LOCATION PLANNING TOOL FOR BIOMASS BOILERS

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DECLARATION

This report contains no material which has been accepted for the award of any other degree or diploma in any University or equivalent institution in Sri Lanka or abroad, and that to the best of my knowledge and belief, contains no material previously published or written by any other person, except where due reference is made in the text of this report.

I carried out the work described in this report under the supervision of Dr. Himan Punchihewa.

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Abstract

Steam boilers constitute an important part of a production facility. Though traditionally, fossil fuel has been used predominantly in steam boilers, the environmental impacts of using fossil fuel and the higher economics have fuelled exploration on alternative fuels such as biomass and in 2016 demand for biomass energy in Sri Lanka has been 194.3 PJ out of which 75.8 PJ has been industry demand which is an increase of 300 TJ compared to previous year.

In light of above, this study has been carried out with the aim of mitigating the environmental impacts of using biomass as a fuel for boilers in Sri Lanka and to improve related economics by developing a location planning tool for biomass boilers & with the objectives of assessing factors that would govern the environmental and financial costs associated with the operation of a steam boiler with respect to heavy oil and biomass variants leading to proposing of a framework to rank the fuel variants based on environmental performance and finances.

Methodology followed in this study was carrying out a life cycle assessment (LCA) to assess the environmental loads of each biomass variant in context via data collected in surveys and analysing reports of 60 steam boilers followed by comprehensive financial analysis and sensitivity analysis enabling comparison of relative contribution of each step in the process.

It was identified due to extremely adverse impact of using fossil fuel, using biomass where sustainable has become the best alternative regardless the location of the boiler and subsequent distance from biomass source to the application, in Sri Lankan Context, consequently the threshold points for switching to biomass lie in the economic factors as cost of transportation dominates whether the process is feasible. Sawdust was identified as the most environmentally friendly fuel followed by wood chips, wood logs and husk respectively. Distances from wood log, husk, wood chip, and sawdust biomass sources to the point of application to equal the financial cost of heavy oil-based boiler operation were identified as 530 km, 554 km, 595.5 km and 604 km respectively. It was identified, ranking order of financial performance of fuels, toggle along with distance from respective biomass source to point of application, such that a fuel more feasible compared to another at similar relatively lower distance from fuel source to point of application would not necessarily be so at higher similar distances. Though husk usage is costlier than sawdust at relatively smaller distances, at similar distances over 140 km from respective fuel source to point of application, sawdust becomes the more viable fuel. Similarly, chips usage though expensive at relatively lower similar distances equivalent to other biomass variants, becomes more viable compared to husk and wood logs at similar distances over 460 km and 355 km respectively.

Precise data on biomass sources in Sri Lanka are lacking and taking measures to develop a biomass resources map would contribute to location planning process of biomass boilers favourably and streamline supply chain process.

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List of Abbreviations

CEB	Ceylon Electricity Board
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
GHG	Greenhouse gas
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
N_2O	Nitrous oxide
NMVOC	Non-methane volatile organic compounds
UK	United Kingdom
USA	United Stated of America
kWh	kilowatt hour
GWh	Gigawatt hour
kt	kilo tonne
MT	Metric tonne
kCal	kilo Calorie
ha	Hectare
LKR	Sri Lanka rupee
Ltr	Litre
MJ	Megajoule
TJ	Terajoule
PJ	Petajoule
PM	Particulate matter

1 Introduction.

Higher environmental and financial costs of fossil fuel have motivated mankind to look into alternative fuels that would mitigate impact to the environment and bottom line consequently using biomass which has long been used as a source of heat energy has begun anew in industrial scale.

Many manufacturing facilities in Sri Lanka are looking to switch to biomass fuel to run steam boilers which are highly energy consuming applications. Demand for biomass primary energy in 2016 has been 194.3 PJ out of which 75.8 PJ has been industry demand in Sri Lanka [1]. The fact that it’s an increase of 300 TJ compared to previous year, suggests that biomass usage continues to rise consequently the need to assess environmental impacts compared to fossil fuel usage is immense and selecting a suitable biomass fuel is of great significance when minimising environmental and financial costs [1]. In this study, factors affecting environmental and financial costs related to operation of boilers have been explored and enlisted in detail in order to rank the alternative fuels studied.

1.1. Introduction to the study

There are many kinds of steam boilers in use today. Fossil fuel fired boilers are the most common which include heavy oil-fired boilers, light oil-fired boilers, natural gas fired boilers etc. Using fossil fuel leaves a mark on earth due to the amount of carbon that are being added to the environment that would take millions of years to trap back.

Nuclear steam generators too exist today. While they produce clean energy, it cannot be ignored that their waste may leave an adverse effect if extreme attention is not paid. Also, no matter how rare it maybe, any simple accident would prove to be extremely catastrophic as shown time and time again in the history from Chernobyl to Fukushima.

Steam generation using biomass, is rapidly gaining popularity in Sri Lanka. As per available recorded data in 2016, Sri Lankan industries have purchased 121,226 m^3 of fuel wood which is an increase of 46% compared to previous year though actual value is possible to be higher due to informal nature of biomass supply chains which is largely carried out by the user’s own lines. 500-700 tonnes of wood chips are consumed daily at export processing zones in Sri Lanka [1]. Biomass has been the most widely used renewable energy source in the global arena as well and one of the oldest along with solar [2].

It can be argued to be a carbon neutral cycle within its limitations. The reason behind this is, once the tree or the concerned bio life is dead it would emit the same amount of carbon to the environment whether it’s subjected to natural decay or burned in a biomass boiler or a stove enabling us to obtain the useful energy output. Also, it must be said the amount of carbon that is emitted to the environment in this process is almost the same amount of carbon absorbed by the said lifeform throughout his life via photosynthesis and net carbon flux from atmosphere to earth's biosphere happens to be one of the most significant natural mechanisms [3]. Therefore, this process is carbon neutral specially if adequate plants are grown that would eventually recapture the CO_2 emitted, however it must be specially noted this is only most accurate where lifeform has died naturally. If the life of said lifeform is ended pre-maturely just to feed to the boiler, while via the same train of reasoning it could be argued that the process is still carbon- neutral, the process as a whole would raise issues in sustainability.

Also, while combustion itself maybe biogenic other processes that involve processing of fuel consume resources and emit emissions and other adverse outputs and to ascertain the total impact of each generation process, a comprehensive life cycle assessment is called for and for this purpose, a life cycle inventory needs to be prepared which is to be categorized according to impact categories

Resource consumption activities in biomass steam boilers are as follows once the biomass is stored at the respective mills.

- Transportation
- Drying process (renewable solar energy is used in Sri Lanka)
- Chipping process (applicable for wood chips)
- Transportation to the final destination – the factory where fuel would be fed to the boiler.
- Combustion of fuel where electricity is required to operate the plant

The output emissions and the input resources vary as per the steam generation process thus it’s required to go through steps of life cycle process of each method to determine the total environment impact of respective method in order to plan the location for a biomass boiler and to determine the most suitable biomass fuel for a particular location and to determine the locations where biomass boilers might not be feasible.

Life cycle assessment is immensely useful to estimate the environmental impact due to the life cycle of a product or process and such environmental impacts can be categorized as climate change, stratospheric ozone depletion, tropospheric ozone creation, eutrophication, acidification, toxicological stress on human health and ecosystems, depletion of resource and many more which incur due to the consumption of resources and emission of the process in context.

Life cycle assessment and cost analysis of steam generation methods via five fuels used in Sri Lanka have been carried out with the goal being to support decision making when selecting a location for a biomass boiler and to determine the most optimum biomass fuel considering the total life cycle cost and related economics. This would help identify opportunities to mitigate pollution control and reduce resource consumption consequently improving overall environmental performance of the process.

1.2. Aims & objectives of the study

The Aim of this study was to propose a location planning tool for biomass boilers based on environmental impacts and associated finances.

Objectives of this study were to:

- determine the factors affecting the environmental and financial costs of operation of a steam boiler in Sri Lankan context,
- analyse the effect of said factors, & to
- rank the alternative fuels based on environmental and financial costs.

1.3. Methodology

a. A literature review was conducted on environmental impacts caused by five different fuels including heavy oil and four biomass variants & detailed study was carried out by referring text books, research papers, journal papers, about theories involving estimation of impact categories of biomass fired steam boilers.

b. An appropriate means of investigation into the above problem was conducted with frequent visits to steam boilers in use and collecting data in regards of environmental and financial factors. Regarding latter data on prices of biomass variants, transportation, labour requirement, electricity consumption etc. were recorded. Emission reports of 60 biomass steam boilers were analysed to estimate environmental impacts. Based on the collected data and reports, life cycle analysis and financial costs were determined.

c. A sensitivity analysis was carried out to determine the effect of variance of transportation distance from respective fuel sources to application, on factors that govern optimum location & biomass variant for the said location and ranking of studied fuels was done based on obtained results.

1.4. Dissertation structure

The dissertation is consisted of six chapters and an abstract has been included portraying a summary of the study. Chapter 01 accounts for the background of the study and illustrates aim, objectives of the study and provides as insight into the study. Chapter 02 is consisted of the literature survey which accounts for the available information on the areas related to the study. Chapter 03 discusses the methodology employed in the study including data collection, life cycle assessment methodology, financial assessment & sensitivity analysis. Chapter 04 includes the results and findings of the study. The results include the factors that affect the environmental impacts, financial impacts and ranking of alternative fuels is provided. A discussion on the obtained results is included in chapter 05. Chapter 06 accounts for the final conclusions on the study along with insights for further work.

2 Literature Review

2.1. Environmental effects of steam generation via fossil fuel combustion

When assessing the environmental and financial costs of heavy oil-fired boilers and biomass fired boilers, it’s imperative to study the major steps involved in biomass residue fired boiler operation namely transportation, drying, chipping process where applicable, combustion of fuel and consumption of electricity from grid to run the plants in context.

Emission of greenhouse gasses predominantly CO_2 is one of the most critical concerns of using fossil fuel. Nature has taken billions of years to trap excess CO_2 from environment via photosynthesis and inside fossil format [4]. As former is part of the natural carbon cycle in the ecosystem, burning biomass is considered carbon neutral while burning fossil is not, due to carbon trapped inside fossil fuel being constituted of carbon that has been taken away from the carbon cycle.

Combustion of fossil fuel leads to transfer of carbon from the permanent storage in the earth’s crust into the atmosphere as greenhouse gases (GHG’s) which is not balanced by any countervailing withdrawal of carbon from the atmosphere. Burning heavy oil distillates from crude oil emits CO_2 adding fresh CO_2 to the environment hence making room for huge adverse environmental impacts that would demand millions of years to trap back.

World has witnessed an increase of 0.77 ^{0}C increase of global temperature over the last century and estimated to reach up to 5.8 ^{0}C by 2100 should the current run of using fossil fuel remains as usual as per the 4th Assessment Report on Climate Change [5]. A point to note is as of 2007, 11 out of the 12 years with the highest temperatures have been recorded from 1995 onwards and steadily on the rise. Sea level which already has risen 3.1 mm is estimated to rise 0.8 m by 2100 thus it’s high time to change our policies on reducing fossil fuel usage.

CO_2, CH_4 and Nitrous oxide are the primary GHGs of concern. By 2007, 5400 million tonnes (Mt) of CO_2 equivalents were being emitted annually from various sources linked to human activities while Sri Lanka alone emitted 12,400 Gg CO_2 which is only 0.04% of the global emission of 29,300 Mt CO_2 with respect to fossil fuel combustion.

Thus, per capita CO_2 emission related to Sri Lanka is merely 648 kg in 2007 which is quite less than that of the global average but by no means this should stop concerned personnel from planning ahead to mitigate CO_2 emissions [5].

Though Sri Lanka has had a long run solely by hydro power, as of 2016 Sri Lanka has generated 66.9% of total generated electricity via thermal power plants accounting 9630 GWH [1]. Even on the world scale Globally, coal combustion alone contributed to whopping

46% of entire CO_2 emissions from fossil fuel out of which 31% has been solely by coal fired power plants [6].

2.2. Environmental effects of steam generation via biomass combustion

15% of the world's total primary energy consumption and 38% of primary energy consumption of developing countries is via biomass [7]. When considering the rural sector of developing countries, this is even higher accounting for more than 90% of total rural energy supply [7].

Using biomass to generate energy, substituting for fossil fuel, leads to replacement of CO_2 emission to be added afresh to the system, by the CO_2 emissions that are already part of the closed loop carbon cycle [8]. This is called as Alternate Fate of Resource which in this case happens to be fossil being left alone as it is unextracted from underground reserves, therefore having no emissions impact [9].

While using biomass residue is environmentally friendly, there are valid counter arguments worthy of notation. Though biomass is generally considered as waste materials left by tree branches or left outs from commercial timber industry such as sawdust, chips etc. and are considered to decay over course of time thus the notation of environmental friendliness, this largely ignores the time factor. While natural decaying process takes years, combustion would emit the carbon fairly quickly hence emitting considerable CO_2 to the environment raising CO_2 concentrations [10]. Due to this time factor which could well be years or decades of difference between combustion and natural decomposition, it's argued by some critics that neutrality of carbon in this context prevails only if time factor is ignored [10].

However, it must be mentioned that storing wood waste without burring too would lead to adverse impacts such as water contamination being dumped into rivers etc. It was observed in the Sri Lankan context unsold sawdust, which has now become very rare and takes place only when quantities available being smaller thus not being economical to transport, are still burned or dumped into water sources which in the first scenario would emit similar amount of CO_2 as in combustion in a boiler and of course would make room for water pollution in the second scenario. Further natural decomposition emits methane which too is very adverse.

Considering above factors, this study has included CO_2 emissions of the biomass burning though biogenic for the purpose of comparison with heavy oil emissions and comparison among biomass variants, themselves.

Though complete combustion of biomass would only produce CO_2 and H_2O, incomplete combustion would lead to adverse GHG emissions of CO, N_20, CH_4, PAH, PM etc. Further transportation, fuel preparation would consume resources and make way for emissions which too have to be taken into consideration [11], [12].

2.3. Existing LCA studies and supply chain model on biomass fired steam boilers

Biomass boilers when operated properly, provide many benefits including environmental, economic and social benefits by expanding local labour market etc. and introduction to biomass can be carried out on large and small scale as a fuel mix with respect to existing boilers or via new boiler installations that run solely on biomass [13].

D. Vlachos1, E. Iakovou1, A. Karagiannidis, A. Toka1 had used five general system components when analysing biomass supply chain for energy production thus:

- biomass collection (from single or several locations),
- pre-treatment (in one or more stages),
- storage (in one or more intermediate locations),
- transportation
- energy conversion [14]

Defining a functional unit is of significance: Maureen E. Puettmann and Michael Milota in "Life-cycle assessment for wood-fired boilers" have had selected the process of combusting 1 kg of wood residue in a boiler as the functional unit where the biomass has been fully dried. A biomass input had been selected opposed to an energy output such as generation of one kg steam to enable usage of a generic boiler that could be of any efficiency [15]. System boundary has been taken thus:

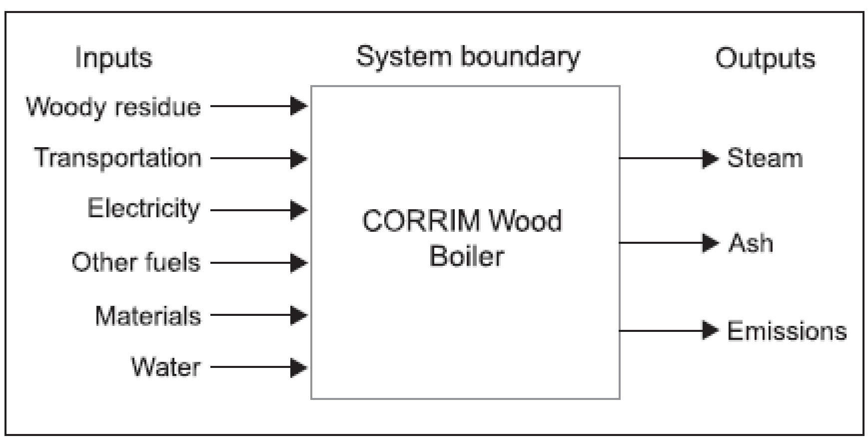


Figure 2.1: System boundary of a biomass boiler

Higher heating value of dry wood fuel has been taken as 20.92 MJ/kg wood and leaving room for evaporation of water in fuel combustion equivalent to 2.4 MJ/kg of wood, 18.52 MJ/kg had been estimated as net energy available. In the study, 5.1 kg steam was taken as produced from 2 kg wood fuel with 50% moisture, taking energy of steam as 2.2 MJ/kg and boiler efficiency being 61% with respect to HHV and 76% with respect to lower heating value [15].

In the LCA study carried out by C. Perilhona, D. Alkadeea, G. Descombesa, and S. Lacoura, CO_2 emission had been calculated using the equation of combustion and composition by weight of dry wood had been taken as
C = 49.0%; H = 5.5%; O = 45.0%; N = 0.5%. For 45% moisture of wet wood, average LHV had been as 9 000 kJ/kg from which dry wood LHV had been calculated as 9 000 / (1 - 0.45) = 16 364 kJ/kg.
CO_2 emission calculated using above has led to 179,52 g of CO_2 by combustion of 100g of dry wood [16].

Impact categories have been selected according to following diagram [16].

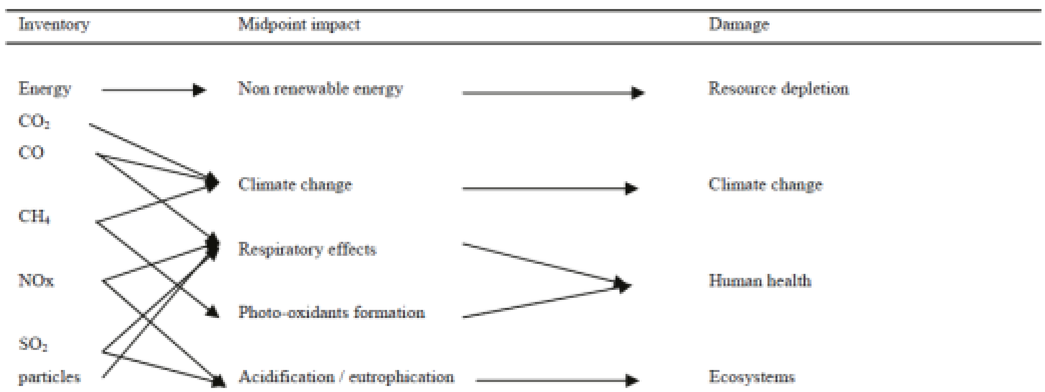


Figure 2.2: Characterisation of impacts

Rather simple impact indicators too have been employed in certain studies. Goglio and Owens' study on small scale electricity generation via LCA had included simple indicators such as, energy output input ratio and CO_2 emissions.
A sensitivity analysis had been concluded to determine factors of high importance [17]. If transportation is relatively small overall impact due to transportation is possible to be neglected as per their study [17].

Tomasz Nitkiewicz and Agnieszka Ociepa Kubicka in "Impact of supply chain solutions on environmental performance of biomass use – LCA-based research case" have used LCA ReCiPe endpoint method with reference to Europe to assess the environmental impacts. Functional unit for LCA study has been defined as life cycle of biomass used to produce 41850 MWh [18]. A sensitivity analyses has been carried out to check variance along with transportation distance [18].

2.4. Biomass fired steam generation in Sri Lanka

Demand for biomass primary energy in industrial sector has been 75.8 PJ in Sri Lanka in 2016 [1]. Cost of biomass operation is relatively less than that of heavy oil-fired systems hence former is gaining popularity in Sri Lanka.

When assessing the environmental and financial costs of heavy oil-fired boilers and biomass fired boilers it's imperative to study the major steps involved in biomass residue fired boiler operation namely transportation, drying, chipping process where applicable, combustion of fuel and consumption of electricity from grid to run the plants in context.

When considering the supply chain, biomass rice husk and sawdust are collected from the rice mills and mills spread around the island. Rice mills are concentrated in certain areas of the island as discussed in Section 3.1.6.

Rice husk, wood log or sawdust collected at the mills are transported to the factory locations where they are sun dried to reduce moisture level.

When producing wood chips, rubber logs are transported to the chipping plants where they are processed are transported to the point of application. This process consumes more energy due to additional transportation incurred and the electrical consumption for the chipping process. The environmental impacts are also relatively higher as chipping plants are supplied grid electricity.

At the factory location, fuel is fed to the boilers where mostly wood logs are fed manually while husk, sawdust and chips are fed via bucket elevator followed by a screw conveyor. Induced blower, forced draft blower, feed water pumps, bucket elevator, conveyor, consume energy from grid which have to be accounted in the analysis.

The boiler is thermally insulated to reduce heat loss. Larger capacity boilers are consisted with a water wall hence having water tubes as well in addition to the general fire tubes hence being called as combination boilers and offer higher efficiencies.

Depending on the model, make and capacity of boiler, biomass boilers may come with an external furnace or internal furnace. The products of combustion process exchange heat to the water and in most cases are led through multi dust cyclones to capture dust particles prior to being sent through chimney. Most biomass boilers possess air preheaters or economizers that help to recover a portion of energy in flue gas.

2.5. Life cycle assessment to determine environmental impact

Life Cycle Assessment (LCA) is a very useful tool in quantifying environmental impacts and compare environmental performance of various processes and enable decision making process. Society of Environmental Toxicology and Chemistry (SETAC), International

Organization for Standardization (ISO) are some of the organizations that have developed Life Cycle assessment methodologies.

Four major steps have been proposed by Society of Environmental Toxicology and Chemistry with respect to life cycle assessment namely:

- goal and scope definition
- inventory analysis
- impact assessment
- improvement evaluation [19]

Given below are the four major steps proposed by the International Organization for Standardization (ISO)

- goal and scope definition
- life cycle inventory analysis
- life cycle impact assessment
- interpretation of the results [20]

Also, a detailed guide for life cycle assessment with respect to ISO 14040 and 14044:2006 standard is given in the handbook by International Reference Life Cycle Data System (ILCD) and Guinee et al.(2002) too have given guidance on same in Handbook on Life Cycle Asssessment [21].

An important point to highlight is, as per ISO standard on LCA, while above steps including selection of impact categories, classification, characterisation are considered mandatory, normalisation and weighting steps are considered as optional.

To dig deep into these, goal and scope definition includes figuring the goal, scope, the functional unit, data categories, defining system boundaries which carry huge significance owing to its huge impact on final results which would yield rather incomplete results where important impacts would have been missed out if selected too narrowly and would make way to demanding of extreme efforts which would not help the cause considerably if selected too wide thus being a burden to the LCA, data quality requirements [22], [23].

To assess the environmental effect of wood fired boilers Maureen E. Puettmann and Michael Milota, have had used life cycle assessment with the goal of creating an LCI process representing the impacts with respect to USA [15].

Next step in the life cycle assessment is inventory analysis which calls for the total inputs and out puts with respect to each step of the concerned process in terms to the environment. A functional unit is to be defined and correlation of data to the said functional unit is to be determined.

➢ Selection of Impact Categories

Just as the name implies an impact category refers to a class representing environmental issues of concern to which certain life cycle inventory analysis results may be assigned [21].

To comply with ISO 14044, impact categories are to be assessed comprehensively while ensuring applicability to the goal and scope of study being carried out. To support comparative assertions that conform to ISO 14044, a comprehensive set of impact categories must be assessed. Impact groups & impact categories are listed in Table 2.1 as provided by Guinee. They should be screened for their applicability to the product, system, or to the reference baseline. Impact categories have been further categorized into three further groups by Guinée et al. (2002) as:

- baseline impact category
- study specific impact category
- other impact category [21]

As per Guinée, all or part of baseline impact categories are to be included in any LCA study while study specific and other impact categories can be picked as applicable. Selecting impact categories is to be carried out with the environmental relevance to the particular goal and scope of a study in context, on mind. Environmental impacts identified by Guinée et al. under each category have been given in Table 2.1 [21].

Table 2.1: Groups of impact categories

Baseline impact categories	Study-specific impact categories	Other impact categories
Climate change	Impacts of ionizing radiation	Desiccation
Depletion of abiotic resources	Odour- malodourous air	Malodourous water
Human toxicity	Noise	Depletion of biotic resources
Photo-oxidant formation	Waste heat	
Acidification	Casualties	
Eutrophication	Impacts of land use- loss of life support function loss of biodiversity	
Ecotoxicity		
Stratospheric ozone depletion		

- **Characterisation of environmental impacts**

This step involves quantifying categorized emissions in terms of a common unit which would help interpret results subsequently and for the purpose of impact characterisation, characterisation factors are employed. characterisation factors are found in literature. In essence this would help interpretation of results as impact for a given category is given in terms of a common unit for the impact category in context.

- **Normalisation**

As defined in the ISO standard 14044, normalisation is a process to calculate the magnitude of the results of impact category indicators, relative to some reference information. It is an optional process that can be done to complement a LCIA. The characterised results of each impact category are divided by a selected reference value, which brings all the results on the same scale (see equation 1).

$N_i = S_i / R_i$, (1)

where, i is the impact category, N_i is the normalised results, S_i is the characterised impact of the impact category i of the system under study, and R_i is the characterised impact of the impact category i of the reference system [24].

The acute significance in normalisation lies in its ability to have various impacts be compared in terms of impact. Generally speaking, normalisation of certain impact categories such as CO_2, fossil resource extractions are of higher accuracy since these processes are well documented.

Region specific normalisation methods have been developed too which would be applicable only to the said region.

- **Interpretation**

Interpretation is the final step in LCA which enables understanding of results and comparison of various scenarios.

2.5.1. Life cycle assessment software

There are many life cycle analysis software packages in existence today which facilitate mechanisms to model life cycle of many products using databases with generic data. (GaBi, SimaPro) are popular commercial software used for this process.

OpenLCA is another very popular software to model life cycle analysis due to its nature being an open source software. While the software itself is free certain data bases have to be commercially purchased if required, hindering its popularity but the fact that data collected manually being able to be fed to the software makes it an attractive choice.

The software OpenLCA has been used while carrying out this study using CML 2001 as life cycle impact assessment method. This software features documentation, reporting, calculations, normalisation etc. along with simulation which if done manually would consume a lot of time.

3 Methodology

Air emission reports of more than fifty steam boilers were studied to estimate the air emissions of biomass variants along with flue gas analysing at site of 12 steam boilers. Rice husk emissions are available in literature. Emission inventories were determined to estimate the environmental impacts of operating a steam boiler. The study included heavy oil-fired boilers and biomass fired boilers.

The continuous availability and quantity of biomass alternative fuels such as (sawdust, paddy husk, etc.) required to generate 1 tonne of steam was estimated based on results of the survey. Transportation loads, cost of biomass variants at source, cost of transportation, labour requirement and associated costs, electricity consumption to run` plants were figured based on data obtained from the study. Thereby total cost per generation of one tonne of steam from and at 100 ^{0}C was determined.

Major steps to be taken into consideration when figuring the life cycle assessment of steam generation process vary as per the fuel being used. Based on the study, for heavy oil-fired systems the major steps taken into consideration are:

- emissions incurred in transportation
- emissions incurred during combustion
- emissions incurred due to electricity required to run the plant

For sawdust, wood log and husk fired boilers too same steps can be pointed out.

For rubber wood chip fired systems following steps were considered:

- emissions incurred during chipping due to electricity
- emissions incurred in transportation
- emissions incurred during combustion
- emissions incurred due to electricity required to run the plant

The inventory determination for the LCA of steam generation of each fuel has been carried out.

3.1. Data collection

3.1.1. Emission inventory of electricity generation

Electricity is used as an energy source in all types of boilers. Electricity is used to run blowers, feed water pumps, conveyors, fuel feeding systems such as bucket elevators etc.

Further its used extensively in the chip production, since the equipment in chipping operations, is operated by electricity. Therefore, it is necessary to consider the impacts due to the emissions of electricity power usage when carrying out the life cycle environmental assessment for boilers.

In early 1990s over 96% of Sri Lanka electricity generation was by hydro power which rapidly began to change with the immense demand for energy which was not able to be met by hydro power dominant electricity generation plan. This made way for thermal power generation such as diesel and heavy oil-fired electricity generation and now coal is used primarily for this purpose and emissions by these plants contribute in a considerable level to the air pollution in Sri Lanka. From the total electricity generation in Sri Lanka in 2016, 66.9% was from thermal power plants, 24.27% was from major hydropower and the balance 8.08% was from the new renewable energy sources [1].

According to the study done by Sri Lanka Sustainable Energy Authority (2016), coal, heavy fuel oil, diesel and naptha are used as fuel in different types of thermal power plants in Sri Lanka. Coal is the predominant fuel and leads to the most emvoronmental impact. Table 3.4 indicates the GHG and other emissions of electricity generation from furnace oil and diesel oil [25]. Emissions mentioned in the table 3.4 are used in the emission inventory calculations of electricity usage in steam production in this study.

The oil-fired CEB power plants generated 2,360.2 GWh, while the coal-fired power plant generated 5,066.9 GWh. The contribution of the coal power plant to generation is 52.6%. The four IPPs generated 2,202.9 GWh [1]. In light of above, electricity generation by oil fired plants is 4563.1 GWh in total. Gross power generation by sector is given in Table 3.1.

Table 3.1: Gross power generation by sector

Fuel	Electricity generation (GWH)
Coal	5066
Light oil	3299
Heavy oil and Naphtha	1263
Other (hydro, solar, wind etc.)	4712
Total	14342

Tables 3.2 portrays contribution percentage with respect to each fuel to the total electricity generation in Sri Lanka.

Table 3.2: Power generation contribution percentages of various fuel categories

Fuel	Percentage of total electricity generation
Coal	35.24
Light oil	23.00
Heavy oil and Naphtha	8.89
Other (hydro, solar, wind etc.)	32.85
Total	100

Total petroleum fuel quantities used for power generation in Sri Lanka is given in Table 3.3. Coal is the fuel used predominantly.

Table 3.3: Total petroleum fuels in power generation

Fuel	Unit	Fuel consumption
Fuel oil (HSFO 180 CST, FO 1500)	Litre (10^6)	188
Residual oil (HSFO 380 CST, FO 3500)	Litre (10^6)	199.3
LSFO 180 CST	Litre (10^6)	139.4
Naphtha	Litre (10^6)	180
Diesel	Litre (10^6)	389.9
Coal	kg (10^6)	2004

In Table 3.4, GHG and other emissions caused by oil due to power generation is given, taken from the Sri Lanka's Second National Communication on Climate Change by Ministry of Environment. Sulphur content is higher in heavy oil, consequently leading to higher SO_2 emissions [25].

Table 3.4: GHG and other emissions by oil due to electricity generation

Fuel		Emissions (Gg)						
Type	**Amount (kt)**	**CO_2**	**CH_4**	**N_2O**	**CO**	**NO_X**	**NMVOC**	**SO_2**
Heavy fuel oil	498.80	1535.58	0.06	0.01	0.30	4.01	0.10	29.93
Diesel	481.59	1530.25	0.06	0.01	0.31	4.17	0.10	2.89
Total		3065.84	0.12	0.02	0.61	8.81	0.20	32.82

Coal contributes immensely to the high environmental impacts caused by electricity generation in Sri Lanka. Effects due to coal have been taken from “Life cycle assessment of coal-fired power production" by Pamela L. Spath, Margaret K. Mann and Dawn R. Kerr and is shown on Table 3.5 [26].

Table 3.5: GHG and other air emissions due to coal

Emissions (g/KWH)						
CO_2	**CH_4**	**N_2O**	**CO**	**NO_X**	**NMVOC**	**SO_2**
996	0.913	0.00443	0.267	3.35	0.213	6.7

3.1.2. Boiler emissions in steam generation

The emissions by fuel combustion in the steam boilers vary as per the fuel being used.

While rice husk emission values have been taken from literature, emissions of furnace oil, wood log, wood chip and heavy oil have been taken by analysing around 60 emission reports of steam boilers.
The emissions of rice husk burning are as shown in Table 3.6 below [27].

Table 3.6: Emissions of rice husk burning

Parameter	Emissions (kg/h) (Rice husk burning rate = 10.63 t/hr.)
CO_2	16,013.56
CO	81.52
NO_2	12.47
SO_2	3.72
TSP	1.03
Fly ash	1,560.00
Bottom ash	323.00

Bottom ash and fly ash account to solid waste. Organic volatile matter dominates husk being 75% by weight and rest is converted into ash during combustion process which itself is approximately 82% amorphous silica which happens to be used to produce special concrete mixes due to husk ash being a quality pozzolan [28]. Akeem Ayinde Raheem and Mutiu Abiodun Kareem in "Optimal raw material mix for the production of rice husk ash blended cement" have given composition of rice husk ash as in below Table 3.7 [28].

Table 3.7: Chemical composition of rice husk ash

Parameter	Percentage Composition
SiO_2	82.14
Al_2O_3	1.34
Fe_2O3	1.27
(CaO)	1.21
Mg	1.96
SO_3	0.17
Na_2O	0.14
K_2O	2.09
P_2O_5	6.44

Average calorific value of rice husk is 13.9 $MJ \cdot kg^{-1}$ [29]. The emissions of rice husk burning mentioned in the table 3.2 are used in the emission inventory calculations of husk fired boiler usage. Paddy with 20% of husk gives 200 kg of husk per one tonne of paddy. Assuming 50% efficiency of husk fired boiler, heat available from the 200 kg of husk will be 300,000 kCal [30].

Sawdust too is being widely used in Sri Lanka as a fuel. Wan Azlina has preseted ultimate analysis of rubber wood sawdust on dry basis thus: [31].

Table 3.8: Ultimate analysis of sawdust

Parameter	Percentage Composition
Carbon	53.4
Hydrogen	6.7
Oxygen	36.8
Nitrogen	3.1

Calorific value of sawdust is approximately 18.3 MJ/kg (dry basis) [31].

- Emission inventory of a sawdust fired boiler

Based on the anaylysis of over 60 steam boiler emission reports, follwing values were determind as average: table 3.9 portrays air emissions of sawdust burning.

Table 3.9: Emissions of sawdust burning

Parameter	Emissions (kg/h) (Sawdust burning rate = 1 kg/hr.)
CO_2	1.1775
CO	0.0025
NO_2	0.0006
SO_2	0.0011
PM	0.0006

When studying wood log fireed boilers, mainly rubber wod log fired boilers were considered but it was observed other biomass variants too have been present in smaller quatities in rubber log fired boilers. Off cuts too are being fed to log fired boilers.

- Emission inventory of a wood log boiler

Emission levels of a manual fed log fired boiler in Sri Lanka are as given in Table 3.10.

Table 3.10: Emissions of wood log burning

Parameter	Emissions (kg/h) (Wood log burning rate = 1 kg/hr.)
CO_2	1.0592
CO	0.0028
NO_2	0.0010
SO_2	0.0011
PM	0.0005

Particulate matter emissions of a wood log fired boiler was less than that of a sawdust fired boiler.

- Emission inventory of a heavy oil boiler

Emission inventory of a heavy oil boiler is given in Table 3.11.

Table 3.11: Emissions of heavy oil-fired boiler

Parameter	Emissions (kg/h) per FO litre/h
CO_2	2.9600
CO	0.0002
NO_2	0.0041
SO_2	0.0274
PM	0.0006

- Emission inventory of a wood chip boiler is given in Table 3.12.

Table 3.12: Emissions of wood chip burning

Parameter	Emissions (kg/h) (Wood log burning rate = 1 kg/hr.)
CO_2	1.2210
CO	0.0025
NO_2	0.0010
SO_2	0.0011
PM	0.0003

3.1.3. Drying of biomass

In Sri Lanka, it’s typically depended on sun drying for drying of rubber wood and this reduces the moisture up to 5-10%. This is a significant advantage not requiring additional energy thanks for non-renewable sources for this process owing due to Sri Lanka being located closer to the equator hence not being susceptible to seasonal variance in sunlight. About two, third of the country receives solar radiation of 4 to 4.5 kWh/m2/day [1].

Normally sun-drying takes one or two days depending on the weather condition.

3.1.4. Emissions in transportation

Sawdust, rice husk, wood log and chips, diesel and heavy oil transportation is one of the most significant factors accounting to the environmental impacts of steam generation process. While sawdust, rice husk could be used with minimum environmental impacts owing to their nature of being by products they still have to be transported which require fossil fuels hence longer the journey the less environmentally friendly the whole process becomes hence the acute significance of the location. For biomass fuel transportation, road transport is employed. Typically, tippers, trucks and lorries are used. 15 km distance from source to application has been assumed for comparison accounting 30 km including the return journey. Emissions incurred during transportation is a significant factor when it comes to life cycle assessments of steam generation processes by various fuels.

Transportation incur during following:

- rice husk transportation from mill to the boiler
- sawdust transportation from mill to the boiler
- rubber log transportation from rubber land/mill to the chipping plant and subsequent transportation of chips from chipping plant to the boiler
- heavy oil transportation from refinery to the boiler

- **Emissions of transportation**

Table 3.13 illustrates amount of diesel fuel used and their emission levels including greenhouse gases and other gases for the road-transport sub sector of Sri Lanka by Ministry of Environment in 2011 in the report under the name “Sri Lanka's Second National Communication on Climate Change” [25].

Table 3.13: Emissions of road transport sub-sector in 2000

	Air Emissions						
	CO_2	CH_4	N_2O	CO	NO_X	NMVOC	SO_2
Emissions (g) per 1kg diesel fuel burn	3,177.50	0.21	0.02	43.33	34.67	8.66	6.00
Emissions (g) per 1MJ diesel fuel burn	73.05	0.0048	0.0005	1	0.8	0.2	0.14
Total Emissions (Gg) with respect to 1175 .15 kt Diesel Fuel	3,734.04	0.25	0.03	50.92	40.74	10.18	7.05

As per Ceylon Petroleum Corporation (2018) data, density and calorific value of auto diesel are 840 kg/m^3 at 15 ^{0}C and 10,500 kCal/kg [32].

This study has used above data in the inventory calculation.

3.1.5. Cost of operation with respect to biomass fuel alternatives

Around 75 mills were surveyed and average costs of biomass variants studied, were as follows as given in Table 3.14 at source. Delivered at site-cost is higher accounting transportation distance.

Table 3.14: Cost of different categories of biomass

Type of biomass	Cost (LKR/kg)
Sawdust (30% moisture)	3.55
Rubber Wood log (30% moisture)	4.20
Wood chip (25% moisture)	7.30
Rice husk	2.80

Biomass requirement to generate 1 tonne of steam from and at 100 ^{0}C with respect to each fuel is given in Table 3.15.

Table 3.15: Biomass requirement to generate one tonne of steam from and at 100 ^{0}C.

Type of biomass	Required Quantity (kg)
Sawdust (30% moisture)	330
Rubber Wood log (30% moisture)	355
Wood chip (25% moisture)	310
Rice husk	370

It was noted often transportation personnel have slightly modified vehicles raising from sides to transport more biomass. Average loads per vehicle type were taken as given in Table 3.16 regardless of slight variation of density of biomass variants considered, based on the survey. Transportation cost has been given as cost per kilometre, which is to be paid for the total distance including the return journey. Most common type of transportation for husk, sawdust and logs is lorry while tipper is used for chip transportation.

Table 3.16: Transportation loads and mileage of various transportation vehicles

Vehicle type	Load (kg)	Kilometres per litre	Cost (LKR/km)
Dimo Lorry	1000	19	45
14.5 Lorry	5000	7	55
Tipper	8000	4	80
Bowser	6600	2.5	NA

- Labour requirement and applicable costs

Labour requirement was found to be 4 labourers per shift of 12 hours for a 6-tonne biomass boiler that is running around the clock. In addition, a licensed boiler operator too has been available. Generally, labour cost was found to be LKR 2,000 per 12-hour shift.

Cost for 4 labourers per shift – LKR 8,000

Cost for 60 shifts considering 25 day working month- LKR 4800,000:

Note: it was observed the operators had been engaged in cleaning work, when the boiler was not running hence cost had remained same.

Boiler operators' cost- LKR 100,000

Steam generation was estimated at 75% capacity as a base-

Steam generation per month – 2700 tonne

Cost of operators per steam 1 tonne = LKR 214.81

Cost for operators for an oil-fired boiler was found to be LKR 83.333 for generation of 1 tonne of steam.

3.1.6. Availability of biomass variants

Most paddy farmers in Sri Lanka harvest twice a year seasonally called Yala & Maha. Though paddy is harvested seasonally, paddy husk is available throughout the year as millers store the paddy purchased from farmers and mill as per user requirements which is rather uniform throughout. Husk is generated in the milling process as a by-product. Generally, 20% of the paddy weight is husk thus Sri Lanka has an availability of 963.84 kilo tonne husk based on the paddy production of 4819.4 kilo tonne in 2015. Rice husk is predominantly available in Polonnaruwa, Anuradhapura and Kurunagala [33].

Table 3.17: Paddy production in Sri Lanka by district

District	Paddy Production ('000 Metric Tonnes)
Colombo	12.7
Gampaha	46.2
Kalutara	68.7
Galle	48.9
Matara	86.9
Ratnapura	65.1
Kegalle	37.4
Kurunegala	496.7
Puttalam	111.8
Kandy	64.7
Matale	121.1
Nuwara Eliya	15.7
Badulla	159
Monaragala	200.7
Jaffna	27
Killinochchi	97.5
Vavuniya	101.3
Mullativu	75.6
Mannar	101.9
Anuradhapura	539.7
Polonnaruwa	630.1
Trincomalee	215.1
Batticaloa	235
Ampara	617
Hambantota	262.9
Udawalawe	152.3
Mahaweli'h'	228.2

Rice husk generated at the milling process is collected and transported to the point of application. Husk is fed to the boiler via a bucket elevator or a conveyor thereby consuming electricity. Also, biomass boiler would possess induced blower and a forced draft blower to carry the combustion process more efficiently which too consume electricity. Ash is generated as a by-product of husk combustion which is 80%-85% consisted of amorphous silica which is used as an additive in cement industry.

- **Rubber wood logs**

Rubber has a 25-year economic life cycle and produce 65 m^3 of logs per hectare upon end of life. In 1995 rubber lands had produced 256,000 m^3 of saw logs on a total of 193,000 ha which was 13% of the national timber production in Sri Lanka.

Rubber has been one of the three main export crops in Sri Lanka and as of 2016, 116477 hectares have been covered in rubber extent [34].

Table 3.18: Extent of rubber plantation by district

District	Hectares
Colombo	7062
Gampaha	3078
Kalutara	29852
Kandy	1230
Matale	1872
Nuwara Eliya	33
Galle	6676
Matara	3731
Hambantota	71
Kuranegala	2855
Badulla	432
Moneragala	1865
Ratnapura	22147
Kegalle	35573
Total	116477

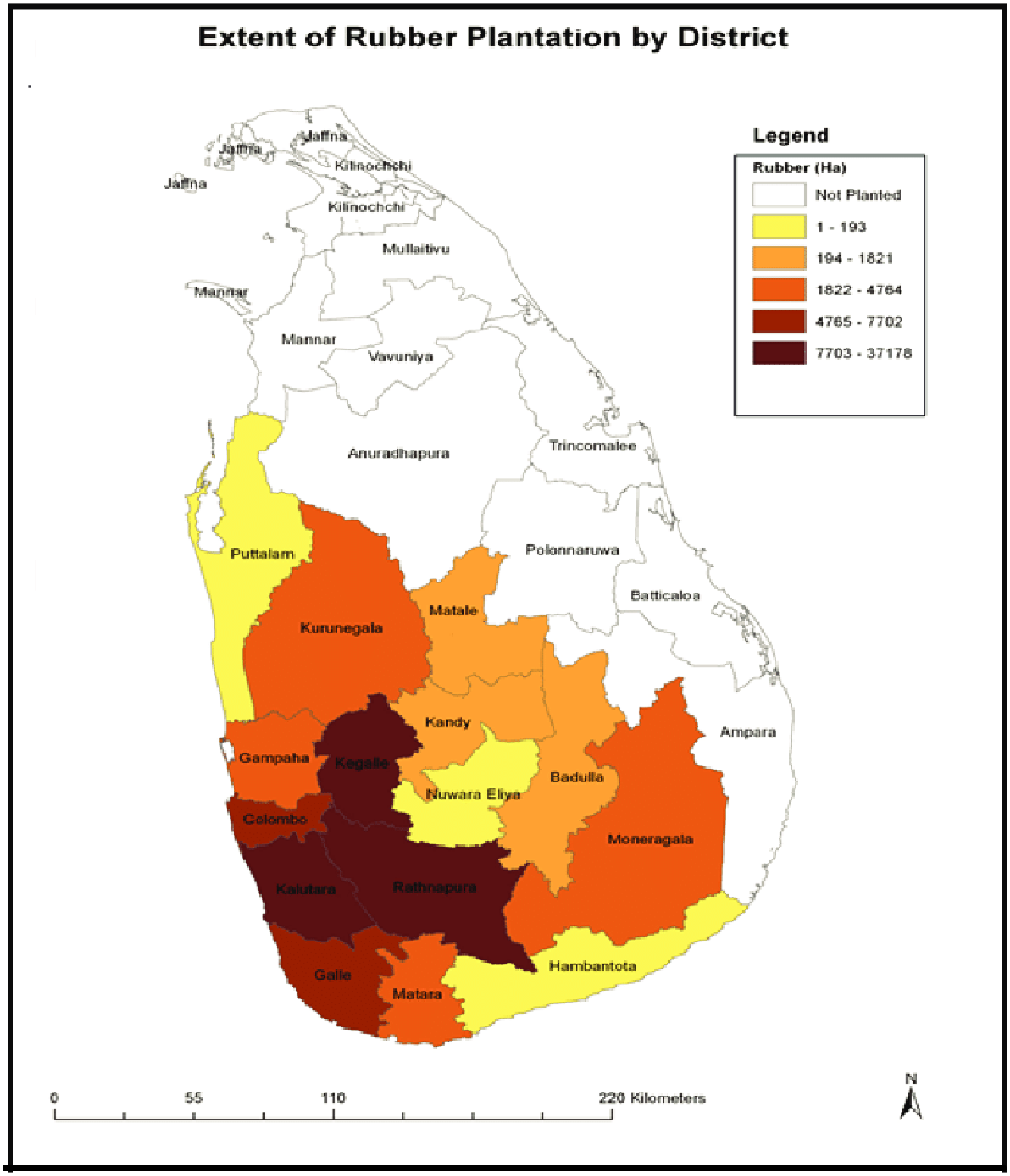


Figure 3.1: Extent of rubber plantation by district (Source: Central Bank annual report-2014)

- **Sawdust**

Sawdust is vastly available in commercial quantities in Moratuwa, Kalutara, Gampaha, Galle, Matara, Badulla, Kandy & Kurunagala. On average 6.14 kg of sawdust can be obtained per 1 cubic feet of sawn timber [35].

Before the shift in using sawdust as a fuel, most mill owners had burned sawdust polluting the air in an uncontrolled manner or left in piles causing severe adverse effects to air, soil and water.

3.1.7. Electricity consumption

Electricity consumption per generation of one-tonne steam varies according to boiler capacity, type of feeding, and the percentage said boiler is loaded.

For husk fired steam boilers, electricity consumption per 1 tonne of steam generation is 7.6 kWh on average however this value varies along with the steam generation percentage of the steam boiler. Electricity demand for a 6-tonne husk fired boiler is as follows.

ID	: 1 No x 30.0 HP
FD	: 1 No x 12.5 HP
Feed pump	: 2 Nos. x 5 HP
Ash feeder in MDC	: 1 No x 0.5 HP
Screw feeder with VFD	: 1 No x 1.0 HP
Bucket Elevator	: 1 No x 4.0 HP

Average electricity load is less than the rated load as blowers and pumps do not run continuously.

Regarding log fired steam boilers, electricity consumption to run a 6 tonne per hour wood log fired boiler is as follows: Wood logs are manually fed to the boiler

ID	: 1 No x 30.0 HP
FD	: 1 No x 12.5 HP
Feed pump	: 2 Nos. x 5 HP
Ash feeder in MDC	: 1 No x 0.5 HP

On the average electric consumption per generation of seam 1 tonne was found to be 3.9 kWh.

Electricity consumption to run a 5 tonne per hour sawdust fired boiler is as follows: Sawdust is fed to the boiler via bucket elevator followed by a screw conveyor.

ID	: 1 No x 30.0 HP
FD	: 1 No x 12.5 HP
Feed pump	: 2 Nos. x 5 HP

Ash feeder in MDC : 1 No x 0.5 HP

Screw feeder with VFD : 1 No x 1.0 HP

Bucket Elevator : 1 No x 4.0 HP

Average electricity consumption is 7.6 kWh per generation of 1-tonne steam.

Mainly rubber wood chips have been considered in this report and considering an 8-tonne packaged chipping plant it was estimated electricity requirement per 1 tonne of chipped rubber wood is 8kwh.

Given below is the load requirement of an 8-tonne wood chip fired boiler.

ID : 1 No x 40.0 HP

FD : 1 No x 15 HP

Feed pump : 2 Nos. x7.5 HP

Ash feeder in MDC : 1 No x 1 HP

Conveyor – bucket elevator – 6 hp

Average electricity consumption to generate 1-tonne steam is 7.6 kWh.

Therefore, considering required chip quantity to produce 1 tonne of steam as 310 kg as found on this survey, on the whole an average 10.08 kWh is required to generate one tonne of steam via wood chip, making it the most energy consuming biomass fuel alternative considered in this study.

Table 3.19: Electricity consumption per generation of one tonne of steam from various biomass variants

Type of biomass	Electric consumption (KWH)
Sawdust	7.6
Rubber Wood log (30% moisture)	3.9
Wood chip (25% moisture)	10.08
Rice husk	7.6

3.2. Life cycle assessment methodology

Environmental performance of steam generation via five different fuels is assessed which includes goal and scope definition, life cycle inventory assessment, impact category identification and assessment.

3.2.1. Goal and scope definition

➢ **Goal of the environmental performance assessment**

Five (05) steam generation methods named as rice husk fired steam generation, rubber wood chip fired steam generation, sawdust fired steam generation, wood log fired steam generation and furnace oil fired steam generation are assessed and compared with the goal of finding means to reduce overall environmental emissions.

- **Rice husk fired boiler**
  Rice husk collected at the rice mills are transported to the facility where they are fired via steam boiler to generate steam. Fuel feeding system is generally a bucket elevator followed by a screw conveyor.

- **Sawdust fired boiler**
  Sawdust collected at the mills are transported to the facility where they are fired via steam boiler to generate steam. Fuel feeding system is generally a bucket elevator followed by a screw conveyor.

- **Wood log fired boiler**
  Waste wood log collected at rubber plantations and mills are transported to the facility where they are fired via boiler to generate steam. Fuel feeding is generally done manually.

- **Wood chip fired boiler**
  Rubber logs collected at rubber plantations and mills are transported to the chipping plant where they are chipped to increase surface area and provide relatively uniform fuel to the boiler compared to logs. Then chips are transported to the facility where they are ultimately fired at the boiler to generate steam. Feeding system is generally bucket elevator followed by screw conveyor.

- **Heavy oil**
  This is the conventional method of generating steam industrially. Heavy oil transported by bowsers are stored at bulk sumps from where they are pumped to the day tank and eventually fired via burner.

➢ **Scope of the environmental performance assessment**

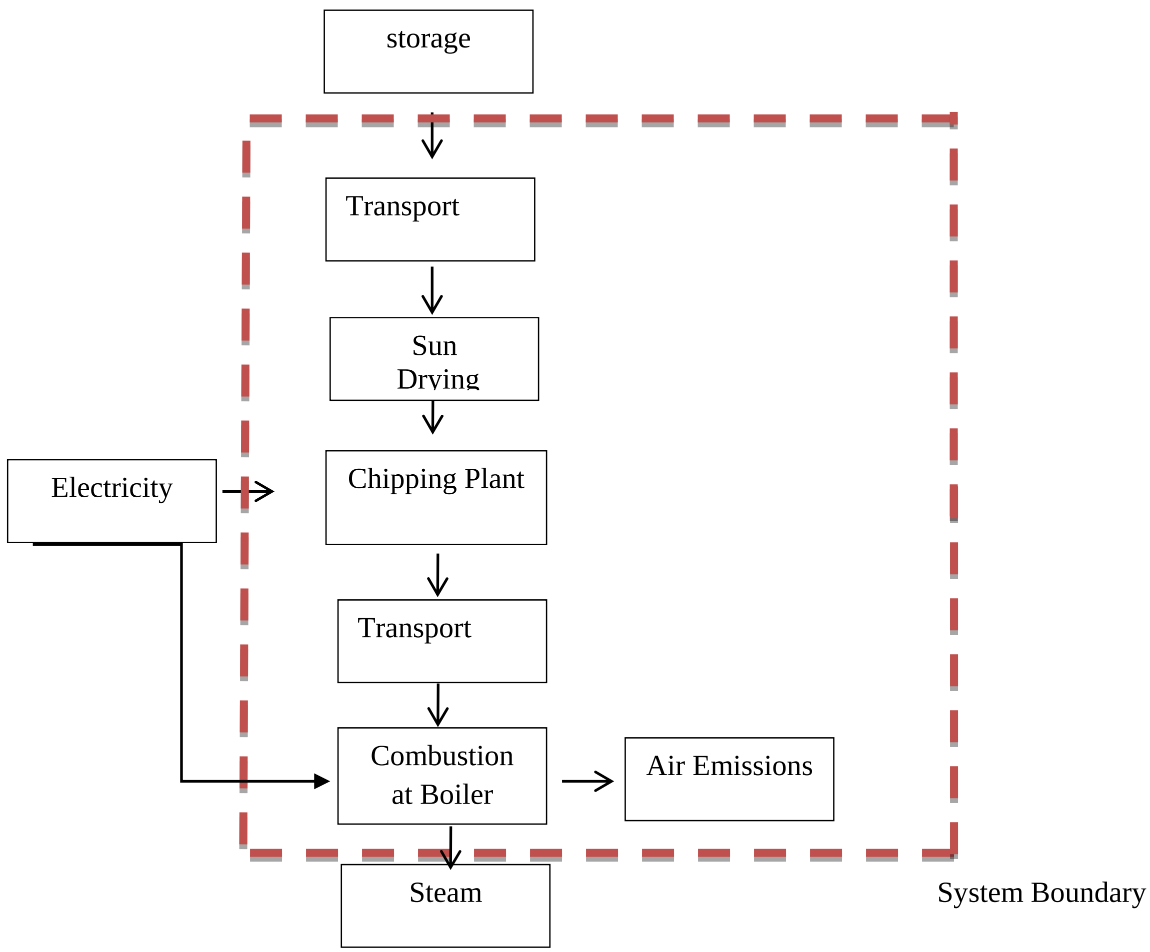
Scope of assessment includes environmental assessment with respect to transportation of fuels, preparation of fuels including chipping process along with consumed electricity and related emissions during combustion process. Gross carbon emission of biomass is considered for the study as net carbon emission is zero considering carbon neutrality. Notable exclusions are environmental impacts of machinery, equipment, related buildings.

- **Functional unit**

In this work the functional unit is taken as "production of one tonne of steam from and at 100 ^{0}C". Steam is generated by heating water from the various heat sources. All the impacts are assessed relative to one tonne of steam from and at 100 ^{0}C.

- **System boundaries**

Defining a system boundary happens to be of great importance. To compare performance of each fuel same boundary was selected where applicable. Chipping process is only applicable for chip fired boilers. Generally, air emissions due to electricity generation with respect to combustion of heavy oil, light oil, coal, air emissions due to transportation and emission due to fuel combustion at the boiler were considered. Process Flow and System Boundary for biomass fired boilers is given in Figure 3.2.



Chipping process is applicable only for wood chip fired boilers.

Figure 3.2: Boundary of biomass fired boilers

Process Flow and System Boundary for heavy fired boilers have been given Figure 3.3

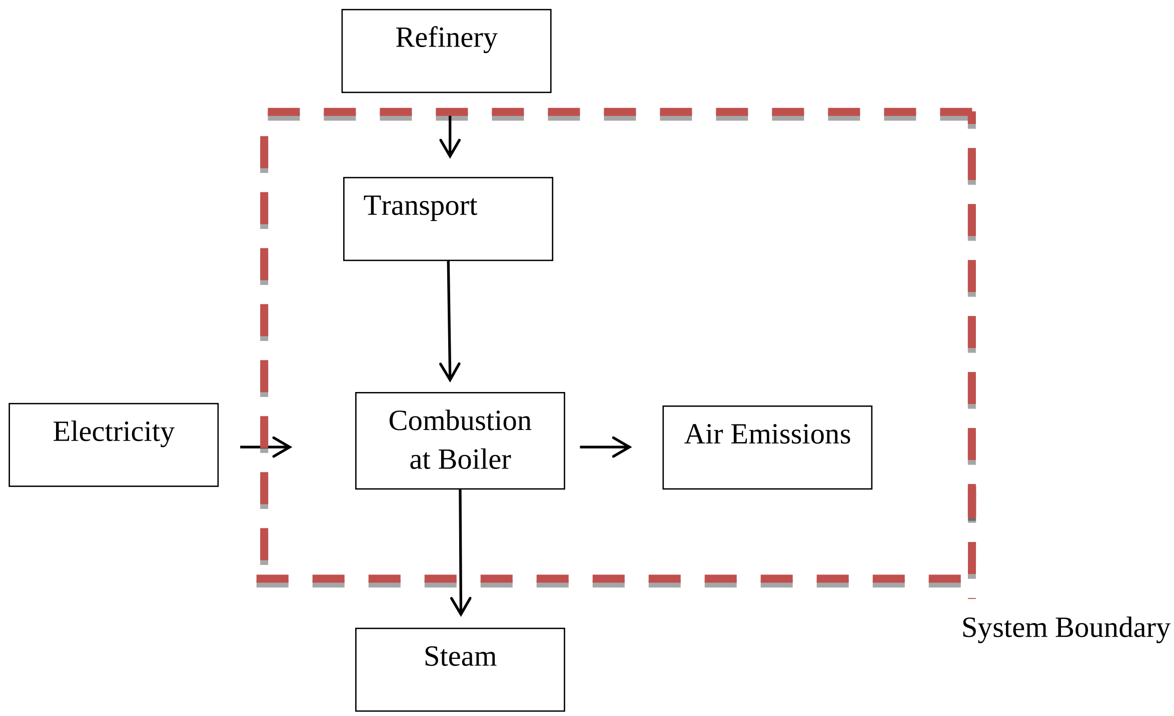


Figure 3.3: Boundary of heavy oil-fired boilers

3.2.2. Life cycle inventory analysis

Inventories of steam generation process of five different steam generation methods as mentioned in section 3.2.1 with respect to generation of one tonne of steam from and at 100 ^{0}C are estimated separately that includes environmental inputs and out puts within the boundary considered. Air emissions such as CO_2, NOx, CO, SO_2, NMVOC, TSP. NH_3, CH_4 have been identified. Results have been given in section 4.1.1.

The data associated with calculation of the environmental inventories of the steam generation processes are taken from various literature sources. Electricity consumption data collected from the survey have been used to estimate electricity emissions for each process. A point to note is that only combustion air emissions have been considered

Sun drying is the most popular drying method for rubber and this method is considered as the drying method in this work. 540 kCal is required to generate 1 tonne of steam from and at 100 ^{0}C.

The average heat value of husk is 3,000 kCal/kg and the husk fired boiler efficiency is 50% [27]. Emissions of rice husk burning mentioned in the table 3.6 are taken as the husk fired boiler emissions.

3.2.3. Life cycle impact assessment

With reference to the environmental burdens figured in inventory analysis as described in section 3.2.2 these burdens in context are assigned relative importance in the overall picture of the respective impact category in this step of life cycle impact assessment where they are further quantified with respect to their impact as opposed to qualitative analysis. Classification and characterisation of life cycle inventory results are carried out where total environmental impact of a given category is given by one particular representative in the respective category thereby enabling comparison of various methods in regard to a said impact category followed by normalisation that makes way for comparison and understanding of contributions of identified impact categories.

➢ **Selection of impact categories**

For the LCA study of steam generation processes and to enable comparison same categories are to be selected for each method. Following impact categories have been considered upon assessment of inventory results:

- climate change
- depletion of abiotic resources
- human toxicity
- photo-oxidant formation
- acidification
- eutrophication

➢ **Classification**

Environmental impacts based on the inventory results are assigned to selected impact categories discussed in section 4.3.1. and the interventions that don't fall under any of said categories are shown separately.

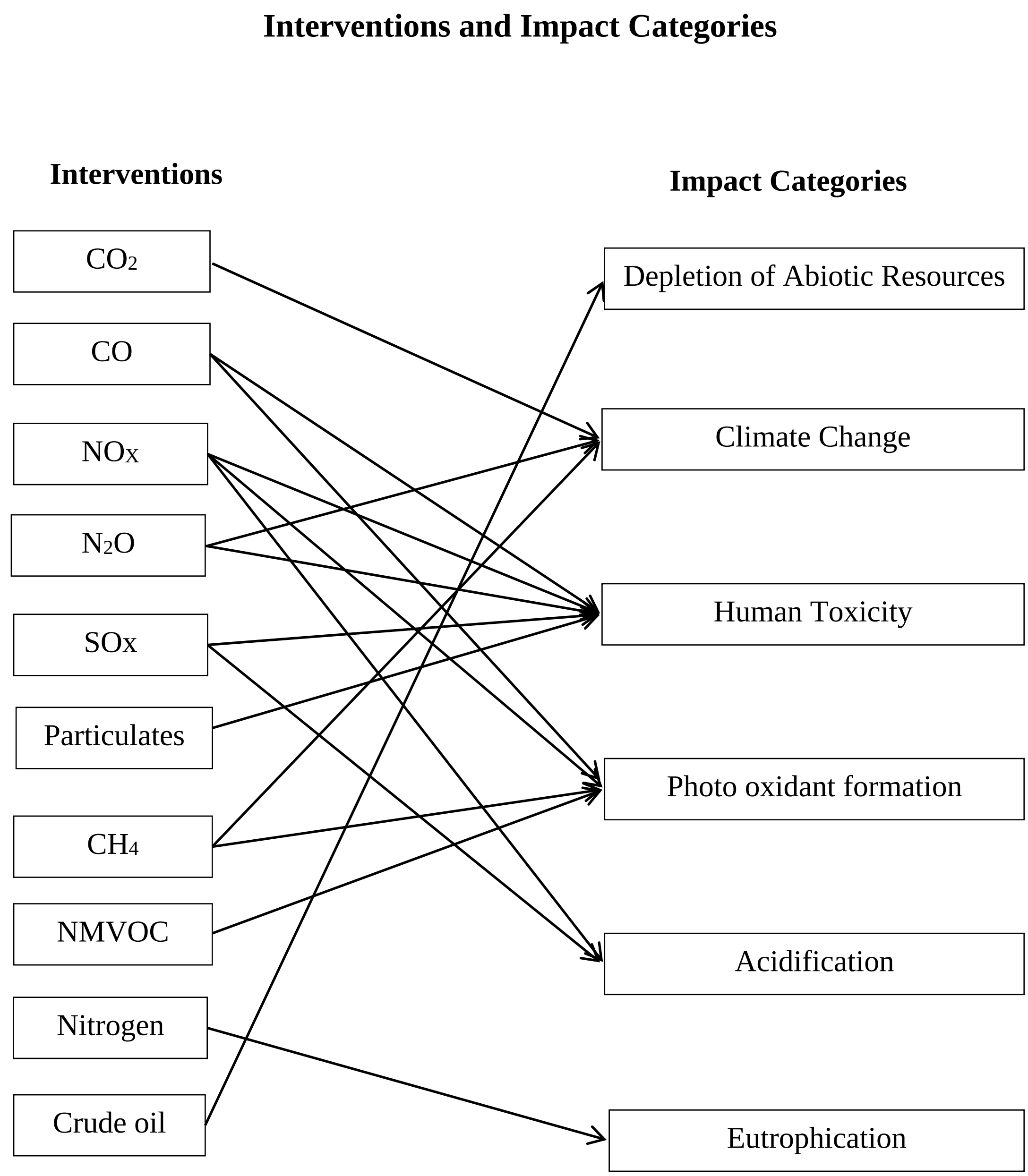


Figure 3.4: Classification of environmental interventions into selected impact categories

- **Characterisation**

In this step, characterisation of impact categories is done employing characterisation factors applicable for each environmental impact. All impacts falling under a given a category is exhibited using a common unit for the said category. This makes way for a single score with same unit a for a given category which enables comparison between various processes.

Characterisation factors for the applicable impacts mentioned in this study and related categories are given in Table 3.20 [19].

Table 3.20: Selected impact categories and respective characterisation factors

Impact category	Related intervention	Characterisation factors	
		Unit	Value
Climate change	Carbon dioxide	kg CO_2 eq./kg	1
	Methane	kg CO_2 eq./kg	21
	Dinitrogen oxide	kg CO_2 eq./kg	310
Depletion of abiotic resources	Diesel (Crude oil)	kg antimony eq./kg	0.0201
Human toxicity	Dust (PM 10)	kg 1,4- DCB eq./kg	0.82
	Sulphur dioxide	kg 1,4- DCB eq./kg	0.096
	Nitrogen dioxide	kg 1,4- DCB eq./kg	1.2
Photo oxidant formation	Carbon monoxide	kg C_2H_2 eq./kg	0.027
	Methane	kg C_2H_2 eq./kg	0.006
	Nitrogen dioxide	kg C_2H_2 eq./kg	0.028
	Nitrogen mono oxide	kg C_2H_2 eq./kg	-0.427
Acidification	Nitrogen oxides (as NO_2)	kg SO2 eq. /kg	0.5
	Sulphur dioxide	kg SO2 eq. /kg	1.2
Eutrophication	Nitrogen	kg PO_4^{-3} eq. /kg	0.42
	Phosphate	kg PO_4^{-3} eq. /kg	1
	COD	kg PO_4^{-3} eq. /kg	0.022

- **Normalisation**

Normalisation helps to compare environmental impact of impact categories and portrays the extent to which a given impact category affects the environment on the whole by establishing a common reference. The characterised result of each impact category is divided by a selected reference value, which brings all the results on the same scale [24]. Normalisation helps to interpret the results of LCA. Reference might be with respect to a community, a person, the entire world as a whole etc and is to be selected in line with the goal of the study [21].

Normalisation factors provided by Guinee (2001) are below with respect to global normalisation for year 1990 [21].

Table 3.21: Normalisation factors

Impact Category	Normalisation factors
Depletion of abiotic resources	3.01E+01 kg antimony eq.yr^{-1}.$capita^{-1}$
Climate change	8.46E+03 kg CO_2 eq.yr^{-1}.$capita^{-1}$
Human toxicity	1.09E+04 kg 1,4- DCB eq.yr^{-1}.$capita^{-1}$
Photo oxidant formation	2.03E+01 kg C_2H_4 eq.yr^{-1}.$capita^{-1}$
Acidification	5.95E+01 kg SO_2 eq. yr^{-1}.$capita^{-1}$
Eutrophication	2.51E+01 kg PO_4^{-3} eq. yr^{-1}.$capita^{-1}$

3.3. Financial analysis of boiler operation with respect to alternative fuels

From the collected data, cost per 1 tonne of steam generation with respect to each fuel was determined taking transport cost as a variable. For the initial analysis as the base case, transportation distance from biomass source to application was taken as 15 km.

While distance from Sapuhaskande refinery to a factory is well above 15 km, the said distance was taken for the purpose of comparison.

The threshold points for each biomass variant were determined based on findings of survey.

3.4. Sensitivity analysis

Sensitivity analysis was carried out to assess the effect of transportation. The sensitivity analysis included varying transportation distance from given biomass variants to point of application. Transportation distance was varied from zero to 500 km to assess the effect.

4 Results

4.1. Framework & tool for location planning of biomass boilers

Core steps in the proposed framework & location planning tool include:

- Data collection
- Life cycle assessment
- Financial assessment
- Sensitivity analysis
- Ranking of potential locations and alternative fuels

Figure 4.1 exhibits a flowchart illustrating the core steps of the framework & tool for location planning of biomass boilers.

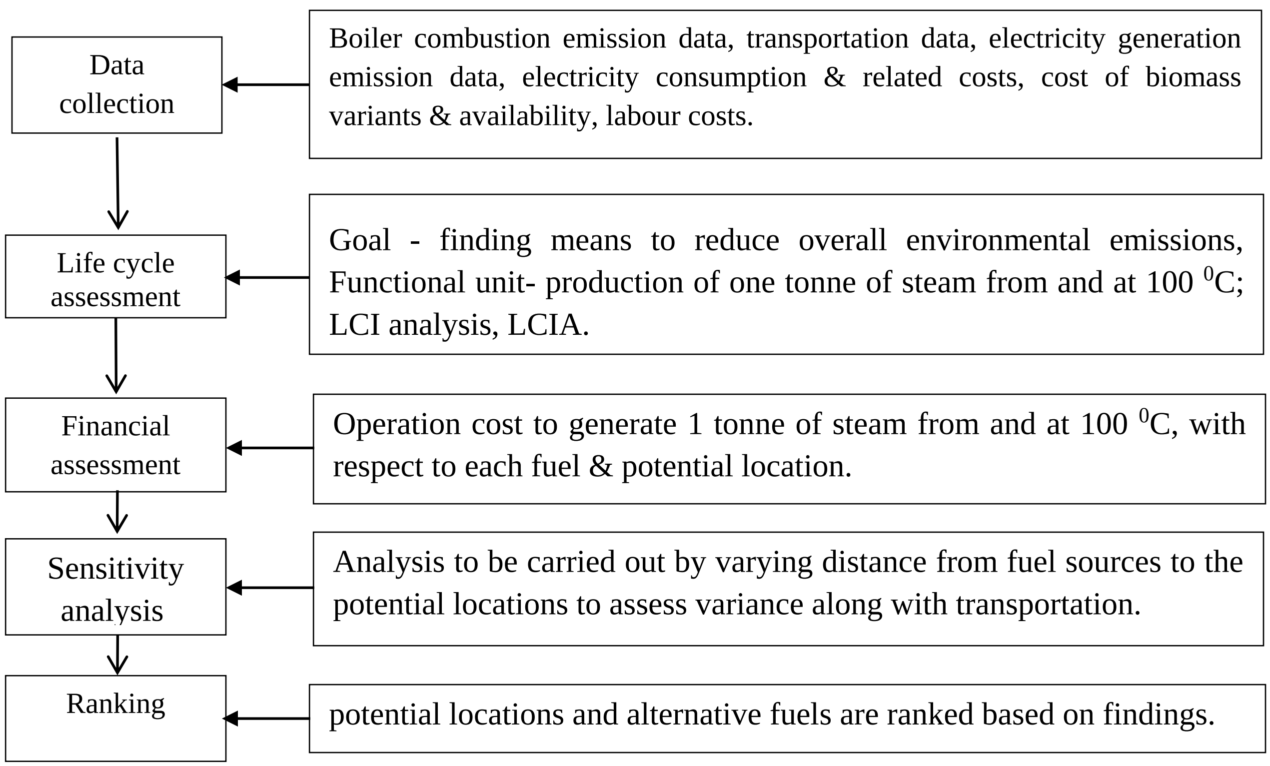


Figure 4.1: Framework & tool for location planning

4.1.1. Data collection

Data regarding the available biomass variants, emission levels, seasonal variance in supply if applicable, available quantities of each variant, are to be recorded mapping the biomass fuel sources. Availability of labour too is to be recorded specially where wood logs are planned to be used.

4.1.2. Life cycle assessment

Life cycle assessment is to be carried out with respect to each fuel and potential location. Emission inventories of transportation, electricity and combustion are to be determined for each fuel corresponding to each potential location and have them assigned to applicable impact categories followed by characterisation and normalisation. Distance from biomass fuel sources to potential locations are to be obtained to determine emissions incurred during transportation.

4.1.3. Financial assessment

Financial assessment is to be carried out with respect to each fuel and potential locations. Cost of biomass variants, required quantity of a particular biomass variant to produce one tonne of steam, transportation method and applicable costs, electricity, operators have to be considered in the assessment.

4.1.4. Sensitivity analysis

A sensitivity analysis is to be carried out varying distances of fuel sources to the potential locations to assess the variance along with distance on environmental loads and finances. This would help decision makers to understand the effect of variance of transportation from respective fuels and how ranking order may toggle in accordance, leading to insight on threshold points.

4.1.5. Ranking

In regards to the findings of above, potential locations and alternative fuels are ranked.

4.2. Validation of case study

To review the proposed framework and location planning tool, a case study has been carried out with respect to data collected in surveys and other means as prescribed in section 3.1 regarding heavy oil and four biomass variants & obtained results are given in below sections.

4.2.1. Life cycle assessment of boiler operation with respect to alternative fuels

In the process of environmental assessment of steam generation using the life cycle assessment approach as prescribed in section 3.2, initially the system boundary was defined and the inventories of inputs and outputs were estimated. These inventories, are presented quantitatively in following sections, along with environmental impacts resulting from them. This enables us to compare impacts by each method studied, and mitigate overall emissions

- **Inventories of steam generation processes**

Inventory of one tonne of steam generation process of each fuel studied, is shown in the Table 4.1. Diesel fuel derived of crude oil is used for transportation. Based on the inventory, classification of impact categories is to be done.

Table 4.1: Inventories of one tonne of steam generation

Major inventories per one tonne of Steam Generation	Fuel				
	Husk	Sawdust	Log	Chips	Heavy oil
Inputs (kg)					
Rice husk	370.00				
Rubber wood			355.00		
Wood chips				310.00	
Sawdust		330.00			
Crude oil	0.80319024	0.77439024	0.531058149	0.956078371	65.24206059
Coal	1.061906922	1.061906922	0.54492592	1.408423917	0.27944919
Air emissions (kg)					
CO	2.773589	0.813781	0.947937	0.799489	0.0185547
CH_4	0.002567	0.002561	0.001343	0.002563	0.00068216
NOx	0.456675	0.199323	0.34236	0.332772	0.27241737
CO_2	562.5695	381.8935	389.6422	383.6241	193.862404
SO_2	0.171863	0.399611	0.392637	0.388828	1.7907767
NH3	0.000264	0.000265	0.000136	0.000350	6.9637E-05
NMVOC	0.002417	0.002168	0.002271	0.002225	0.00090167
PM	0.017633	0.20000	0.158958	0.090675	0.03894784
VOC	0.000570	0.00057	0.000293	0.000756	0.00015013

- **Environmental impact assessment of steam generation**

Environmental impact assessment of processes studied are as follows:

- **Classification**

By assessing the results of inventory analysis, applicable impact categories were selected which happened to be climate change, acidification, depletion of resources, human toxicity, eutrophication and photo-oxidant formation and the identified burdens were assigned to selected impact categories.

Air emissions such as CO_2, CH_4 contribute largely to climate change being greenhouse gases and latter would contribute to photo oxidant formation as well. CO a product of incomplete combustion and NO_x would lead to photo oxidant formation and human toxicity while NO_x would further contribute to acidification along with SO_X which is also responsible for contributing towards human toxicity.

Eutrophication is mainly incurred due to emissions in transportation and electricity generation.

Though fossil too would regenerate over a long period of time, since it would not be generated in a life span of human life or in foreseeable future, it's considered as depletion of resources.

- **Characterisation of impact categories**

Classified impacts are then characterised as described in section 3.2.3 and the results of these characterised environmental impacts of one tonne of steam generation from and at 100 ^{0}C are shown in the Table 4.2.

Table 4.2: Characterisation results of impact categories

Impact Category	Unit	Chip	Heavy oil	Husk	Log	Sawdust
Acidification potential	kg SO2-Eq	4.74E-01	2.15E+00	2.13E-01	4.77E-01	4.80E-01
Climate change	kg CO2-Eq	3.86E+02	1.94E+02	5.71E+02	3.93E+02	3.84E+02
Eutrophication potential	kg NOx-Eq	1.73E-02	7.46E-03	1.75E-02	1.39E-02	6.44E-03
Human toxicity	kg 1,4-DCB-Eq	1.28E-01	2.11E-01	3.29E-02	1.81E-01	2.08E-01
Photochemical oxidation	kg ethylene-Eq	3.99E-02	8.63E-02	8.28E-02	4.41E-02	4.08E-02
Resources	kg antimony-Eq	2.28E-02	1.31E+00	2.33E-02	1.43E-02	1.79E-02

The environmental impacts of sun drying process can be considered as insignificant. Depletion of abiotic resources is caused by transportation due to diesel consumption and by consumption of grid electricity due to usage of fossil oil and coal.

Above results can be presented relative to the impact categories concerned such that for each category, the maximum result is set to 100% and the results of the other variants are displayed in relative proportion to the said maximum result. The relative results are presented in Figure 4.1.

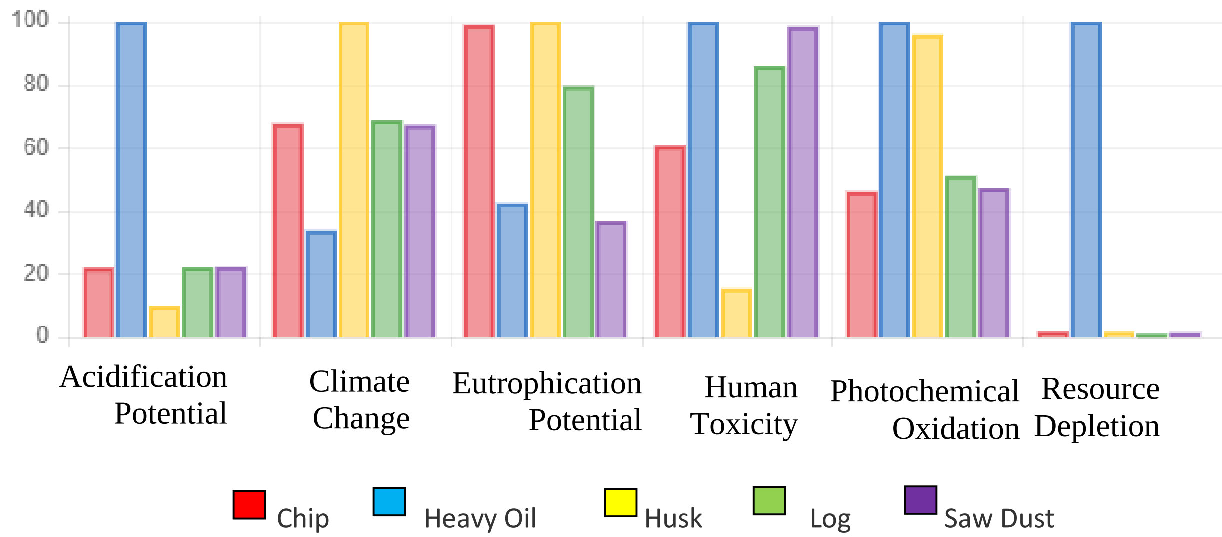


Figure 4.2: Relative results

To understand the effect on impact categories by each process, relative contributions have been assessed as presented in Table 4.3 to Table 4.7 with respect to each fuel variant studied.

Table 4.3: Relative contribution of each process of husk fired steam generation

Impact category	Transportation %	Electricity %	Combustion %
Acidification potential	3.06	24.15	72.78
Climate change	0.15	0.76	99.08
Eutrophication potential	64.26	35.73	
Human toxicity	34.13	28.09	37.76
Photochemical oxidation	0.09	2.36	97.54
Resources	23.01	76.98	

When analysing relative contributions of processes in context, combustion has been the step responsible for most impact. Acidification, climate control is higher in combustion due to sulphur and carbon emissions. Photochemical oxidation too is highly contributed by combustion process mainly due to carbon monoxide emissions caused by incomplete combustion. Human toxicity is contributed rather evenly by the three steps considered just led by combustion. Eutrophication is mainly caused by transportation while resources depletion is mainly incurred by consumed electricity.

Table 4.4: Relative contribution of each process of wood log fired steam generation

Impact category	Transportation %	Electricity %	Combustion %
Acidification potential	1.31	5.55	93.14
Climate change	0.22	0.57	99.21
Eutrophication potential	76.28	23.72	
Human toxicity	5.94	2.62	91.44
Photochemical oxidation	0.09	2.36	97.54
Resources	35.85	64.15	

When analysing contributions of environmental impacts of a wood log fired boiler, combustion has been found to be the main contributor. Impacts due to electricity consumption is less as logs are manually fed to the boiler.

Table 4.5: Relative contribution of each process of wood chip fired steam generation

Impact category	Transportation %	Electricity Chipping %	Electricity - Boiler %	Combustion %
Acidification potential	1.32	2.68	8.21	87.79
Climate change	0.21	0.28	0.85	98.66
Eutrophication potential	62.8	9.15	28.05	
Human toxicity	8.62	1.78	5.45	84.15
Photochemical oxidation	0.18	1.21	3.69	94.92
Resources	21.5	19.31	59.19	

In a wood chip fired boiler environmental impacts due to electricity consumption is relatively more than other biomass variants studied due to additional electricity usage in the chipping process.

Table 4.6: Relative contribution of each process of sawdust fired steam generation

Impact category	Transportation %	Electricity %	Combustion %
Acidification potential	1.19	10.61	88.2
Climate change	0.21	1.13	98.66
Eutrophication potential	60.53	39.47	
Human toxicity	4.61	4.25	91.14
Photochemical oxidation	0.17	4.79	95.04
Resources	21.05	78.95	0

In sawdust fired boilers too, main contribution to impacts has been due to combustion process.

Table 4.7: Relative contribution of each process of heavy oil-fired steam generation

Impact category	Transportation %	Electricity %	Combustion %
Acidification potential	0.15	0.63	99.22
Climate change	0.18	0.59	99.23
Eutrophication potential	77.25	22.75	
Human toxicity	2.76	1.15	96.09
Photochemical oxidation	0.03	0.6	99.37
Resources	0.15	0.36	99.49

In heavy oil-fired boilers, impacts are largely due to combustion process which consumes fossil fuel relentlessly. In most impact categories compared to that, contributions due to other steps seem almost negligible.

- **Normalisation of environmental impacts**

Normalised results of base case are given in Table 4.8.

Table 4.8: Normalised results

Impact category	Chip	Heavy oil	Husk	Log	Sawdust
Acidification potential	7.96E-03	3.61E-02	3.59E-03	8.02E-03	8.17E-03
Climate change	4.56E-02	2.29E-02	6.75E-02	4.64E-02	4.54E-02
Eutrophication potential	6.90E-04	6.76E-05	6.98E-04	5.55E-04	6.51E-04
Human toxicity	1.17E-05	1.88E-05	3.02E-06	1.66E-05	2.00E-05
Photochemical oxidation	1.97E-03	4.25E-03	4.08E-03	2.17E-03	2.01E-03
Resources	7.58E-04	4.36E-02	7.73E-04	4.76E-04	7.54E-04

When comparing normalised results heavy oil has had led to heavy impacts when compared to biomass fuel variants. Acidification, resource depletion, photochemical oxidation is heavily caused by heavy oil. Climate change impact is relatively affected more by biomass variants considering gross CO_2 emissions.

Normalised results bar chart is given on Figure 4.3

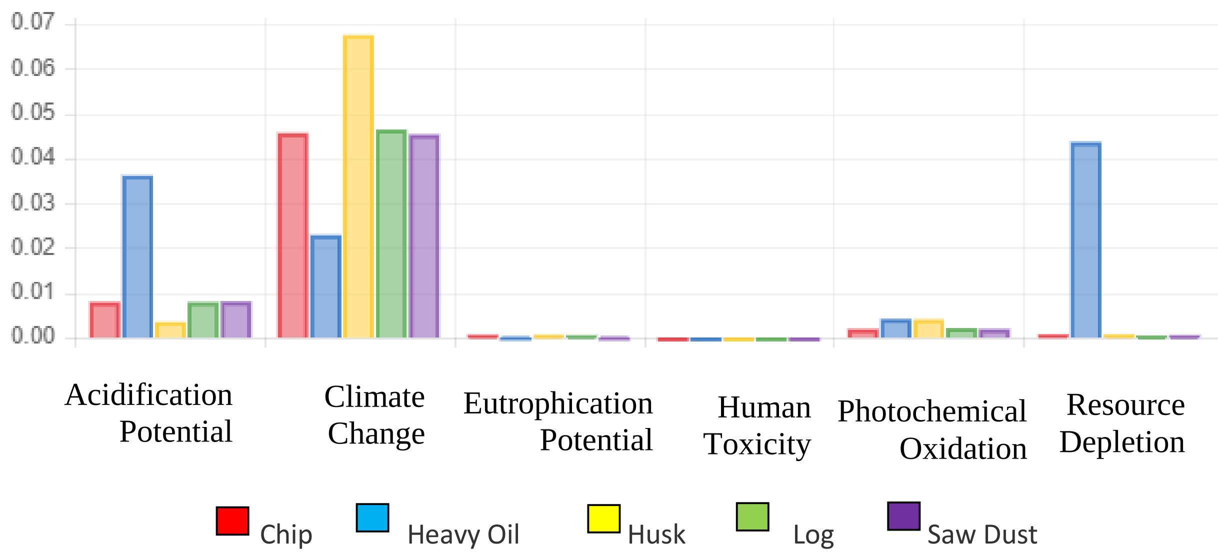


Figure 4.3: Normalised results

Overall environmental impacts of using heavy oil is so immense even when carbon neutrality is not considered. Thus, transportation distance of biomass variants was raised to 1000 km to check relative environmental impacts. Environmental impact load comparison regarding heavy oil transportation distance as 100 km and biomass variants as 1000 km has yielded following results as presented in Table 4.9. Single score results are presented in Table 4.10.

Table 4.9: Characterised results at transportation distances of 1000 km

Impact category	Unit	Chip	Heavy oil	Husk	Log	Sawdust
Acidification potential	kg SO2-Eq	6.94E-01	2.16E+00	4.25E-01	6.80E-01	6.75E-01
Climate change	kg CO2-Eq	4.14E+02	1.95E+02	6.00E+02	4.20E+02	4.10E+02
Eutrophication potential	kg NOx-Eq	3.71E-01	2.12E-02	3.76E-01	3.58E-01	3.36E-01
Human toxicity	kg 1,4-DCB-Eq	4.87E-01	2.25E-01	3.96E-01	5.30E-01	5.42E-01
Photochemical oxidation	kg ethylene-Eq	4.28E-02	8.64E-02	8.53E-02	4.65E-02	4.31E-02
Resources	kg antimony-Eq	1.87E-01	1.32E+00	1.96E-01	1.80E-01	1.77E-01

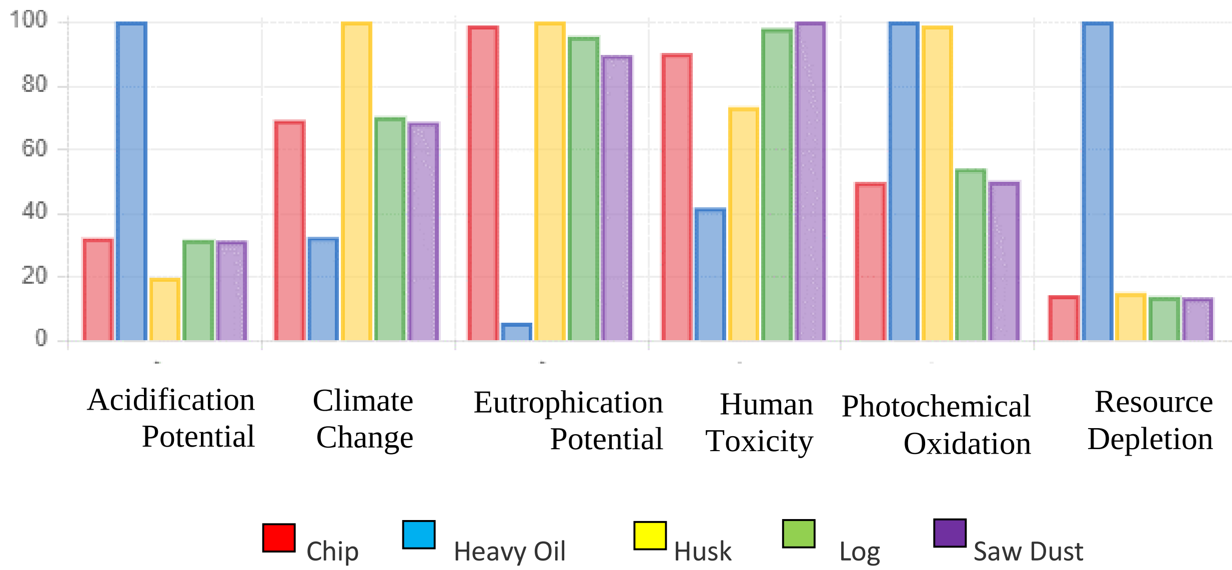


Figure 4.4: Relative results at transportation distances of 1000 km

Table 4.10: Single scores at transportation distances of 1000 km

Impact category	Chip	Heavy oil	Husk	Log	Sawdust
Acidification potential	1.17E-02	3.63E-02	7.14E-03	1.14E-02	1.13E-02
Climate change	4.89E-02	2.30E-02	7.09E-02	4.97E-02	4.85E-02
Eutrophication potential	1.40E-02	8.44E-04	1.50E-02	1.43E-02	1.34E-02
Human toxicity	4.47E-05	2.06E-05	3.63E-05	4.86E-05	4.97E-05
Photochemical oxidation	2.11E-03	4.26E-03	4.20E-03	2.29E-03	2.12E-03
Resources	6.22E-03	4.38E-02	6.53E-03	5.99E-03	5.88E-03
Total	**8.30E-02**	**1.08E-01**	**1.04E-01**	**8.37E-02**	**8.13E-02**

Heavy oil usage has been identified as the fuel with most adverse effects to the environment even when the transportation distance of a particular biomass fuel in context is 1000 km, consequently when analysing the results, it is evident heavy oil leads to most adverse environmental impacts regardless the location of application, in Sri Lankan context.

4.2.2. Financial analysis of boiler operation with respect to alternative fuels

Operation cost to generate 1 tonne of steam from and at 100 ^{0}C was carried out based on the data collected in the survey, and is given in Table 4.11 and 4.12.

Table 4.11: Operational cost of one tonne of steam without accounting transportation

Operation cost per 1-tonne steam generation	Heavy oil	Wood log	Husk	Wood chip	Sawdust
Fuel Consumption(kg)	67	355	370	310	330
Fuel price per unit at site (LKR)	92	4.2	2.8	7.3	3.55
Fuel Cost per steam 1 tonne (LKR)	6,164	1,491	1,036	2,263	1,172
Operator Cost (LKR/steam 1 tonne)	83	214	214	214	214
Electricity load per steam 1 tonne (KWH)	2	3.9	7.6	7.6	7.6
Electricity cost per steam 1 tonne (LKR)	29	55	106	106	106
Total cost per steam 1 tonne (LKR)	6,277	1,760	1,357	2,584	1,493

Following table illustrates cost per generation of one tonne of steam with respect to various fuel alternatives considered considering 30 km as the distance from fuel source to the point of application.

Table 4.12: Operational cost of one tonne of steam accounting transportation - Base case

Operation cost per 1-tonne steam generation	Heavy oil	Wood log	Husk	Wood chip	Sawdust
Fuel Consumption	67	355	370	310	330
Fuel price per unit at site (LKR)	92	4.2	2.8	7.3	3.55
Fuel Cost per steam 1 tonne (LKR)	6,164	1,491	1,036	2,263	1,172
Operator Cost (LKR/steam 1 tonne)	83	214	214	214	214
Electricity load per steam 1 tonne (KWH)	2	3.9	7.6	7.6	7.6
Electricity cost per steam 1 tonne (LKR)	29	55	106	106	106
Total cost per steam 1 tonne (LKR)	6,277	1,760	1,357	2,584	1,493
Transportation cost (LKR/km)		120	120	160	120
Distance (km)		30	30	30	30
Total cost (LKR)	**6,277**	**2,016**	**1,623**	**2,770**	**1,730**

For wood logs, sawdust and husk transportation, data regarding a lorry was considered while for wood chips, the data related to tipper lorry was considered as was the case generally in practice.

Following simple model can be presented based on the findings of the study to represent the cost of steam generation of 1 tonne with respect to biomass fuel i:

$G_i = C_i*S_i + O_i + E_i*U_i + (T_i*D_i*S_i/Li)$

G_i= Cost of steam generation of 1 tonne with respect to biomass fuel i

C_i = Cost per kg of biomass variant i

S_i= Required mass of fuel I to generate Steam 1 ton

O_i = Operators' cost to generate 1 tonne of steam with respect to biomass i

E_i= No of electricity units required to generate 1 tonne of steam

U= Cost of one unit

T_i= Transportation cost per km

D_i = Distance from biomass source to point of application

L_i= Maximum load with respect to biomass variant i regarding the mode of transport in context

Based on the findings of the study, the above equation can be simplified with respect to the biomass variants studied thus:

for husk - G_h= 1357+ (120*D_h*370/5000)

for sawdust- G_S= 1493+ (120*D_s*330/5000)

for logs- G_l= 1760+ (120*D_l*355/5000)

for chips- G_C= 2584+ (160*D_c*310/8000)

Based on above, following threshold points were identified:

Distance from each biomass variant source to the point of application to equal the financial cost of heavy oil-based operation is as follows:

wood log – 530 km

wood chip – 595.5 km

husk - 554 km

sawdust- 604 km

4.2.3. Sensitivity analysis based on distance

Single score LCA results of the sensitivity analysis is presented in Table 4.13.

Table 4.13: Single score LCA results of sensitivity analysis

Transportation 5 km		Transportation 30 km		Transportation 100 km		Transportation 1000 km	
	Single Score		**Single Score**		**Single Score**		**Single Score**
Chip	5.634E-02	Chip	5.702E-02	Chip	5.890E-02	Chip	8.30E-02
Husk	7.593E-02	Husk	7.663E-02	Husk	7.859E-02	Husk	1.04E-01
Log	5.696E-02	Log	5.763E-02	Log	5.951E-02	Log	8.37E-02
Saw-dust	5.641E-02	Saw-dust	5.704E-02	Saw-dust	5.876E-02	Saw-dust	8.13E-02

Oil is by far the worst performing fuel with respect to environmental aspects.

Husk is the worst biomass fuel variant studied.

Wood log has performed better than husk.

Wood chips performs better than sawdust regarding smaller equal distances from source to point of application but sawdust usage starts performing better from 15 km from source or 30 km including return journey.

Therefore, it can be concluded that best to worst fuels in terms of environmental impacts are sawdust, wood chips, wood logs, husk and heavy oil respectively at a distance from 15 km from fuel source to point of application and regarding said distances being less than 15 km leads to wood chips being better compared to sawdust regarding impacts.

From the findings of the financial analysis, its evident operation by husk is more economical compared to other biomass variants studied, when considering relatively smaller distances from fuel sources. In fact, provided other biomass variant sources are available at point of application freely (i.e. zero transportation cost) husk is still feasible at given distances from source to the point of application to equal the financial cost of mentioned variant as prescribed below:

- wood chip – 138.17 km
- sawdust- 15.25 km
- wood log- 45.40 km

However, with reference to the sensitivity analysis given below, varying distance from respective fuel source to point of application, it's been identified that husk is not the most economical fuel at all distances. Results table of the sensitivity analysis of above is given in Table 4.14.

Table 4.14: Financial cost variance of steam generation via sawdust and husk along with distance from fuel source

Distance from Sawdust source to the application(km)	Distance from husk source to the application (km)	Cost per steam tonne by sawdust (LKR)	Cost per steam tonne by husk (LKR)
0	0	1,493	1,357
0	5	1,493	1,401
0	10	1,493	1,445
0	15	1,493	1,490
0	20	1,493	1,534
40	50	1,809	1,801
100	100	2,285	2,245
140	140	2,601	2,600
150	150	2,681	2,689
200	200	3,077	3,133

Though at relatively smaller distances husk is more economical, based on the sensitivity analysis it's identified at a distance of 140 km or above for similar distances of sawdust and husk from fuel source to the point of application, sawdust is more feasible.

Following sensitivity analysis illustrates cost variance along with distance with respect to fuels husk and chips and the results table is given in Table 4.15.

Table 4.15: Financial cost variance of steam generation via wood chips and husk along with distance from fuel source

Distance from Husk source to the application(km)	Distance from chip source to the application (km)	Cost per steam tonne by Husk (LKR)	Cost per steam tonne by Chips (LKR)
0	0	1,357	2,584
50	0	1,801	2,584
100	0	2,245	2,584
138	0	2,582	2,584
200	50	3,133	2,894
300	300	4,021	4,444
400	400	4,909	5,064
440	440	5,264	5,312
455	455	5,397	5,405
460	460	5,441	5,436

Wood chip is costlier than husk with respect to per kg cost but overall cost per 1 tonne of steam generation gets less than that of husk for similar distances from fuel source to point to application in excess of 460 km.

Similarly results from sensitivity analysis can be summarized as follows:

- For high pressure applications:

Only husk, sawdust and chips are possible to be used out of the biomass variants studied.

1. Initially based on the financial analysis its observed that even if sawdust is available at the point of application without any transport cost, husk is more economical provided it’s available in a radius of 15.25 km.

2. However, this gap is gradually diminished along with increase of distances from sawdust source and husk source to the point of application consequently cost using sawdust or rice husk per 1-tonne steam generation becomes equivalent when respective distance is 140 km for both fuels. From this point on i.e. when distances are above 140 km and are equal, sawdust becomes the more feasible alternative.

3. When comparing sawdust and wood chip, wood chip doesn't become viable with respect to sawdust till the distance from fuel source to point of application exceeds 600 km, and as it's not feasible to use biomass itself compared to heavy oil at similar extreme distances, sawdust would remain a better cost alternative compared to chips.

4. Initially husk is more feasible such that its more economical compared to wood chips even if additional distance to husk source is greater than 138 km. Similar to the case of husk and sawdust, chips begin to close the gap between chip usage and husk usage cost due to more efficiency such that at a distance of 460 km from husk source or chip source, cost becomes equivalent. From this point on chips are more cost effective for similar distances from husk source to the point of application.

- For low and medium pressure applications

    1. Husk is the most feasible fuel for smaller distances but eventually gets run over by sawdust at a distance of 140 km as per above case. Wood log usage is costlier than husk and sawdust at all times in this context.

    2. Wood chip is the most expensive at relatively smaller distances but becomes more feasible compared to husk when distance to fuel source to application equals 460 for both fuels and with respect to wood logs, chips become more economical when said distance equals 355 km.

    3. Wood chip usage is always costlier than sawdust usage in this context.

4.2.4. Ranking alternative fuels

- Based on environmental performance

Based on the findings of the LCA heavy oil was found to be the most adverse fuel being used. Rice husk is the next inline followed by wood logs. Wood chips have performed relatively well compared to above and sawdust has been the friendliest environmental fuel out of the ones considered.

- Based on financial performance

- For high pressure applications

Initially for relatively smaller equal distances from respective fuel source to the point of application, husk is more feasible, however at equal distances over 140 km, sawdust is more viable and for equal distances over 460 km, wood chip usage is more economical compared to husk. Sawdust is always more economical compared to chips in this context.

- For low and medium pressure applications

Husk is the most feasible fuel for smaller distances but eventually gets run over by sawdust at a distance of 140 km as per above case. Wood chip is the most expensive at relatively smaller distances but becomes more feasible compared to wood log at similar distances over 355 km and 460 km compared to husk. Wood log usage is always more expensive than that of husk or sawdust.

Table 4.16: Ranking of fuel variants based on environmental & financial factors

Rank (Best to worst)	**Criteria**	
	Environmental performance	**Financial performance***
1	Sawdust	Husk
2	Wood chip	Sawdust
3	Wood log	Wood log
4	Husk	Wood chip
5	Heavy oil	Heavy oil

- *Notes:

- At equal distances over 140 km, sawdust is more viable and for equal distances over 460 km, wood chip usage is more economical, compared to husk.
- Wood chip is the most expensive biomass fuel variant at relatively smaller distances but becomes more feasible compared to wood log at similar distances over 355 km and 460 km compared to husk.

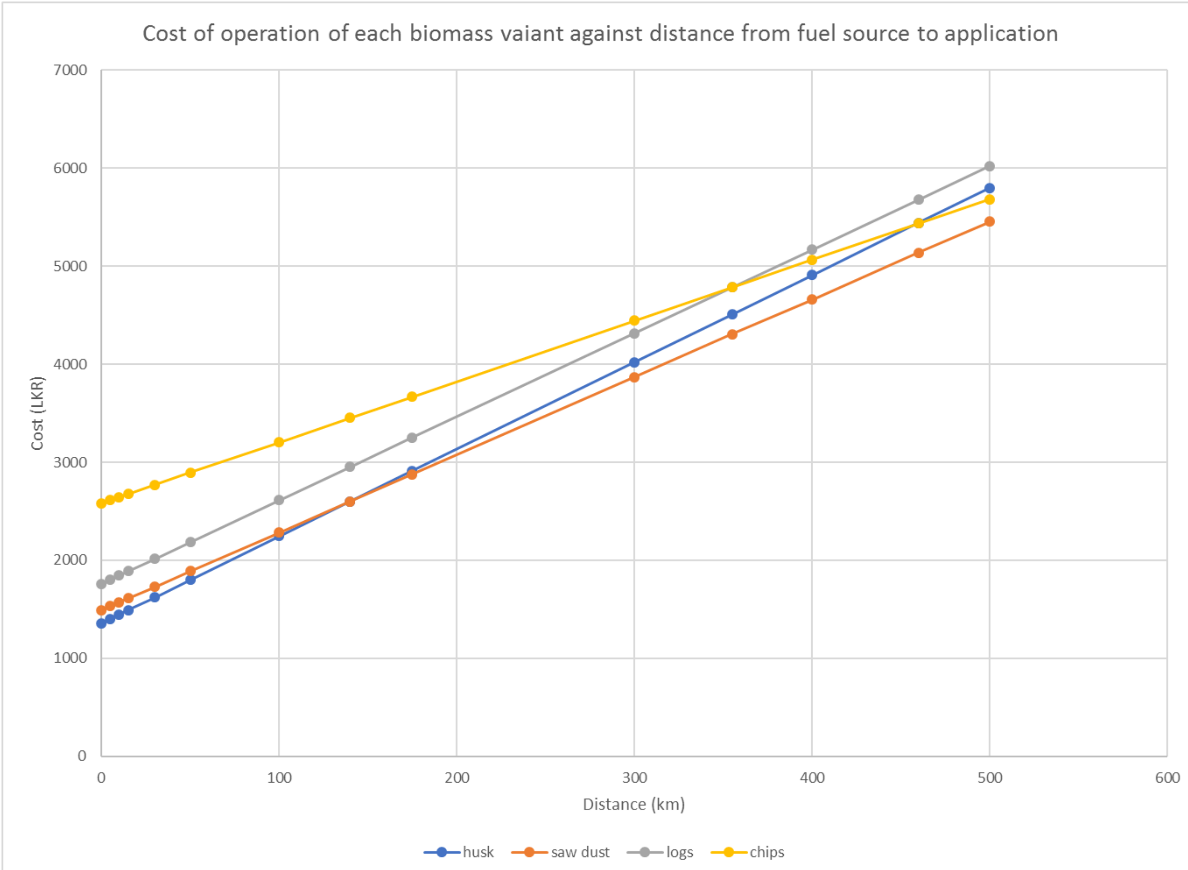


Figure 4.5: Operational cost variance of biomass variants along with distance from fuel source

5 Discussion

The study involved analysing processes involved in steam generation with respect to five fuels in Sri Lanka. The findings of the study can be used in identifying the most cost-effective biomass variant with respect to a given location and understating the life cycle impacts of steam generation via biomass compared to fossil fuel and follow sustainable measures in its supply chain.

Gross carbon emissions were taken into consideration in this study. When analysing the results, it is observed that using fossil oil leads to the largest adverse environmental impacts by far other than for notably climate change impact due to gross CO_2 emissions being considered and had it not been so, effect due to heavy oil would have been greater in this regard too. Therefore, on the whole, based on the results, it can be concluded that regardless the location of the factory in which the boiler system is placed, using biomass always leads to the minimum impact in Sri Lankan context. Sample calculation assuming transportation of 500 km from biomass fuel source to point of application accounting to 1000 km taking return journey which could be taken as the lengthiest journey considering the size of Sri Lanka, still has led to a less adverse impact than using fossil fuel as shown. Thus, constraint on opting for biomass would rely on economic factors as cost of biomass would increase along with transportation distance eventually diminishing the economic advantage of biomass usage. When analysing literature on above, it was observed most studies have by default excluded CO_2 due to claim on carbon neutrality [36]. However, claim on carbon neutrality of biomass burning is now attracting lot of debate in contrary to the earlier view [37]. While it is true, carbon is stored in plants due to photosynthesis and they emit the carbon absorbed when burnt or left to decay naturally hence the claim on carbon neutrality, this is true only when, time, a factor of utmost significance is ignored as while natural decaying takes considerable time ranging from years to decades, combustion emits the carbon instantaneously. While latter would eventually be absorbed by biosphere, the time required for the process would take a toll on environment [3], [4], [10].

During the 1820-2015 period, global mean surface temperature has already increased by about 1.0 ^{0}C. The world would fall into an irreversible status if carbon percentage reaches point of no return and taking measures to reduce them after this critical point would be fruitless therefore assuming carbon emissions due to burning biomass would be absorbed by biosphere in future undefined period thus assuming it's totally environmentally friendly is not prudish [38]. However, most policy makers have assumed carbon neutrality ignoring time factor and many studies too have assumed same further strengthening above hypothesis.

It was identified in this study, to generate 1 tonne of steam from and at 100 ^{0}C, CO_2 emissions from the fuels heavy oil, sawdust, wood chip, wood log and husk are respectively 193 kg, 381 kg, 383 kg, 389 kg and 562 kg. Gross CO_2 emissions due to biomass usage regarding energy generation being higher, compared to fossil fuel has been shown on many studies [39], [40], [41]. This study has taken gross carbon emissions incurred during combustion as a factor to show the effect in a broad picture and have identified biomass burning as a fuel is still more environmentally friendly given the context in Sri Lanka considering size and biomass availability rather than the default approach of many studies taking CO_2 emission as zero and reaching the same conclusion.

Globally however this might not be the case. European Union has set renewable energy usage target of 20% and 27% by 2020 and 2030 respectively [42]. This has made way for greater demand for biomass. In light of this many members of EU are importing biomass in the form of wood pellets due to limitation on forest resources available in European Union. Fossil fuel contributed heavily to this process considering shipping and production of wood pellets [43]. In 2016, UK alone imported 4.2 Million tonnes of wood pellets from USA [44]. This has led to much significant adverse effects to the environmental due to emissions incurred in transportation accounting as the largest contributor to the GHG emissions in the supply chain being 44% CO_2 equivalent GHG or 71,750 tonnes of same per shipment from Florida to Netherlands [43]. Therefore, while this would vary case by case, generally in the global scenario the constraint of using biomass lying in financial factors is true only to the extent total carbon neutrality and zero net CO_2 emissions are considered [45].

For similar distances, husk has been the biomass fuel with most adverse environmental impacts. There’s a significant energy loss due to 20% hot ash amount and photochemical oxidation is higher due to higher CO and NO_X levels [46]. Wood logs have performed relatively well, compared to husk usage but overall emissions and efficiency is possible to be increased with less moisture in fuel. Chips are next in line and despite its high energy consumption from grid which are produced largely by fossil fuel including coal, in Sri Lanka leading to considerable environmental emissions and related environmental damages, chips have performed well due to reduced particulate matter and higher efficiency. At extremely smaller equal distances from fuel source to point of application, chips have done better compared to sawdust, but from 15 km onwards sawdust is the more environmental friendlier fuel. Sawdust has been identified as the most environmentally friendly fuel out of the alternatives studied due to higher surface area leading to increased efficiency. However, due to presence of fine particulates matter, draft balancing is to be carefully carried out.

Environmental loads of steam generation vary depending on the method of generation employed. Although the biomass firing process is environmentally friendly and provides more cost-effective steam generation as at now, it’s not as efficient as oil fired boilers. Biomass boilers studies have had efficiency levels between 50% to 63% while heavy oil-fired boilers have had efficiency levels hovering around 81%. On the whole, environmental impact of using biomass is significantly lower than using fossil fuel. At times, it gives the illusion that biomass boilers lead to more environment impact considering air emissions but it’s observed that this is due to the higher particulate matter included in the air emissions of biomass boilers compared to oil fired boilers which is quite noticeable due to black smoke. Also, when by products are used such as rice husk, sawdust, rubber tress that have died naturally are employed to be fed to the boiler, this process is extremely environmentally friendly compared to fossil fuel fired steam generation process in Sri Lankan context.

Use of wood chip though of higher financial impact compared to other biomass categories discussed in this study, are used mainly where relatively higher-pressure steam is required which is a challenge when using wood logs due to lower surface area while in comparison sawdust and wood chip possess a higher surface area enabling them to provide heat quickly. Husk is also possible for this purpose. Thus, for lower pressure steam requirements of same transportation lengths husk is preferred and sawdust and wood log come in line thereafter respectively. For higher pressure steam requirements, husk and sawdust are preferred and use of wood chip for this purpose becomes viable when transportation cost of husk or sawdust gets higher and where wood chip would be available in rather close proximity. Also, it has to be noted some prefer to use wood chips despite higher environmental impact and cost due to lower particulate matter emission at site, which would lead to seemingly cleaner air emission due to much clearer flue gas. Wood chip, sawdust and wood log lead to higher particulate matter emissions generally, which result in relatively darker smoke from chimney giving the perception of relatively higher environmental loads.

Since using biomass leads to considerable financial savings most manufacturing facilities are turning towards biomass but selecting the type of biomass is somewhat overlooked since saving seems so attractive no matter what the biomass variant is. However, paying careful attention and selecting the most suitable biomass variant considering availability, required steam pressure, distance from potential sources would save transportation considerably and mitigate environmental impacts incurred in overall process along with enhanced financial savings. Facilities in Sri Lanka using biomass as a fuel as of now too can make use of the findings of the study to analyse their own biomass supply chains and improve the performance of them focusing on key areas that would demand attention to reduce life cycle impacts. Study reveals methodology to select the most cost effective and environmentally friendly fuel for an existing facility too which would help achieve significant cost savings, enhanced sustainability and environmental performance.

Cultivating short cycle planation to energy harvesting purpose such as gliricidia would help a country like Sri Lanka immensely relying heavily on fossil fuel which is a huge foreign exchange burden and Government of Sri Lanka has already declared gliricidia as the fourth plantation crop [47]. Gliricidia yields around 25-40 m^3 wood per ha [47]. Sri Lanka has spent 23.5% of all export earnings to import fossil fuel in 2016 having total oil imports increased by 18% accounting to total imported amount being 3,658.7 tonnes which takes a huge toll on economy [1]. Energy harvesting short cycle plantations prove to be environmentally friendly and carbon emissions would truly be carbon neutral barring carbon consumed at various other process which would be minor compared to total harvested energy, as the plants have been grown for the sole purpose of this thus carbon absorbed would actually be carbon, absorbed while ensuring conservation of existing carbon pools such as forests [47].

Further study on life cycle assessment of short cycle plantations for energy harvesting in Sri Lanka is to be carried out to assess the total impacts. Developing a bio resources map in Sri Lanka too would prove to be significant when mitigating overall life cycle emissions in biomass usage as a fuel and improve related economics.

6 Conclusions

The study is comprised of environmental and financial assessment of a biomass fired boiler, and the results of the study can be used to reduce the overall environmental and financial impacts of operation of a biomass fired boiler.

Emissions incur in transportation, electricity generation and combustion processes thus it's imperative to reduce same in order to mitigate overall environmental emissions. Study reveals that using biomass is by far the least adverse method to generate steam industrially, regardless the location in Sri Lankan context and subsequent distances from respective biomass fuel sources to point of application, and constraint of using biomass lies in the financial factors due to transportation as lengthier the journey, the costlier the delivered at site biomass would be thus negating the economic advantage of switching to biomass from heavy oil. Globally too this mostly holds true when carbon neutrality of biomass burning is considered.

Framework identified in this study for location planning of biomass boilers, includes core steps of data collection, life cycle assessment, financial analysis, sensitivity analysis and ranking of potential locations and biomass fuel variants.

Distances from wood log, husk, wood chip, and sawdust biomass sources to the point of application to equal the financial cost of heavy oil-based operation are 530 km, 554 km, 595.5 km and 604 km respectively, as per the study with respect to Sri Lanka. Husk is identified as the next least friendly fuel considered in this study followed by wood logs, chips and sawdust. Cost of generation of one tonne of steam from and at 100 ^{0}C considering 30 km distance from fuel source to point of application is respectively LKR 6277, 2770, 2016, 1730 and 1623 for the fuels heavy oil, chips, logs, sawdust, and rice husk. Though husk usage is costlier than sawdust at relatively smaller distances, at similar distances over 140 km from respective fuel source to point of application, sawdust becomes the more viable fuel. Similarly, chips become more viable compared to husk and wood logs at similar distances over 460 km and 355 km respectively. Wood log usage is found to be more expensive than that of husk or sawdust with respect to current context at similar transportation distances while operation by sawdust is found to be more economical always compared to chip usage in current context.

This study involved assessing environmental and financial aspects of wood residue. Further work needs to be extended to carrying out LCA of crops cultivated for the sole purpose of energy harvesting. Furthermore, developing a comprehensive bio resources map in Sri Lanka would help the location planning of biomass boilers significantly.

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