A LEAST COST LONG -TERM ENERGY SUPPLY STRATEGY FOR SRI LANKA, FOR THE USAGE OF PETROLEUM, COAL AND NATURAL GAS

B. C. Pasindu

128772 A

Dissertation submitted in partial fulfillment of the requirements for the Degree Master of Science in Electrical Installations

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

April 2016

DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

……………………………………….

Signature of the candidate Date:

(B. C. Pasindu)

The above candidate has carried out research for the Masters Dissertation under our supervision.

………………………………………….

Signature of the supervisor Date:

(Dr. K.T.M. Udayanga Hemapala)

………………………………………….

Signature of the supervisor Date:

(Mr. K. K. W. Siriwardana)

ABSTRACT

Long term energy sector planning is essential for a country to acquire sustainable development in all its social, economic and environmental dimensions. Further it will ensure the energy supply security of the country. Energy supply side needs to deal with technical, economic and environmental assessments of all energy supply options such as natural resources, energy imports, energy exports, etc. Also the energy supply side should follow policy directives of the government and should take all other related constraints in to account. Similarly the demand side too has to deal with the assessment of future energy needs of various consumption sectors, policy directives, etc.

Sri Lanka being a country scant of fossil fuels mainly depends on imports of petroleum and coal. Even though coal is used for electricity generation only, petroleum products are being used for variety of applications. Further, at the moment Sri Lanka does not deal with Natural Gas (NG) to fulfill its energy needs. However, potential NG fields have been found in Sri Lanka during the recent past. Therefore analyzing the viability of using NG is a timely requirement.

The software MESSAGE was used to model the energy chains associated with Petroleum, Coal and NG. The model was validated by comparing it with results of LTGEP of CEB and results of the initial natural gas utilization road map.

Under results, modernization of the existing refinery, introducing NG to the energy sector, and introducing electric vehicles have become economically viable options in the long run. Further, coal has become the most economical option for electricity generation. In addition, construction of a urea plant has become more economical than importing urea.

This model can be used in the planning stages of introducing a new technology, new energy source, or any other major change in the energy sector.

Key words: Long Term Energy Planning, Energy chain modeling, Least Cost, Technical, Economical.

ACKNOWLEDGEMENT

Foremost, I pay my sincere gratitude to Dr. K.T.M. Udayanga Hemapala and Mr. Kanchana Siriwardena who encouraged and guided me to conduct this research and on perpetration of final dissertation.

I extend my sincere gratitude to Dr. Nalin Wickramarachchi, Head of the Department of Electrical Engineering and all the lectures and visiting lectures of the Department of Electrical Engineering for the support extended during the study period.

Further, I Extend my sincere gratitude to Mr. Damitha Kumarasinghe (Director General), Mr. Gamini Herath (Deputy Director General), Mr. Chamath Goonawardena (Director - Regulatory Affairs) and Mr. Palitha Sirimal (Director - Human Resources) of Public Utilities Commission of Sri Lanka (PUCSL) for supporting me during the study period.

I would like to take this opportunity to extend my sincere thanks to following experts who gave their support to conduct my work. Mr. Raja Amaratunga (Consultant - petroleum sector expert of PUCSL), Mr. EM Piyasena (Petroleum sector expert), Mr. NRR Jayasekara (Refinery Manager of Ceylon Petroleum Corporation), Ms. AS Premakanthi (Department of Economic and Scheduling of Ceylon Petroleum Corporation) and Mr. Lathika Attanayake (Electrical Engineer of Ceylon Electricity Board).

My thanks extend to International Atomic Energy Agency for providing the software MESSAGE.

It is a great pleasure to remember the kind co-operation extended by the colleagues in the post graduate program and my friends.

Further, I would like to thank my parents, my sister and my wife Moditha who helped me to continue the studies during the entire MSc program.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
Bcm	Billion cubic meters
BTU	British Thermal Unit
CEB	Ceylon Electricity Board
CPC	Ceylon Petroleum Corporation
GWh	Giga watt hour
IAEA	International Atomic Energy Agency
kcal	kilo calorie
kWh	kilo watt hour
LECO	Lanka Electricity Company (Pvt) Ltd.
LKR	Sri Lankan Rupee
LNG	Liquefied Natural Gas
LOLP	Loss of Load Probability
LPG	Liquefied Petroleum Gas
LTGEP	Long Term Generation Expansion Plan
Mcf	Million cubic feet
MoPRE	Ministry of Power and Renewable Energy
MJ	Mega joule
MW	Mega watt
NCRE	Non-Conventional Renewable Energy
NCV	Net Calorific Value
NG	Natural Gas
O&M	Operation and Maintenance
PJ	Peta Joule
PUCSL	Public Utilities Commission of Sri Lanka
scf	Standard cubic feet
SEA	Sustainable Energy Authority
SLSEA	Sri Lanka Sustainable Energy Authority
t	Tonne (1,000 kg)
USD	United States Dollar

1 INTRODUCTION

1.1 Background

Long term energy sector planning is essential for a country to acquire sustainable development in all its social, economic and environmental dimensions. Further it will ensure the energy supply security of the country. Energy supply side needs to deal with technical, economic and environmental assessments of all energy supply options such as natural resources, energy imports, energy exports, etc. Also the energy supply side should follow policy directives of the government and should take all other related constraints in to account. Similarly the demand side too has to deal with the assessment of future energy needs of various consumption sectors, policy directives, etc.

Sri Lanka being a country scant of fossil fuels mainly depends on imports of petroleum and coal. Even though coal is used for electricity generation only, petroleum products are being used for variety of applications such as transportation, electricity generation, industrial uses, etc.

Further, at the moment Sri Lanka does not deal with Natural Gas (NG) to fulfill its energy needs. However, potential NG fields have been found in Sri Lanka during the recent past. Therefore it is worth analyzing the viability of using NG for future energy needs of Sri Lanka.

In demand side, the transport sector of Sri Lanka has just begun to move towards a new era of electrical vehicles. Effects of introducing such technologies are also should be analyzed through software, targeting maximum benefits to the country. Also NG can be used as a raw material to manufacture urea. Therefore viability of constructing a urea plant to fulfill future urea demand too can be studied.

1.2 Problem statement/justification

Presently a comprehensive study on future energy planning is being done only for the electricity sector of Sri Lanka and it is the well-known Long Term Generation Expansion Plan, prepared by Ceylon Electricity Board. LTGEP considers only the electricity sector of Sri Lanka and derives its results using optimization software named Wein Automatic System Planning (WASP). WASP facilitates only for the modeling of energy supply chain associated with electricity generation.

Results of the LTGEP are valid only for electricity sector. However, since petroleum Coal and NG can be used not only for electricity generation, but also for other applications such as transportation and industrial uses, when considering all those sectors, results of the LTGEP might become invalid.

Therefore analyzing a model covering the energy chains associated with petroleum, coal, NG and electricity will give more accurate results for the future energy sector of Sri Lanka. The software package "Model for Energy Supply Strategy Alternatives and their General Environmental Impacts" (MESSAGE) of International Atomic Energy Agency can facilitate the modeling and simulating of such model.

1.3 Motivation

The outcome of this project is to derive a least cost long term energy plan considering the usage of petroleum, coal and NG to fulfill the future energy needs of the country. It will help the decision makers of the energy sector of Sri Lanka (The Government, MoPRE, PUCSL, CEB, CPC, etc.) to minimize the overall cost and to maximize the benefits to the society.

1.4 Objectives of the study

The Objective of the study is to prepare a model to formulate the least cost long-term energy supply strategy for Sri Lanka for the Usage of Petroleum, Coal and Natural Gas. The Planning horizon is from 2016 to 2035.

1.5 Methodology

For the timely completion of the research, the work flow was arranged in the manner given below.

i. **Literature Survey**

Under the literature survey, literatures in relation to long term energy planning were referred. Some of the papers contained long term energy planning exercises where the software package MESSAGE was used. The findings of the literature survey and other related information are discussed in section 2.

ii. **Finalizing energy demand forecast for the planning horizon**

Energy demand forecast is an essential part of this research. Demand forecasts for all the energy types should be determined by a separate study and should be fed in to MESSAGE. Demand forecasts for this study were found out from published documents by responsible government institutions of Sri Lanka including CEB and MOPRE.

iii. **Identifying necessary data for modeling in MESSAGE.**

In preparation of the model, MESSAGE needs a large number of input data related to energy sector of Sri Lanka. The required input data relates to technical, financial and economic parameters of fuels, technologies and new investment options. All the input data for the model was extracted (and some were adjusted so that they are in line with the software package MESSAGE) from published documents by responsible government institutions of Sri Lanka including CEB, SLSEA, MOPRE and Central Bank of Sri Lanka. Some of the information was directly requested from respective institutions. (e.g.: information related to the petroleum refinery was directly requested from the refinery office of CPC)

iv. **Modeling.**

The energy networks related to Sri Lanka's energy sector covering coal, petroleum, NG and electricity were modeled using the software package MESSAGE. Section 4 gives a comprehensive description in this regard.

v. **Defining cases for simulation.**

A base case was developed and was run. Then another eight cases were modeled under sensitivity analysis to assess the changes in results with respective to changes in assumed future scenarios. Details on the sensitivity analysis are given under section 10.

vi. **Validation of the results**

The results obtained in this research were validated by comparing them with other published reports in relation to the energy sector of Sri Lanka. Section 12 describes the validation procedure.

1.6 Contributions

A least cost long term energy plan considering the usage of petroleum, coal and NG to fulfill the future energy needs of the country is novel concept in Sri Lanka. Even though this kind of exercise is practiced in CEB it only covers the electricity sector of the country. Therefore the results of this research will help the decision makers of the energy sector of Sri Lanka (The Government, MoPRE, PUCSL, CEB, CPC, etc.) to minimize the overall cost and to maximize the benefits. Eventually the people and the economy of the country will be benefited through implementation of the results of this study.

Further preparing a least cost long-term energy supply strategy for Sri Lanka, for the usage of petroleum, coal and natural gas in a rolling basis with a frequency of less than that of LTGEP of CEB (e.g.: Once in every 4 years) will give the decision makers of the energy sector of Sri Lanka a better platform to take decisions. Also a model like this should be used in the planning stages of introducing a new technology, new energy source or any other major change to the energy sector.

1.7 Organization

Rest of this dissertation is organized as follows.

- Section 2 summarizes the literature survey.
- Sections 3, 4, 5, 6, 7 and 8 explain the preparing of the model of the study
- Section 9 gives the results of the study
- Section 10 discusses about the sensitivity analysis
- Sections 11 and 12 discuss about the limitations of the model and the validation of the model respectively
- Sections 13 discusses on the conclusions of the research.

2 LITERATURE REVIEW

A thorough literature review was done at the outset of this research to identify the principles of a long term planning exercise related to an energy sector of a country. Further there was a need of identifying a suitable software package for modeling the energy sector of Sri Lanka. This section summarizes the information gathered through the literature review and the key findings of it.

LTGEP of CEB 2015 – 2034 – [1]

One of the main texts referred in this study was LTGEP of CEB 2015 – 2034. However, this particular report is yet to be approved by PUCSL. Even though, this LTGEP was not approved yet, the information available in it was used since they are more updated and refined compared to the previously published LTGEP (LTGEP of CEB for 2013 – 2032, [6])

2.1 General Information

The national energy system of a country is structured in a supply network (physical flow model) including energy levels (e.g.: final energy level, secondary energy level and primary energy level) and the domestic energy resources (oil, gas, uranium, coal mines, etc.) [3].

The energy levels mentioned above are linked using conversion technologies (e.g.: extraction, treatments, generation, transportation, distribution, etc.). Those technologies include both available technologies and future candidate technologies. Energy imports and energy exports (if available) are also considered at the secondary and final energy levels.

Technologies are defined by Activity & Capacity. The Activity of a technology specifies input and output energy, efficiency, variable O&M cost and the user imposed limits and bounds on activity. Capacity of a technology describes the installed capacity, investment cost, fixed O&M cost, plant factor, construction period, and economic life time, in addition to the imposed limits on the installed capacity, investment cost and penetration factor. [3]

2.2 Energy Planning Software currently used in Sri Lanka

Presently a comprehensive study on future energy planning is being done only for the electricity sector of Sri Lanka by CEB. They use the software packages given below in preparing the LTGEP [1].

a. SDDP and NCP Models - developed by PSR (Brazil)

   Stochastic Dual Dynamic Programming (SDDP) model is an operation planning tool which simulates the hydro and thermal generation system to optimize the operation of hydro system. Short term dispatch analysis is carried out using NCP software.

b. MAED Model – developed by IAEA

   The Model for Analysis of Energy Demand (MAED) is used for demand projections in the electricity sector.

c. Wein Automatic System Planning (WASP) – developed by IAEA

   Generation Planning Section uses the WASP package (WASP IV) for its expansion planning studies.

d. MESSAGE Software - developed by IAEA

   Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is used to analyze the Base Case Plan.

All these software packages are used by CEB for electricity planning. Since the software package MESSAGE can facilitate the modeling of total energy sector of a country, it was used in this research to model the energy sector in Sri Lanka especially for the usage of Coal, Petroleum and NG.

2.3 Overview for MESSAGE

Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is a model designed for the optimization of energy system covering a defined planning horizon. The model was developed by International Atomic Energy Agency (IAEA).

The software MESSAGE can be used to model and evaluate alternative energy supply strategies under certain constraints. The modeling procedure based on building the energy flows network. Energy flows networks represent the conversions of an energy starting from its primary situation (or resource situation) and ending at its final energy level. Figure 2-1 shows a typical energy flows network used in a MESSAGE model [4].

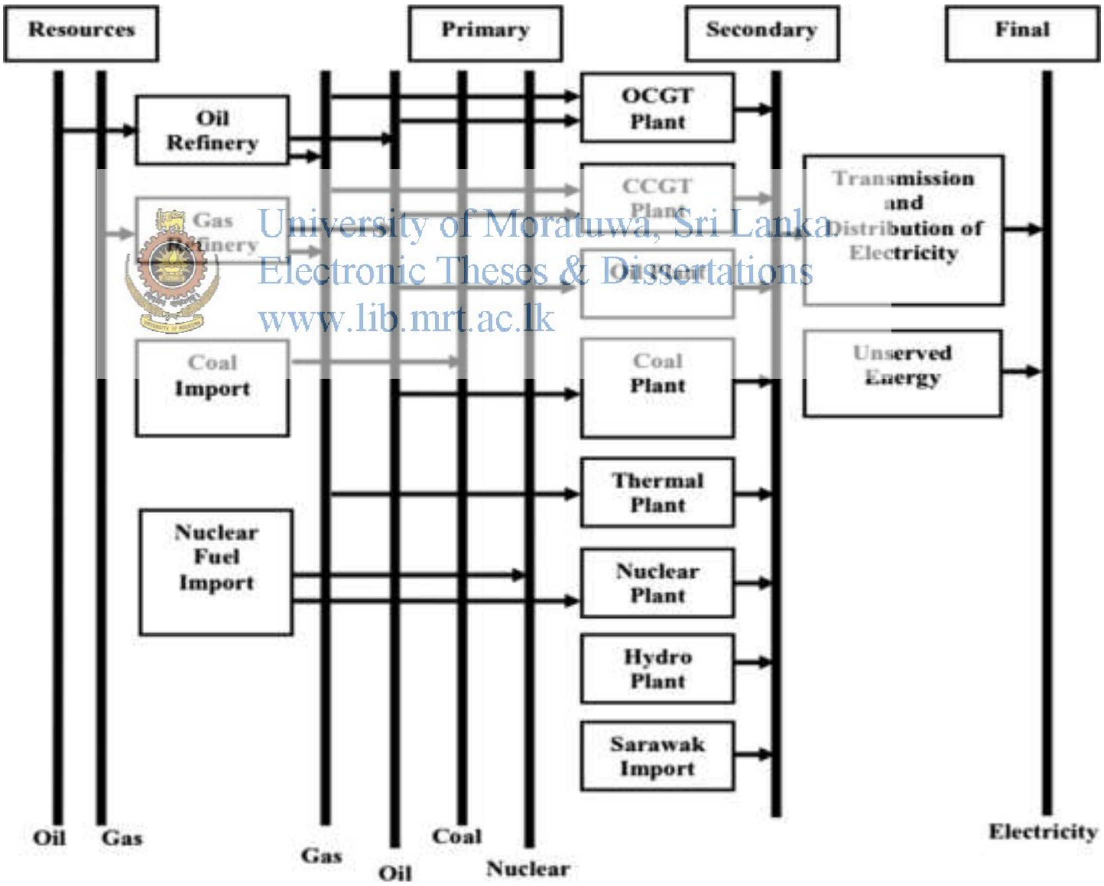

Figure 2-1: A typical energy flows network used in a MESSAGE model

In between the primary energy level and the final energy level, there can be several other energy levels. In Figure 2.1 there are four main energy levels namely

"Resources", "Primary", "Secondary" and "Final". The Final energy level represents a pre-determined energy demand, which is distributed according to the types of consumption like heat, motor fuel, electricity, etc.

Using MESSAGE, the performance of a particular technology can be compared with its alternatives on a life cycle analysis basis under different national or local conditions.

e.g.: Consider the meeting the final electricity demand of a country. This demand can be met by a number of options such as petroleum, NG, coal, etc. The software MESSAGE selects optimal solution taking into account the whole technology cost of investment operation and maintenance and fuel cost at constant price of the base year (the discount rate should be specified).

Modeling an energy system using MESSAGE can accommodate items like time frame, load region, energy levels, energy forms, technologies, resources, demand and constraints. Respective descriptions on some of the key items are given below.

<u>Time frame:</u>

The period of study of the modeling is known as the time frame. There is no need of modeling details related to each and every year in the planning horizon. As an alternative a method given below can be stated.

- The study period cover the time horizon of 2003 – 2030 with the time step of 2 years for the first model period 2003–2007, 3 years for the period 2007–2010 and 5 years for the other periods 2010 – 2030. The year 2002 represents the base year where as the year 2003 represents the starting year in the optimization process (first model year). [3]

<u>Load regions:</u>

The software MESSAGE allows modeling the energy consumption patterns of the country with respect to time / season. The seasonal variations of energy demand have to be input to the model. However if the seasonal variation of energy demand is not significant, the model can be prepared assuming uniform rate of energy consumption throughout a certain year. Given below is the method used in [3] in modeling the energy system of Syria.

- Following the present variation character of the Syrian electricity load curve observed during the last years, each year is divided into 4 seasons of different length corresponding to the weather conditions in Syria, every season is divided into 3 day types (working days, holidays and weekend days) and every day is again divided into 4 time zones of different lengths. Following this scheme each year is totally divided into 48 load regions. The length of every load region corresponds to its time share during the year, which is considered to be the same for all modeling years.

Final energy demand:

The MESSAGE methodology needs externally specified demand forecast depending on additional analysis on the demand side. Models like MAED are used for such demand forecasts. Further the econometric analysis used in LTGEP of CEB to prepare the demand forecast for electricity sector is also a well-known technique.

Energy exchange:

MESSAGE offers a possibility of modeling the energy exchange between the national system and other external system at primary or secondary level. This feature enables the comparative assessment between internal consumption or exporting of an energy carrier and importing another alternative to comply with the demand taking into account the energy system structure and availability of national resources. [3]

Energy Levels:

A description on energy levels is given in 2.2 Overview for MESSAGE. Further the Figure 2.1 elaborates on energy levels and connection of them using technologies.

2.4 Nature of Results of a MESSAGE Model

Some of the key results of the model in relation to [3] are given below. It gives an idea about the output which is produced by the software package MESSAGE.

Figure 2-2 gives an idea about the energy values in future year with respect to the pre-defined energy levels throughout the planning horizon. [3]

Figure 2-3 is a table representing the output values of the model. It indicates the “Shares of secondary energy by fuel type (before electricity generation)” in relation to [3].

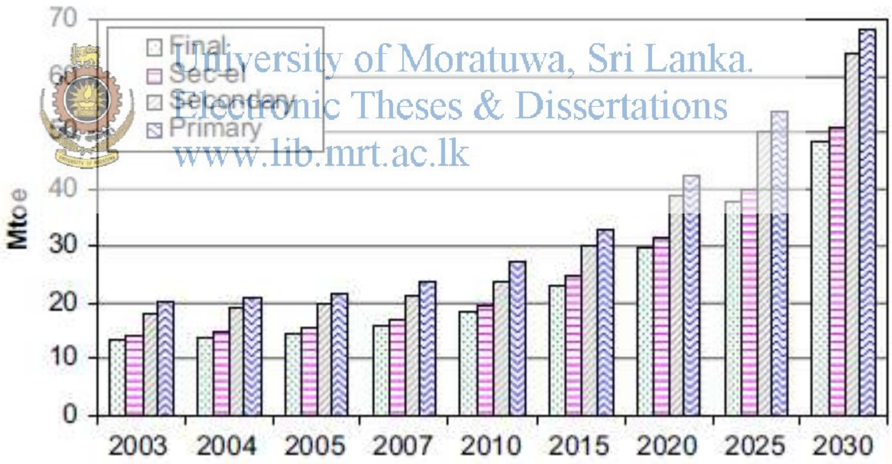

Figure 2-2: Development of energy flow in the Syrian energy system. Source [3]

Table 4
Shares of secondary energy by fuel type (before electricity generation).

	2003	2004	2005	2007	2010	2015	2020	2025	2030
Diesel (%)	32.3	32.2	33.0	32.5	27.3	28.6	26.4	28.7	30.3
Gasoline (%)	6.9	6.8	6.9	7.1	7.1	7.5	7.3	7.3	7.4
HFO (%)	23.2	25.3	24.7	16.0	20.9	22.3	28.0	30.2	34.2
LPNG (%)	4.4	4.4	4.5	4.6	4.7	4.9	4.7	4.7	4.6
NG (%)	23.1	22.1	21.6	30.9	30.9	27.9	20.1	15.7	12.2
Asphalt (%)	3.7	3.6	3.6	3.6	3.4	3.3	2.8	2.6	2.3
Heavy products (%)	2.3	2.2	2.2	2.0	2.5	2.1	2.1	1.6	1.3
Hydro+wind (%)	3.1	2.5	2.4	2.1	2.0	1.7	1.3	1.0	0.8
Traditional	1.0	1.0	1.0	1.0	0.9	0.9	0.7	0.6	0.5
Solar	0.0	0.0	0.0	0.2	0.4	0.8	2.0	2.0	2.0
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	4.6	5.7	4.5
Total annual (Mtoe)	18.13	19.00	19.41	20.37	23.37	29.72	39.09	50.26	64.54

Figure 2-3: Shares of secondary energy by fuel type (before electricity generation). Source [3]

<u>Sensitivity Analysis:</u>

Sensitivity analysis is an essential part of a long term energy plan. The objective of doing a sensitivity analysis is to cover the various sources of uncertainty resulting from mathematical simplification (for instance linearization of various parameters), adopted assumptions and estimations made to prepare some input data.

The results of sensitivity analysis are very useful for policy formulation of energy sector as it help in identifying the weight of different economic, technical, financial and environmental dimensions and their implications [3].

2.5 Importance of Environmental Factors in Energy Planning

The effect of environmental factors is vital in energy planning. As a an example, for two decades, CEB had prepared and planned for coal – fired power plants to satisfy the foreseen electricity demand of the country. But these plans had stalled as a result of local concerns over environmental and possible social impacts [5]. Eventually CEB could build coal power plants and presently they are in operation. However, there was a huge delay in building them.

Some countries like Sweden the country's energy policy is incorporated with factors related to climate change and other environmental factors. During 2009, Parliament approved a new climate and energy policy on the basis of the Government's Bills No. 2008/09:162 and 2008/09:163. The two bills go under the common name of "A joint climate and energy policy", says the energy policy of Sweden [7]. This shows the current trend of the world towards energy planning, incorporating the environmental issues.

The report "The Hidden Costs of Electricity: Comparing the Hidden Costs of Power Generation Fuels" [14] discusses about the hidden costs in the electricity sector. The list of hidden costs includes "Planning and cost risk, Subsidies and tax incentives, Climate change impacts, Air pollution impacts, Water impacts, Land impacts, and other impacts".

MESSAGE allows modeling the impacts on environmental implications due to the energy sector activities. The paper [2] examines the global impacts of a policy that internalizes the external costs (related to air pollution damage, excluding climate costs) of electricity generation using a combined energy systems and macroeconomic model. Starting point are estimates of the monetary damage costs for SO_2, NO_X, and particulate matter per kWh electricity generated, taking into account the fuel type, sulfur content, removal technology, generation efficiency, and population density. Internalizing these externalities implies that clean and advanced technologies increase their share in global electricity production [2].

However, to internalize these costs into a MESSAGE model needs an initial study on environmental aspects.

2.6 Electric Vehicles

During the last few years Sri Lankans have been using electric vehicles, especially cars. The technological advancements in the field of electric vehicles have contributed for this popularity. Since the people tend to buy electric vehicles, it can be thought that they are more economical in the individual level over the conventional gasoline/diesel powered cars. However, the lack of a policy at the national level for phasing in electric vehicles is a prevailing problem in Sri Lanka.

No other country in the world has a higher share of electric cars than Norway [15]. The conclusion of the survey on Norwegian electric vehicle users states that electric vehicles, in most cases, replace the use of traditional cars with emissions, not other environmental modes of transport. They (the users) need strong incentives to move to new and unknown technology to reduce emissions and traffic noise [15].

The main conclusion from the Norwegian experience, for other countries to learn from, is that the purchase price for an electric vehicle must be competitive with a similar car model. In Norway, this is achieved with a combination of high taxes on cars with high emissions and zero tax for zero emissions cars [15].

3 MESSAGE MODEL OF SRI LANKAN ENERGY SYSTEM

3.1 Present Situation of Sri Lanka's Energy Sector

The Energy Balance of Sri Lanka is annually prepared by Sri Lanka sustainable Energy Authority. The Energy Balance gives an analysis of energy sector performance of Sri Lanka during the considered year. The latest available Energy Balance prepared by SLSEA is the "Sri Lanka Energy Balance 2014" Table 3-1 shows a breakdown of total energy demand of the country with respect to the energy source.

Table 3-1: Breakdown of total energy demand of the country

Energy Source	Demand in PJ	Percentage
Biomass	205	53%
Petroleum	136	36%
Coal	3	1%
Electricity	40	10%
Total	383	

Figure 3-1 depicts the information in Table 3-1.

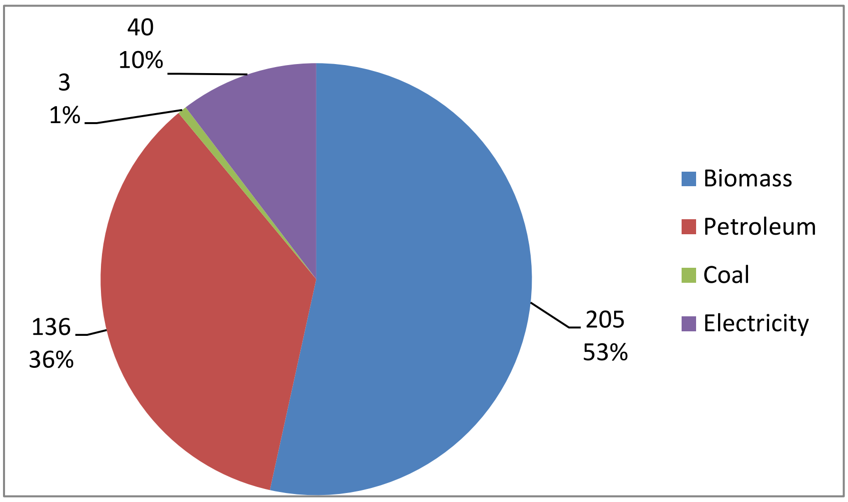

Figure 3-1: Breakdown of total energy demand of the country

53% of the total energy demand of the country is fulfilled by biomass. Usage of biomass is predominant in industrial, household and commercial sectors. Petroleum which accounts for 36% of the total energy demand of the country is used in transport, industrial, household and commercial sectors.

There is a small share for coal (1%) mainly in industrial sector. However this does not depict the usage of coal for generation of electricity.

Given below is a list of energy sources available in the international market, which can be used to fulfill energy needs in Sri Lanka.

a. Petroleum
b. Coal
c. Natural Gas (Both NG and LNG)
d. Nuclear Energy

Currently Nuclear Energy and NG is not used to fulfill energy needs in Sri Lanka. Further, new energy supply technologies such as biofuels and hydrogen and electricity storage have emerged as alternatives to the conventional technologies mentioned above. However, use of these technologies for energy supply purposes is still limited in Sri Lanka. [11]

3.2 Natural Gas – An Option for Future Energy Needs of Sri Lanka

Using NG as an option for Sri Lanka's energy needs has been discussed during the recent past. Some agencies have done studies on it and a few reports can be found in relation to NG usage in Sri Lanka.

Further CEB has been considering about electricity generation plants run by LNG in their LTGEP during the recent past. However, the results of the LTGEP suggest that LNG plants are not viable for electricity generation (however, under a few sensitivity cases, LNG plants have become viable).

The reason for importing LNG rather than NG is due to the longer distance of Sri Lanka from the countries having NG resources like Bangladesh. The supply of gas from Bangladesh via an offshore pipeline will not be economic at existing pricing structures, and would be at best marginal with lower export gas prices than those prevailing in JV agreements in Bangladesh. [9].

A major breakthrough in this discussion was taken place due to the discovery of natural gas deposits in the sea off the Kalpitiya Peninsula. Following the discovery of NG in Sri Lanka, studies were undertaken to explore ways and means of using this new energy resource in Sri Lanka. “Initial Natural Gas Utilization Road Map” [10] prepared by Sri Lanka Carbon Fund (Pvt) Ltd outlines a strategy for the development of natural gas industry in Sri Lanka. This report has been submitted to the Petroleum Resources Development Secretariat in October 2014. The information provided in this report has been used in preparing the MESSAGE model for Sri Lanka.

NG is popular as a clean source of energy. It is the preferred fuel in the domestic sector for spatial heating and cooking, in the industrial sector for generating thermal energy and in the power and transport sectors for generating motive power. [10]

Today, natural gas has a share of about 21-22% in the generation of both the total energy and electricity, and the outlook is that this share will grow in the future, particularly in Asia with an increasing demand in India, China and Japan. [10] Further NG can be used as a feedstock in industries such as manufacturing of urea and methanol.

3.3 Selection of Energy Networks to the Model

Even though biomass is the predominant energy source of the energy sector of Sri Lanka (contributes 53% of the total energy demand), it was not considered under this model due to the reasons given below.

a. Still the commercial value of biomass is not significant with respect to the other energy sources / fuels included in this study.
b. Biomass market is not controlled by government or any other regulatory body of Sri Lanka. Therefore results of this study cannot be applied on biomass market.

Therefore energy flows networks related to biomass were not considered under this study. Therefore only the energy networks associated with the sources given below were considered under this study.

a. Petroleum
b. Coal
c. Natural gas and liquefied natural gas
d. Nuclear (for electricity generation)

4 BUILDING THE ENERGY SUPPLY NETWORKS – ENERGY LEVELS

Three main energy levels were taken into consideration in building the energy supply networks of Sri Lanka. Further, in this study the electricity generation from Hydro power plants and NCRE power plants has not been considered. The rationale behind this is described in Section 5.4 "Demand Forecast - Electricity".

1. Primary energy level
2. Secondary energy level
3. Final energy level

4.1 Primary energy level

Primary energy level contains the followings.

a. Coal

   Two types of coal are considered under this. They are "Coal West-South" and "Coal Trinco". These two cases have been taken in LTGEP (2015-2034) too. Even though the chemical composition is the same in both these types, its cost differs due to the fact that "Coal West South" possesses a barging cost. Thereby cost of "Coal West-South" is higher than that of "Coal – Trinco".

b. Crude Oil
c. LNG (Imported)
d. NG (Extracted indigenously)
e. Nuclear

4.2 Secondary energy Level

Secondary energy level includes the followings

a. Refined petroleum products

   Given below is a list of refined petroleum products considered in this model

i. Diesel

ii. Gasoline

iii. Fuel oil (Both FO 180 and FO 380 were aggregated)

iv. Avtur

v. Naphtha

vi. LPG

vii. Kerosene

b. Electricity (Generation)

4.3 Final energy level

Components of the final energy level are given below.

a. Avtur
b. Coal (Industrial)
c. Diesel (Household and Commercial)
d. Diesel (Transport)
e. Diesel (Industrial)
f. Fuel oil (Household and Commercial)
g. Fuel oil (Industrial)
h. Kerosene (Household and Commercial)
i. Kerosene (Industrial)
j. LPG (Household and Commercial)
k. LPG (Industrial)
l. NG (Household and Commercial)
m. NG (Industrial)
n. NG (Transport)
o. Electricity (Transport)
p. Electricity (Distribution)
q. Urea

Even though urea is not energy, it was included in to the energy flows network by comprising it into the final energy level. The methodology of including it in to the energy flows network is described in section 5.

5 BUILDING THE ENERGY SUPPLY NETWORKS – DEMAND FORECAST

MESSAGE needs demand forecasts for energy forms included in Final energy level. The demand forecast has to be specified externally depending on a suitable analysis on the demand side. This section describes the demand forecasts used in the research.

5.1 Demand Forecast – Industrial Sector

Demand forecast for industrial sector is available with the report Initial Natural Gas Utilization Road Map [10]. Table 5-1 shows the demand forecast for industrial sector used in the model. Industrial demand forecast includes the individual forecasts for kerosene, LPG, fuel oil, diesel and coal. Electricity demand of the industrial sector is separately considered under electricity demand forecast.

Table 5-1: Demand forecast – Industrial sector

All the values are in MWyr (1MWyr = 0.11 GWh)						
Year	**Kerosene**	**LPG**	**F Oil**	**Diesel**	**Coal**	**Total**
2016	40	51	203	98	107	499
2017	42	54	204	99	112	511
2018	45	57	205	100	116	524
2019	48	61	206	101	121	537
2020	51	65	207	101	126	550
2021	55	69	208	102	131	565
2022	59	73	209	103	136	580
2023	63	78	209	104	142	596
2024	67	82	210	105	147	612
2025	72	88	211	106	153	630
2026	76	93	212	107	159	648
2027	81	99	213	108	166	667
2028	87	105	214	109	172	687
2029	93	112	215	110	179	709
2030	99	119	216	111	186	730
2031	106	126	217	112	194	754
2032	113	134	218	113	201	778
2033	120	143	218	114	210	805
2034	128	151	219	115	218	832
2035	137	161	220	116	227	861

The report [10] discusses about two scenarios (namely NG1 and NG2) under which the introduction of NG can be done to the industrial sector. Under NG1 scenario, low level of penetration of NG has been assumed, while a high level has been assumed under NG2 scenario. [10]

In this analysis the viability of scenario NG1 was tested with the MESSAGE model. Table 5-2 shows the amounts of energy which can be fulfilled by NG in relation to each energy form.

Table 5-2: Forecast for amounts of energy to be fulfilled by NG in the industrial sector

All the values are in MWyr (1MWyr = 0.11 GWh)					
	Kerosene to NG	**LPG to NG**	**Fuel Oil to NG**	**Diesel to NG**	**Total**
2023	2	2	5	3	11
2024	3	4	11	5	23
2025	5	7	16	8	36
2026	8	9	21	11	49
2027	10	12	27	13	62
2028	13	16	32	16	76
2029	16	19	37	19	91
2030	19	23	42	22	107
2031	23	28	48	25	123
2032	27	33	53	27	140
2033	32	38	58	30	159
2034	37	44	64	33	178
2035	43	50	69	36	198

It can be seen that NG is not proposed to use as a substitute for coal, but for all the other energy forms.

Figure 5-1 depicts the proposed demand forecast for industrial sector with the introduction of NG from 2023 onwards.

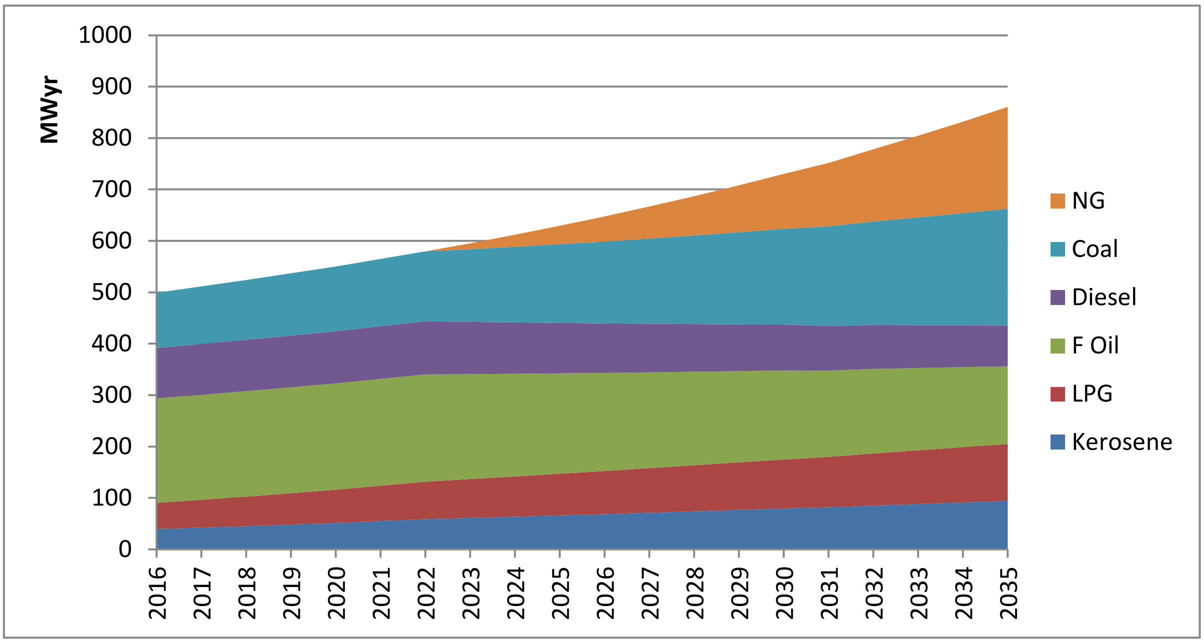

Figure 5-1: The proposed demand forecast for industrial sector with the introduction of NG

5.2 Demand Forecast – Transport Sector

Demand forecast for transport sector is available with the report Initial Natural Gas Utilization Road Map [10]. Table 5-3 shows the demand forecast for diesel and gasoline used in the model.

Table 5-3: The demand forecast for diesel and gasoline in transport sector

All the values are in MWyr (1MWyr = 0.11 GWh)			
	Gasoline	Diesel	Total
2016	1,490	2,572	4,062
2017	1,617	2,700	4,317
2018	1,744	2,829	4,573
2019	1,893	2,970	4,863
2020	2,042	3,111	5,153
2021	2,218	3,265	5,483
2022	2,394	3,418	5,812
2023	2,599	3,588	6,187
2024	2,803	3,758	6,561
2025	3,043	3,945	6,987
2026	3,282	4,132	7,414
2027	3,563	4,336	7,899
2028	3,843	4,541	8,384
2029	4,173	4,768	8,941
2030	4,503	4,994	9,497
2031	4,888	5,242	10,130
2032	5,273	5,489	10,762
2033	5,724	5,762	11,485
2034	6,174	6,034	12,208
2035	6,703	6,334	13,037

The report [10] discusses about two scenarios (namely NG1 and NG2) under which the introduction of NG can be done to the transport sector. Under NG1 scenario, low level of penetration of NG has been assumed, while a high level has been assumed under NG2 scenario. [10]

In this analysis the viability of scenario NG1 was tested with the MESSAGE model. Table 5-4 shows the amounts of energy which can be substituted by NG in relation to gasoline and diesel.

Table 5-4: The amounts of energy which can be substituted by NG in relation to gasoline and diesel – Transport sector

All the values are in MWyr (1MWyr = 0.11 GWh)			
	Gasoline to NG	Diesel to NG	Total
2023	52	72	124
2024	112	151	263
2025	182	236	419
2026	263	330	593
2027	356	433	790
2028	461	544	1,005
2029	583	666	1,249
2030	720	799	1,519
2031	878	942	1,820
2032	1,055	1,098	2,153
2033	1,256	1,265	2,521
2034	1,482	1,448	2,930
2035	1,740	1,644	3,383
2036	2,025	1,857	3,881
2037	2,351	2,085	4,436
2038	2,711	2,334	5,045
2039	3,120	2,597	5,717
2040	3,570	2,886	6,456

Plan for introducing electricity for transport sector

Electric vehicles have been becoming popular among Sri Lankans. However there has not been any proper plan or a cost benefit analysis in national level for introducing electric vehicles. Therefore it is hard to understand if introducing electric vehicles is beneficial to the national economy of the country. (In individual level it seems to be beneficial and that is why people tend to use electric vehicles.)

To analyze the viability of introducing electric vehicles, a plan was prepared and fed in to the model. The plan is as follows.

- <u>Plan for substituting electric vehicles for gasoline vehicles:</u>
  In 2020, 5% of the total forecasted demand from gasoline vehicles to be substituted by electric vehicles. It will gradually be increased to 35% in 2035.

- <u>Plan for substituting electric vehicles for diesel vehicles:</u>
  In 2025, 5% of the total forecasted demand from diesel vehicles to be substituted by electric vehicles. It will gradually be increased to 25% in 2035.

Table 5-5 shows the resulting plan for transport sector.

Table 5-5: Plan for introducing NG for transport sector

All the values are in MWyr (1MWyr = 0.11 GWh)					
	Gasoline	**Diesel**	**NG**	**Electricity substituting gasoline**	**Electricity substituting diesel**
2016	1,490	2,572	-	-	-
2017	1,617	2,700	-	-	-
2018	1,744	2,829	-	-	-
2019	1,893	2,970	-	-	-
2020	1,940	3,111	-	102	-
2021	2,063	3,265	-	155	-
2022	2,179	3,418	-	215	-
2023	2,255	3,509	124	286	-
2024	2,326	3,607	263	364	-
2025	2,398	3,503	419	456	197
2026	2,462	3,512	593	558	289
2027	2,524	3,506	790	677	390
2028	2,575	3,497	1,005	807	499
2029	2,622	3,472	1,249	960	620
2030	2,655	3,445	1,519	1,126	749
2031	2,680	3,398	1,820	1,320	891
2032	2,689	3,348	2,153	1,529	1,043
2033	2,680	3,274	2,521	1,774	1,210
2034	2,655	3,198	2,930	2,037	1,388
2035	2,604	3,094	3,383	2,346	1,584

Figure 5-2 depicts the proposed demand forecast for transport sector with the introduction of NG and electricity.

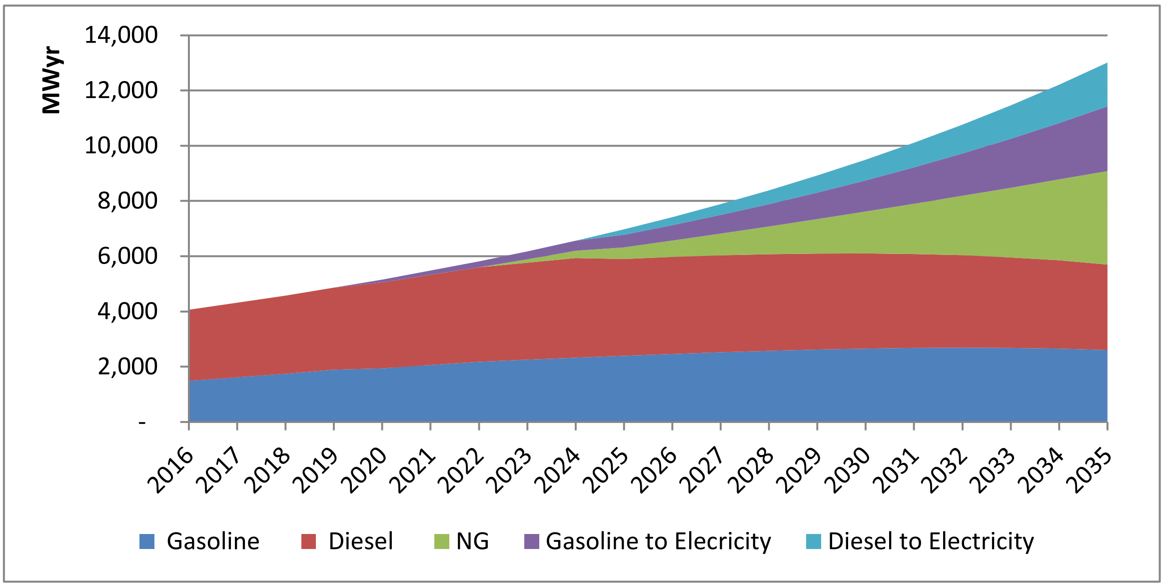

Figure 5-2: The proposed demand forecast for transport sector with the introduction of NG and electricity

Efficiency of electric vehicles is better than that of oil powered vehicles. This effect is taken into consideration in the model. Table 5-6 describes the calculation.

Table 5-6: Calculations on internalizing the efficiency of electric vehicles into the model

Description	Value	Unit	Reference
Fuel economy of an Electric car	2.18	km per MJ	[8]
Fuel economy of a gasoline car	21.70	km per liter	
Density of gasoline	0.76	kg/liter	[11]
Fuel economy of a gasoline car	28.52	km per kg	
Calorific value of gasoline	43.82	MJ/kg	[11]
Fuel economy of a gasoline car	0.65	km per MJ	
Efficiency of an electric car : Efficiency of a gasoline car	3.35	ratio	

This ratio of efficiencies was taken in to consideration in the MESSAGE model. Further the same ratio was taken for diesel vehicles too.

The sources/fuels which can be used in transport sector such as, hydrogen, compressed air and biogas are excluded in this study.

5.3 Demand Forecast – Household and Commercial Sectors

Demand forecast for household and commercial sectors is available with the report Initial Natural Gas Utilization Road Map [10]. Table 5-7 shows the demand forecast for household and commercial sector used in the model.

Demand for household and commercial sectors includes the individual forecasts for kerosene, LPG, fuel oil and diesel. Electricity demand forecast for household and commercial sector was taken into account under electricity demand forecast.

Table 5-7: The demand forecast for household and commercial sector

All the values are in MWyr (1MWyr = 0.11 GWh)				
	Kerosene	LPG	F Oil	Diesel
2016	189	357	43	21
2017	192	383	45	22
2018	196	409	47	23
2019	200	439	49	24
2020	204	469	51	25
2021	208	503	53	27
2022	212	537	55	28
2023	217	575	57	29
2024	221	614	59	31
2025	226	659	62	32
2026	230	703	64	34
2027	235	754	67	36
2028	239	805	69	37
2029	244	863	72	39
2030	249	922	75	41
2031	254	989	78	43
2032	259	1,055	81	45
2033	264	1,132	85	48
2034	270	1,208	88	50
2035	275	1,296	91	53

The report discusses about two scenarios (namely NG1 and NG2) under which the introduction of NG can be done to the household and commercial sectors.

Under NG1 scenario, low level of penetration of NG has been assumed, while a high level has been assumed under NG2 scenario. [10]

In this analysis the viability of scenario NG1 was tested with the MESSAGE model. In this scenario a plan is given for introducing NG as a substitution of the part of LPG demand. Table 5-8 shows the details in relation to the given plan.

Table 5-8: Plan for introducing NG as a substitution for LPG – Household and commercial sector

All the values are in MWyr (1MWyr = 0.11 GWh)		
	LPG	NG
2016	357	0
2017	383	0
2018	409	0
2019	439	0
2020	469	0
2021	503	0
2022	537	0
2023	575	0
2024	614	0
2025	659	0
2026	675	28
2027	692	60
2028	708	97
2029	724	138
2030	737	184
2031	750	237
2032	760	296
2033	768	361
2034	773	435
2035	776	517

Figure 5-3 depicts the proposed demand forecast for household and commercial sectors with the introduction of NG.

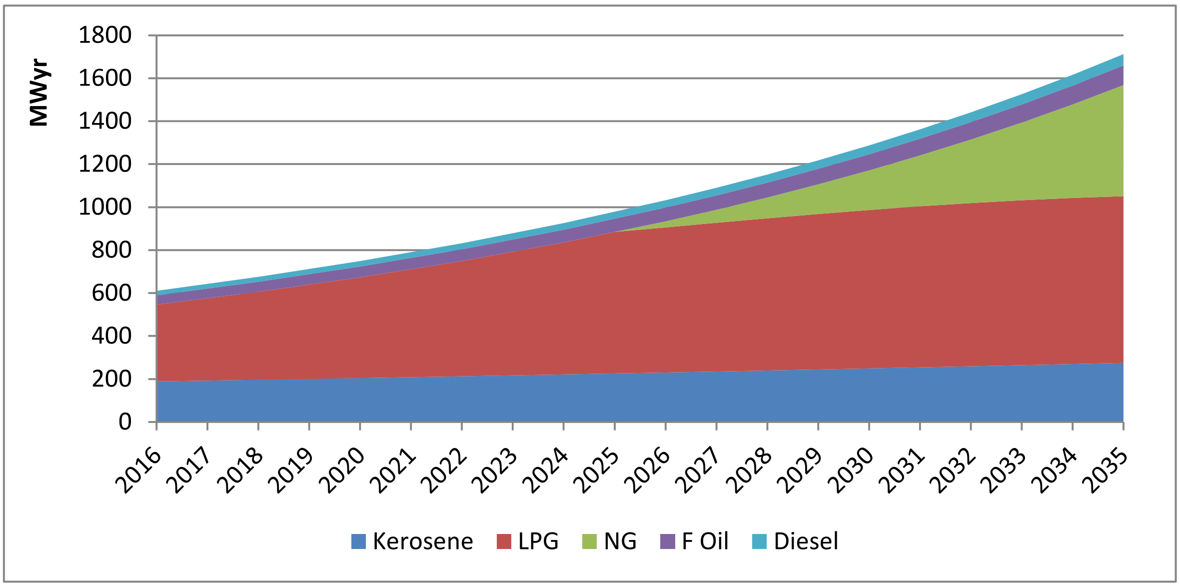

Figure 5-3: Demand forecast for household and commercial sectors with the introduction of NG

5.4 Demand Forecast - Electricity

LTGEP (2015-2034) of CEB contains a demand forecast for the electricity sector. The forecast is based on an econometric model. The demand forecast available with the LTGEP (2015 – 2034) was adjusted so that it suits the MESSAGE model. The adjustment done and the reasons for doing so are described below.

1. In this study, electricity generation from hydro plants is not considered. The reasons are given below.
   a. Since electricity from hydro plants is always cheaper than that from thermal plants, there is no competition for hydro plants with Coal, Petroleum or NG. First option should be hydro.
   b. Finding the electricity demand forecast which should be fulfilled by thermal plants, can be derived through the information given in LTGEP (2015 – 2034).

The equation given below was used to derive the electricity demand forecast which should be fulfilled by thermal plants [1]. A reserve margin of 20% was included in to the demand forecast.

$$ED_{th}(n) = 1.2ED(n) - [EH\ (n) + ENC(n)]$$

ED_{th} *(n)* = Electricity demand which should be fulfilled by thermal plant in year n

ED (n) = Forecasted electricity demand for year n

EH (n) = Expected electricity generation from hydro plants in year n

ENC (n) = Expected electricity generation from NCRE plants in year n

ED (n), EH (n) and ENC (n) are available in LTGEP (2015 – 2034) for all the years under planning horizon.

Table 5-9 shows the resulting values of ED_{th} *(n)* for the planning horizon.

Table 5-9: Calculations on electricity demand forecast to feed into the model

All the values are in MWyr (1MWyr = 0.11 GWh)				
Year	ED	1.2ED	EH+ ENC	ED_{th}
2016	1,536	1,843	748	1,095
2017	1,640	1,968	819	1,149
2018	1,752	2,102	889	1,213
2019	1,871	2,246	925	1,321
2020	1,999	2,399	1,007	1,392
2021	2,098	2,517	1,042	1,476
2022	2,201	2,642	1,083	1,558
2023	2,310	2,772	1,111	1,662
2024	2,425	2,910	1,141	1,769
2025	2,546	3,055	1,167	1,889
2026	2,674	3,208	1,181	2,027
2027	2,808	3,370	1,211	2,159
2028	2,949	3,538	1,234	2,304
2029	3,094	3,712	1,266	2,446
2030	3,243	3,892	1,290	2,602
2031	3,397	4,076	1,308	2,769
2032	3,554	4,265	1,334	2,931
2033	3,717	4,461	1,364	3,097
2034	3,888	4,665	1,398	3,267
2035	4,065	4,878	1,451	3,428

5.5 Demand Forecast - Urea

NG can be used to produce urea. Since NG is plays a major role in this study, producing urea is taken in to consideration. Further the report “Initial Natural Gas Utilization Road Map [10]” discusses about building urea plants to cater the urea demand in future. The said report gives a demand forecast for urea under two scenarios namely NG1 and NG2. The demand forecast and other details related to the scenario NG1 was taken in to consideration in this study.

The report “Initial Natural Gas Utilization Road Map [10]” discusses about manufacturing of Ammonium Sulphate and Dimethyl Ether by NG and it gives demand forecasts for them too. However, they were not taken in to consideration in this analysis since the amounts of them in the demand forecast are very small compared to that of urea.

The MESSAGE model deals with energy flow networks. Therefore it does not directly support to build up a network where NG is used for manufacturing urea. To mitigate this mismatch an NG equivalent for urea was taken in to consideration. Next part of this section describes the methodology of adaptation of NG equivalent for urea.

Table 5-10: NCV value of NG – Unit conversions

Description	Value	Unit	Remarks
NCV of NG	37,255	kJ/m3	[10]
NCV of NG	1,054.942384	kJ/cf	1 cf = 0.0283168 m3
NCV of NG	1.05×10^{12}	J/Mcf	

Using the NCV of NG, the equivalent given below is derived.

$$1 \times 10^{15} \text{ J/yr} = 2.6 \text{ Mcf/day}$$

Using this equivalent, the NG demand was converted in to energy. Then the model was fed with those energy values to reflect the urea demand forecast. Table 5-11 shows the equivalent energy values along with NG demand forecast. Urea manufacturing is planned to start from 2025 onwards.

Table 5-11: The equivalent energy values along with NG demand forecast

	NG requirement	
	NG requirement (Mcf/day)	Energy (MWyr/yr)
2025	63	768
2026	63	768
2027	63	768
2028	63	768
2029	63	768
2030	79	961
2031	79	961
2032	79	961
2033	79	961
2034	79	961
2035	95	1,153

6 BUILDING THE ENERGY SUPPLY NETWORKS – TECHNOLOGIES

Technologies are used for connecting two energy levels which results either in conversion the energy form (e.g. producing electricity from gas) or just energy transforming or distributing [3]. To be consistent with the LTGEP (2015-2034) of CEB it was taken as 1 USD = 131.55 LKR in all the calculations.

The MESSAGE model prepared under this research includes both existing and future candidate technologies. Each technology is defined by activity and capacity variables. Given below is a briefing on Activity and Capacity of a certain technology.

1. Activity:

   Activity specifies input and output energy, efficiency, variable O&M cost and the user imposed limits on activity.
2. Capacity:

   Capacity describes the installed capacity, investment cost, fixed O&M cost, plant factor, construction period, and economic life time, investment cost, etc.

Table 6-1 describes the names and the descriptions of input variables fed in to the model along with their units.

Table 6-1: The names and the descriptions of input variables

Variable	Unit
Main input	MWyr
Main output	MWyr
Efficiency	Share
variable O&M cost	USD/kWyr
Plant factor	Share
Minimum utilization	Share
Plant life	Years
Investment cost	USD/kW
Construction time	Years
Fixed cost	USD/kW/Year
Unit size	MW

Further MESSAGE allows the user to define more than one activity of a technology for alternative mode of operation. The user can impose limits or bound on technology such as maximum capacity that can be built on a technology, or maximum and minimum levels of output from a technology. [3]

This section describes the technologies (both existing and candidate) used in the model.

6.1 Technologies – Existing Refinery

Details related to the existing refinery were taken from the refinery office of CPC. Given below are the values calculated using the received data from the refinery office, along with respective assumptions and calculations.

Table 6-2 shows the shares of products of the refinery.

Table 6-2: Shares of products of the existing refinery – (energy-wise)

Product	Energy (GWh) from 2000 - 2013 [11]	Share
LPG	3,103	0.01
Petrol	32,264	0.10
Avtur	21,250	0.06
Kerosene	21,474	0.07
Naphtha	17,230	0.05
Diesel	93,439	0.28
Fuel Oil	115,257	0.35
Total Energy input from crude oil	328,213	

In MESSAGE the technologies are modeled with respect to the output. Since the refinery has more than one output, a primary output should be selected. The maximum share of the outputs is owned by fuel oil and therefore it is selected as the primary product. Therefore the capacity of the refinery was calculated based on the output of fuel oil. All the other outputs are secondary outputs and they were too fed in to the model.

Table 6-3 shows the information related to fixed cost and variable O&M cost of the refinery for the period 2012-2014. Average annual costs were calculated in USD terms.

(1 USD = 131.55 LKR)

Table 6-3: Information related to fixed cost and variable O&M cost of the existing refinery

Year	Total Cost	Variable O&M	Fixed
2012 (in LKR)	3,497,128,672	664,917,724	2,832,210,948
2013 (in LKR)	3,660,880,487	784,933,927	2,875,946,560
2014 (in LKR)	3,235,473,803	69,299,805	3,166,173,998
AVERAGE (LKR)	3,464,494,321	506,383,819	2,958,110,502
AVERAGE (USD)	26,335,951	3,849,364	22,486,587

Table 6-4 describes the calculation of the "Capacity of the refinery", "Fixed cost" and "Variable O&M cost".

Table 6-4: Summary on calculation for variables related to existing refinery

Description	Value	Unit	Remarks
Annual energy output from fuel oil	8,233	GWh	[11]
Annual energy output from fuel oil	939,801	kWyr	
Capacity of the refinery	940	MW	Assuming a uniform production throughout the year
Fixed cost	23.93	USD/kW/Year	
Variable O&M cost	4.10	USD/kWyr	

Table 6-5 gives a summary of the variables fed in to the model with respect to the existing refinery.

Table 6-5: Input variables – existing refinery

Variable	Value	Unit
Main input	Crude oil	
Main output	Refer Table 14	
Efficiency	0.35	Share
variable O&M cost	4.10	USD/kWyr
Plant factor	1	Share
Minimum utilization	0	Share
Plant life	35	Years
Investment cost	0	USD/kW
Construction time	0	Years
Fixed cost	23.93	USD/kW/Year
Unit size	940	MW

6.2 Technologies – Sapugaskanda Oil Refinery Expansion and Modernization (SOREM)

Details related to SOREM were obtained from the refinery office of CPC. Table 6.6 shows the shares of products of the SOREM.

Table 6-6: Shares of products of the SOREM – (energy-wise)

	kgs per day	Calorific Value (kcal/kg)	kWyrs per day	Share
LPG	259,000	10,600	364	0.02
Gasoline	2,759,200	10,900	3,990	0.21
JetA1	1,029,300	10,500	1,434	0.08
Kerosene	384,000	10,500	535	0.03
Diesel	7,281,900	10,500	10,144	0.55
Total crude input	13,807,400	10,150	18,593	

Since SOREM has more than one output, a primary output should be selected. The maximum share of the outputs is owned by diesel and therefore it is selected as the primary product. Therefore the capacity of the SOREM was calculated based on the output of diesel. All the other outputs are secondary outputs and they were too fed in to the model as secondary outputs.

Table 6-7 shows the information related to investment cost, fixed cost and variable O&M cost of the SOREM. All the costs were calculated in USD terms. (1 USD = 131.55 LKR)

Table 6-7: Costs in relation to SOREM

Description	Value	Unit	Remarks
Capital Cost	2,000,000,000	USD	Rounded value
Fixed O&M cost per year	58,000,000	USD	Rounded value
Variable O&M cost per year	11,750,000	USD	Rounded value

Table 6-8 describes the calculation of the investment cost of the SOREM.

Table 6-8: Calculation - The investment cost of the SOREM

Description	Value	Unit	Remarks
Annual energy output from diesel	3,702,644	kWyr	
Capacity of the refinery	3,703	MW	Assuming a uniform production throughout the year
Investment cost	540.15	USD/MW	

Table 6-9 shows the information taken from the refinery office in relation to the fixed cost and the variable O&M cost of SOREM.

Table 6-9: Information on fixed cost and variable O&M cost of SOREM

Description	2015	2020	2025	2030	2035	2040
Fixed O&M (USD millions per year)	30.7	53.9	61	68.9	78	88.2
Variable O&M (USD millions per year)	7	10.6	12	13.6	15.4	17.4

Using the values taken from the refinery office, “Fixed cost” and “Variable cost” was calculated for each year of the planning horizon (see Table 6-10). In these calculations the daily diesel output is taken as 10,144 kWyrs and the capacity of the

SOREM is taken as 3,702,644 kW (with respect to the output of diesel, which is the primary output).

Table 6-10: Calculated values for fixed cost and variable O&M cost of SOREM

Year	Variable O&M Cost (USD/kWyr)	Fixed O&M Cost (USD/kW/yr)
2021	2.94	14.94
2022	3.01	15.32
2023	3.09	15.71
2024	3.17	16.09
2025	3.24	16.47
2026	3.33	16.90
2027	3.41	17.33
2028	3.50	17.75
2029	3.59	18.18
2030	3.67	18.61
2031	3.77	19.10
2032	3.87	19.59
2033	3.96	20.08
2034	4.06	20.57
2035	4.16	21.07

Table 6-11 gives a summary of the variables fed in to the model with respect to the SOREM project.

Table 6-11: Summary on input variables – SOREM project

Variable	Value	Unit
Main input	Crude oil	
Main output	Refer Table 18	
Efficiency	0.55	Share
variable O&M cost	Refer Table 22	USD/kWyr
Plant factor	1	Share
Minimum utilization	0	Share
Plant life	50	Years
Investment cost	540.15	USD/kW
Construction time	5	Years
Fixed cost	Refer Table 22	USD/kW/Year
Unit size	3703	MW

6.3 Technologies – Existing Thermal power Plants

Table 6-12 provides an introduction to the power plants considered under this section along with their respective capacities (both CEB owned and IPPs). Two small dendro power plants (13MW and 10MW) were included in the LTGEP (2015 – 2034), but they were excluded in this analysis.

Table 6-12: Existing thermal power plants

Code	Plant Name/Description	Capacity (MW)
GT 1-6	Small GTs at Kelanitissa	64
Sapu	Sapugaskanda	68
Sapu Ex	Sapugaskanda Extension	72
GT 7	GT7 at Kelanitissa	113
Asia	Asia Power	48
KCC	Kelanitissa Combined Cycle	161
AES	AES Kelanitissa	163
Col	Colombo Power	60
Kera CC	Kerawalapitiya CC	270
Noro Coal	Norochchole Coal	825
NPo	Nothern Power	30
UJ	Uthuru Janani	27
AES2	Extension of AES Kelanitissa (PPA expires in 2022	163

Table 6-13 shows a summary of the details in relation to existing thermal power plants. The details are based on the information taken from LTGEP (2015 – 2034) of CEB and PUCSL.

Table 6-13: Details on existing thermal power plants

	Efficiency	Var cost (O&M)	First Year	Plant Factor	Plant Life	Unit size	Fixed Cost	Min. power
		USD/kWyr			years	MW	USD/kW/yr	MW
GT	0.21	6.75	2015	0.61	2	64	42.7	16
Sapu	0.38	59.74	2015	0.76	4	68	121	17
Sapu Ex	0.43	17.18	2015	0.83	10	72	111	9
GT 7	0.3	52.38	2015	0.51	8	113	2.52	79
Asia	0.39	142.61	2015	0.81	3	48	54.7	6
KCC	0.45	28.29	2015	0.83	18	161	26.6	98
AES	0.45	10.25	2015	0.9	8	163	18.6	68
Col	0.39	107.49	2015	0.79	5	60	72.1	15
Kera CC	0.38	121.33	2015	0.76	20	270	28.3	108
Noro Coal	0.36	30.57	2015	0.81	26	275	60.2	200
NPo	0.39	264.11	2015	0.78	5	30	13.4	5
UJ	0.39	86.81	2015	0.87	26	27	24.96	9
AES2	0.45	10.25	2023	0.9	10	163	26.6	68

Notes:

- Investment cost and construction time for these plants were taken as zero.
- Plant life was determined by the equation given below.

Plant life = Year of retirement – 2015+1

Therefore the plant life in the Table 25 does not reflect the actual plant life of the pant.

6.4 Technologies – Candidate Power Plants

Table 6-14 provides an introduction to the power plants considered under this section along with their respective capacities, full load efficiencies and construction costs. These figures are based on the details available in LTGEP (2015 – 2034) of CEB and details taken from PUCSL.

Table 6-14: Candidate thermal power plants

Plant	Net Capacity (MW)	Construction Cost (USD/kW)	Full Load Efficiency %	Plant Life (Years)	Construction time (Years)
GT Diesel 35	35	784.9	0.281	20	1.5
GT Diesel 105	105	533.8	0.301	20	1.5
CombinedCycle144	144	1198.6	0.466	30	3
CombinedCycle288	288	969.4	0.481	30	3
Coal_Trin227	227	1385.6	0.33	30	4
Coal_270	270	2119.4	0.384	30	4
SuperCrit_Coal564	564	2269.7	0.41	30	4
CCLNG287	287	1259	0.479	30	3
Nuclear	552	5705.3	0.32	60	5

Table 6-15 shows the values with respect to candidate electricity power plants. These figures are based on the details available in LTGEP (2015 – 2034) of CEB and details taken from PUCSL.

Table 6-15: Details on candidate thermal power plants

Plant	Fixed O&M Cost (USD/kW/Month)	Variable O&M Cost (USD Cts/kWh)	Variable O&M Cost (USD/kWyr)	Fixed O&M Cost (USD/kW/yr)	Plant Factor
GT Diesel 35	0.690	0.557	48.8	8.28	84%
GT Diesel 105	0.530	0.417	36.5	6.36	84%
CombinedCycle144	0.549	0.470	41.2	6.588	84%
CombinedCycle288	0.414	0.355	31.1	4.968	84%
Coal_Trin227	2.920	0.560	49.1	35.04	84%
Coal_270	4.470	0.590	51.7	53.64	85%
SuperCrit_Coal564	4.500	0.590	51.7	54	85%
CCLNG287	0.381	0.497	43.5	4.572	84%
Nuclear	7.620	17.600	1541.8	91.44	89%

6.5 Technologies – Urea Plant

Under this study, a typical urea plant of output capacity of 500,000 t/yr was considered [10]. The manufacture of 1 ton of urea is estimated to consume approximately 23 kcf of NG [10]. Table 6-16 explains the major steps of the calculation of cost details related to a urea plant of output capacity of 500,000 t/yr.

Table 6-16: Calculation details on urea plant

Description	Value	Unit	Remarks
NG requirement for a plant of capacity 500,000 t/yr	11,500,000	kcf/year	[10]
NG requirement	31.51	Mcf/day	
NG requirement	12.12	PJ/year	For NG, 1PJ/yr = 2.6 Mcf/day
NG requirement	384	MWyr/year	
Plant capacity	384	MW	
Plant capacity	384,260	kW	
Cost	200,000,000	USD	[10]
Investment Cost	520.48	USD/kW	
Overheads	1.95	USD/million BTU	
	0.00000195	USD/BTU	
	0.000000002	USD/J	1 BTU = 1056 J
O&M cost of Urea Plant	58.21	USD/kWyr	

Without manufacturing urea in Sri Lanka, it can be directly imported. Urea price for direct imports was calculated and the respective details are provided in Table 6-17.

Table 6-17: Calculation – Urea price for direct imports

Description	Value	Unit	Remarks
Urea purchase price (Direct)	550	USD/ton	[10]
Therefore urea purchase price in terms of NG	23.91	USD/kcf	23 kcf of NG is needed to produce 1 ton of Urea [10]
	0.02	USD/scf	
Cost of urea with respect to energy content in urea	0.000024	USD/BTU	1 scf (NG) = 1,000 BTU [10]
	0.000000023	USD/J	1 BTU = 1056 J
	0.08	USD/kWh	
	714.13	USD/kWyr	

Even though urea is not a fuel, its energy content was found to include it in the supply chain of urea of the model. Therefore urea price was calculated in USD/kWyr.

6.6 Technologies – NG Distribution Network

A distribution network for NG is an essential item to be discussed in this study. The cost of NG distribution was determined and fed into the model.

If NG is successfully introduced to Sri Lanka, there will be a need of supply about 10 Bcm/year. A pipeline network to cater a throughput of about 15 – 30 Bcm/year will cost about one billion USDs [10]. Therefore a pipeline network of such caliber will be more than enough to cater Sri Lanka's NG demand. Therefore the cost of pipeline network for NG distribution was taken to be 1,000,000,000 USD.

6.7 Technologies – Maximum NG production from Indigenous Resources

According to the report "Initial Natural Gas Utilization Road Map [10]", the maximum expected NG production from indigenous resources was 210 Mcf/day. Therefore this constraint was fed into the MESSAGE model. If the actual demand exceeds 210 Mcf/day, the remaining NG should be imported (as LNG).

7 BUILDING THE ENERGY SUPPLY NETWORKS – COST OF FUELS

This section describes the fuel prices used in the MESSAGE model. Calculations are summarized and tabulated. In these calculations, latest available fuel prices were used.

Given below are two common conversion factors used in the calculations in this section.

1 kcal = 4.184 kJ

1 bbl = 119.24 liters

7.1 Cost of Fuels – Crude Oil

Table 7-1 explains the calculation of crude oil cost. Raw details on crude oil prices were based on the information obtained from the refinery office of CPC.

Table 7-1: Calculation of crude oil cost

Description	Value	Unit	Remarks
Crude Oil imported in 2014	1,757,925	Metric Tons	Information from the Refinery
Average calorific value	10,161	kcal/kg	Information from the Refinery
Energy content in crude oil	2,369,926	kWyr	1 kcal = 0.001162 kWh
Cost of importing crude oil (in 2014)	196,977,065,343	LKR	Information from the Refinery
Cost of importing crude oil (in 2014)	1,497,355,115	USD	1 USD = 131.55 LKR
Variable cost for imported crude oil	632	USD/kWyr	

7.2 Cost of Fuels – Coal

Prices of coal can be directly found from the LTGEP (2015 – 2034) of CEB. The prices are shown in Table 7-2 for the two types of coal “Coal – West South” and “Coal – Trinco”.

Table 7-2: Calculations – Coal price

“Coal –West South”	Price USD/kcal	0.00001553
	Price USD/kWyr	117.05
Coal - Trinco	Price USD/kcal	0.00001485
	Price USD/kWyr	111.93

7.3 Cost of Fuels – Gasoline, Kerosene and Diesel

Prices of gasoline, kerosene and diesel were found using the information provided in [11]. Table 7-3 summarizes the results.

Table 7-3: Calculations - Prices of gasoline, kerosene and diesel

Fuel	Description	Value	Unit	Remarks
Gasoline	Calorific value	10,473.58	kcal/kg	[11]
	density =	761.00	kg/m3	[11]
	Price	101.74	USD/bbl	[11]
	Price	806.85	USD/kWyr	
Kerosene	kcal/kg =	10,389.66	kcal/kg	[11]
	density =	785.50	kg/m3	[11]
	Price	112.30	USD/bbl	[11]
	Price	869.81	USD/kWyr	
Diesel	kcal/kg =	10,182.45	kcal/kg	[11]
	density =	846.00	kg/m3	[11]
	Price	112.18	USD/bbl	[11]
	Price	823.16	USD/kWyr	

Import price for Avtur could not be found in any of the references. Therefore cost of avtur was taken as equal to cost of kerosene.

7.4 Cost of Fuels – Fuel Oil and LPG

Prices of fuel oil and LPG were found using the information provided in [11]. Table 7-4 summarizes the results.

Table 7-4: Calculations - Prices of fuel oil and LPG

Fuel	Description	Value	Unit	Remarks
FO 180	Calorific value	9,750.00	kcal/kg	[11]
	Price	561.14	USD/t	[11]
	Price	0.000058	USD/kcal	[11]
	Price	433.79	USD/kWyr	
FO 380	Calorific value	9,750.00	kcal/kg	[11]
	Price	554.23	USD/t	[11]
	Price	0.000057	USD/kcal	[11]
	Price	428.45	USD/kWyr	
LPG	Calorific value	10,955.66	kcal/kg	[11]
	Price	858.21	USD/t	[11]
	Price	0.000078	USD/kcal	[11]
	Price	590.43	USD/kWyr	

For the MESSAGE was fed with a common price for fuel oil and it was taken as the average price of FO 180 and FO 380.

7.5 Cost of Fuels – Naphtha, LNG and Nuclear

Prices of Naphtha, LNG and Nuclear are available in the information obtained from PUCSL (The values used by CEB in preparing WASP model for LTGEP). Those values were used in the MESSAGE model.

Table 7-5: Calculations - Prices of Naphtha, LNG and Nuclear

Fuel	Price	Unit	Remarks
LNG	0.000054	USD/kcal	Information from PUCSL
	409.43	USD/kWyr	
Naphtha	0.00008282	USD/kcal	Information from PUCSL
	624.24	USD/kWyr	
Nuclear	0.0000116	USD/kcal	Information from PUCSL
	87.43	USD/kWyr	

7.6 Cost of Fuels – Indigenous NG

The report Initial Natural Gas Utilization Road Map [10] there were three prices were considered for indigenous NG (Given below).

1. 5 USD/million BTU = 149.32 USD/kWyr
2. 10 USD/million BTU = 298.64 USD/kWyr
3. 15 USD/million BTU = 447.95 USD/kWyr

For the base case of the study NG price was taken as 298.64 USD/kWyr. Other two values were used in the sensitivity analysis.

8 BUILDING THE ENERGY SUPPLY NETWORKS – ENERGY FLOWS NETWORKS

The demand forecast for each energy form is to be fulfilled. In this model all possible ways of fulfilling those demands were taken in to consideration. This section describes about energy flows networks, a pictorial descriptions which elaborate the ways of fulfilling demands

8.1 Energy Flows Networks – Natural Gas

Figure 8-1 shows the energy flows networks for NG sector.

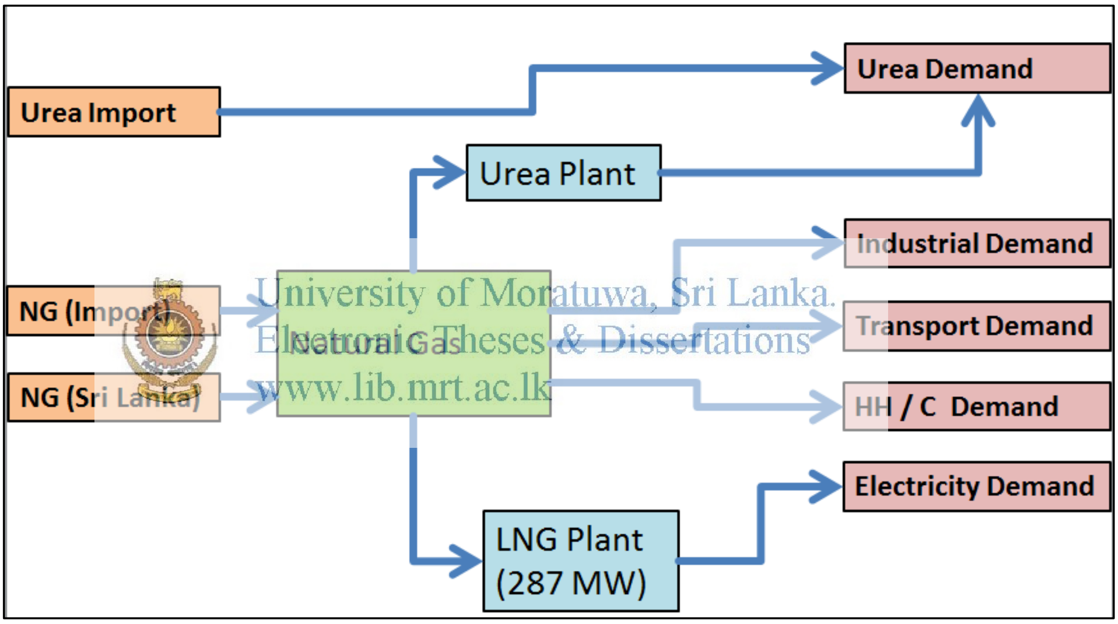

Figure 8-1: Energy flows networks for NG sector

- Natural gas has two ways of initiation.
  1. Imported as LNG
  2. NG found in Sri Lanka
- Forecasted NG demand was fed in to the model individually for sectors given below.
  1. Industrial sector
  2. Transport sector

3. Household and commercial sector

- NG plants can be used to generate electricity.
- Urea demand forecast can be fulfilled through the modes given below.
  1. Importing Directly
  2. Manufacturing urea within the country by urea plants

8.2 Energy Flows Networks – Petroleum (Supply side)

Figure 8-2 elaborates the energy flows networks for the supply side of the petroleum sector.

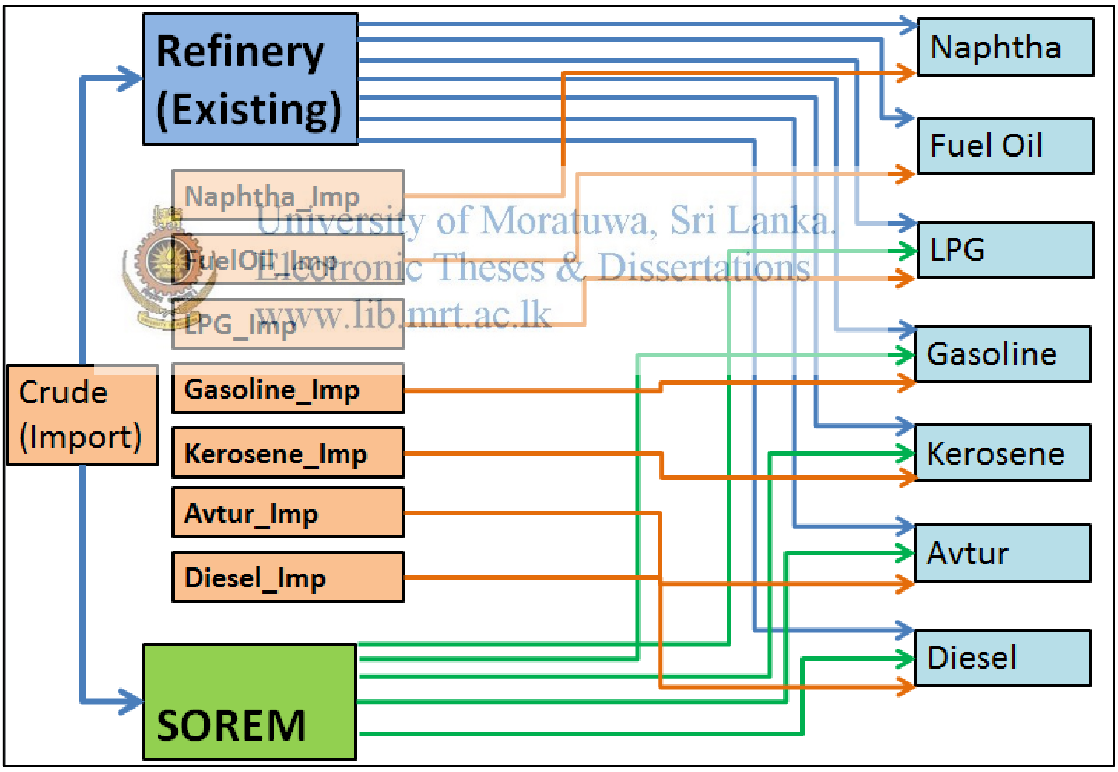

Figure 8-2: Energy flows networks for the supply side of the petroleum sector

Sri Lanka's petroleum sector consists of seven major refined petroleum products. The list of those products is given below along with their respective way of initiation.

1. Naphtha – Importing directly or as a output from the existing refinery
2. Fuel oil – Importing directly or as a output from the existing refinery

3. LPG - Importing directly, as a output from the existing refinery or as an output of SOREM
4. Gasoline - Importing directly, as a output from the existing refinery or as an output of SOREM
5. Kerosene - Importing directly, as a output from the existing refinery or as an output of SOREM
6. Avtur - Importing directly, as a output from the existing refinery or as an output of SOREM
7. Diesel - Importing directly, as a output from the existing refinery or as an output of SOREM

8.3 Energy Flows Networks – Petroleum (Demand side)

Figure 8-3 shows the energy flows networks for the demand side of the petroleum sector.

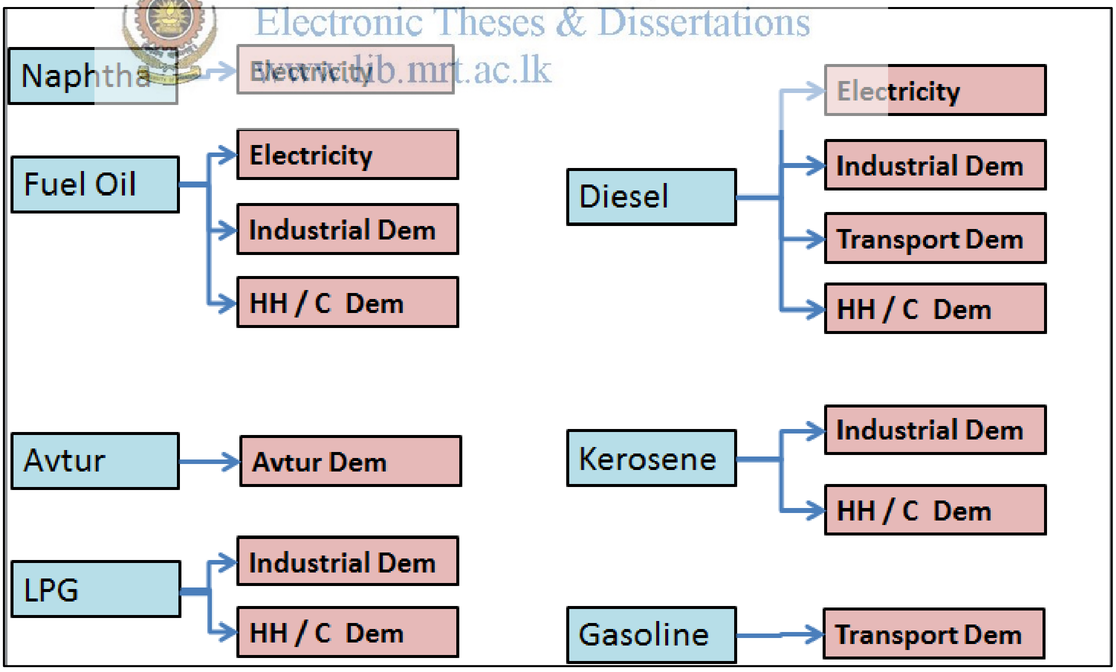

Figure 8-3: Energy flows networks for the demand side of the petroleum sector

The details related to the demand side of the refined petroleum products are given below.

1. Naphtha – Generation of electricity
2. Fuel oil – Industrial demand, "household and commercial" demand and electricity generation
3. LPG - Industrial demand and "household and commercial" demand
4. Gasoline – Transport demand
5. Kerosene - Industrial demand and "household and commercial" demand
6. Avtur – Avtur demand for jet engines / aviation
7. Diesel - Industrial demand, "household and commercial" demand, transport demand and electricity generation

8.4 Energy Flows Networks – Coal

Figure 8-4 shows the energy flows networks for the energy chains associated with coal.

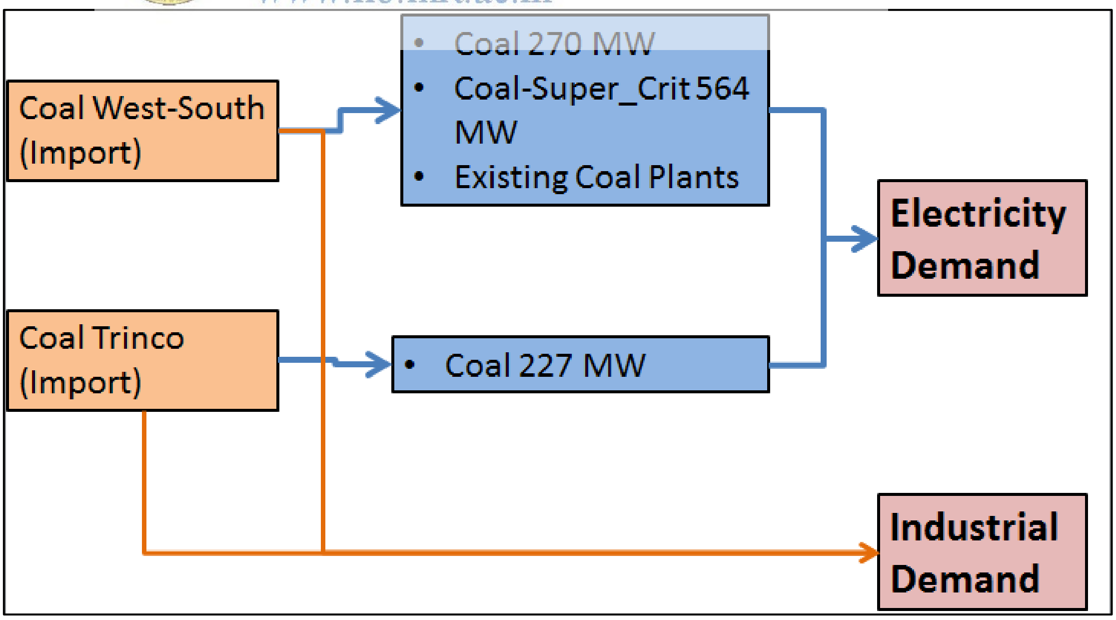

Figure 8-4: Energy flows networks for the energy chains associated with coal

- Initiation of coal to Sri Lanka's energy picture is segregated to two alternatives.
  1. Coal (West – South)
  2. Coal (Trinco)

  Coal (Trinco) is cheaper than Coal (West – South) since there is not any barging cost.
- The electricity demand can be fulfilled by coal through coal power plants.
- There is a small industrial demand for coal too.

8.5 Energy Flows Networks – Nuclear

Figure 8-5 shows the energy flows networks for the energy chains associated with nuclear.

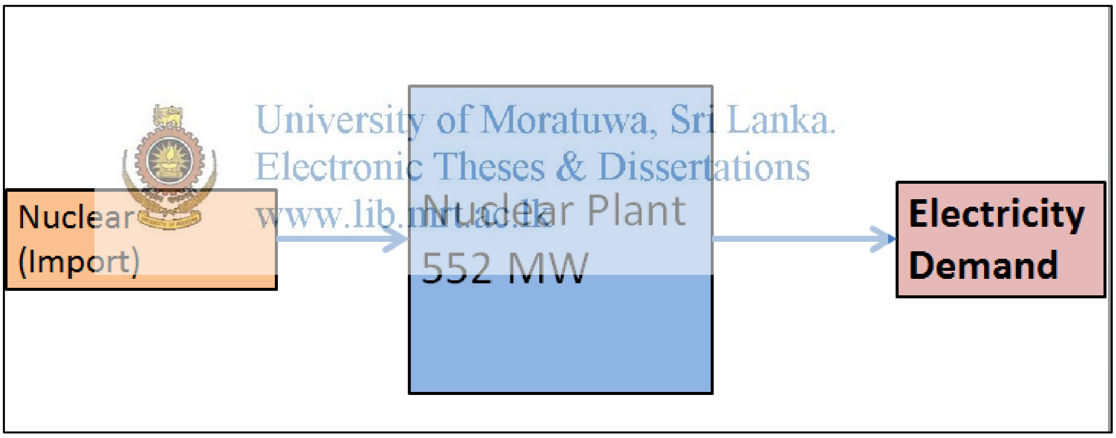

Figure 8-5: Energy flows networks for the energy chains associated with nuclear

In the model, the nuclear power plants were analyzed as an alternative option for electricity generation.

9 MESSAGE MODEL – RESULTS OF THE BASE CASE

MESSAGE model provides the least cost plan to fulfill the forecasted energy demand with available fuel sources. However it does not provide the cost of the plan in net present value. Therefore to quantify the total cost of the plan, NPV value of the output of the model was calculated using the software package MS-Excel.

- For the base case, a discount rate of 10% was assumed.
- NPV value of the solution = 61,274 USD Millions

9.1 Fuel Imports

Table 9-1 shows the MESSAGE output on fuel imports.

Table 9-1: MESSAGE output on fuel imports

All the values are in MWyrs (1MWyr = 0.11GWh)										
Year	Coal	Crude Oil	LNG	Avtur	Diesel	F Oil	Gasoline	Kerosene	LPG	Naphtha
2016	1,964	-	-	549	2,691	992	1,490	228	408	297
2017	1,968	-	-	564	2,821	1,137	1,617	235	437	297
2018	1,976	-	-	580	2,952	1,309	1,744	241	467	297
2019	1,977	-	-	596	3,464	1,176	1,893	248	500	297
2020	1,982	-	503	612	3,440	997	1,940	256	533	297
2021	4,288	-	198	625	3,394	261	2,063	263	571	-
2022	4,304	6,454	399	121	-	264	823	78	480	-
2023	4,887	6,618	398	120	-	261	866	79	519	-
2024	5,381	6,733	484	123	35	259	912	83	558	-
2025	6,012	6,607	1,420	145	-	257	1,010	94	608	-
2026	6,612	6,623	-	157	-	255	1,071	100	626	-
2027	7,218	6,611	-	172	-	253	1,136	108	647	-
2028	7,880	6,595	-	186	-	251	1,190	116	666	-
2029	8,565	6,550	-	204	-	250	1,246	125	685	-
2030	9,311	6,500	407	221	-	248	1,290	134	703	-
2031	10,129	6,415	777	243	-	246	1,333	144	719	-
2032	10,954	6,325	1,186	265	-	246	1,361	154	735	-
2033	11,838	6,192	1,638	290	-	244	1,380	167	748	-
2034	12,760	6,054	2,140	316	-	244	1,383	179	759	-
2035	13,714	5,865	2,888	346	-	243	1,372	193	769	-

The details in Table 9-1 are depicted in Figure 9-1.

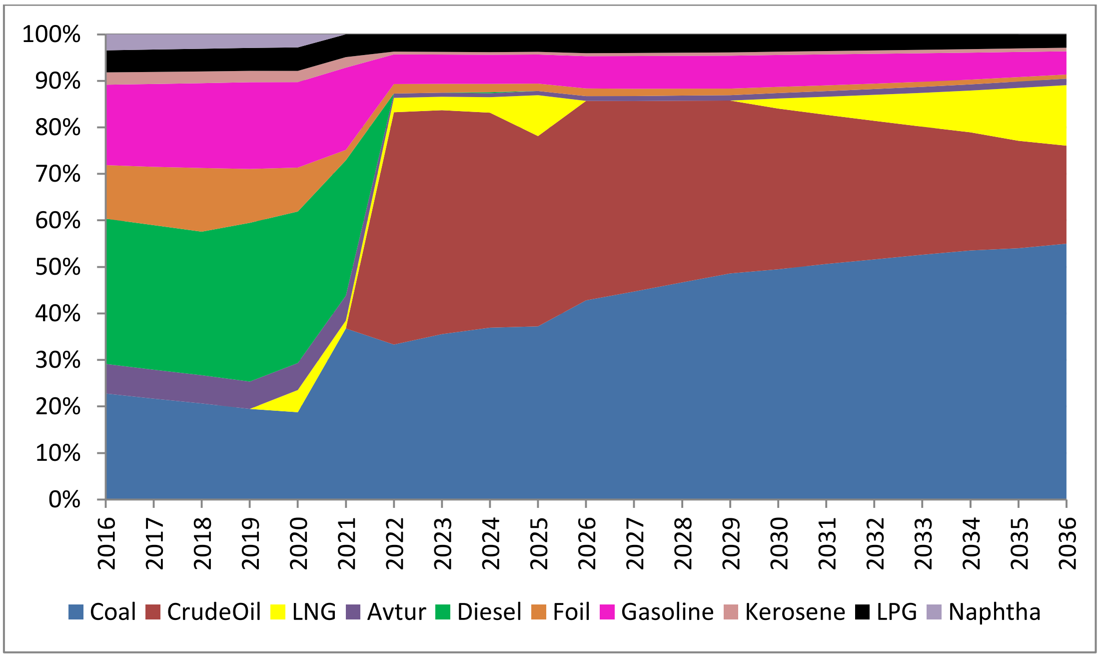

Figure 9-1: MESSAGE output on fuel imports – in percentages

Given below is a list of findings extracted through the output of the model.

9.2 Petroleum sector

a. The refined petroleum products should be imported until 2021. Once the SOREM comes in to the picture in 2022, it is better to import crude oil and refine them in the modernized refinery, SOREM.

b. According to the output of the model, the existing refinery is not a viable option to refine petroleum products. The model does not recommend importing crude oil before the SOREM is done. The model suggests importing refined products directly, rather than using the existing refinery until 2021.

c. The total gasoline demand of the country will be partly fulfilled by the production of SOREM. The remaining requirement of gasoline should be imported directly.

d. The total LPG demand of the country will not be fully entertained by the production of SOREM. The rest of the LPG demand should be imported directly.
e. However, almost the entire diesel demand of the country can be fulfilled through SOREM output after 2022. (Diesel is the predominant output of SOREM)

9.3 Electricity Generation

Figure 9-2 depicts the nature of proposed power plants by the model (excluding the existing power plants and their retirements). It should be noted that a considerable amount of these future electricity generation accounts for transport sector too (details related to transport sector are provided later of this section).

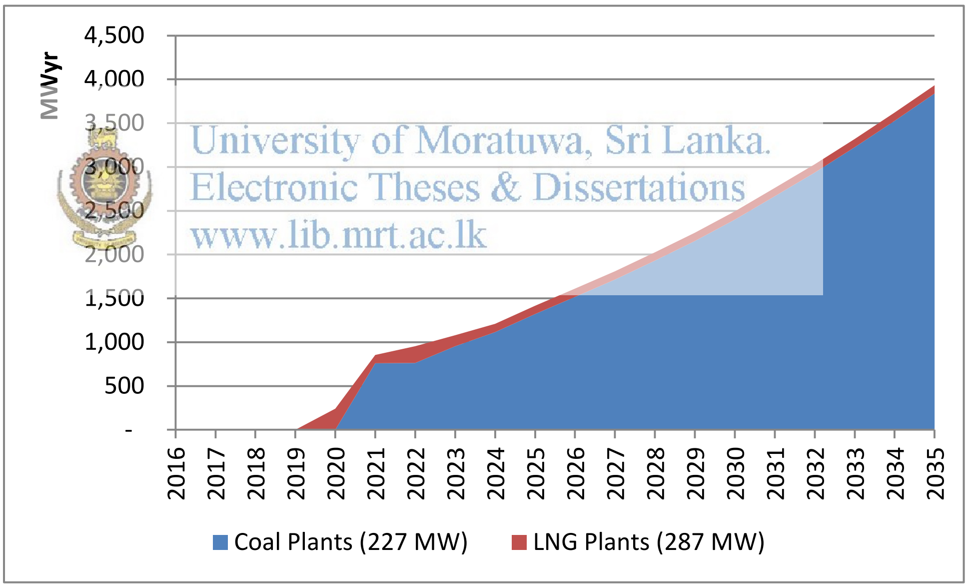

Figure 9-2: Output of the model - proposed power plants

a. LTGEP of CEB [1] suggests that the future electricity sector should be dominated by coal. However, the report Initial Natural Gas Utilization Road Map [10] proposes to use NG/LNG plants for electricity generation in a higher scale. These two reports give results which are totally different from each other.
b. According this model, the future electricity sector will be dominated by coal. This result is coherent with the output of the LTGEP of CEB. However, the

MESSAGE model proposes LNG as a viable option for electricity generation, even though its contribution is very low. This small discrepancy is due to the reasons given below.

- LTGEP only considers about electricity sector. Therefore it does not take the uses of LNG other than electricity generation in to consideration. When considering all the uses of LNG into consideration LNG becomes a viable option for electricity generation.
- This model considers about indigenous NG of Sri Lanka where LTGEP of CEB does not consider about it.
- None of the references mentioned above ([1] and [10]) contain a comprehensive modeling of the Sri Lanka's energy sector. Therefore the results of this model are much accurate than those of [1] and [10], because this model covers a vast area of the energy sector of Sri Lanka than [1] and [10] do.

c. Using Electricity for Transport Sector has become a viable option according to the output of the model.

- According to the output of the MESSAGE model, the plan fed in to the model for using electricity for transport sector is viable. However it increases the electricity demand of the country by a considerable margin. Table 9-2 describes the future usages of electricity for the sectors given below.
  1. As electricity to be distributed among consumers
  2. As an energy source for transport sector

Table 9-2: Output of the model - future usages of electricity

All the values are in MWyrs (1MWyr = 0.11GWh)		
	Electricity for distribution	**Electricity for transport sector**
2016	1,843	0
2017	1,968	0
2018	2,102	0
2019	2,246	0
2020	2,399	102
2021	2,517	155
2022	2,642	215
2023	2,772	286
2024	2,910	364
2025	3,055	653
2026	3,208	847
2027	3,370	1,067
2028	3,538	1,306
2029	3,712	1,580
2030	3,892	1,875
2031	4,076	2,211
2032	4,265	2,572
2033	4,461	2,984
2034	4,665	3,425
2035	4,878	3,930

Figure 9-3 represents the contents in Table 9-2 graphically.

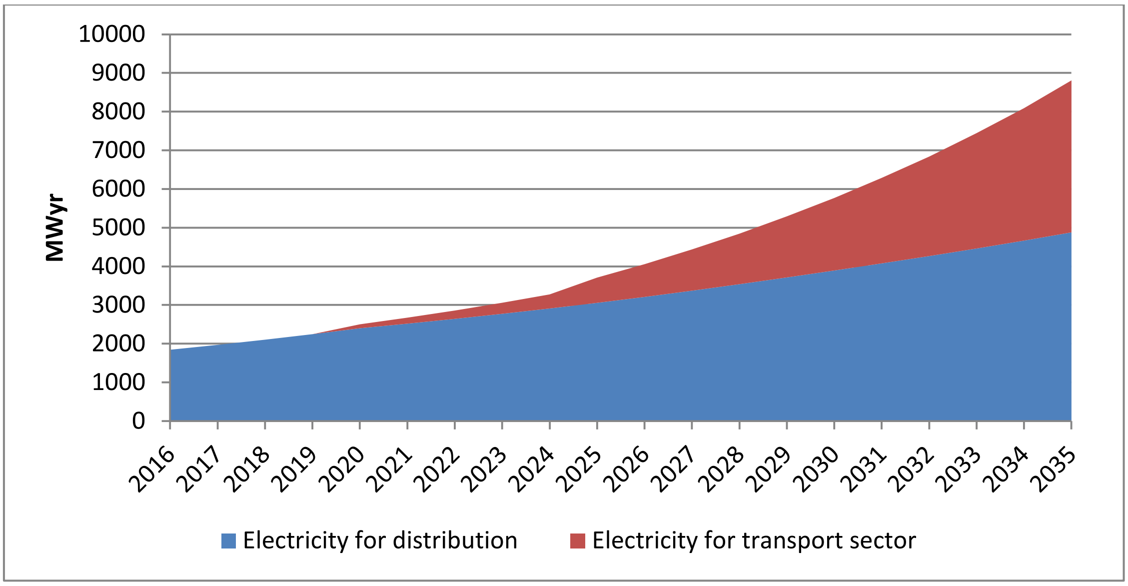

Figure 9-3: Output of the model - future usages of electricity

9.4 NG Sector

Table 9-3 describes the future of the NG sector of the country as the model suggests. NG will be used in industrial sector, transport sector, household and commercial sector, electricity generation and as a feedstock to the urea plant.

Table 9-3: Model output – NG sector (imports and indigenous)

All the values are in MWyrs (1MWyr = 0.11GWh)		
	LNG (Imported)	**NG (Sri Lanka)**
2016	-	-
2017	-	-
2018	-	-
2019	-	-
2020	503	-
2021	198	-
2022	399	-
2023	398	-
2024	484	-
2025	1,420	-
2026	-	1,636
2027	-	1,878
2028	-	2,144
2029	-	2,444
2030	407	2,562
2031	777	2,562
2032	1,186	2,562
2033	1,638	2,562
2034	2,140	2,562
2035	2,888	2,562
2036	3,498	2,562

Figure 9-4 depicts the model output on the future NG sector.

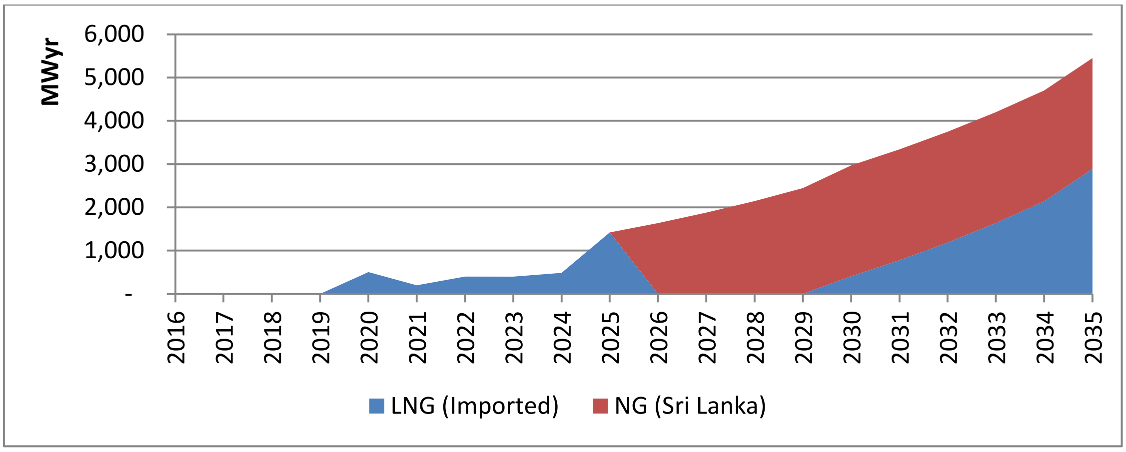

Figure 9-4: Model output – NG sector (imports and indigenous)

a. Even though NG (Sri Lanka) is expected to be available from 2022 onwards, this model suggests it is economical to use them from 2026 onwards. Until 2026 LNG should be imported to fulfill the energy needs related to NG.

b. After 2030 the total requirement of NG will be fulfilled partly by NG (Sri Lanka) and the rest by LNG (imported)

c. Further using NG to manufacture urea is given as a viable option by the model, rather than importing urea directly. Therefore urea plants should be built accordingly in future to fulfill the urea requirement. Table 9-4 gives the MESSAGE output in relation to future urea demand.

Table 9-4: Model output – Fulfilling the urea demand

In Mega cubic foot				
	Urea (From Urea Plants)	Urea (Imports)	Total demand	No of Plants (0.5 Mt/year)
2025	63	0	63	2
2026	63	0	63	2
2027	63	0	63	2
2028	63	0	63	2
2029	63	0	63	2
2030	78.8	0	78.8	3
2031	78.8	0	78.8	3
2032	78.8	0	78.8	3
2033	78.8	0	78.8	3
2034	78.8	0	78.8	3
2035	94.5	0	94.5	3

9.5 Results in general

Table 9-5 describes output of the model in relation to future fuel/energy source mix. Contribution from Hydro and NCRE related to electricity generation was taken from [1]. NG includes both imports (LNG) and NG (Sri Lanka).

Table 9-5: Model output - Future fuel/energy source mix

All the values are in MWyrs (1MWyr = 0.11GWh)					
	Refined Petroleum	Crude Oil	Coal	NG	Hydro and NCRE (Electricity Only)
2016	6,655	-	1,964	-	748
2017	7,109	-	1,968	-	819
2018	7,590	-	1,976	-	889
2019	8,175	-	1,977	-	925
2020	8,075	-	1,982	503	1,007
2021	7,176	-	4,288	198	1,042
2022	1,765	6,454	4,304	399	1,083
2023	1,845	6,618	4,887	398	1,111
2024	1,969	6,733	5,381	484	1,141
2025	2,114	6,607	6,012	652	1,167
2026	2,210	6,623	6,612	868	1,181
2027	2,315	6,611	7,218	1,110	1,211
2028	2,410	6,595	7,880	1,376	1,234
2029	2,509	6,550	8,565	1,676	1,266
2030	2,596	6,500	9,311	2,008	1,290
2031	2,685	6,415	10,129	2,378	1,308
2032	2,760	6,325	10,954	2,787	1,334
2033	2,830	6,192	11,838	3,239	1,364
2034	2,882	6,054	12,760	3,741	1,398
2035	2,923	5,865	13,714	4,297	1,451

Percentage-wise representation of the details of the Table 9-5 is given in Figure 9-5.

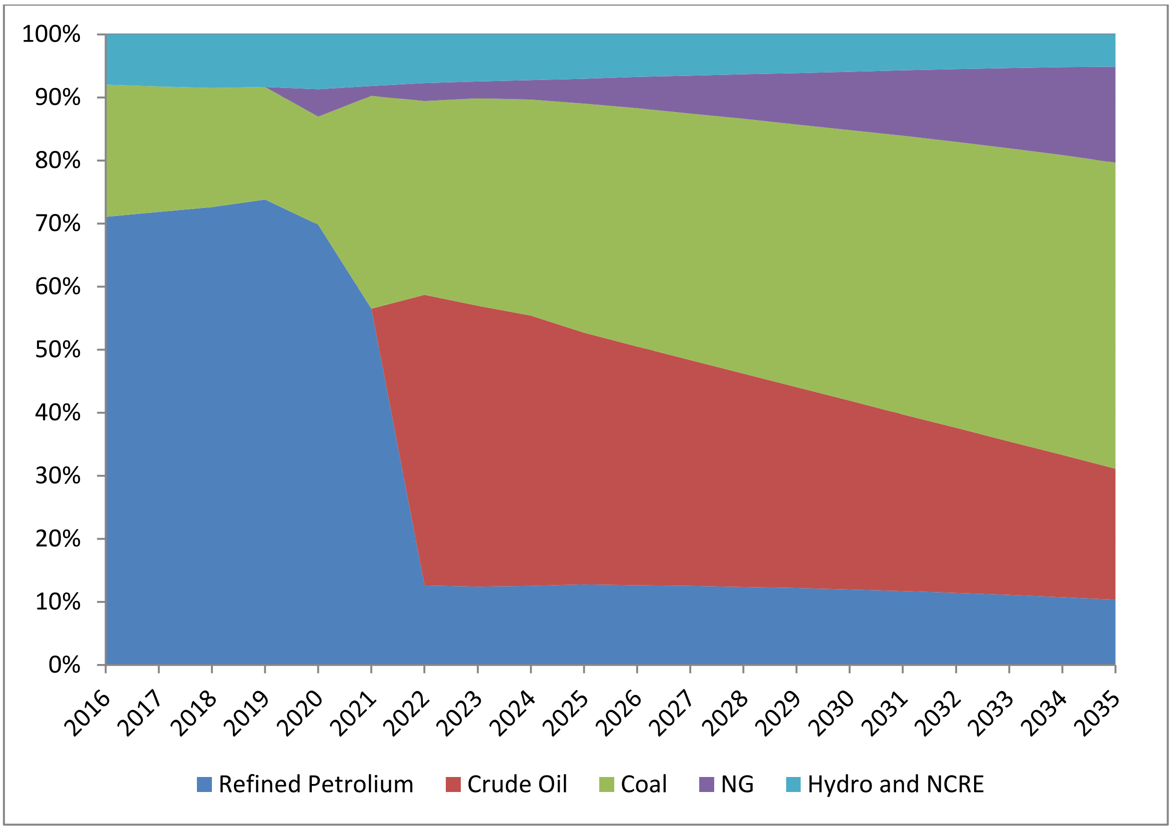

Figure 9-5: Model output - Future fuel/energy source mix (in percentages)

9.6 Transport Sector - Energy Share by Fuel

With the introduction of electricity to the transport sector, the future energy share will be different from that at present. Table 9-6 describes the energy share by fuel in relation to the transport sector.

Table 9-6: Model output - Energy share by fuel in relation to the transport sector

All the values are in MWyrs (1MWyr = 0.11GWh)				
	Diesel	Gasoline	Electricity	NG
2016	2,572	1,490	-	-
2017	2,700	1,617	-	-
2018	2,829	1,744	-	-
2019	2,970	1,893	-	-
2020	3,111	1,940	102	-
2021	3,265	2,063	155	-
2022	3,418	2,179	215	-
2023	3,509	2,256	286	124
2024	3,607	2,326	364	263
2025	3,503	2,398	653	419
2026	3,512	2,462	847	593
2027	3,506	2,524	1,067	790
2028	3,497	2,575	1,306	1,005
2029	3,472	2,622	1,580	1,249
2030	3,445	2,655	1,875	1,519
2031	3,398	2,680	2,211	1,820
2032	3,348	2,689	2,572	2,153
2033	3,274	2,680	2,984	2,521
2034	3,198	2,655	3,425	2,930
2035	3,094	2,604	3,930	3,383

Figure 9-6 depicts the energy share by fuel in relation to the transport sector, as percentages.

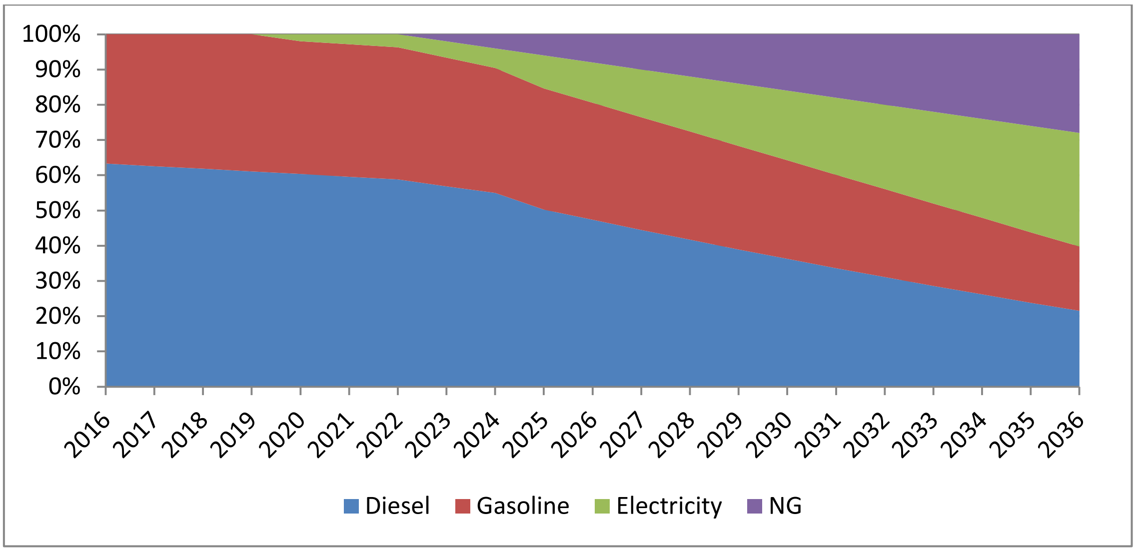

Figure 9-6: Model output - Energy share by fuel in relation to the transport sector

9.7 Industrial Sector - Energy Share by Fuel

Table 9-7 represents the fuel-wise energy picture for the industrial sector as proposed by the model.

Table 9-7: Model output - Fuel-wise energy picture for the industrial sector

All the values are in MWyrs (1MWyr = 0.11GWh)						
	Coal	Diesel	Fuel oil	Kerosene	LPG	NG
2016	108	98	203	40	51	-
2017	112	99	204	42	54	-
2018	119	100	205	45	57	-
2019	121	101	206	48	61	-
2020	126	101	207	51	65	-
2021	131	102	208	55	69	-
2022	136	103	209	59	73	-
2023	142	102	204	61	76	11
2024	147	100	200	64	78	23
2025	153	98	195	66	81	36
2026	159	96	191	68	84	49
2027	166	95	186	71	87	62
2028	172	93	182	74	90	76
2029	179	91	177	77	93	91
2030	186	89	173	80	95	107
2031	194	87	168	82	98	123
2032	201	85	164	85	101	140
2033	210	83	160	88	104	159
2034	218	82	156	91	107	178
2035	227	80	151	94	111	198

Figure 9-7 depicts the fuel-wise energy picture for the industrial sector as proposed by the model.

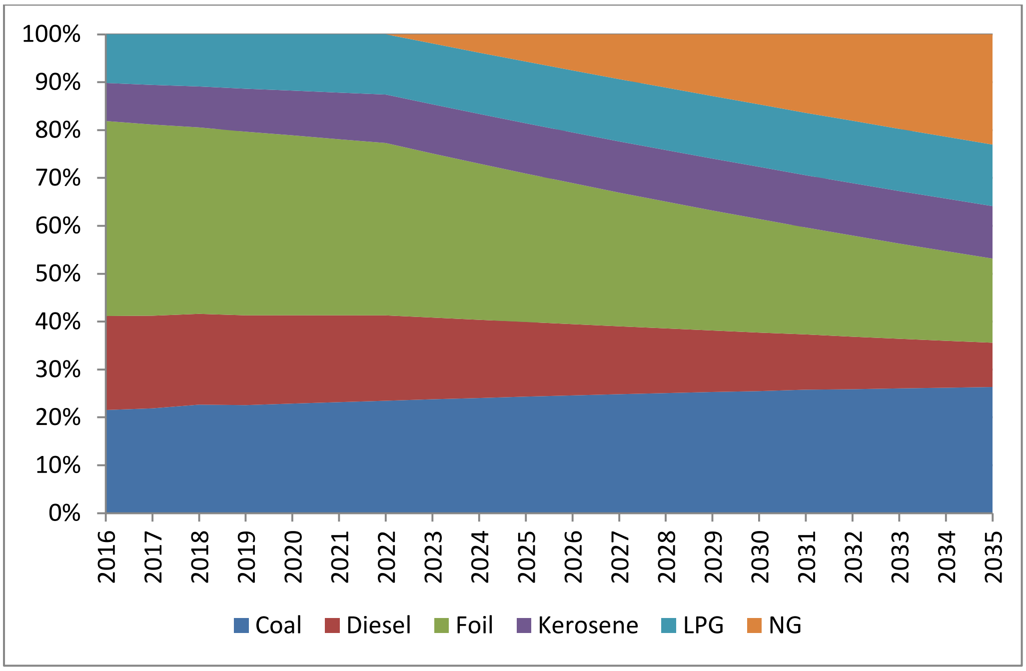

Figure 9-7: Model output - Fuel-wise energy picture for the industrial sector (in percentages)

The electricity consumption of industrial sector has been excluded in this section.

9.8 Household and Commercial Sector - Energy Share by Fuel

Table 9-8 represents the fuel-wise energy picture for the household and commercial sector as proposed by the model.

The electricity consumption of household and commercial sector has been excluded in this section.

Table 9-8: Model output - Fuel-wise energy picture for the household and commercial sector

All the values are in MWyrs (1MWyr = 0.11GWh)					
	Diesel	Fuel Oil	Kerosene	LPG	NG
2016	21	43	189	357	-
2017	22	45	192	383	-
2018	23	47	196	409	-
2019	24	49	200	439	-
2020	25	51	204	469	-
2021	27	53	208	503	-
2022	28	55	212	537	-
2023	29	57	217	575	-
2024	31	59	221	614	-
2025	32	62	226	659	-
2026	34	64	230	675	28
2027	36	67	235	692	60
2028	37	69	239	708	97
2029	39	72	244	724	138
2030	41	75	249	737	184
2031	43	78	254	750	237
2032	45	81	259	760	296
2033	48	85	264	768	361
2034	50	88	270	773	435
2035	53	91	275	776	517

Figure 9-8 depicts the fuel-wise energy picture for the household and commercial sector as proposed by the model.

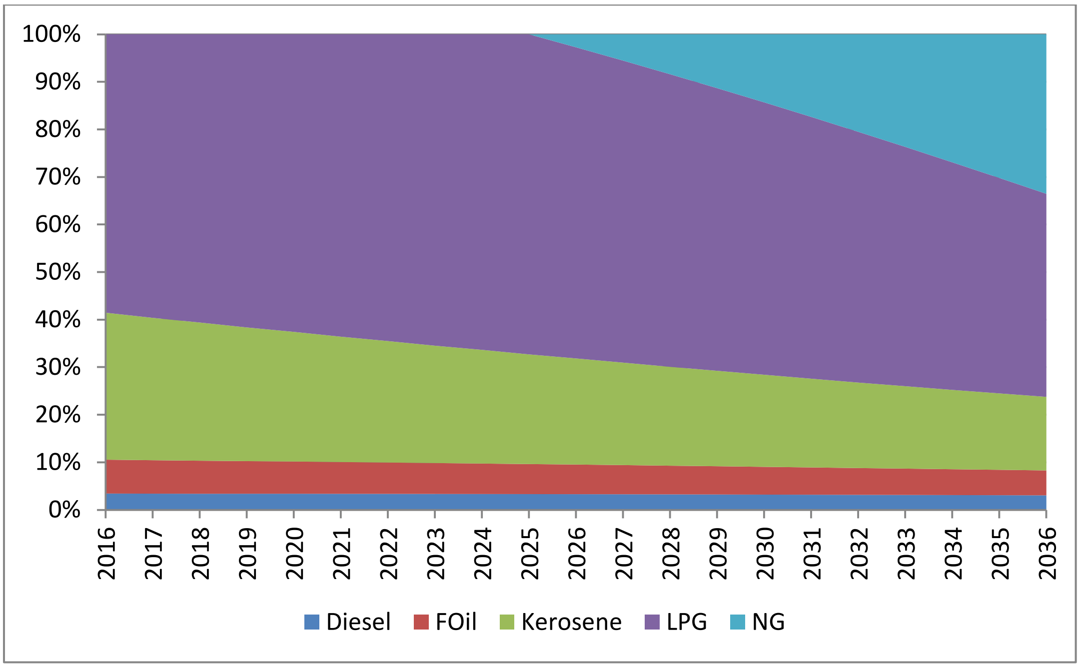

Figure 9-8: Model output - Fuel-wise energy picture for the household and commercial sector (in percentages)

10 SENSITIVITY ANALYSIS

Sensitivity analysis was done to examine the changes in the output of the base case under different scenarios. Under this part, 8 different cases were considered. This section describes the results of the sensitivity analysis. Respective NPV values for each case were calculated using MS Excel, through referring to the output of the MESSAGE model.

10.1 Sensitivity Analysis – High Discount Rate Case

- In this case the discount rate was taken as 15%. All the other parameters were kept unchanged with respect to the base case.
- NPV value of the solution = 43,297 USD Millions
- Results:
  a. The Output of the MESSAGE model related to this case did not show any major change with compared to the results of the base case.

10.2 Sensitivity Analysis – Low Discount Rate Case

- In this case the discount rate was taken as 3%. All the other parameters were kept unchanged with respect to the base case.
- NPV value of the solution = 114,013 USD Millions
- Results:
  a. The output of the base case suggested keeping a small share for NG in electricity generation. In this scenario NG is not suggested as a viable option to be used in generation of electricity.
  b. Apart from that there is not any major change with compared to the results of the base case.

10.3 Sensitivity Analysis - High LNG and NG Price Case

- In this case the prices of imported and indigenous NG were taken to be 50% high with compared to the base case values. All the other parameters (including urea price for direct imports) were kept unchanged with respect to the base case.
    a. Price of imported LNG = 614.14 USD/kWyr
    b. Price of indigenous NG = 447.95 USD/kWyr
- NPV value of the solution = 62,390 USD Millions
- Results:
    a. In this case the model output suggests delaying the construction of urea plants by one year. In the base case the first urea plant comes in 2025, but in this case it delays to 2026.
    b. The total number of urea plants in the base case was 3, by 2035. In this case it is only 2. Therefore a part of the country's urea demand should be fulfilled by importing urea. Table 10-1 describes the suggested plan by the model for urea manufacturing/importing under this case.

Table 10-1: Model output - urea manufacturing/importing (high LNG and NG price case)

In Mega cubic foot				
	Urea (From Urea Plants)	Urea (Imports)	Total demand	No of Plants (0.5 Mt/year)
2025	0	63	63	
2026	63	0	63	2
2027	63	0	63	2
2028	63	0	63	2
2029	63	0	63	2
2030	63	16	79	2
2031	63	16	79	2
2032	63	16	79	2
2033	63	16	79	2
2034	63	16	79	2
2035	63	32	95	2
2036	63	32	95	2

c. The output of the base case suggested keeping a small share for NG in electricity generation from future power plants. In this scenario NG is not suggested as a viable option to be used in generation of electricity. The model selects coal as the alternative.

d. Proposed result of the industrial sector under this case differs from that under the base case. The share of the NG has decreased with respect to that of the base case. Table 10-2 gives the summary of the results. (Table 9-7 gives the summary for the base case)

Table 10-2: Model output – Share of NG in industrial sector (high LNG and NG price case)

All the values are in MWyrs (1MWyr = 0.11GWh)						
	Coal	**Diesel**	**Fuel oil**	**Kerosene**	**LPG**	**NG**
2016	108	98	203	40	51	-
2017	112	99	204	42	54	-
2018	119	100	205	45	57	-
2019	121	101	206	48	61	-
2020	126	101	207	51	65	-
2021	131	102	208	55	69	-
2022	136	103	209	59	73	-
2023	142	102	209	61	78	4
2024	147	100	210	64	82	9
2025	153	98	211	66	88	13
2026	159	96	212	68	84	28
2027	166	95	213	71	87	36
2028	172	93	214	74	90	45
2029	179	91	214	77	93	54
2030	186	89	216	80	95	65
2031	194	87	215	82	126	48
2032	201	85	217	85	134	55
2033	210	83	218	88	143	63
2034	218	82	219	91	151	70
2035	227	80	220	94	161	79

e. Apart from the above instances, there is not any major change with compared to the results of the base case.

10.4 Sensitivity Analysis – Low LNG and NG Price Case

- In this case the prices of imported and indigenous NG were taken to be 50% low with compared to the base case values. All the other parameters (including urea price for direct imports) were kept unchanged with respect to the base case.
  a. Price of imported LNG = 204.71 USD/kWyr
  b. Price of indigenous NG = 149.32 USD/kWyr
- NPV value of the solution = 59,589 USD Millions
- Results:
  a. According to the output of the model, the share taken by NG in electricity generation has increased and that of coal has decreased (from future power plants). Figure 10-1 illustrates the output of the MESSAGE model under this scenario. (Refer Figure 9-2 for the respective graph of the base case)

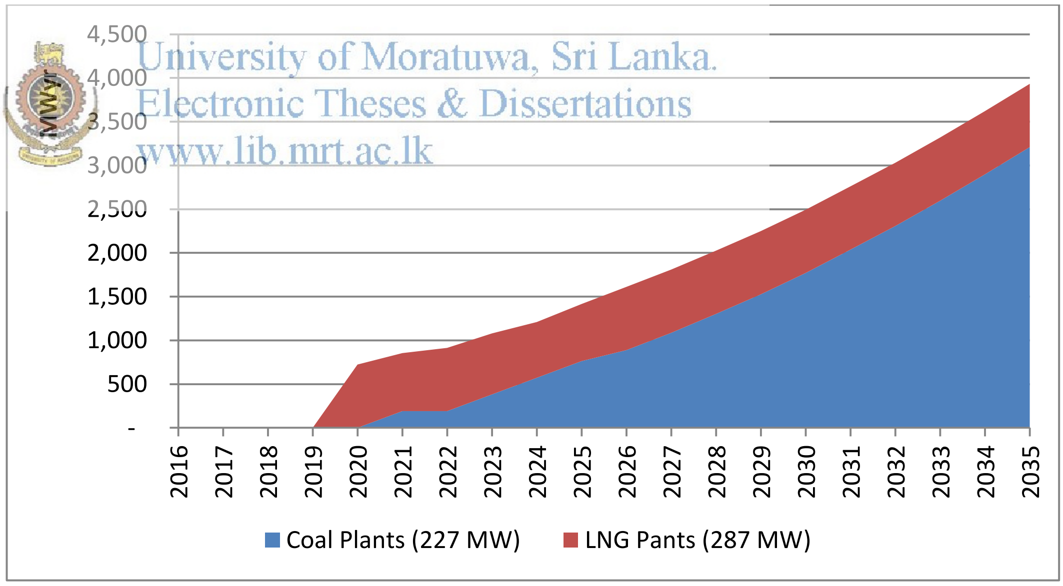

Figure 10-1: Model output - Proposed power plants (low LNG and NG price case)

  b. Apart from that there is not any major change with compared to the results of the base case.

10.5 Sensitivity Analysis – High Coal Price Case

- In this case the price of coal was taken to be 50% high with compared to the base case value. All the other parameters were kept unchanged with respect to the base case.
  a. Price of Coal (West South) = 173.02 USD/kWyr
  b. Price of Coal (Trinco) = 167.89 USD/kWyr
- NPV value of the solution = 63,561 USD Millions
- Results:
  a. According to the output of the model, there was not any major change with compared to the results of the base case

10.6 Sensitivity Analysis – Low Coal Price Case

- In this case the price of coal was taken to be 50% low with compared to the base case value. All the other parameters were kept unchanged with respect to the base case.
  a. Price of Coal (West South) = 61.09 USD/kWyr
  b. Price of Coal (Trinco) = 55.96 USD/kWyr
- NPV value of the solution = 58,875 USD Millions
- Results:

a. The output of the base case suggested keeping a small share for NG in electricity generation from future power plants. In this scenario NG is not suggested as a viable option to be used in generation of electricity. The model selects coal as the alternative.

10.7 Sensitivity Analysis – High Petroleum Price Case

- In this case the prices of all the petroleum products and crude oil were taken to be 50% high with compared to the base case value. All the other parameters were kept unchanged with respect to the base case. Table 10-3 shows the prices used in this case.

Table 10-3: Prices of fuel – High petroleum price case

Item	Price	Unit
Crude Oil	948	USD/kWyr
Gasoline	1,210	USD/kWyr
Diesel	1,235	USD/kWyr
Avtur	1,305	USD/kWyr
Kerosene	1,305	USD/kWyr
LPG	886	USD/kWyr
Fuel Oil	647	USD/kWyr
Naphtha	736	USD/kWyr

- NPV value of the solution = 85,180 USD Millions
- Results:

b. According to the output of the model, there was not any major change with compared to the results of the base case

10.8 Sensitivity Analysis – Low Petroleum Price Case

- In this case the prices of all the petroleum products and crude oil were taken to be 50% low with compared to the base case value. All the other parameters were kept unchanged with respect to the base case. Table 10-4 shows the prices used in this case.

Table 10-4: Prices of fuel – Low petroleum price case

Item	Price	Unit
Crude Oil	316	USD/kWyr
Gasoline	403	USD/kWyr
Diesel	412	USD/kWyr
Avtur	435	USD/kWyr
Kerosene	435	USD/kWyr
LPG	295	USD/kWyr
Fuel Oil	216	USD/kWyr
Naphtha	245	USD/kWyr

- NPV value of the solution = 37,048 USD Millions
- Results:
  a. According to the results of the model under this case, SOREM becomes nonviable. The model suggests importing all the petroleum products as the optimal solution. Table 10-5 shows the fuel imports as suggested by the model under this case. (Respective details for the base case is given in Table 9-1)

Table 10-5: Model output - fuel imports (low petroleum price case)

	Coal	Crude Oil	LNG	Avtur	Diesel	Fuel Oil	Gasoline	Kero-sene	LPG	Naph-tha
2016	1,964	-	-	549	2,691	995	1,490	228	408	297
2017	1,968	-	-	564	2,821	1,140	1,617	235	437	297
2018	1,976	-	-	580	2,952	1,309	1,744	241	467	297
2019	1,977	-	-	596	3,464	1,176	1,893	248	500	297
2020	1,982	-	-	612	4,102	997	2,042	256	533	297
2021	4,298	-	-	625	3,394	399	2,063	263	571	70
2022	4,881	-	-	637	3,550	265	2,179	271	609	-
2023	4,887	-	76	649	3,640	405	2,307	278	653	147
2024	5,470	-	159	661	3,738	409	2,439	285	697	12
2025	6,054	-	1,018	674	3,634	412	2,580	292	747	47
2026	6,899	-	-	687	3,642	276	2,462	299	796	-
2027	7,505	-	-	701	3,636	280	2,524	306	852	-
2028	8,167	-	-	714	3,627	283	2,575	313	910	-
2029	8,852	-	-	728	3,603	287	2,622	321	973	-
2030	9,598	-	-	741	3,575	291	2,655	329	1,040	-
2031	10,416	-	-	756	3,528	294	2,947	336	1,112	-
2032	11,241	-	-	771	3,479	299	3,296	344	1,189	-
2033	12,125	-	-	785	3,405	303	3,663	353	1,271	-
2034	13,047	-	-	800	3,330	307	4,054	361	1,359	-
2035	14,001	-	314	815	3,226	311	4,343	369	1,454	-
2036	15,074	-	536	827	3,117	316	4,555	378	1,554	-

Figure 10-2 depicts the percentage-wise fuel imports.

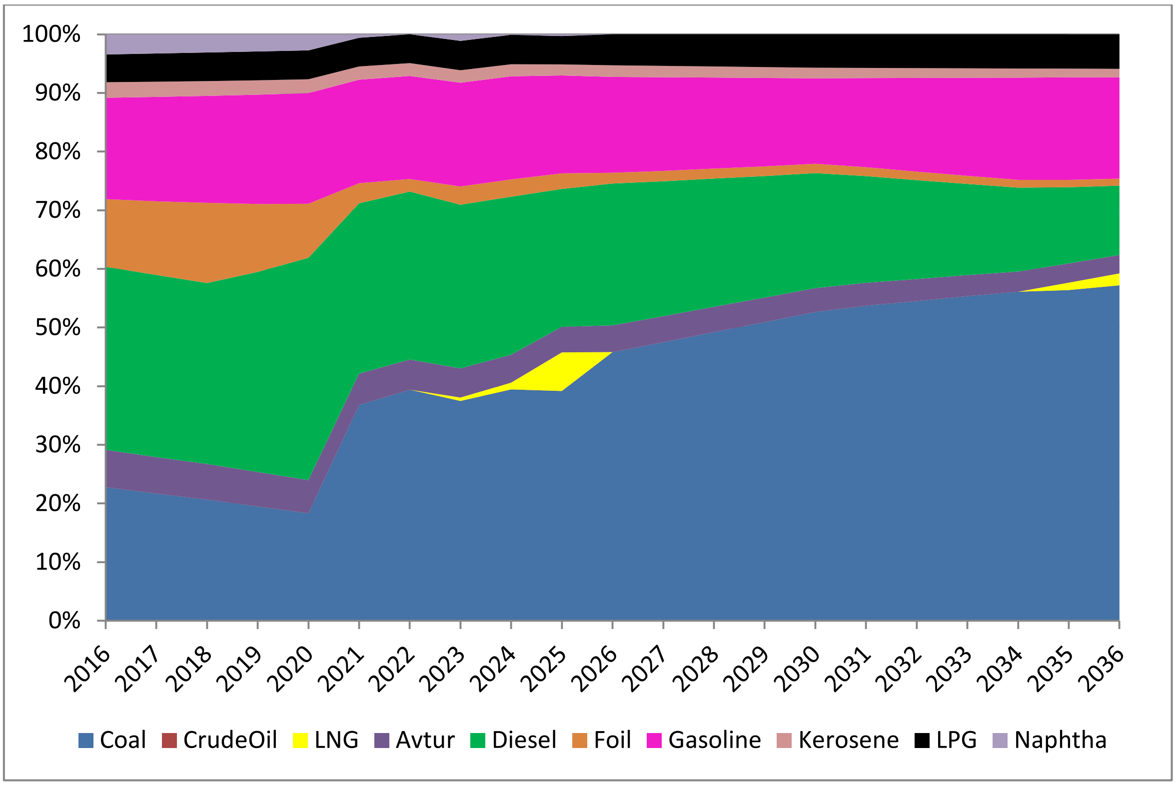

Figure 10-2: Model output - fuel imports in percentages (low petroleum price case)

b. The output of the base case suggested keeping a small share for NG in electricity generation from future power plants. In this scenario NG is not suggested as a viable option to be used in generation of electricity. The model selects coal as the alternative.

11 LIMITATIONS OF THE MODEL

The model prepared using MESSAGE under this study has some limitations. This MESSAGE model excludes the aspects given below with respect to electricity sector.

a. Information related to hydro plants
   Since electricity generation from hydro plants is cheaper than that from coal, petroleum or NG, it was not taken into consideration. Demand forecasts fed in to the model considers only the electricity demand that should be fulfilled by thermal power plants.

b. Further this model does not take the variables such as Peak Demand, LOLP, Rainfall, etc. too into consideration.

Therefore the results of this model in relation to the electricity sector should be fine-tuned through a separate electricity planning exercise such as LTGEP of CEB.

Also this model does not consider the seasonal variations of energy demand in to account. However since this is a long term plan, precise details on seasonal variations in energy demand throughout a year is not that important.

Further, the model prepared under this study does not include the effects of environmental costs. This limitation occurred due to the unavailability of environment-specific input data to be fed into the model. With inclusion of these environmental effects in to the model, it will give an optimal plan rather than a least-cost plan.

12 VALIDATION OF THE MODEL

To validate the model it is essential to compare the results of the model with the results of a reference study. However since there is not any published information related to future energy plan of Sri Lanka, there is a lack of reference studies to be compared with the results of this study.

As an alternative way of validation, the results of the model related to the electricity sector were compared with the results of the LTGEP of CEB separately.

Further the results of the model related to phasing in NG to Sri Lanka were compared with the respective results of the report "Initial Natural Gas Utilization Road Map" [10].

Given below is a description of the validation procedure under the said two approaches.

Considering the results related to electricity sector

Only the electricity sector of Sri Lanka was modeled with MESSAGE using the information given in LTGEP of CEB for 2013 – 2032 [6]. Then the results of the MESSAGE model were compared with the base case results of LTGEP for 2013-2032. Table 12-1 shows the comparison of the results.

Table 12-1: Comparison - Results of LTGEP and the MESSAGE model (2013 – 2032)

Item	LTGEP 2013 - 2032	MESSAGE Model (Only for Electricity Sector)
No of new 300 MW Coal plants (up to 2032)	12	13
No of new 250 MW Coal plants (up to 2032)	2	2
No of new240 MW LNG plants (up to 2032)	0	1
No of new 75 MW Gas Turbines (up to 2032)	3	0
No of new 105 MW Gas Turbines (up to 2032)	1	2

It can be seen that there is a strong coherence between the results of LTGEP 2013 – 2032 and results of the MESSAGE model. The reasons for slight differences are lined up below.

- LTGEP of CEB considers a number of parameters related to the electricity sector such as LOLP, rainfall data, spinning reserve, maximum demand, etc. However, the MESSAGE model only takes the electricity energy demand in to consideration.
- Even though, LTGEP does not select LNG plants, the MESSAGE model selects it. When considering only the electricity sector (this is done in LTGEP), it might not be economical to use LNG plants for electricity generation. However, when taking all the other applications of NG related to Sri Lanka's energy sector (this was done in MESSAGE model), it is economical to use LNG plants for electricity generation.

Considering the results related to NG sector

The report "Initial Natural Gas Utilization Road Map" [10] suggests several options on using NG in future. Under the base case scenario, the plans of phasing in of NG to Sri Lanka's energy sector were fed in to the model as inputs and they were tested using the model.

e.g.: Plans for Industrial sector, Transport Sector, Household and Commercial sector, etc.

The MESSAGE model suggests that those plans mentioned in the report "Initial Natural Gas Utilization Road Map" [10] as viable plans for phasing in NG to Sri Lanka.

(Details are provided under the Chapter 9, "MESSAGE MODEL – RESULTS OF THE BASE CASE")

However, even though the model suggests that the plans included in [10] are viable plans, those plans may not be the optimum plans for phasing in NG to Sri

Lanka. To find the optimum plan for phasing in NG, a number of different plans should be tested (using different constraints and conditions) and the respective NPV values of those plans should be calculated. Then the user of the model can pick the plan with the least NPV value as the best plan to phase in NG under a given set of constraints/conditions.

13 DISCUSSION AND CONCLUSIONS

1. Petroleum Sector

The main component related to the petroleum sector is the refinery. As stated in the results of the study and in the sensitivity analysis, it is clear that the most economical option is to implement SOREM project. In the sensitivity analysis, SOREM becomes nonviable only in the "Low Petroleum Price (50% Low)" case. In all the other scenarios, SOREM becomes viable.

This suggests that least cost option includes the implementation of SOREM project. However, to implement the expansions and modernizations to the existing refinery, it takes about five years. Therefore the earliest possible year of having the upgraded refinery is 2022. For the period 2016 to 2021, the output of the model suggests to import the refined petroleum products directly, rather than using the existing refinery. It proposes that using the existing refinery cannot be justified at the least cost energy plan. (Details are given in Table 9-1: MESSAGE output on fuel imports)

- Existing refinery should be upgraded to SOREM (First year of operation = 2022)
- If upgrading of the refinery (SOREM) is not possible, it is more economical to import petroleum products rather than using the existing refinery.

2. Electricity Sector

As discussed in the Results, the MESSAGE model suggests using coal as the best option for electricity generation. Two types of coal pants were fed in to the model and the model selects 227 MW coal plants (which uses Coal – Trinco) over 275 MW coal plants (which uses Coal – West South). There is a small contribution from NG plants to fulfill electricity demand.

However, the model does not select any new power plant run by diesel, naphtha or fuel oil. Also it does not select nuclear power plants.

Respective information is given in the section 9.3 and depicted in the "Figure 9 2: Output of the model - proposed power plants".

- Coal is the most economical option for electricity generation in the planning horizon.

3. Phasing in of NG/LNG

According to the output of the model, using NG for Transport/Industrial/Household and Commercial sectors is economically viable. (Section 9.6, Section 9.7, Section 9.8) The plans fed into the model were accepted by the model as least cost options. Therefore the policies should be prepared and decisions should be taken targeting introduction of NG to the energy sector.

Even in the sensitivity analysis done for high NG/LNG price case, NG has become viable for Transport Sector and the Household and Commercial Sector under the given plans. There is a slight reduction in future NG usage for industrial sector with respect to the base case. (Section 10.3, Sensitivity Analysis - High LNG and NG Price Case)

- Using NG for Industrial/Transport/Household and Commercial sectors should be promoted through suitable policy decisions by relevant authorities.

4. Electricity for transport sector

Using Electricity for Transport sector was tested using a specified plan (Details are given in Section 9.6). The model suggests that the given plan is economically viable.

Introducing electric vehicles for public transport (including railways) should be taken into consideration by the policy makers and required incentives should be given to increase the number of electric vehicles.

Even in the sensitivity analysis, the plan for using electricity for transport sector remains as an economically viable solution.

.

- The policies should be prepared targeting accelerated introduction of electric vehicles with proper incentives to the people.

5. **Fulfilling the urea demand**

   The model output proposes that manufacturing urea within the country is more economical than importing urea. (Section 9.4, Table 9-4: Model output – Fulfilling the urea demand)

   Further, in the sensitivity analysis, except in the "Sensitivity Analysis - High LNG and NG Price Case" (Section 10.3), the model suggests fulfilling the urea demand completely through urea plants as the best option. (The total number of urea plants is 3, throughout the planning horizon, each with 0.5 MT/year production capacity) However, in the "High NG/LNG price case", the model proposes to have only two urea plants in the planning horizon and to fulfill the remaining urea demand through direct urea imports.

- The decisions and policy directives should be taken to build up urea plants to fulfill the urea demand of the country.

Further to the conclusions it is recommended to prepare A Least Cost Long-Term Energy Supply Strategy for Sri Lanka, for the Usage of Petroleum, Coal and Natural Gas in a rolling basis with a frequency of less than that of LTGEP (e.g.: Once in every 4 years)

A model like this should be used in the planning stages of introducing a new technology, new energy source or any other major change to the energy sector.

REFERENCES

[1] *Long Term Generation Expansion Plan 2015 – 2034*. Sri Lanka: Ceylon Electricity Board, 2015.

[2] Ger Klaassena and Keywan Riahi. "*Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO*" in Energy Policy 35 (2007) 815–827, 2007.

[3] A. Hainoun, M. Seif Aldin, and S Almoustafa. "*Formulating an optimal long-term energy supply strategy for Syria using MESSAGE model*" in Energy Policy38 (2010) 1701–1714, 2009.

[4] S.M.C. Fairuz, M.Y. Sulaiman, C. H. Lim, S. Mat, B. Ali, O. Saadatian, M. H. Ruslan, E. Salleh, K. Sopian. "*Long term strategy for electricity generation in Peninsular Malaysia – Analysis of cost and carbon foot print using MESSAGE*" in Energy Policy 62 (2013) 493–502, 2013.

[5] Chandra Seneviratne, Rupert Taylor. "*Natural Gas – a brighter future for Sri Lanka*", 2003.

[6] *Long Term Generation Expansion Plan 2013 – 2032*. Sri Lanka: Ceylon Electricity Board, 2015.

[7] *Energy in Sweden 2010*, Swedish Energy Agency, 2010

[8] Martin Eberhard and Marc Tarpenning *"The 21st Century Electric Car"*, Tesla Motors Inc., 2006

[9] *Sri Lanka Natural Gas Options Study (Prepared for: USAID-SARI/Energy Program)*, Sri Lanka: Nexant, 2003.

[10] *Natural Gas – New Energy Resource in Sri Lanka (Phase 1 – Initial natural gas utilization road map)*, Sri Lanka: Petroleum Resources Development Secretariat, Sri Lanka, 2014.

[11] *Sri Lanka Energy Balance – 2014*, Sri Lanka: Sustainable Energy Authority of Sri Lanka, 2015.

[12] *Sri Lanka Energy Balance – 2013*, Sri Lanka: Sustainable Energy Authority of Sri Lanka, 2014.

[13] *Sri Lanka Energy Balance – 2012*, Sri Lanka: Sustainable Energy Authority of Sri Lanka, 2013.

[14] Geoff Keith, Sarah Jackson, Alice Napoleon, Tyler Comings, and Jean Ann Ramey *"The Hidden Costs of Electricity: Comparing the Hidden Costs of Power Generation Fuels"*, 2012, Synapse Energy Economics Inc., 2012

[15] Petter Haugneland, *"Norwegian electric car user experiences 2014"*, European Electric Vehicle Congress Brussels, Belgium, 3rd – 5th December 2014

[16] Dr. Nourah AbdulRahman Al-Yousef. "*Modeling and Forecasting the demand for Crude Oil in Asian Countries*", 2005

[17] *MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (User Manual*, International Atomic Energy Agency, 2007

[18] *Renewable Power Generation Costs in 2012*, International Renewable Energy Agency, 2012