to introduce biodiesel.	Legislation can strengthen the legal position of introducing biodiesel to rail.
Economic			

Maintenance and maintenance costs	+	The parts which need replacing in vehicles that use biodiesel are different from that of diesel. But this has limited impacts on the cost.	This provides a benchmark for rail, but locomotives will have different aging conditions for components and thus different maintenance requirements for automobiles.
Learning curve and economies of scale in production	+	As more knowledge is gained the marginal cost of producing biodiesel will likely decrease.	Producing biodiesel for road or rail will be the same, therefore rail will experience reduced biodiesel production costs.
A rise in demand for biodiesel	+	A rise in demand can lead to several advantages in the biodiesel industry such as economies of scale, reduced GHGs, and the possibility of increased energy security. However, increased NO_x emissions could damage the health of the public adding a financial burden to the health care system	Bulk buying leads to a decrease in marginal costs.
Cost of feedstock	+	The cost of biodiesel feedstock leads to an increase in the overall price of biodiesel making it less competitive against diesel	The extra cost in the production stage will likely lead to increased prices for rail users
Crude oil prices	+ –	As oil prices increase biodiesel will likely become more competitive. However, the opposite is also possible with a decrease in oil prices.	As biodiesel is a substitute for diesel the cost of diesel's raw material (crude oil) will influence biodiesel prices

Social			
Employment increase	**+**	There is an increase in employment across the supply chain.	If the biodiesel industry already existed in a country, then the extra employment gained from introducing biodiesel to rail would not be as great as a country where the industry did not exist.
Technological			
Refuelling and blending	**+**	There are recommendations for the length of time to store biodiesel. There are different options for blending biodiesel and diesel. No changes are needed for low blends	The use of biodiesel in lower blends does not need modifications in refuelling stations.
Higher blend	**+**	Germany has used B100, but this was after rigorous testing and working with car manufacturers	Governments need to work with locomotive manufacturers
Environmental			
Environmental change	**+**	CO_2, PM, CO, HC, and SO_2 are reduced with the use of biodiesel. The larger the blend the bigger the reductions. However, NO_x increases.	Generally, emissions and pollutants are reduced.

6.4.1 The Political and Policy Side of Introducing Biodiesel to Rail

There are two sides to the “P” of the PESTLE framework the policy side and the political side but is closely linked. Both play a key role in introducing biodiesel to the road, and consequently, rail. Policies influence the areas of the PESTLE framework. This is a key lesson for rail, that the wider effects and consequences, both direct and indirect, need to be considered when issuing policies. Biofuels need to be understood in their historical socio-economic contexts (Oliveira et al., 2017). Policy makers prefer to use a combination of mandate and tax credits in conjunction (De Gorter and Just, 2010). However, this is not always the best approach, other considerations can influence the outcome of such measures and will be explained in further detail in this section:

- The political setup of a country
- The elasticities of the biofuel and fossil fuel
- Whether the fossil fuel price is endogenous or exogenous
- If a mandate is binding or non-binding

These variables add uncertainty over whether to enter the biofuel market (Markel et al., 2018). Another aspect that can lead to uncertainty is the political structure of a country because it could have several influences. There was a military rule in Brazil during the bioethanol programme. When the country had control over gasoline and ethanol, growth and uptake of ethanol were largely successful. Even though the government had control over ethanol production and the state-owned oil company, there was a degree of flexibility that allowed for high uncertainties in the industry. It also considered the demographic of the country, whereby they issued varying federal and state taxes, and they did not take a one size fits all approach (Nuñez and Önal, 2016). This shows that while policies are important when introducing a new fuel to a market, flexibility within those policies is just as important. Just because a country's industry is heavily state-owned, this does not mean that introducing biodiesel will automatically be successful. For example, the Indian government wanted to introduce a 20% biofuel usage target by 2017 (Basavaraj et al., 2012); however, this target has fallen short, partly because of the lack of clarity and consequences of the government policies. There was confusion in understanding the policies (Saravanan et al., 2018), in that farmers claim that the government is unclear about the price of seeds, where to grow the crops, and the type of crops that should be grown (Biswas and Pohit, 2013). This shows that, even though the government may have large controlling power over the industry, the programme can still fail.

There are two possibly contentious areas when introducing biodiesel to the market. The first is the relationship between politics and the corporate sector (Oliveira et al., 2017), and the level of influence that the corporate sector has over politicians. The second is the reasoning of promoting biodiesel initially. Often, the main reason is to reduce GHGs and reliance on fossil fuels; however, a government needs to decide how much they are willing to sacrifice to achieve this. For example, biofuels are often more expensive than fossil fuels, so the cost of a blend (if desired) will be more expensive than unblended fossil fuels. Either this cost is passed onto the consumer, or the government absorbs it. The government must decide the cost it is willing to pay to lower GHGs.

Regulating policies can be strengthened using legislation, which is mandatory (Hao et al., 2018). Different legislation in different countries has been used when attempting to introduce biodiesel to the road. In the EU, legislation about biofuels is generalized. The EU issues directives, such as the Renewable Energy Directive (European Commision, 2009), which promotes the production and promotion of renewable energy, and each member state then enacts its legislation. This may not be as effective and thorough as more focused and specific legislation. For example, Brazil was clear in its plans of setting targets and had a structure as to how to achieve its goals. The success of Brazil passing legislation could be partly due to the political structure of the country. The military government had few opponents to object to their ethanol plans. In a democracy, it could be more difficult to pass legislation because of opposition. Nevertheless, legislation can only strengthen the introduction of biodiesel to rail.

6.4.2 The Economics of the Policy Instruments Used and their Application to Rail

While it is easy to set policy, understanding the consequences of the policy is not. Policies have a direct impact on the entire economy. Mandates and tax exemptions can be standalone or used in conjunction with one another. A mandate can lead to modest gains in biofuel production, exports, and reduction in GHGs (Khanna et al., 2016). Tax money is not used to foot the bill of a mandate; instead, consumers pay with higher prices at the pump (De Gorter and Just, 2010). A mandate can be binding or non-binding. Binding means the fuel suppliers are forced to supply more biofuel than they otherwise would; non-binding means that they are already supplying more than the mandate states (Thompson et al., 2011). A high gasoline price means that a non-binding mandate will have little impact on the market (Ziolkowska et al., 2011). This is because the oil companies are already using more biofuel than is being asked of them, so a high gasoline price would have little impact on the amount of biofuel being used.

With a tax exemption, the question that is always asked is who pays? While in Germany and the US tax exemptions have increased the use of biofuel, policy makers need to be careful that the fuel price is not so low that the consumption of fuel begins to increase, with the consequence of higher GHGs (Ziolkowska et al., 2011). Conversely, abolishing tax exemptions can lead to consumers reverting to fossil fuels as they will likely become cheaper than their biofuel counterparts. This would lead to increased GHGs. There is a tradeoff; society can have a cleaner environment at the expense of higher fuel prices (Nuñez and Önal, 2016). This once again highlights that politicians and the rail sector need to understand and clarify the reasoning behind their choice to use biodiesel.

A combined approach of using a mandate and tax incentive is often advised (Lapan and Moschini, 2012, De Gorter and Just, 2010). The experience of the road transport sector in using policy to promote biofuels shows that a combined approach will likely provide the most positive results. However, this approach may also increase demand above the required mandates when demand for biofuel is high, especially during times of higher oil prices (Babcock, 2010). However, the tax exemptions can offset the increased price of the mandate (Ziolkowska et al., 2011), and using a tax exemption on a binding mandate contradicts the biofuel policy (De Gorter and Just, 2010). The tax would be acting as a subsidy, leading to a likely increase in both biofuel and fossil fuel consumption, which leads to increased GHGs (Khanna et al., 2016). This section does not recommend a particular policy that rail should adopt. Were it to introduce biodiesel but seeks to highlight that understanding the consequences of a policy is a complex issue.

6.4.3 Social Implications and Acceptance of Using Biodiesel in the Rail Sector

Biofuels can result in rural economic development by employing more people across the supply chain. This would likely lead to a higher standard of living; however, this could once again depend on the policies chosen. Assuming a mandate would lead to increased costs on the fuel, society would pay the marginal difference. The increased wages from the workers would pay towards this extra cost. However, this could be outweighed by some of the benefits that biofuels bring such as lower GHGs and pollutants (Nuñez and Önal, 2016). This is not always the case as some policies can lead to increased GHGs and thus lower social welfare (Khanna et al., 2016). Some statistics show an increase in jobs in Brazil, but at the same time, Brazil has been criticized by rural development movements for labor exploitation (Oliveira et al., 2017). This highlights the issue that clarity and transparency are vital when introducing such a scheme, and all aspects along the supply chain need to be considered by governments.

The rail sector and rail companies need to understand the benefits of using biodiesel. They should be educated not only in engineering but also to understand the cost and social impact of biodiesel. They should understand the benefits of using biodiesel and how to make that marketable to their consumers. It may be difficult for rail users to switch between brands of trains due to the structure of the rail network in most countries, but it is possible to change the mode of transport to reflect support for the most carbon-friendly one. This is a positive point that encourages the introduction of biodiesel to road and rail, and they need to work together to avoid a negative modal shift.

6.4.4 The Technological Aspects of using Biodiesel in Locomotives

While the basic principle of both a diesel-powered locomotive and the road vehicle is the same (compression-ignition engine), the maintenance needs may be different. Factors that may impact these needs could be the distance travelled and the age of vehicles (locomotives may be older because of their lifespan).

1. Considering the lifespan of a locomotive there may be materials in older models, such as metals, that degrade if biodiesel is used. It may take longer to use biodiesel in the rail sector because of the lower frequency of locomotive replacement compared to road transport. However, until rolling stock is replaced, it may be possible to work with manufacturers to establish the maximum blends they will allow when certain conditions are met. When locomotives need replacing, the rail companies must work with the manufacturers to help increase the possibility of using higher blends in the engine. If the government or biodiesel advocates help fund the development of biodiesel in rail and a partnership with engine manufacturers, the chances of using higher blends could become increase.

2. This in turn may affect the cost of the overall maintenance. While the current understanding is that there are few changes in maintenance costs, it may differ for rail. Therefore, this is the benchmark for maintenance costs, but checks and pilot tests would need to take place to assess if there is a similar trend to that of road.

6.4.5 Environmental Consequences of using Biodiesel in the Rail Sector

Pollutants could be reduced by 1%–7% by using B20 (Basha et al., 2009, Fritz, 2004, Sze et al., 2007) and 10%–30% by B100 in comparison to conventional diesel. Significant reductions of both HC and CO were observed; B20 could reduce HC and CO emissions by 21% and 17%, while B100 could reduce HC and CO emissions by 24%

and 34% respectively. However, there are debates on HC and PM emissions for B20 blend; some believe this should be a lot lower (Fritz, 2004). Tests have indicated that there is an increase in NOx, HC, and CO emissions when the locomotive is in an idle state while using B20 (Prueksakorn et al., 2010). Were the use of biodiesel to increase, then these emissions would also increase, putting human health at risk. GHGs are reduced in the rail sector when introducing biodiesel with a reduction of 70% for B100 over the lifecycle of producing biodiesel (Whitaker and Heath, 2010, Sharma and Strezov, 2017).

Another aspect other than the technological side that can affect the environmental impact of using biodiesel is the policy side. For example, if the tax exemptions are too high and result in an increase in fuel consumption, emissions could increase. Once again, this highlights the importance of understanding the consequences of policies.

6.5 INDIA LEARNING LESSONS FROM THE ROAD TRANSPORT SECTOR

So far, this thesis has only been applying biodiesel to accommodate single lines. However, were India to introduce biodiesel across the country this would require new policies. Indian Railways would need to understand the impact and practicality of introducing such policies including economic, social, and technological effects.

6.5.1 Using biodiesel across India’s rail network

For the financial year, 2014/15 Indian Railways had 5,714 diesel and 5,016 electric locomotives covering 1,147,190 passenger-km and 68,261 (ten lakhs[5]) net tonnes km (Ministry of Statistics and Programme Implementation, 2018). In 2017 Indian Railways used approximately 2.55 billion litres of diesel costing the government Rs 11,000 crores (110 billion).

6.5.2 The policies needed in India

There have been several biodiesel policies and initiatives in place for years, such as a target of 20% usage of biofuel by 2017 (this did not apply to the railways). There has been considerable research conducted on the policies implemented in India with

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[5] 100,000 (one hundred thousand)

some interesting conclusions. Little academic research has been carried out on the use of biofuels in Indian locomotives but there are government studies available.

According to Basavaraj et al. (2012), the government supported the following policies:

1) A 20% biodiesel and bioethanol blend by 2017
2) Biodiesel production from non-edible seeds and waste
3) Wasteland to produce the feedstock
4) Supporting farmers to grow the crops with a Minimum Support Price (MSP)
5) Incentives for second-generation biofuels
6) Unrestricted movement of biofuels
7) Setting up a National Biofuel Coordination Committee and a Biofuel Steering Committee

From the outset, the government appeared proactive in promoting biodiesel by setting up special committees. But the issue is much more complex because the multiple stages along the supply chain need specific policies applied (Basavaraj et al., 2012). Setting the policies is not difficult; it is understanding the economics behind them and how each of the policies will affect the overall economy that is complex (De Gorter and Just, 2010). De Gorter and Just(2010) explored the different policies and bundles that could be used along the supply chain of ethanol and concluded with the following recommendations for government:

1) Mandates appear superior to other policies
2) Bundling policies (i.e. using combined policies at the same time) may have adverse effects
3) Biofuel policies have proved inferior in helping the market expand

Even though there is an underlying problem that initiatives are not always fully implemented, De Gorter and Just (2010) were still optimistic that India would meet its target. However, there appears to be confusion in understanding the policies (Biswas and Pohit, 2013). Farmers claim that the government is unclear about the price of seeds, where to grow the crops and the type that should be grown.

Kumar et al.(2012) attempted to break down the policies which were implemented for a 20% biofuel use target by 2011/2012. There were problems in producing enough biodiesel and purchasing price policies. But generally, the literature seemed optimistic about meeting the 2017 target if policies are implemented and followed through (Biswas and Pohit, 2013, Basavaraj et al., 2012, Biswas et al., 2010, De Gorter and Just, 2010, Kumar et al., 2012).

These policies were primarily for road transport and have not fared well as they have not met their targets. Indian Railways has committed to using B5 in its locomotives (Indian Railways, 2019). At present they are looking at procuring biodiesel from trade deals and investing in further production facilities. There is also speculation that a blend of 25% biodiesel is being considered. While Indian Railway's effort to mitigate climate change through biodiesel should be commended there is a lack of evidence to show which policies are needed to support this transition. The failure to meet targets for the road transport sector has concluded that policies were unclear and not sufficiently robust.

6.5.3 The economics of using biodiesel in Indian Railways

Financially, biodiesel produced from palm stearin is more expensive than diesel unless there are significant increases in the price of crude oil. Indian Railways would need to cover this extra cost. Fuel costs are already a large proportion of the total cost, so using biodiesel would increase the overall cost. However, this would also reduce crude oil imports which have been increasing year on year. In December 2018 India imported the equivalent of 4,543.645 barrels/day; this is an increase from 4,341.414 barrels/day in December 2017 (CEIC, 2019). Fluctuating oil prices could have a significant impact on the trade balance. If crude oil prices are forecast to increase, then it is worth investing in biodiesel for the long term.

While there may need to be a significant capital investment in the industry to produce the fuel, the economy and Indian Railways would likely reap future benefits. It is possible to import the extra demand for biodiesel; however, if the country wishes to ensure energy security, then this would not be met by substituting crude oil importation for biodiesel. This also supports the argument for producing the feedstock in India as opposed to the current approach of importing it.

Were India to base its assessment of using biodiesel on economic costs then it is a positive outlook for not only the biodiesel industry but also India’s economy. However, unfortunately, this conclusion is not as simple as it may seem. One of the assumptions for this thesis is that the production facilities' costs are not included. Were India to introduce biodiesel to other parts of the network then investment in new facilities would likely be needed.

Approximately 20,000km of the railway network has not been electrified (Kajarekar, 2020). If India wanted to use biodiesel instead of electric traction the model could be scaled to accommodate 20,000km. An aspect that is not included in this thesis is the cost of new production facilities. However, here they would need to be taken into consideration. Scaling up the biodiesel production industry to meet this demand can be seen in 6-4.

Table 6-4: Scaling up the present to accommodate using B5 on unelectrified railways lines

	Current parameters	**Future parameters**
Distance (km)	482	20,000
Diesel Consumption (95%)	20,207,344 litres 577,353 litres/year 1,582 litres/day	838,478,991 litres 23,956,543 litres/year 65,634 litres/day
Biodiesel Consumption (5%)	1,273,665 litres 36,390 litres/year 100 litres/day	52,849,168 litres 1,509,976 litres/year 4,137 litres/day

Total biodiesel capacity in India	670 million litres[1] (in 2019, from a range of feedstocks)	No extra capacity needed

Source:[1] Statistica, 2021

The amount of biodiesel needed to use continuously on the rail network to cover 20,000km a day would be 1,509,976 litres/year. India can produce 670 million litres of biodiesel per year. No new facilities would need to be built to accommodate the extra demand needed. However, rail is not the only sector that can use biodiesel. If India wanted to use more biodiesel in the rail sector, then it would need to look at the bigger picture to assess the extra demand created alongside demand in other sectors.

As well as the demand from other sectors for biodiesel there are variables in the rail sector that would need to be taken into consideration were this model to expand to other parts of India. Variables that would likely need to change or be considered include:

- If the gradient varied over the route then this would change the fuel consumption, for example, steeper slopes would mean that more biodiesel and diesel were needed, which would increase the emissions and costs. If the terrain was uneven, it may also be more expensive to build the overheads to accommodate the electric trains. Although the higher the gradient the colder the temperature which would limit the use of biodiesel.
- The amount of time the locomotive spent in more populated areas. The longer the locomotive spent in a populated area the higher the pollutants would be and thus the costs. There are separate costs, which are higher, for pollutants that are emitted in more densely populated areas. This would increase the non-monetary costs of diesel and biodiesel. Although the non-monetary costs are a smaller portion of the total compared to the monetary ones the effect may be negligible.

- The density of traffic on the route. If there is more traffic on a route, then the duty cycle would change. If the locomotive spends more time in a lower notch, then fuel consumption would increase.
- Different states and railway zones will have different prices for fuel and electricity which could affect the financial analysis. Although it is likely this would be minor, as the fuel prices (biodiesel and diesel) would vary by the same level.

The model could be applied to many parts of India, but there are limits especially if the variables above had a prominent role in the routes.

6.5.4 Social side

If India were to invest in new facilities to meet the extra demand for biodiesel, this would increase employment during construction and also during operation. The use of biodiesel will likely cost more, especially in the short term; the question is who will pay for this? Passenger rail tickets are already heavily cross-subsidised from freight (Kamboj and Tongia, 2018). India’s goal is to shift more freight onto the railways (Indian Railways, 2019), but with the possibility of increased prices, this could make this shift more challenging.

6.5.5 Technological

Indian Railways can apply the following lessons of introducing biodiesel to the rail network:

1) Up to B20, there would likely be little or no change in the maintenance cost or lifespan of the locomotives.
2) To use biodiesel, especially higher blends, IR needs to work with the manufacturers to validate the warranty when using alternative fuels in the engine.
3) The locations where Indian Railways can use biodiesel are limited due to the chemical and physical properties of the fuel. The pour point of biodiesel is higher than diesel and therefore in colder climates, it may not be possible to use biodiesel.

6.5.6 Environmental

The biodiesel lifecycle absorbs CO_2 back into the system much more quickly than diesel. Other GHGs are a concern because these depend on farming methods. However, another big concern of using biodiesel is the emission of local pollutants. NOx from the tailpipe emissions are higher than for diesel, and other pollutants such as CO and PM still exist. Airborne pollutants and dirty water are negative consequences of producing biodiesel and this could result in possible health problems for the local population (Ribeiro, 2013). Poorer people will likely suffer the most as they will be unable to afford to move away from areas where facilities are built. This links closely to the social implications of using biodiesel. If people suffer ill health more frequently because of the pollutants, then this would put a strain on health services.

6.6 SUMMARY

The road transport sector is rich in research and experience in introducing biodiesel. The experience of using biodiesel in the road sector is varied with both successes and failures. The relevant lessons for rail are:

- Using biodiesel can reduce most GHGs and pollutant emissions, with potential health benefits.
- Tax incentives and mandates have promoted the production and consumption of biodiesel. Such incentives will likely be required for the rail sector too.
- The financial cost of using biodiesel is higher than fossil fuels, with the price of feedstock an important constituent. These extra costs will likely be absorbed by the consumer or taxpayer. The cost competitiveness of biodiesel fuel will also depend on global oil prices.
- Maintenance costs are more difficult to determine for rail due to the differences with the vehicles. This highlights the importance of working with locomotive manufacturers and train operators to determine these costs.
- The use of biodiesel in small blends may not require any modification to existing locomotives. However, warranties of locomotives for biodiesel blends are an important area requiring consultation.

- The longer life of rail locomotives compared to road vehicles may be a barrier to the rapid adoption of higher blends of biodiesel.
- The suitability of existing infrastructure and required modifications play a key role in introducing biodiesel into the market. This may be easier for rail compared to the road sector as fewer fuelling stations will be required.
- Policies and governance structures have an important role in the transition to biofuel. A study of the political economy of transitions in the road sector will be useful for rail.

Most of these lessons could be applied to India’s expansion of biodiesel. However, there are some tough choices for India to make when adopting biodiesel on the rail network. One of the most important choices will be determining who will pay for the extra cost. This choice will have an impact on the other areas such as a social impact and will then need to be worked into policies and legislation.

7 Conclusion

7.1 INTRODUCTION

This chapter concludes the thesis. It analyses and explains how each chapter has addressed the objectives of the thesis. There are also sections on the limitations of the study and further work.

7.2 A COMPARISON OF DIESEL AND BIODIESEL AND ITS SUBSEQUENT BLENDS

There is a substantial amount of evidence that shows that biodiesel produced from palm stearin is more environmentally friendly than diesel; this study supports the literature. One pollutant which is not environmentally friendly is NOx. For B5 NOx increased by 0.4% compared to B0. NOx emissions continue to increase as more biodiesel is added to the blend, at B100 NOx increases by 9% compared to B0.

Overall, in this thesis biodiesel is more expensive than diesel for all blends, but on a per litre basis, B100 is the least expensive although the amount is negligible with a difference of Rs 0.22 per litre between the most expensive (B50) and the least expensive (B100). Indian Railways purchases biodiesel at the same price it does for diesel. However, what makes biodiesel more expensive is its lower energy content.

This thesis has highlighted the importance of including an economic analysis when assessing alternatives to eliminate distortions from the market and include externalities. As mentioned above diesel is more financially viable than B5. However, B5 is more economically viable than diesel by a little under Rs 16 million over 35 years. This highlights that it is important to give the true cost to an economy rather than just the cost to an individual business or government body.

At present the Indian government imports the raw materials to process biodiesel, but to understand whether it would be more economical to use a feedstock cultivated in India it was important to investigate the possibility of using a feedstock grown in

India. This potentially has extra benefits including increased job opportunities, extra energy security, and reduced transportation costs.

7.3 A COMPARISON OF BIODIESEL PRODUCED FROM MALAYSIAN IMPORTED PALM STEARIN AND INDIAN GROWN JATROPHA

Biodiesel produced from jatropha is like biodiesel produced from palm stearin when estimating environmental effects, both in terms of GHG emission and local air pollutants. It in only NOx which increased compared to using B0. B5 NOx increases by 0.5% and B100 by 10.6%.

Financially, jatropha is more viable than palm stearin by Rs 1 million over 35 years. However, jatropha based biodiesel is not more financially viable than diesel, it would cost Rs 13.8 million more to use B5 (jatropha derived) compared to B0. The reason for the differences is due to the energy content. Jatropha based biodiesel has a higher energy content compared to palm stearin-based biodiesel but is lower than diesel.

From an economic perspective jatropha based biodiesel performs worse than both palm stearin-based biodiesel and diesel (Rs 37.5 million and Rs 21.6 million respectively). It is difficult to compare these results to other literature because of differences in geographical locations and the parameters used. The literature showed inconsistencies when comparing work that included palm stearin and jatropha individually and separately.

This thesis analysed variables that could potentially the outcome of the analysis. These were:

1) Importing biodiesel produced from palm stearin directly from Malaysia instead of importing the feedstock and producing the biodiesel in India.
2) Changing the cost of palm stearin.
3) Change the jatropha cultivation costs
4) Including a shadow price on the foreign exchange if imports.
5) Including the biodiesel production plants costs.

Only a few of the variable changes in this sensitivity analysis alter the outcome of the analysis. These include:

1) The increase in palm stearin feedstock cost.
2) The inclusion of a higher shadow price (25%) resulted in biodiesel produced jatropha becoming economically feasible compared to B0.
3) When the construction costs of the plant facility are included.

Using jatropha grown in India could increase energy security by not having to rely on imported feedstock. Importing palm stearin as feedstock does not eliminate an item from the trade balance as it just replaces imported crude oil. Using jatropha would also boost jobs, mainly in the cultivation stage. However, jatropha is still considered unreliable because of the lack of research into the yield and it has shown inconsistencies in its robustness. Therefore, caution should be taken if Indian Railways decides to use biodiesel produced from jatropha in their rail network.

7.4 THE USE OF ELECTRIC TRACTION COMPARED TO B5 WITH THE BIODIESEL PRODUCED FROM PALM STEARIN

Indian Railways could use both biodiesel and electric traction as alternatives to diesel; therefore, it was important to consider both in this analysis. Electric traction has lower GHGs compared to diesel – diesel is 138% higher. However, electric traction is 100% higher compared to B100. N_20 is the only GHG where electric traction has a lower value compared to B100.

Operating a locomotive is cheaper, by Rs 1,485 million over 35 years, compared to using B5. However, this is when the cost of electrifying the route is excluded. When it is included then electric traction becomes more expensive, by Rs 9,640 million, compared to B5.

The economic analysis is like the financial one where when the infrastructure costs of electrifying lines are excluded then it is cheaper, by Rs 3,600 million compared to B5. When infrastructure costs are included then electric traction becomes less feasible. One of the sensitivities was to investigate the traffic density of the route to test the breakeven i.e. when electric traction becomes economically feasible with infrastructure costs included. The breakeven is between four and five return journeys with four journeys resulting in B5 being cheaper by Rs 1,653 million. Five return journeys result in electric traction being cheaper by Rs 304 million. If there were a high density of traffic on the route, then the economics of using electric traction become much more favourable.

Electric traction is an investment for the long term which benefits from higher speeds and better reliability. If Indian Railways decided to electrify this route then other variables would likely need to be included such as the environmental impact of building the infrastructure. However, there are two concerns about using electric traction:

1) India already faces an energy deficit and may struggle to meet the extra demand if electric traction was used. A few years ago, the demand for railways was guaranteed and therefore electricity would be taken away from industry and residential. This was an opportunity cost through industry losing business and profits and the residential sector still using dirty fuels such as coal and biomass. However, more recently because of the global Covid pandemic the future demand for rail is unknown. With very few people being allowed to travel there was a drop in demand for using the railways for both work and discretionary uses (Bhaduri et al., 2020). With a lower demand for transport in general this did have a positive impact on the environment and improved air quality (Ghosh et al., 2020). The demand for rail in the future is uncertain, as Bhaduri et al. (2020) state many influences could affect someone’s decision to travel in the future. Other factors may include having to show a Covid passport or certificate to use the railways and some States are already doing (Nag, 2022). However, doing this may take time to organise e.g. apply for passports or certificates and thus delay passengers returning to using the rail net work.
2) The electricity mix at present is dominated by coal thermal power. With a higher demand for electricity on the railways in a business-as-usual context,

more coal would be needed. This is primarily transported by rail which would cause more traffic on the network, which is already highly congested.

Even though electric traction has more benefits than biodiesel, India continues to pursue the use of biodiesel. Until India has addressed its electricity deficit, installed 100% electricity to residential dwellings, and become greener in its generation, biodiesel should be promoted more than electric traction. India can learn lessons from the road sector and other countries that have either successfully or unsuccessfully introduced biodiesel. The main barrier that India has faced in the past is a lack of robust policies. These are key to introducing biodiesel to the rail network.

7.5 THE LESSONS LEARNED FROM THE ROAD TRANSPORT SECTOR AND HOW THEY CAN BE APPLIED TO THE RAIL SECTOR AND INDIA

The road transport sector has received much more attention in introducing biodiesel compared to the rail sector. This chapter concluded that policy is key to introducing biodiesel.

While it is easy to set policy understanding the wider impacts and consequences is more difficult. This is a lesson for both the rail sector and Indian Railways. The Indian government previously tried to introduce biodiesel to the road sector but failed to meet its targets. A lesson from the road transport sector in India is to ensure that initiatives are communicated clearly – for example in India farmers were unclear about the purchasing price policies and therefore did not grow crops to be produced into biodiesel.

Biodiesel is more expensive therefore policies are needed to increase the supply of biofuels. Two of these are including a mandate, a tax exemption or a combination of both. The question of introducing these policies is who will pay for them. If a government introduces policies there is little the rail sector would be able to do other than adhere to them. However, if fuel prices increase because of the policy introduced the rail companies would potentially need to decide who absorbs the costs, them or their customers. Whichever choice is made the important factor is that fuel costs would likely increase with the introduction of biodiesel into the rail transport sector as has already been seen in the road transport sector.

There are many social benefits to using biodiesel including increased job opportunities along the biodiesel supply chain.

Successful introductions of biodiesel into the road transport sector have been a result of good communication between governments and consumers, such as encouraging the switch to environmentally friendly options by offering financial incentives and communicating the environmental benefits of using biodiesel.

It is more difficult to apply this lesson to the rail sector because even though rail companies could communicate the benefits of using biodiesel it is unclear how this could impact the rail user. The structure of most rail networks means that it would be difficult for rail users to switch which company they travel with, but it is possible to change the mode of transport to reflect support for the most carbon-friendly one.

The combustion engine for a locomotive and a road vehicle are similar and therefore the impact of using biodiesel will also be similar. So, the lessons learned such as needing additional maintenance and the need to extend engine warranty from the road transport sector can be applied to the rail sector.

GHGs and pollutants have been reduced when using biodiesel in the road transport sector except for NOx which increases. This thesis showed something similar with emissions decreasing when using biodiesel.

There are three recommendations for India that have arisen from this chapter:

1) India needs a robust policy that is clear and considers the various parameters associated with introducing biodiesel to the rail network. The policy needs to be communicated clearly to all those who will be impacted by it.
2) Clarity on the reasoning for pursuing the use of biodiesel on the rail network There was a financial drive for Brazil because importing crude oil was becoming too expensive and for the EU it was an environmental drive.

3) India needs to assess how easy it is to pass the policies through the various levels of bureaucracy.

7.6 SUMMARY OF THE CHAPTERS

Biodiesel is a feasible alternative to diesel. It is more environmentally friendly compared to diesel. From a financial perspective, it is more expensive to use biodiesel but not from an economic one. However, it is important to consider different feedstocks, for example, it is economically feasible to use biodiesel produced from palm stearin but not jatropha.

Electric traction is a high priority for India and is more feasible in certain circumstances compared to biodiesel and diesel. For example, if the route has a higher density of traffic, it becomes more justified to electrify the lines. However, on lines that are less densely trafficked it does not justify the high initial investment. This makes biodiesel the most viable alternative to diesel. It is beneficial to both the environment and the economy. It is recommended in this thesis, through the analysis of different chapters, that biodiesel, preferably produced from palm stearin, should be used by Indian Railways in the highest blend possible. The Indian government needs to set clear and robust policies if biodiesel is to be a success on the rail network.

7.7 LIMITATIONS TO THIS WORK

7.7.1 Data

This work has its limitations which are primarily related to the data used. Nearly all data in the public domain for India provides overall summaries. As such, there is a lack of raw data available that could be used in the model. This issue was more concerning for diesel modelling, so data from the GREET database had to be used. In some cases, data from other countries, which was modified where possible, was used to compensate for the lack of data from India which is in the public domain. Other studies and documents have also recognised the difficulty in obtaining data from India e.g. subsidies for the use and production of fossil fuels.

Other limits to the data were the lack of literature about palm stearin directly. There is more data relating to palm oil; therefore, more data is used from palm oil rather than palm stearin. Were data only relating to palm stearin used then results may differ slightly because of the different physical and chemical properties of palm stearin to palm oil.

The sensitivity analysis highlighted that the model is sensitive to the price of palm stearin as a feedstock, a higher shadow price (for jatropha based biodiesel) and the construction costs of biodiesel production facilities. These variables need special attention when modelling the use of biodiesel in the rail sector.

7.7.2 Comparison to other studies

Several studies examine the environmental perspective of using diesel and its alternatives; these give a comparison to the results which have been found in this thesis. However, it is difficult to compare directly with such studies, especially LCAs, because of the system boundaries and aim of the LCAs. There is also the element of the author's interpretation of the model. The task of comparing to other studies for the financial and economic section proved even more difficult, due to the lack of literature. For the available literature, it is a similar situation to that of the environmental section; there are unknown parameters and the author's interpretation is required, hence making it difficult to understand all the parameters and assumptions made.

7.8 FURTHER WORK

There are several ways in which this thesis could be developed further:

1) More feedstocks can be included in the modelling, such as used cooking oil and animal fat. These feedstocks meet the Indian government's requirement of not using edible seeds. Further to this, the cultivation of growing feedstock takes up land and materials, so by using waste material this stage of the supply chain is eliminated. Indian Railways has already explored the use of used fish oil, but primarily from an engine and environmental

perspective. More work could be carried out in this area to analyse the financial and economic costs.

2) Further exploration into the costs of using biodiesel could be developed, such as the extra cost of the facilities needed to expand the use of biodiesel across the network at various blend levels.
3) Finally, this model has had a primary focus on passenger trains. The model could further be expanded to explore the use of alternatives for freight on the railways. In recent years there has been a shift of freight from rail to road. However, there is a push to shift it back to rail. For Indian Railways to maximise GHG and pollutant savings the rail network needs to be as green as possible.

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9 Appendices

APPENDIX 1: INPUTS TO THE LCA FOR BIODIESEL PRODUCED FROM PALM STEARIN; CULTIVATION

Table 8-1 Inputs to the LCA for biodiesel produced from palm stearin; cultivation

	Pleanjai et al. (2007)	Silalertruksa et al. (2012)	Pleanjai and Gheewala (2009)	Papong et al. (2010)	De Souza et al. (2010)	
	1 tonne of oil	1 tonne biodiesel	1 tonne biodiesel	1 tonne biodiesel *	1 ha of palm trees/4 tonnes of biodiesel	**Total:**
Unit	kg	kg	kg	kg	Application and yield kg/ha yr	
Input						
FFB	5755			4170		
Electricity (kWh)	80	65.888	34.78	80		
Steam (m3)	2.1					
Water (m^3)	3.33					
Diesel (l)	5.01	5.112	54.41	0.00296	74.4	18.6
Output						
Wastewater (m^3)	2.95					
Fibre	1740	787.248			2747	686.75
Shell	350	337.392	457.58	242.1	1221	305.25
Decanter cake	180					
EFB	3300	1349.568		1080		
Ash	40	270.368				

CPO	Need 1.14 tonnes				4172	
Kernel		337.392	374.38			

Lam et al. (2009a)	Kittithammavong et al. (2014)			Silalertruksa et al. (2012)		**Average**
per tonne of FFB	1 litre biodiesel		**Total**	1000l	**Total**	
	kg/l		Density 0.8746		Density 0.8746	
				4014	4589.526641	4838.175547
20	0.17073	170.73	195.2092385	58	66.31603019	77.45618124
						2.1
	0.01881	18.81	21.50697462			3.33
0.56	0.0088	8.8	10.06174251	4.5	5.145209239	12.36273897
						2.95
				693		1986.999333
				297		582.6644
						180

				1188		1909.856
						155.184
				832		
						711.772

APPENDIX 2: INPUTS TO THE LCA FOR BIODIESEL PRODUCED FROM PALM STEARIN; OIL EXTRACTION

Table 8-2: Inputs to the LCA for biodiesel produced from palm stearin; oil extraction

	Pleanjai et al. (2007)	Silalertruksa et al. (2012)	Pleanjai and Gheewala (2009)	Papong et al. (2010)	De Souza et al. (2010)	
	1 tonne of oil	1 tonne biodiesel	1 tonne biodiesel	1 tonne biodiesel	1 ha of palm trees/4 tonnes of biodiesel	**Total:**
Unit	kg	kg	kg	kg	Application and yield kg/ha yr	
<u>Input</u>						
FFB	5755			4170		
Electricity (kWh)	80	65.888	34.78	80		
Steam (m3)	2.1					
Water (m^3)	3.33					
Diesel (l)	5.01	5.112	54.41	0.00296	74.4	18.6
<u>Output</u>						
Wastewater (m^3)	2.95					
Fibre	1740	787.248			2747	686.75
Shell	350	337.392	457.58	242.1	1221	305.25
Decanter cake	180					
EFB	3300	1349.568		1080		
Ash	40	270.368				
CPO	Need 1.14 tonnes				4172	
Kernel		337.392	374.38			

Lam et al. (2009a)	Kittithammavong et al. (2014)			Silalertruksa and Gheewala (2012)		**Average**
per tonne of FFB	1 litre biodiesel		**Total**	1000l	**Total**	
	kg/l		Density 0.8746		Density 0.8746	
				4014	4589.526641	4838.175547
20	0.17073	170.73	195.2092385	58	66.31603019	77.45618124
						2.1
	0.01881	18.81	21.50697462			3.33
0.56	0.0088	8.8	10.06174251	4.5	5.145209239	12.36273897
						2.95
				693		1986.999333
				297		582.6644
						180
				1188		1909.856
						155.184
				832		
						711.772

APPENDIX 3: INPUTS TO THE LCA FOR BIODIESEL PRODUCED FROM PALM STEARIN; TRANSESTERIFICATION

Table 8-3: Inputs to the LCA for biodiesel produced from palm stearin; transesterification

	Pleanjai et al. (2007)	Silalertruksa et al. (2012)	Pleanjai and Gheewala (2009)	Papong et al. (2010)		De Souza et al. (2010)	
	1 tonne of biodiesel	1 tonne biodiesel	1 tonne biodiesel	1 kg of biodiesel		1 ha of palm trees/4 tonnes of biodiesel	**Total:**
Unit	kg	kg	kg	kg		Application and yield kg/ha yr	
Input							
Palm oil (CPO)	1140						
Methanol (kg)	150	212.432	180	0.18	180	396	99
Sodium hydroxide (kg)	8	9.088	10	0.00586	5.86	24	6
Electricity (kWh)	256.5	97.696	297	0.0005	0.5		
Steam (MJ)							
Circulated water (m^3)	0.2	211.296					
Output							
Glycerine	320	229	180	210			
Oil cake							
Emissions		120.416 kg CO2 eq					
Final product	1000	1000	1000	1000			

Lam et al. (2009a)	Rotwiroon et al. (2012)		Kittithammavong et al. (2014)			Silalertruksa and Gheewala (2012)		**Average**
per tonne of biodiesel	1 kg of biodiesel		1 litre biodiesel		**Total**	1000l	**Total**	
	kg		kg/l		Density 0.8746		Density 0.8746	
	1.22	1200						1170
			0.18659	186.59	213.3432426	187	213.81	178.3696101
			0.00589	5.89	6.734507203	8	9.15	7.832792264
256.5	0.4	110	0.00685	6.85	7.832151841	86	98.33	186.0044442
1360	0.293 (kg)							1360
	0.393 (kg)					1.86	2.13	1.163343243
								243

APPENDIX 4: INPUTS TO THE LCA FOR BIODIESEL PRODUCED FROM JATROPHA; CULTIVATION

Table 8-4: Inputs to the LCA for biodiesel produced from jatropha; cultivation

	Kumar et al. (2012b)	Ajayebi et al. (2013)				Reinhardt et al. (2007)			
	1 tonne of jatropha biodiesel	1 kg of biodiesel jatropha			1 tonne biodiesel	kg/ha*yr			
	Irrigated	Base Case	Best Case	Worst Case	Average/Total	Today	Optimised	Best	Average
Input									
N fertiliser	100 kg/ha					48 kg	81	141	141
P fertiliser	144 kg/ha	155.5	129.6	194.4	159.8	19	31	56	56
K fertiliser	100 kg/ha					53	89	139	139
Urea g		155.5	129.6	194.4	159.8				
Water		24.7	20.6	30.9	25400.0				
Diesel used	105 kg/ha	16.5	13.7	20.6	16.9				
Electricity production and use									
Output									
Seeds	533 kg CO2/ton biodiesel	3296.7	3296.7	3296.7	3296.7	1418 kg/ha*yr	2382	4436	4436
Fruit						2270 kg/ha*yr	3811	6572	6572
Oil						402 kg/ha*yr	676	1381	1381
GHG									

Whitaker and Heath (2010)			Eshton et al. (2013)			Hou et al. (2011)		
jatropha		Total	1 tonne biodiesel		Total:	1 MJ		Average
Base Case Value	Unit		Unit	Value		Unit	Jatropha	
			kg ha y	81	81	kg	19.4	107.3333
31	kg/ha-yr	31	kg ha y	31	31	kg	5.4	84.36667
89	kg/ha-yr	89	kg ha y	89	89	kg	3.6	92.66667
								159.8
6	litres per tree							25400.0
86	litres/ha-yr	86	km L	75.93		kg	3.33	50.29833
						kWh	1.69	
1.5	kg sundried seeds/tree-yr							3866.35
			t ha	34				
0.35	mass oil/mass total seed		kg seeds	0.33				
0.01	g N2)/g	fertiliser				kg	22.6626	

APPENDIX 5: INPUTS TO THE LCA FOR BIODIESEL PRODUCED FROM JATROPHA; OIL EXTRACTION

Table 8-5: Inputs to the LCA for biodiesel produced from jatropha; oil extraction

	Kumar et al. (2012b)			Ajayebi et al. (2013)			
	1 tonne of biodiesel		Total	1 kg of biodiesel			
				Base Case	Best Case	Worst Case	Average/Total
Input							
Seeds (tonnes)	3.86635			3296.7g	3296.7	3296.7	3.2967
Hexane	4 kg/ton seed	15.4654	15.4654	13.1g	13.1	13.1	13.1
Steam	280 kg/ton seed	1082.578	1082.578				
Heat				2.97 MJ	2.97	2.97	2.97
Electricity	55 KWH/ton seed	212.64925	212.64925	0.18 kWh	0.18	0.18	180
Water (m^3)	12,000 kg/ton seed	46396.2	46.4	39.6 kg	39.6	39.6	39
Extraction							
Output							
CO2	330 kg CO2/ton biodiesel						
Jatropha oil				1050 g	1050	1050	
Seed cake							
Fertiliser from seed cake				54.8 g	39.1	91.4	

Eshton et al. (2013)	Hou et al. (2011)		

						Average
Unit	Value	Total	Unit	Jatropha		
3.86635			tons	3.33		3.581525
						14.2827
			GJ	3.07		1082.578
						2.97
kWh kg seeds	0.075	290	kWh	231.97		227.5418
						42.7
kg seeds	0.33	1276	tons	1		1162.948
kg seeds	0.67	2590	tons	2.33		2590.455
			kg	5.73		
			kg	2.84		

APPENDIX 6: INPUTS TO THE LCA FOR BIODIESEL PRODUCED FROM JATROPHA; TRANSESTERIFICATION

Table 8-6: Inputs to the LCA for biodiesel produced from jatropha; transesterification

	Kumar et al. (2012b)		Ajayebi et al. (2013)				
	1 tonne of biodiesel	Total	1 kg of biodiesel				1 tonne biodiesel
			Base Case	Best Case	Worst Case	Average	Total
Input							
Jatropha oil			1050 g	1051 g	1052 g	1051	1051
Methanol	117 kg/ton biodiesel	117	124.9 g	124.9	124.96	124.9	124.9
Sodium hydroxide	12.8 kg/ton biodiesel	12.8	10.5 g	10.5	10.5	105	105
Sulphuric acid			15.8 g	15.8	15.8	15.8	15.8
Electricity	130 MJ/ton biodiesel	36.11	0.041 kWh	0.041	0.041	0.041	41
Steam	660 kg/ton biodiesel	660					
Circulated water	55 M3	55	0.14 kg	0.14	0.14	0.0041	41
Output							
Glycerine	0.125 kg/kg biodiesel	113.398125	113.3 g	113.3	113.3	113.3	102.7840605
Oil cake	1050 kg/ton biodiesel	1050					
Final product			1000g	1000	1000		
Price							
Biodiesel	39.77 Rs/kg						
Crude Glycerine	12 Rs/kg						
Cake	1.68 Rs/kg						
Fruit hulls	0.83 Rs/kg						
Seed shells	1.45 Rs/kg						

Prune material	1.22 Rs/kg						

Hou et al. (2011)			**Average**
1 ton biodiesel			
Unit	Jatropha	Total	
kg	1018	1018	1034.5
kg	96	96	112.6333333
			58.9
			15.8
kWh	40	40	39.03666667
			660
			48
kg	93.35	93.35	103.1773952
			1050
tons	1		

APPENDIX 7: MONETARY COSTS FOR PRODUCING BIODIESEL FROM PALM STEARIN

Table 8-7: Monetary costs for producing biodiesel from palm stearin

Input	Cost	Unit	Notes/Calculations	Reference
Palm stearin	37,181.05	Rs/tonne	$679.23/tonne importing (2016) $710.14/tonne (Adjusted to 2018 prices) Rs 12,874.86/tonne (adjusted via PPP exchange rate) Taxes then included: Countervailing tax- 12.5% Special countervailing tax- 4% Customs Cess- 3% Total: 19.5% tax	Seair (2018), Exim Guru (2019)

			Absent of taxes- (Rs 2,510.60) 10,364.26 No price increases of palm stearin because as literature states it is difficult to forecast, so included in a sensitivity analysis	Abdullah and Wahid (2010)
Water	131.98	Rs/m3	60 Rs/litre 97.76 (Adjusted for 2018 inflation) 35% sewage charge 131.976 Rs/m3 Very little information on the forecast of water prices in India specifically, but very low prices	Hyderabad Metropolitan Water Supply and Sewage Board (2011) Geography Notes (no date)

Methanol	17,092.82	Rs/tonne	Rs 21,095.19/tonne importing (2016 and including duty) Rs 23,638.83/tonnes (adjusted to 2018 prices) (Rs 4,609.57185) Rs 19,029.26/tonne shows the increase in methanol from 2020 to 2035 so can use this % to show the increase in this model- roughly 0.04 per year (compound)	Infodriveindia (2019) Maus (2019)
Sodium hydroxide	60-100	Rs/kg	Average is taken, lots of different companies	Indiamart (2019)
Glycerine	12	Rs/kg	2010 price 21.4 (adjusted to 2018 prices)	Kumar et al. (2012b)

Maintenance	10,744,817.92	Rs/year	Total: 215,598,000 Rs 35 tonnes per day produced (12,775 tonnes per year) 16,879.56 Rs/tonne/year 16.88 Rs/kg/year 14.76 Rs/litre/year 10,744,817.92 Rs/year (based on amount needed for) Maintenance cost considered as constant through the lifetime of a project	Southern Online Bio Technologies Ltd. (2018) Ong et al. (2012)
Transport to end use	0.73	Tonne/km	2014 price 2018 price 0.73 Tonne/km	Planning Commision (2014) de Bok (2017)

			Like transport by rail The cost of this depends on future energy prices Electric traction: continue using coal as the dominant the prices go up, but switching to renewables then likely to decreases Highly uncertain, but this presents some possible scenarios	
Maintenance of locomotives	15.28	Rs/km	Maintenance has remained reasonably stable Evidence on rolling stock life trends is limited	Indian Railways (2015) Arup (2009)

APPENDIX 8: MONETARY COSTS FOR PRODUCING DIESEL

Table 8-8: Monetary costs for producing diesel

Input	Cost	Unit	Notes/Calculations	Reference
Crude oil	33.43	Rs/kg	4679.909 Rs/barrel (2018 average) 140 kg/barrel 33.43 Rs/kg	Indexmundi (2019a)
Electricity	5.65	Rs/kWh	Forecasting pricing of electricity has received less attention than other areas As mentioned earlier it depends on the	Telangana State Electricity Regulatory Commission (2018) Varma and Sushil (2019) Gulagi et al. (2017)

			direction India goes in relating to coal. An increase in renewables could lead to a decrease in coal.	
Natural gas	216.37	Rs/mmbtu	0.027% increase over the past 20 years annually, this will continue for the lifetime of the project	Indexmundi (2019b)
Transport to end use	0.64	Tonne/km	0.76588	Planning Commision (2014)

APPENDIX 9: MONETARY COSTS FOR PRODUCING BIODIESEL FROM JATROPHA

Table 8-9: Monetary costs for producing biodiesel from jatropha

Input	Cost	Unit	Notes/Calculations	Reference
Cultivation	784090.5-167059.39	Rs/year	Cultivation costs vary year on year depending on the stage of the crop ie at the beginning the costs are higher because of the initial work needed to cultivate the plants such as ploughing and sowing	Goswami et al. (2011), Ariza-Montobbio and Lele, (2010), Punia, (2007), Saturnino et al., (2005)

Transport to biodiesel facilities	0.61	Tonne/km		Planning Commision (2014)
Diesel	45.47	Rs/litre	Likely that this will increase over time, but the amount needed is small so would not likely make a difference 2018 price Rs 45.47 Rs/litre	Railway Board (2014)
Oil cake	2.44	Rs/kg	2018 price Rs 2.44 Rs/kg	Kumar et al. (2012b)

APPENDIX 10: MONETARY COSTS FOR PRODUCING BIODIESEL FROM ELECTRIC TRACTION

Table 8-10: Monetary costs for producing biodiesel from electric traction

Input	Cost	Unit	Notes/Calculations	Reference
Infrastructure costs	35000000	Rs	ADB lending India USD 750 million 3,378 km of work to be completed USD 222,024.87/km 15,721,581.04 Rs/km This price is set and would not likely increase.	Railway Pro (2019)
Locomotive cost	265,537,500	Rs	USD 3 billion 800 electric locomotives to be manufactured This is a one off cost for this project Work out the cost for one and then adjust for inflation	NDTV (2015)

Transport costs (coal)	0.8	Rs/tkm	0.64 Rs/tkm adjusted for inflation	Planning Commision (2014)
Maintenance	850,127	Rs	799,595 Rs/yr Must adjust for inflation	Nalbandian-Sugden (2016)
Maintenance of locomotives	6.2	Rs/km	5.42 Rs/km must adjust for inflation	Indian Railways (2015)

APPENDIX 11: PURCHASING POWER PARITY (PPP) EXCHANGE RATES COMPARED TO USD

Table 8-11: Purchasing Power Parity exchange rates compared to USD

	GBR	INR	EU28
1990	0.64405	5.75955	
1991	0.662861	6.340546	
1992	0.669795	6.755002	
1993	0.671932	7.248701	
1994	0.666834	7.806002	
1995	0.714011	8.339502	0.842177
1996	0.713773	8.810382	0.852617
1997	0.708746	9.223113	0.863279
1998	0.720725	9.854948	0.864507

1999	0.725819	10.00424	0.872337
2000	0.704514	10.138195	0.876249
2001	0.694392	10.231045	0.868116
2002	0.689877	10.450766	0.858914
2003	0.69665	10.642758	0.848337
2004	0.688467	10.950977	0.846226
2005	0.707619	11.05912	0.849901
2006	0.697211	11.418592	0.827809
2007	0.709924	11.762826	0.824273
2008	0.701691	12.536125	0.790276
2009	0.709928	13.196079	0.760596
2010	0.702299	14.20806	0.765287
2011	0.706052	15.109435	0.754435

2012	0.701634	16.013302	0.755761
2013	0.695248	16.733715	0.734622
2014	0.698444	16.986392	0.73713
2015	0.692365	17.152326	0.751375
2016	0.698632	17.522908	0.72752
2017	0.691089	17.72917	0.706071
2018	0.700184	18.127587	0.708252

Source: OECD, 2019

APPENDIX 12: INFLATION RATE SOURCES

Inflation rates from the following sources:

For the USA: US Inflation Calculator, 2019

For Europe: European Central Bank, 2019

For India: Macrotrends, 2019