A Feasibility Study of Development and Implementation of Smart Energy System for 100% Renewable Energy and Transport Solutions in Sri Lanka

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Dedication

To my mother, daughters Ayodhya and Lydia, son Sudam and my wife Theja for their love and support during my studies.

Acknowledgement

I would like to express my gratitude to several people without whom this thesis would not have been completed.

First, I want to express my special thanks and appreciation to my current Director of Studies Dr Kamyab Givaki who replaced my former Director of Studies Professor Naren Gupta, who retired during my studies. To both Professor Naren Gupta and my supervisor Dr Ozveren Suheyl, I wish to record my thanks for their exceptional guidance, support, advice and generous time allocation given during this research. Their excellent reassurance and encouragement allowed me to grow and develop as a researcher and gave me the opportunity to collaborate with Denmark Aalborg University.

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My sincere gratitude and thanks go to my family and my wife Theja, my two daughters Ayodhya and Lydia and my son Sudam. All are the source of hope, joy and inspiration which has kept me going, not only throughout this four-year journey but over the last nine years of my higher education. I cannot overlook the contribution of my mother Margaret. I appreciate all her prayers and help during my research which impacted positively on my concentration for studying.

I am also grateful for the support of my brother and his family at this time and thank them for always being there for me.

I want to take this opportunity to thank Theja’s parents and family for their incredible support during my higher studies period.

This PhD dissertation is the result of work carried out between November 2015 and November 2019, and I hope you will find the contents of this dissertation thought-provoking and worthwhile to read.

Declaration

I, Wattala P R S S Fernando, declare that I am the sole author of this thesis, titled "A Feasibility Study of Development and Implementation of Smart Energy System for 100% Renewable Energy and Transport Solutions in Sri Lanka".

The all work reported in this thesis is original research carried out wholly by myself under the supervision of Dr Kamyab Givaki, Professor Naren Gupta and Dr Ozveren Suheyl. I have consulted all references cited, and this PhD thesis has not been previously accepted for a higher degree

List of Publications

Topic	Authors	Status	Conference/Journal
The sustainable waste management system for Abertay University (2016)	Wattala Fernando, Allison Dixon	Published	4th International Conference on Sustainable Waste Management System 2016, Limassol, Cyprus
Investigation and Critical Evaluation of Sustainable Waste Management Practices at Abertay University (2017)	Wattala Fernando, Allison Dixon	Published	UREKA2017 (2nd International Conference of the Urban Research and Education Knowledge Alliance), Edinburgh
The Electricity Infrastructure in Sri Lanka Then, Now and Hereafter (2017) Electronic ISBN: 978-1-5386-2344-2	Wattala Fernando, Naren Gupta, C Suheyl Ozveren	Published	UPEC2017 (52nd International Universities' Power Engineering Conference) –Crete, Greece
Design of Optimum Configuration of a Hybrid Power System for Abertay University Campus (2018) Electronic ISBN: 978-1-5386-4340-2	Wattala Fernando, Naren Gupta, C Süheyl Özveren	Published	IEEE conference at Moscow, Russia (ElConRus2018)
Renewable energy resources and technologies applicable to Sri Lanka (2019) Electronic ISBN: 978-1-83953-124-8	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Published	The rpg2019 (International Conference of Renewable Power generation), Shanghai, China
Feasibility Study of Small-Scale Battery Storage Systems Integrated with Renewable Generation Technologies for Domestic household in Sri Lanka (2019) Electronic ISBN: 978-1-7281-3349-2	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Published	UPEC2019(54th International Universities' Power Engineering Conference) – Bucharest, Romania

Feasibility Study of Power Generation from Municipal Solid Waste Incineration System in Sri Lanka. (2020)	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Presenting at IEEE Conference Canada The REPE 2020	IEEE 3rd International Conference on Renewable Energy and Power Engineering, Toronto, Canada
Feasibility Study of Power Generation from Anaerobic Digester based on CHP plants in Sri Lanka. (2020)	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Presenting at IEEE Conference Canada The REPE 2020	IEEE 3rd International Conference on Renewable Energy and Power Engineering, Toronto, Canada
The Sri Lankan energy regulations and market reviews	Wattala Fernando, Naren Gupta, C Süheyl Özveren Hanchen Xiao C Sajeewa	Writing & presenting at IRSEC'20 Conference	IRSEC'20 (Eighth Edition of the International Renewable and Sustainable Energy Conference) at Morocco
The Electricity Infrastructure in Sri Lanka Past, Now and Future Renewable Energy Targets	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Final stage writing to submit Elsevier journal	Energy- The International Journal https://www.journals.elsevier.com/energy
Renewable energy resources and technologies practice in Sri Lanka	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Final stage writing to submit Elsevier journal	Energy- The International Journal https://www.journals.elsevier.com/energy
The first step toward the 100% renewable energy system for Sri Lanka	Wattala Fernando, Naren Gupta, C Süheyl Özveren Kamyab Givaki	Writing to submit Elsevier journal	Energy- The International Journal https://www.journals.elsevier.com/energy

List of abbreviations

Mtoe- million tons of oil equivalent

TWh- terawatt hour

GW- gigawatt

GHG- greenhouse gases

CO_2- carbon dioxide

Gt- gigatons

UNFCCC- united nations framework convention on climate change

IPCC- intergovernmental panel on climate change

Tm^3- trillion cubic meters

IEA- International Energy Agency

CCS- Carbon capture and storage technologies (CCS)

CHP- Combined heat and power plant

PV- Photovoltaic

RET- Renewable-energy and Energy-efficient Technologies

RES- Renewable energy source

V2G- Vehicle to grid

LECO- Lanka electricity company

CEB- Ceylon electricity board

PPP- Private power plants

PPP- Private power plants

CHP- Combined heat and power

EP- EnergyPLAN

V2G-Vehicle to grid.

LECO- Lanka electricity company.

PV-Photovoltaic

DC- Direct current

EfBF-Energy from biofuel.

CEA- Central environmental authority

MSW- Municipal solid waste

SEASL- Sustainable energy authority of Sri Lanka

ADB- Asian development bank.

GDP- Gross domestic production.

CSP- Concentrated solar power.

CCR-Carbon capture recycling

CEEP-Critical Excess Electricity Production.

EEEP-Exportable Excess Electricity Production

ABSTRACT

Sri Lanka as a developing country is facing existential energy challenges. Total electricity consumption was 12.79 TWh in 2016 and is projected to increase about 6 times to 71.97 TWh by 2050. The projected energy demand will exceed supply in a few years. A transition to 100% renewable energy (100RE) supply will address fuel security, and environmental concerns.

This study investigates the potential quantity of renewable energy sources in Sri Lanka for a transition to a 100RE future. This thesis reports a detailed feasibility study framework and case studies for the development and implementation of 100% renewable energy supplied Smart Energy Systems and Transport future for Sri Lanka.

The feasibility study framework and the case study analyses are based on a long-term energy system model of Sri Lanka using the EnergyPLAN model. Sri Lanka should have a potential install capacity of grid-connected wind, solar photovoltaic, dammed hydro, river hydro and biomass to achieve 100% renewable energy solution, and the estimated values are 14430 MW, 15600 MW, 1576 MW, 753 MW and 394 MW, respectively. Different development scenarios towards 100RE are used to study the pathway towards 100RE. These scenarios are based on a staged increase of renewable energy such as biomass. The scenarios also include conversions to electrical vehicles, waste to energy, H_2 usage and dump charge system for transport.

The results prove that a pathway for 100RE is possible. The 100RE pathway ensures energy security and mitigates environmental impacts. The pathway includes improvements in industrial energy intensity and utilising efficiency and conservation potentials. Fuel demand for the industry will be supplied through a high share of biomass usage. Bioenergy and electrification integration are key to the solution, all remaining fuel consumption is converted to solid biomass.

The results show that there are technically feasible pathways to achieve 100RE solutions for Sri Lanka with the present and predicted renewable energy technologies. Sri Lanka can meet the future energy demand without importing energy with the complementary socio-economic and socio-political approaches

CHAPTER 1

1.INTRODUCTION

This chapter describes the main challenges and the solutions in the energy sector related to energy and the environment. Secondly, the chapter defines the role and prospects for renewable energy and transition to 100% renewable energy solution.

The critical elements in a smart energy system are then presented along with the research question, which will guide the research in this dissertation. Finally, the research limitation, resolutions and structure of the thesis are outlined.

1.1 Problem statement

In the Asian continent, countries like Sri-Lanka will face severe energy security and sustainability challenges in the coming decades. Sri Lanka needs to secure and utilise sustainable energy supplies for its socio-economic development, to ensure demand security (market stability), minimize the impact of oil/energy prices on the economy, and reduce dependency on fossil fuels. Secure and sustainable energy supplies require a long-term strategy to ensure the availability of energy resources and their prompt supply in various forms, in adequate quantities. Energy suppliers should be available at prices, which are affordable for all consumers that will not adversely affect the performance of the economy and which will provide for the well-being of its citizens without unacceptable or irreversible impact on the environment. Present relatively low energy consumption levels, spurred by a desire for rapid economic growth are fuelling a growing demand for energy, leading to a whole set of issues such as unknown demand, worsening energy security, aggravated by highly volatile energy markets, increasing concern about environmental sustainability and climate change, inadequate infrastructure and lack of access to financing.

1.1.1. Energy and environment

In 2018, the primary energy supply in the world was equal to 161,250 terawatt hours (TWh), while the primary energy supply in 2017 was 156,710 TWh [1,2]. Fig 1-1 shows the world total primary energy supply by fuel in 2018 [1,2]. Most of the energy supply globally is achieved by combusting fossil fuels such as oil (54,220 TWh), coal (38,488 TWh) and natural gas (43,870 TWh), nuclear energy (7109 TWh), hydroelectricity (11,035 TWh) and renewable energy (6528 TWh) only accounted for a small part (4%) of the overall primary energy supply although hydro is the most highly used renewable energy source in global

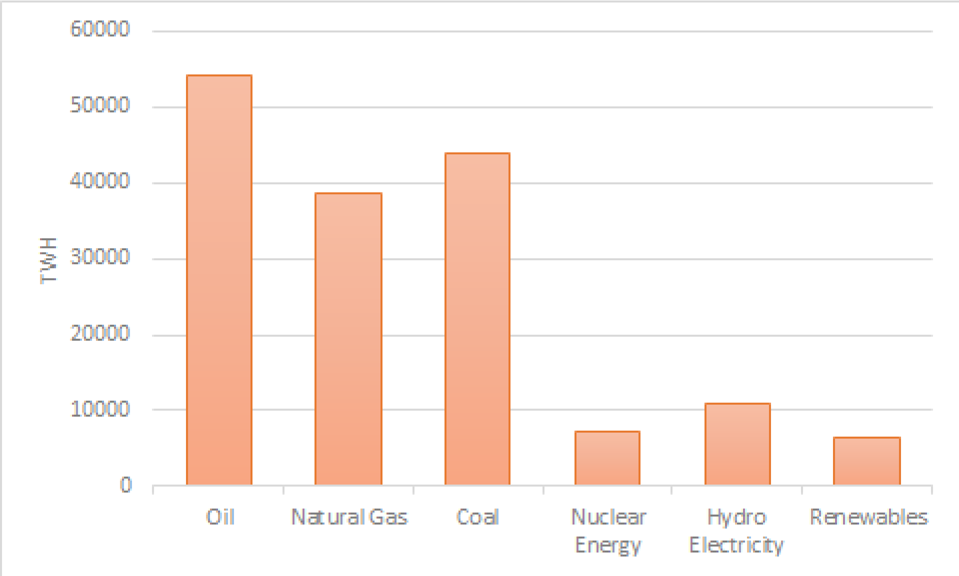


Fig 1-1 World total primary energy supply 2018 by fuel.

In 2018 the global share of energy supply from fossil fuels was 84.7% of the entire primary energy supply, and other remaining 15.3% comes from nuclear, hydro and renewable energy sources. This universal dependence on combusting fossil fuels for primary energy supply is causing energy-related issues, including environmental problems, security of energy supply and cost competitiveness [2]. In 1980, the global primary energy demand was only 83,829 TWh, but this had increased approximately two-fold to 161,250 TWh by 2018 due to the increasing industrialization, high energy demand in less developed countries and inefficiencies in energy management. Further energy increases can be expected in the near future [1].

The total worldwide electricity generation in 1980 was an 8283.6-terawatt hour (TWh) and is increased to 26,614.8 TWh in 2018. In 1980, the installed capacity of power generation was 1945 gigawatt, (GW) and increased to 7700 GW to cater for the current electricity generation needed in 2017. The global electricity generation typically is achieved by combusting fossil fuels such as oil (802.8 TWh), coal (10,100.5

TWh) and natural gas (6182.8 TWh), nuclear energy (2701.4 TWh), hydroelectricity (4193.1 TWh) ,renewable energy (2480.4 TWh) and other energy sources (153.8 TWh) Fig 1-2 illustrates the world gross electricity production by source, and it describes how 64% of fossil fuel share was utilized to supply current electricity production in 2018 [2, 3].

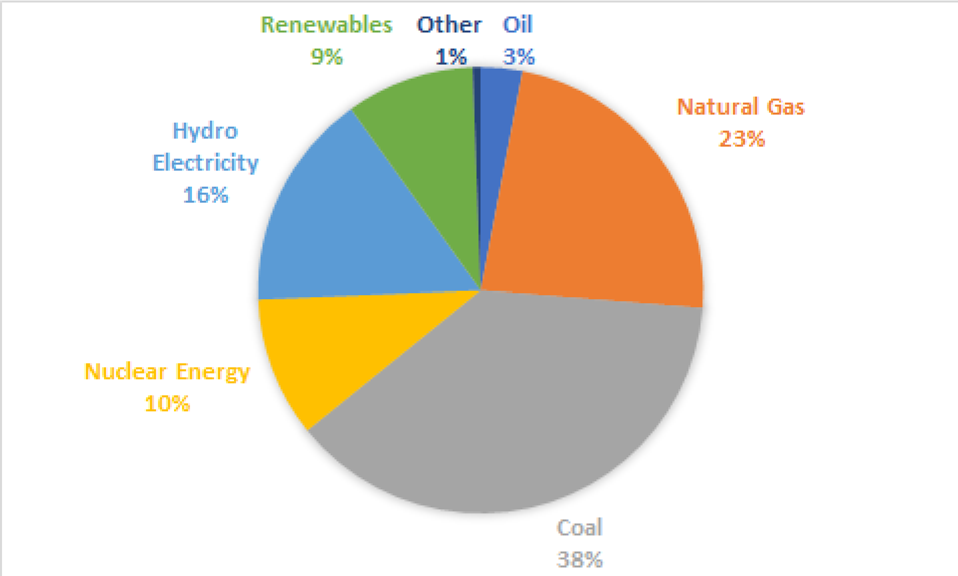


Fig 1-2 World gross electricity production by source, 2018

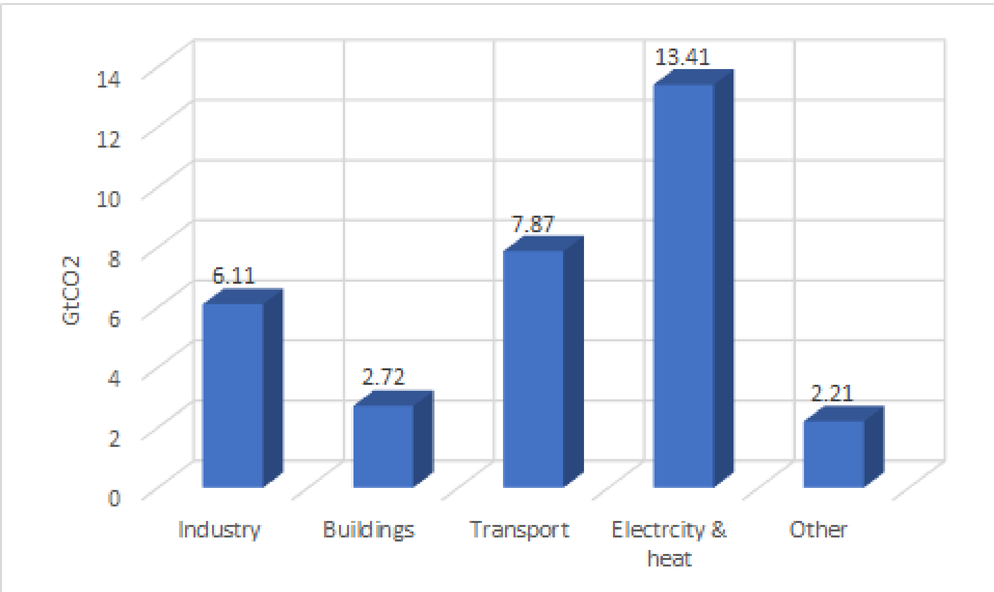


Fig 1-3 World CO_2 emissions by sector 2016

The greenhouse gases (GHG) play a vital role in maintaining a habitable planet temperature, and without these gases, the earth's typical temperature would be -18°C [4]. Carbon dioxide (CO_2) is one of the primary greenhouse gases in the earth's atmosphere and it is the largest contributor to climate change. In order to reduce CO_2 emission, the amount of fuel used on a regular basis should be significantly less [4].

In 1990, a total of 19.89 gigatons ($GtCO_2$) of CO_2 were produced globally through fuel combustion from America 6.06, Asia 5.83, Europe 7.18, Africa 0.53 and Oceania 0.29 $GtCO_2$. There were 32.31 $GtCO_2$ of global CO_2 emissions in 2016 from fuel burning, and an approximate similar amount in 2015 with 42% of emissions coming from electricity and heat generation through burning fossil fuels as illustrated in Fig 1-3 [5].

As of today, America 7, Asia 17.43, Europe 5.05, Oceania 0.44 and Africa 1.16 $GtCO_2$ are responsible for the global CO_2 emissions [5]. Asia is the leading source of emissions, reaching 17.4 $GtCO_2$, and this value is twice the level of America's emission and three times that of Europe emission. According to diverse regional dynamics, China and India accounted for more emissions in the Asia. China is the biggest CO_2 emitter of any country in the world due to the world's most significant energy production and consumption. Its electricity production relies on coal electricity generation and transportation trusts on fossil fuel. China's energy consumption consists of industry, agriculture, waste and mining, and both production and consumption sectors produce CO_2 massively into the environment. After China, India is the next account holder for CO_2 emission in Asia due to the current economic growth and development. Electricity, heat, industry and transportation are the most prominent production sectors, and agriculture, land-use change, industrial process and waste are the most significant consumption sectors of carbon emission. Mainly according to the United Nations Framework Convention on Climate Change (UNFCCC) Annex I, America and Europe have implemented the best sustainable practices in decreasing CO_2 emissions since 2000 [5,6].

Meanwhile, due to the vast growth of the industrial revolution, increased CO_2 emissions have led to the collapse of the global carbon cycle and this has resulted in a global warming. Global warming has the potential to impact on ecological, physical and health factors, weather measures, seawater level rise and water systems. An Intergovernmental Panel on Climate Change (IPCC) established in 1988 was set up to study different characteristics of climate change and protect the planet from global warming [5]. The 5th assessment of Intergovernmental Panel on Climate Change (IPCC) in 2014 describes impact, adaptation, and vulnerability of climate change. According to the 2016 Paris agreement all related parties agreed to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C" [4].

1.1.2 The role of energy in development.

Access to the affordable, secure and clean energy for all inhabitants is a dominant parameter to the growth of economy and reduction of poverty. Currently, economic growth is shifting from an agricultural-based economy towards a knowledge-based economy with massive industrialisation. Due to this structural change of economy, the level and pattern of energy consumption, type of fuels and energy technologies utilisation in the industry have changed. Fig 1-4 shows the final energy use per capita and fuel mix in selected low, middle and high-income countries. When the country is wealthier, the energy sector does not rely on traditional biomass and electricity use, and the per capita energy use rises [7].

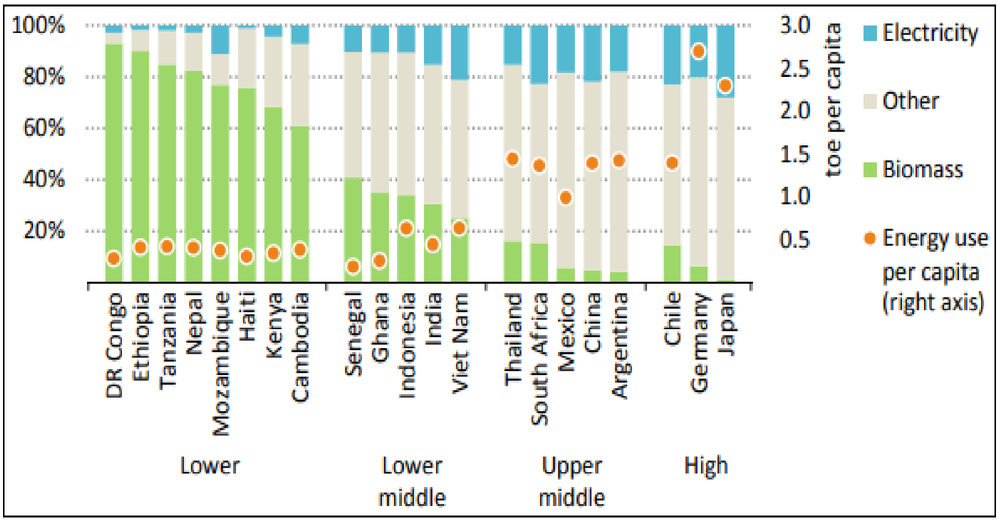


Fig 1-4 Final energy use per capita and fuel mix in low, middle and high-income countries, 2015 [7]

1.1.3 Energy and sustainable development.

Global fossil fuel reserves will be declining over time. At the end of 2018 oil, gas and coal reserves total capacity was 1730 billion barrels, 196.9 trillion cubic meters (Tm^3) and 1055 billion tonnes and under the current production oil, gas and coal accounted for 50, 50.9 and 132 years, respectively. The enormous long-term nuclear power generation is under threat; the volume of uranium in the world is insufficient, and most of the nuclear plants are being decommissioned due to health and safety precautions [8,9].

There is no single pathway for how the world will use energy in the coming decades based on the trends and policies that we see today. Global energy demand is set to grow by more than a quarter by 2040 with all growth coming from developing economies such as China and India. Low-carbon technologies and natural gas meet more than 80% of this increase in demand and electricity usage will be doubled.

On this pathway, global carbon emissions keep on rising. The world falls short of goals to achieve such as universal energy access, improve the air quality, minimise freshwater pollution, reduce coastal pollution, decrease deforestation, expand biodiversity and improve global climate worsening. To overcome all above impacts world needs robust, sustainable energy development strategies and thus achieve more low-carbon power sources and renewables provide the main pathway to universal energy access and an even greater focus on energy efficiency. Reaching climate goals means wind, solar, biomass and other renewable energy generation to be developed and utilised faster. In addition, it requires new technologies such as carbon capture, utilisation and storage to enter the scene at scale. There are future multi-energy solutions available in the world and actions by governments will be decisive in determining the path all relative stakeholders will need to follow. According to the International Energy Authority (IEA), the world energy outlook has introduced two main methods to discover a possible energy solution mechanism to achieve well-behaved long-term global climate changes in cooperation with exiting energy policies [5].

1. New Policies Scenario (NPS)
2. Sustainable Development Scenario (SDS)

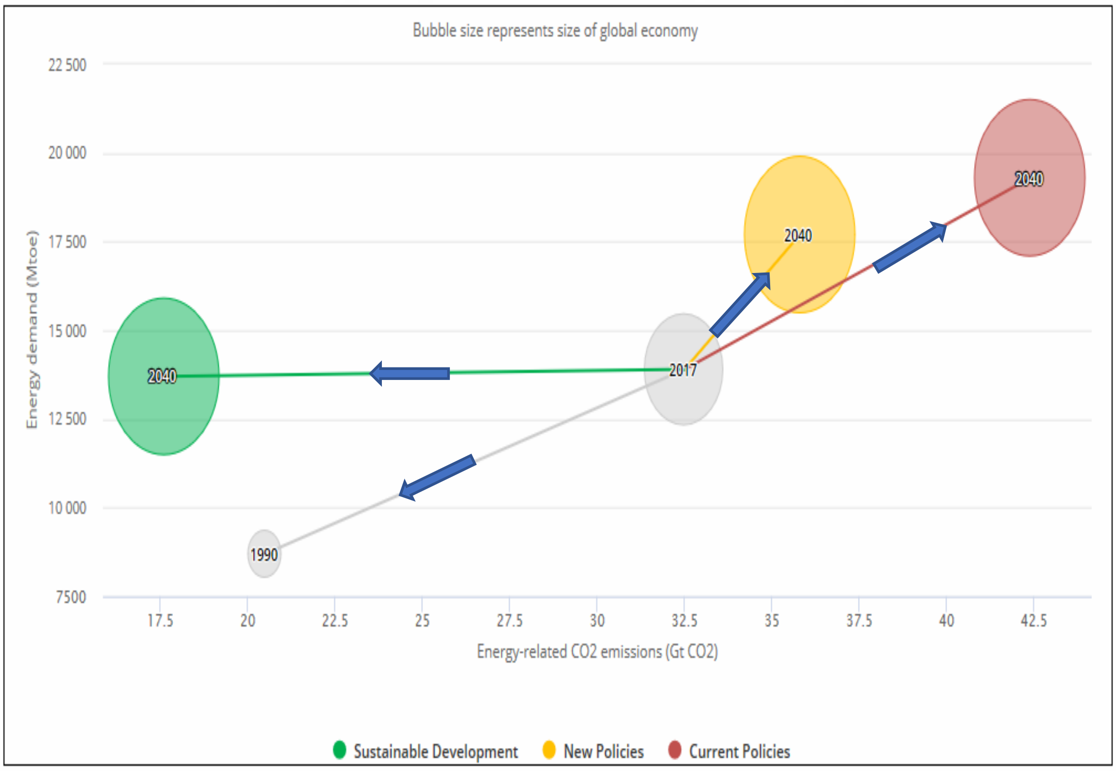


Fig 1-5 World primary energy demand and energy-related CO_2 emissions by scenario [5]

The new energy policy decisions were more attractive to the centralised energy planning approach [9]. However, the global energy planning systems are currently moving to the decentralised (District Energy) systems due to the efficiency of the system and its potential as a cost-effective way of providing energy access to rural communities. This situation needs to move towards sustainable development scenarios to increase reliance on clean, renewable energy resources, improve energy efficiency and encourage new energy conversion technologies to protect the climate and ecosystem. Fig 1-5 illustrates the world primary energy demand and energy-related CO_2 emissions by NPS and SDS scenarios [5, 7].

According to the above Fig 1-5, three different CO_2 emission values can be seen in 2040. If the world follows the current policies, new policies and sustainable development scenarios to fulfil the 2040 world energy demand, the estimated CO_2 emission would be about 42.5,36 and 17.5 $GtCO_2$, respectively. The world needs to follow sustainable development scenario to achieve manageable primary energy needs and CO_2 emission.

By considering the importance of introducing renewable resources and energy efficient technologies, it is vital to integrate country's national energy planning with a SDS strategy solution to advance energy access, air quality and climate objectives and develop a universal energy system.

Consequently, undermentioned features expand and maintain socio-economic benefit from energy by introducing sustainable development scenario to the national energy policies [10].

1) Increase energy security
2) Increase energy access
3) Increase the harnessing of renewable supplies
4) Increase the efficiency of supply and end-use
5) Reduce of pollution.

1.2 Energy sector challenges and solutions

There are precise energy sector challenges that can be identified within the energy sector such as secure energy supply, energy prices, availability for resources, land use consequences, climate and environmental change, energy access and health.

National and local transmission systems operatives are responsible for delivering energy to consumers at the right place and time. For a successful, secure energy supply, there are some parameters that need to be considered such as

1. Frequency and capacity of energy production
2. Awareness of global energy market challenges
3. Availability of utilising supplementary variable renewable energy sources
4. Having an affordable energy price (a crucial assessment factor in evaluating possible energy solutions)

Depletion of resources and energy capacity shortage are the most noticeable features within the availability of resources. Global energy consumption is based on fossil fuel but, in the future, there is a concern about fossil fuel reserves. However, most renewable energy resources do not face depletion excluding biomass.

New world land use for energy projects, urban developments, agriculture and ecosystems is another critical challenge. Due to the implementation of biomass, as compared to non-renewable energy sources, land-use intensity is changing from 0.1

m^2/MWh to 500 m^2/MWh. In addition, land use for nuclear, natural gas and coal (underground) respectively reaches 0.1, 0.2 and 0.2 m^2/MWh. When considering renewable energy sources, the land-use intensity for wind, geothermal, hydropower (large dams), solar PV and Biomass individually achieves 1, 2.5, 10, 10 and 500 m^2/MWh, respectively [11].

Climate and environmental change have also been one of the critical challenges in the energy sector over the past decades. The impacts of climate change can be categorized as migration, water security, human health, biodiversity, rural areas, cities, food security, political and social security and disasters and all above impacts originate from GHG emission via energy sector [11].

According to the International Energy Agency (IEA), energy access is defined as "a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity overtime to reach the regional average".

Fig 1-6 illustrates the share of the population without electricity access above and below the poverty line in selected countries in 2016.

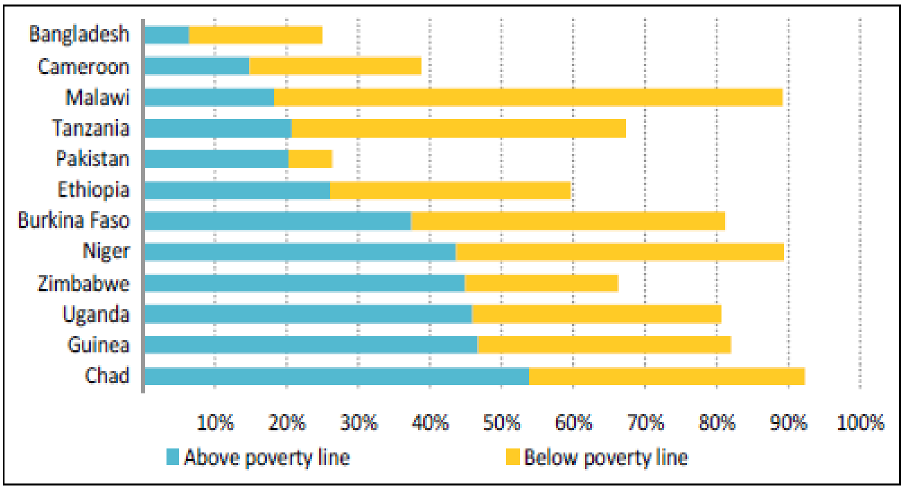


Fig 1-6 Share of the population without electricity access above [7]

According to the Fig 1-6, there are some developing countries where people are living above the poverty line. However, there is no access for electricity due to the obstacles such as inadequate policy implementations, lack of energy infrastructure and high cost of energy connection from the national grid.

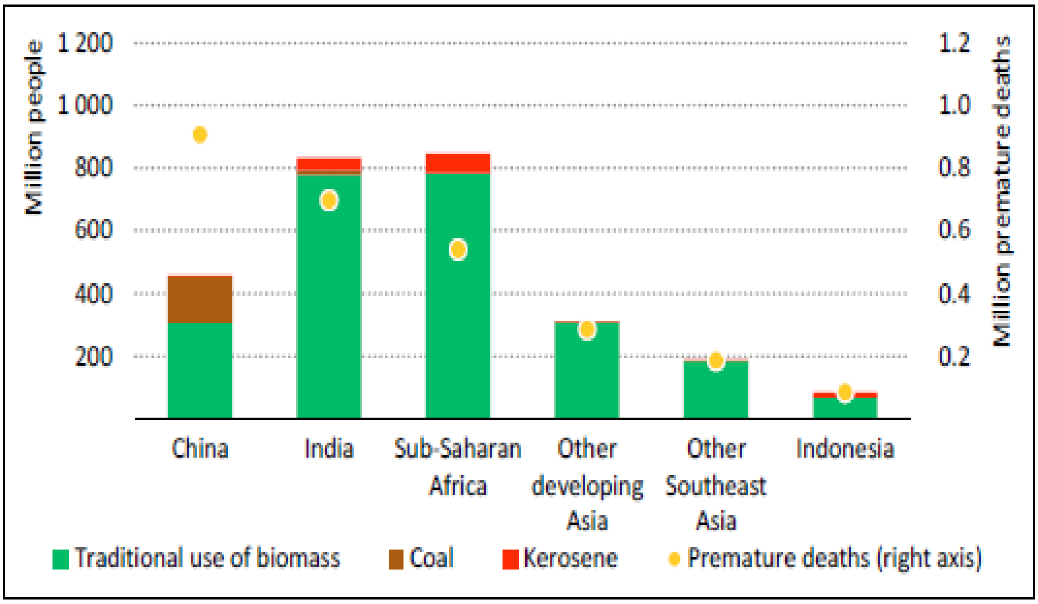


Fig 1-7 Population without access to clean cooking by fuel and region [7]

In modern Asia, nearly 70 million people are living above the poverty level, but without accessing electricity [7]. Health is also another essential parameter associated with energy access. Some countries still use kerosene lamps, candles and different kind of fuel which is realising pollutant air for lighting purposes directed to health problems. Also, some countries heavily rely on solid biomass and coal for cooking. It is another crucial factor for the health-related problems with energy access, and according to Fig 1-7, there are 2.8 million premature deaths in 2015 globally due to the lack of energy access [7].

For the above-described energy challenges, there are abundant undermentioned solutions which have been discussed, proposed and implemented during the past and up to the present day.

1. Nuclear power
2. Energy efficiency technologies (Energy demand-side solutions)
3. Carbon capture and storage technologies (CCS)
4. Clean energy mechanisms, new policies and reforming fuel subsidies
5. Various biomass technologies to mitigate climate change
6. Smart energy systems
7. Electric vehicle technologies and sustainable transport systems.
8. Bioenergy expertise

9. Integration of variable renewable energy technologies (solar and wind) [12 13].

1.3 Energy situation in Sri Lanka

Sri Lanka has an ample potential of hydro energy, thermal energy and other renewable energies for the electricity generation. Enormous strides have already been made since 2016, realizing a 3% contribution of power generation from non-conventional (solar and wind) renewable energy at present, through the employment of several, innovative policy instruments. Sri Lanka's current energy generation depends on thermal energy power plants such as fossil fuel energy sources (such as diesel and coal). The transition from fossil fuels towards the integration of more and more renewable energy requires rethinking and redesign of energy systems in Sri Lanka. New research development means more focus on the electricity sector to solve the integration puzzle between smart energy systems and renewable energy systems.

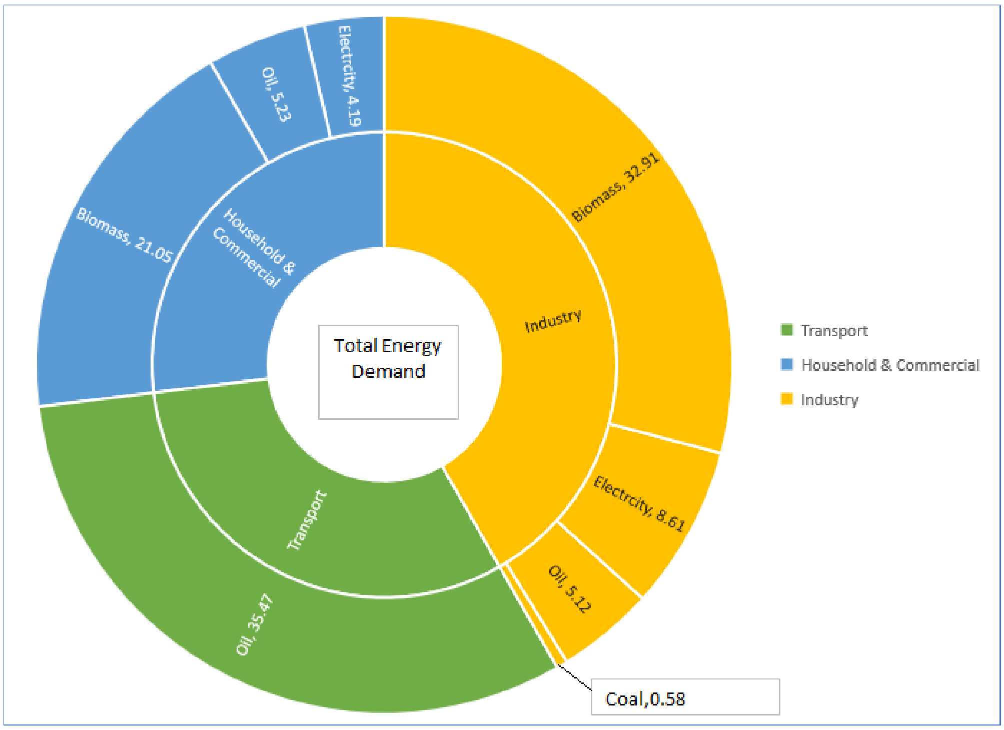


Fig 1-8 Sri Lanka energy demand 2016 (TWh)

Sri Lankan's energy consumption can be separated into three divisions: transportation, industry and household and commercial consumption as illustrated in Fig 1-8. According to the Fig 1-8 the transport sector fully relies on oil and the main sources of energy in the industry sector are coal, oil, electricity and biomass. The third sector household and commercial sector depend on oil, electricity and biomass.[14]. Meanwhile, from imported fossil fuel, approximately 40% is used for electricity generation, and the rest is consumed by transportation and other household consumption in Sri Lanka: which is an extremely volatile situation in the current economic climate.

The industry sector is Sri Lanka's most significant energy consumption sector with a share of 42% of the final energy demand, followed by the transport and household and commercial sectors with shares of 31% and 27% respectively [15].

Hereafter this thesis discusses the energy data related to 2016 because when starting the research, the latest available data obtained from 2016.

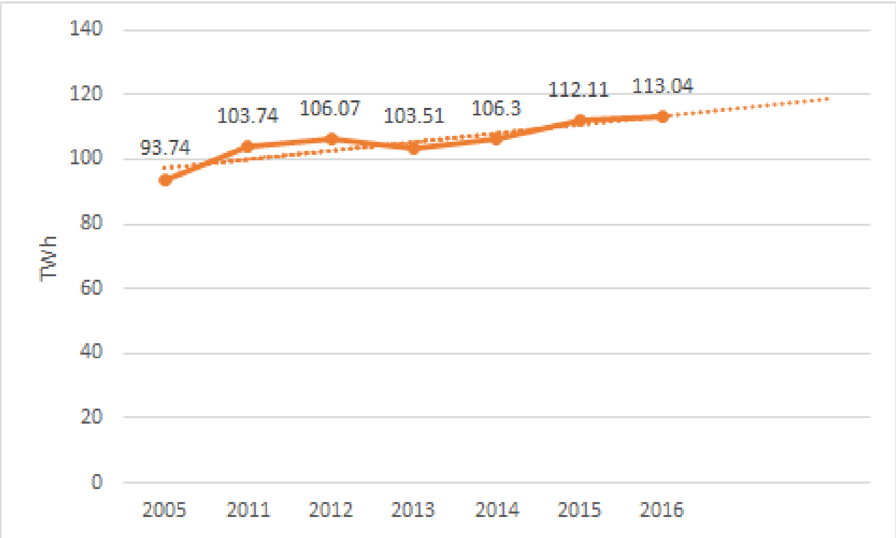


Fig 1-9 Sri Lanka total energy demand in TWh from 2005-2016

Fig 1-9 illustrates the total energy demand in Sri Lanka from 2005 to 2016. According to Fig1-9, the total energy demand of the country was around 113.04 TWh in 2016, and it consisted of 53.96 TWh of biomass, 45.71 TWh of petroleum, 12.79 TWh of electricity and 0.58 TWh of coal [14].

Sri Lanka's energy demand is currently being catered for by several energy sources consisting of both indigenous non-fossil fuels such as biomass and imported fossil fuels such as oil and coal. The remainder is made up of other indigenous sources which include large hydro and renewables such as solar, small hydro and wind.

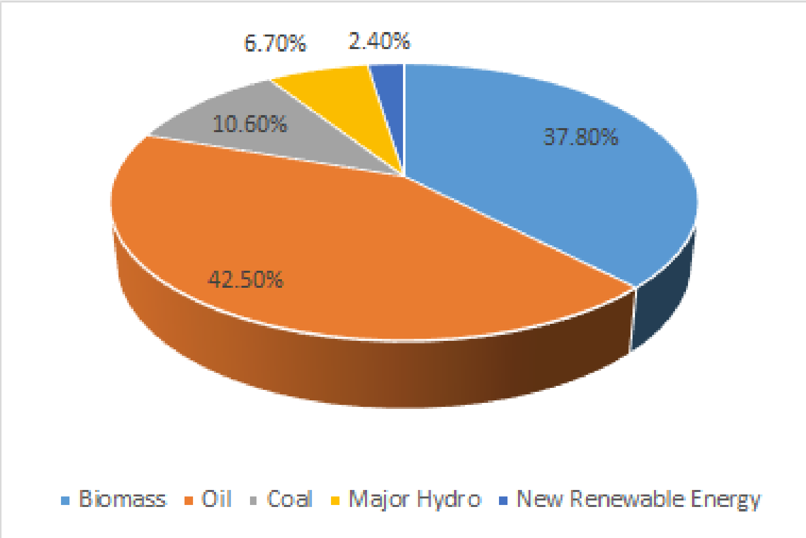


Fig 1-10 Sri Lanka primary energy supply 2016

In 2016, the country's primary energy supply was 144.33 TWh, and this mainly consisted of 54.54 TWh of biomass, 61.3 TWh of oil, 15.24 TWh of coal, 9.76 TWh of major hydro, and 3.49 TWh of new renewable energy such as small hydro projects, wind and solar [14,15]. The majority of Sri Lankan's energy is consumed by electricity generation, followed by transportation and household sectors. The oil demand of Sri Lanka has increased heavily after 2016 due to the growth of the transport sector.

Fig 1-10 shows that 46.9% of the total primary energy supply in 2016 is from indigenous (biomass + dammed hydro + new renewable) energy resources and Sri Lanka must import other fossil fuels such as oil and coal to meet the balance.

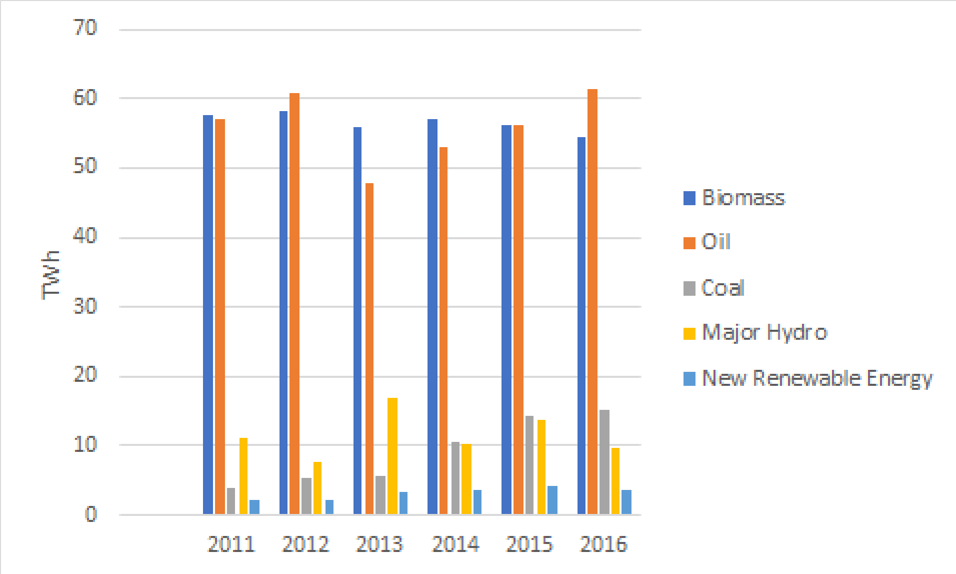


Fig 1-11 Sri Lanka's final total energy supply in TWh from 2011-2016

Fig 1-11 illustrates the final total energy supply of each fuel over the period 2011-2016 in Sri Lanka. In 2016 petroleum experienced the highest growth fuel in Sri Lanka. The use of biomass and oil is nearly equal from the period 2011 to 2016. The growth in the use of coal as a result of its use as an alternative for other fuels to generate electricity to fulfil household and commercial and industrial sectors' electricity requirement. Due to high rain and droughts hydropower utilisation increased and decreased during those past years. The use of new renewable energy such as mini-hydro, solar and wind power generation has increased significantly since 2011 due to the government's new regulations to achieve a 100% renewable energy solution for Sri Lanka's electricity generation.

In 2016, Sri Lanka electricity demand accounted for 12,785 GWh of primary energy consumption. This electricity demand consists of 4219.05 GWh of domestic and religious purpose, 3835.5 GWh of industrial, 2812.7 GWh of commercial and 255.7 GWh of hotel consumption. The 1662.05 GWh electricity sales for private power companies as bulk supply [14].

Table 1-1 Sri Lanka electricity generation in 2016

Source	Generation- GWh 2016	%
Major Hydro	3481	24.68%
Thermal (Oil)	4461	31.53%
Thermal (Coal)	5047	35.67%
New Renewable Energy	1160.1	8.12%
Total	14,149.1	100

Table 1-1 shows the Sri Lanka electricity generation in 2016 and indicates that the most popular renewable energy source for producing electricity is hydro. Thermal (Coal) energy is becoming more popular due to 900 MW coal plants having been recently commissioned. Also, Sri Lankan energy authorities still use Thermal (Oil) plants to fulfil peak electricity demand throughout the year. According to the Tab 1-1, nearly 32.8% of electricity generation is achieved by primary hydro and new renewable energy sources. If authorities introduce renewable energy sources to the system to replace thermal (Oil & Coal), Sri Lanka can achieve a 100% renewable energy scenario for electricity generation by 2050 [14, 15].

1.4 Role and prospects for renewable energy in global

Fig 1-12 shows that the global estimated renewable energy share in 2016 and new renewable share from the global total final energy consumption is about 10.4% without traditional biomass and nuclear [16]. The 5.4% (3.7%+ 1.7%) highest share of renewable electricity generation from modern renewable energy, and it consists of hydropower (3.7%), wind, solar, biomass, geothermal and ocean power (1.7%). The second-highest share is 4.1% accountable for renewable thermal energy and followed by 0.9% for transport biofuels. Traditional biomass share is 7.8% and primarily used for cooking in most countries and for heating in developing countries. The total renewable energy share is 18.2% of total final energy consumption [16].

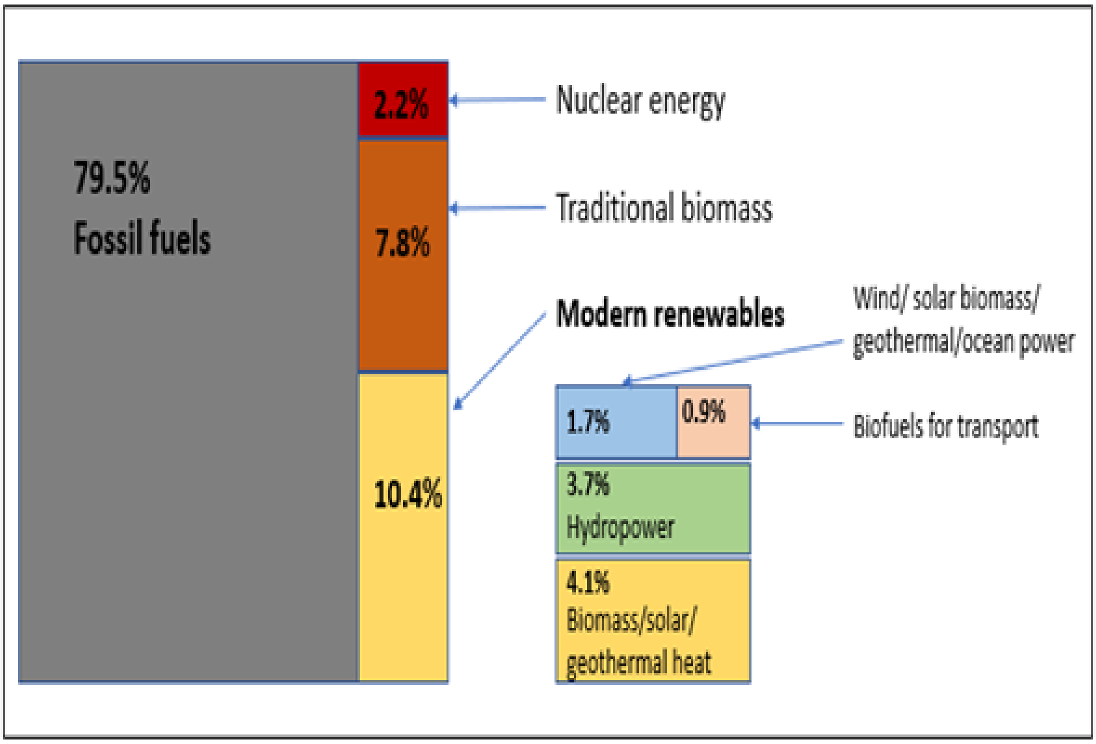


Fig 1-12 Global estimated renewable share of total final energy consumption, 2016

1.4.1 Global renewable energy potential

There are numerous reports, publications and opinions [8-10, 12, 16-17] about global renewable energy potential. According to the Special Report Renewable Energy (SRREN) published by IPCC in 2012, there is a technical potential to achieve 100% renewable energy solutions to fulfil current primary energy demand.

Fig 1-13 shows the total global technical renewable energy potential through 2050, and it shows how many times the regional renewable energy potential can fulfil their current primary energy demand.

According to Fig 1-13 global available renewable energy technologies such as solar, wind, geothermal, hydro, ocean and bioenergy use to achieve nearly 12,000 exajoules (EJ) in 2050.(1EJ= 278 TWh approximately) China and Europe primary energy demand could be fulfilled 2.5 times over, while South America, Africa and Oceania regions primary energy demand could be supplied by over 50 times by using above renewable energy technologies [17].

Nature offers a broad range of renewable energy sources like ocean energy, geo- and solar thermal, photovoltaics, bioenergy, wind, hydropower and solar thermal electricity.

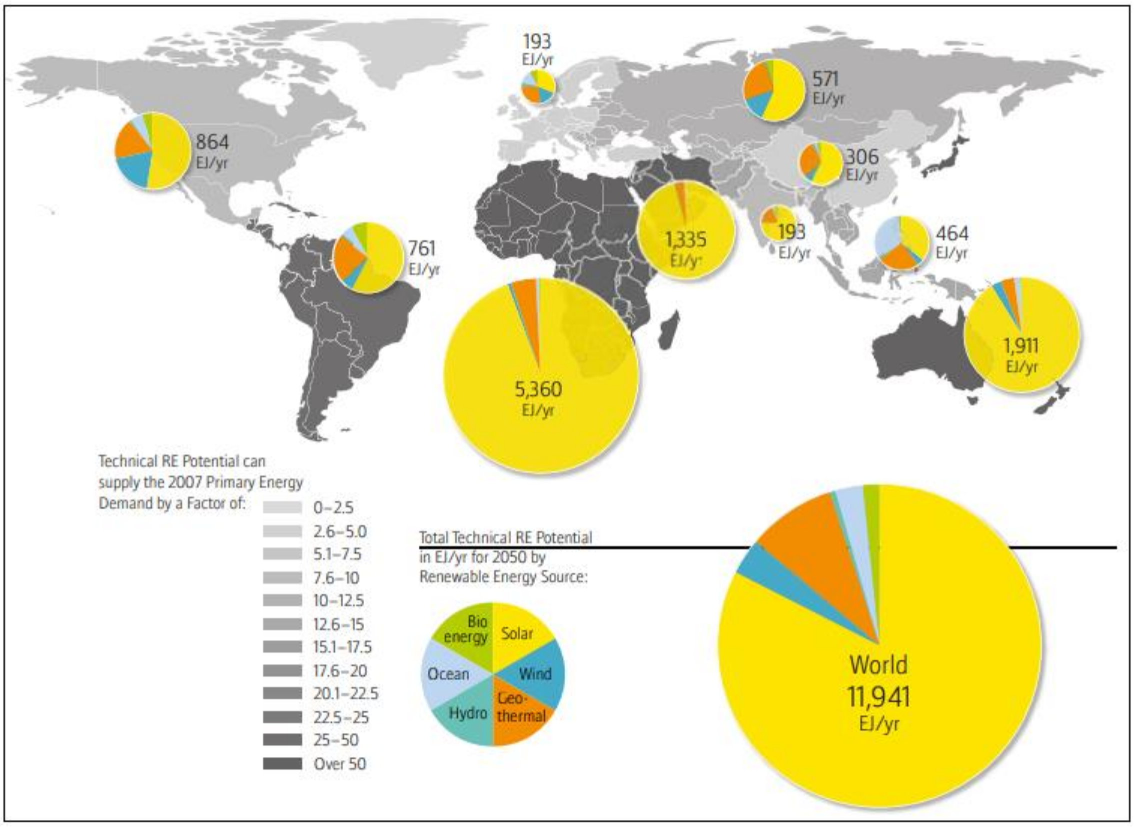


Fig 1-13 Total global technical renewable energy potential in EJ/year for 2050 [18]

Fig 1-14 illustrated the energy resources of the world. According to that figure, constant flow of energy amounts to about 3,000 times the total present-day energy consumption of the whole of humankind. The current global power requirement for eight years can produce in one day from the sunlight which reaches the earth. This incredibly rich source of energy has not been harvested and grip for many centuries in industrialised societies due to the lack of technology and energy gathering. In the modern world, many technologies are capable of harvesting maximum potential from renewable energy resources efficiently to fulfil a planet hungry for energy. However, it is necessary to identify and define the type of potential when outlining the availability of renewable energy sources considered for the case study. There is not a single definition of the different types of potentials of renewable energy sources, but significant literature distinguishes and defines three types of potential: theoretical, technical and economic potential [18].

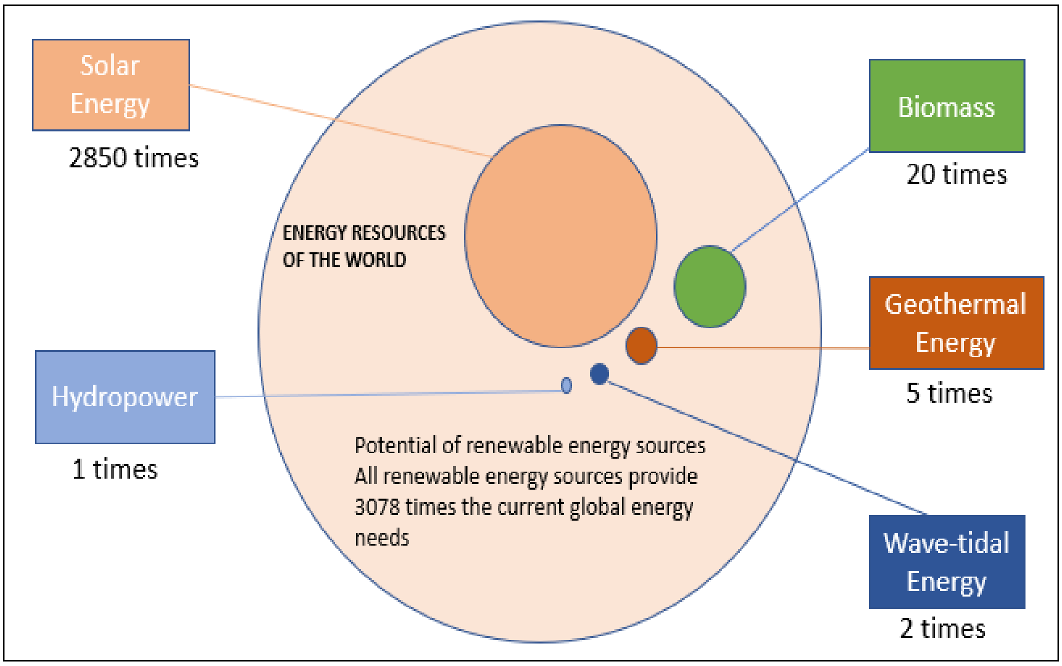


Fig 1-14 Energy resources of the world

A- **Theoretical Potential-** This is the highest level of potential in the hierarchy and is based on current scientific data and research. To derive the theoretical potential general physical parameters must be considered, such as energy resource availability, quantity, the time frame of accessibility and available region.

B- **Technical Potential-** This level calculates the conditions of technical limitations and considering parameters such as available land areas for the resource, conversion efficiency of technologies and accessibility for raw materials. Research and development (R&D) methods, data analysis, weather and technical reports have been used in the past years to calculate the technical potential of renewable energy resources.

C- **Economic Potential**- The economic potential is the proportion of the technical potential that can be realised economically. Hence, the economic potential considers the cost of technologies, renewable energy resources, human resources and land area. Also, other parameters such as energy markets, energy demand and competition of other markets are considered to calculate the economic potential of the renewable energy resource.

1.5 Transition to 100% renewable energy solution.

Globally more than 70% of international organisations experts agree to see the technical possibility for 100% renewable energy transition accept in the most challenging sector called transport [16,17].

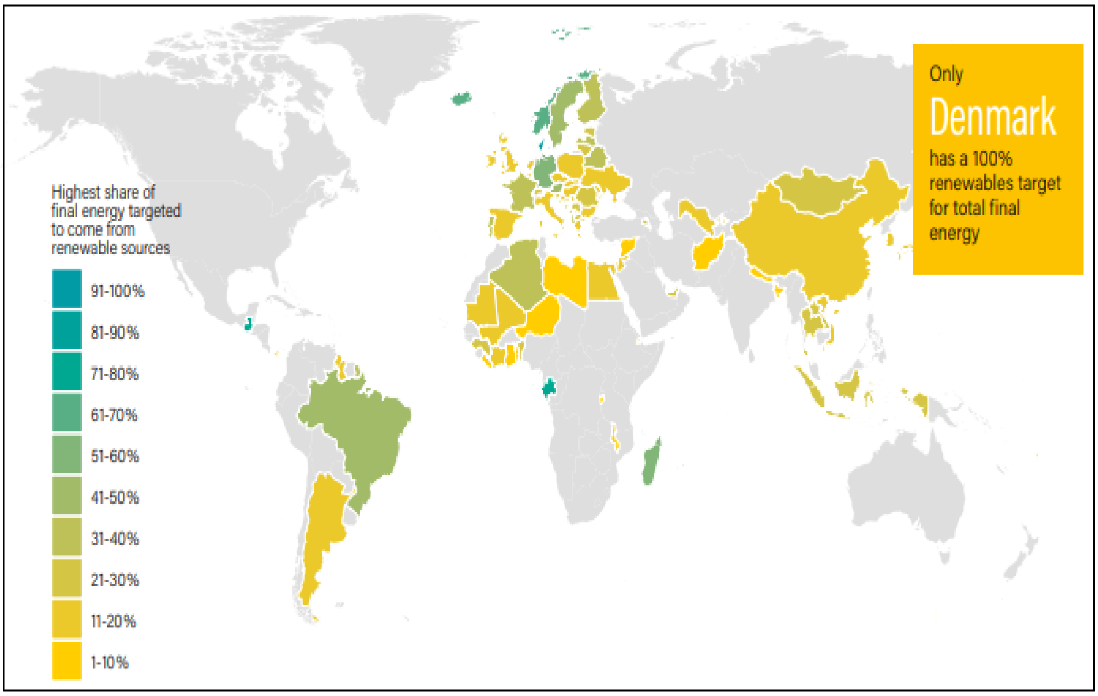


Fig 1-15 National Targets for Share of Renewable Energy in Final Energy End-2017 [17]

According to experts' outcomes, political and geopolitical performance is one of the critical factors to achieve a 100% RE solution. Also, there are vital obstacles identified such as existing fossil fuel infrastructure competition, the less economic diversity of fossil fuel exporting countries, and lack of awareness about renewable energy economics and failure of investment in energy infrastructure [17]. Energy market issues from indirect and direct fossil fuel subsidies, fragile long-term thinking of energy policy and absence of precise policies about high penetration of renewable energy system are some significant barriers to achieve 100% renewable energy transition [15, 16].

The world new renewable energy targets need to fulfil power generation, transport, heating and cooling. Most renewable energy targets focus on power generation. By 2030, there will be forty-two countries reaching national targets for renewable energy for transport and forty-eight countries achieving national targets for renewable energy used for heating/cooling. Currently about 85 provinces, states or countries have goals for more than 50% of renewable electricity. Nearly 150 countries have national targets for renewable energy in power by 2050 and Denmark is the only country currently that has 100% renewable energy targets for the total energy. Fig 1-15 shows the national targets for the share of renewable energy in final energy at the end of 2017 [16].

When discussing the transition to 100% renewable energy solution, there is an abundant range of technologies offering energy services in the form of electricity, heating and cooling as well as transport solutions. Table 1-2 shows the renewable energy sources such as bioenergy, wind, hydropower, all solar technologies as well as geothermal and ocean energy and form of energy technologies that can be harnessed from the above renewable resources [18].

Table 1-2 Renewable energy sources and technologies

Source	Electricity	Heating and Cooling	Transport
Wind	Onshore Offshore		
Hydro	Small Hydropower (10MW) Large Hydropower (>10MW)		
Solar	Photovoltaics (PV) Concentrated Solar Power (CSP)	Solar Thermal	
Ocean	Wave; Tidal; Thermal; Osmotic		
Geothermal	Conventional Geothermal Electricity (hydrothermal); Electricity ORC and Kalina Cycle; Enhanced geothermal systems (EGS); Supercritical fluids	Direct Use Ground Source Heat Pumps	
Bioenergy	Biomass Biogas	Biomass Biogas	Bioethanol Biodiesel Biogas

1.6 Smart energy system

The smart energy system concept has used within this thesis to build the framework for a 100% renewable energy solution for Sri Lanka. Infrastructure designs and operation of future energy systems are the main key features of the smart energy system, and it always approaches the most effective and low-cost solutions. The technologies and sectors will coordinate, influence and integrate each other within the future renewable energy system. The smart energy system viewpoint is helping to design a substitute 100% renewable energy system using a range of technologies and sectors by considering a variety of evaluation factors [19].

"Smart energy systems are defined as an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each sector as well as for the overall energy system" [20].

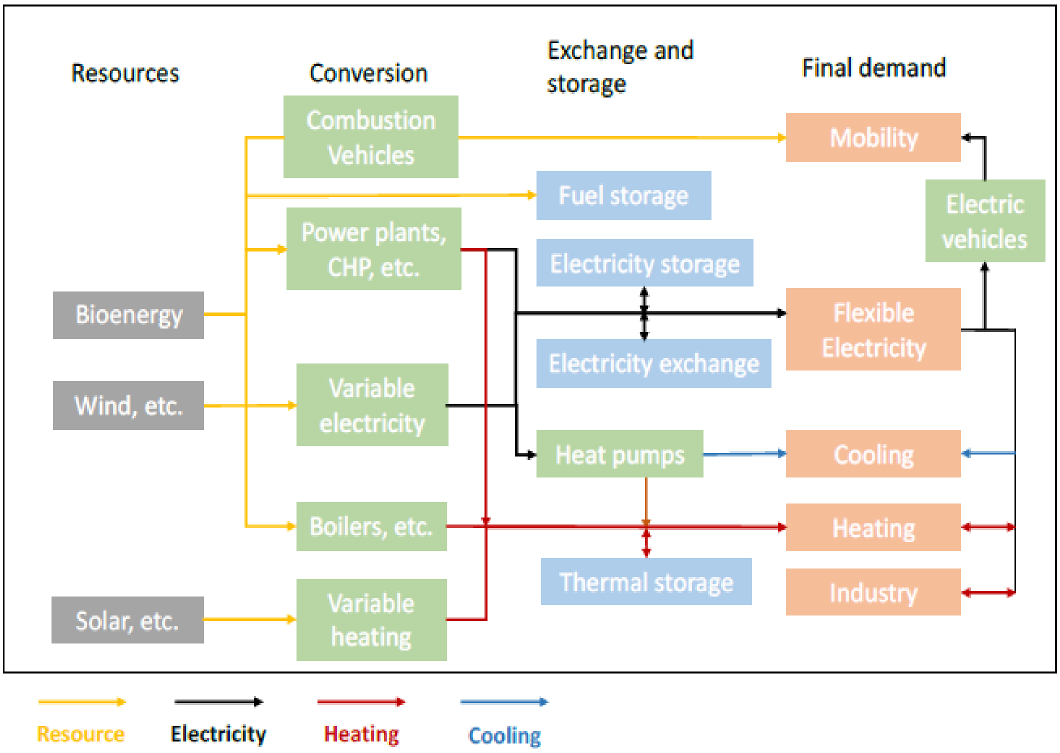


Fig 1-16 The elements of a smart energy system [19]

Fig 1-16 illustrates the elements in a smart energy system, and it consists of resources, conversion, exchange and storage technologies as well as demands. To achieve 100% renewable energy system, the above mentioned four elements have a role to play.

In smart energy systems, three types of measures are necessary to achieve a 100% renewable energy system.

A Changes on the demand side

In this section concerning to reduce demand for heating, cooling and transport sector and it helps to reduce energy production and associated energy losses. The reduction of energy demand and production can achieve through typical measures such as building refurbishments, improvements in technology efficiencies and reductions in mobility demands within the related sectors.

B Changes to system efficiency

This category is aiming to design the energy system in order to enhance overall system efficiency. Typical measures could include the integration of heat pumps, CHP plants, energy storages and electric vehicles

C. Changes to resources and production technologies

This final category, discourses energy production and the types of energy resources that are used for energy production. The integration of future renewable electricity sources such as wind, solar power, biomass technologies, solar thermal and geothermal can use to enhance the system

The smart energy systems concept focuses on three types of grids in a future energy system:

1. Smart electricity grid
2. Smart thermal grid
3. Smart gas grid

A. Smart electricity grid: According to Aalborg University EnergyPLAN research team "*Smart electricity grids are defined as electricity infrastructures that can intelligently integrate the actions of all users connected to the – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic, and secure electricity supplies*" [20].

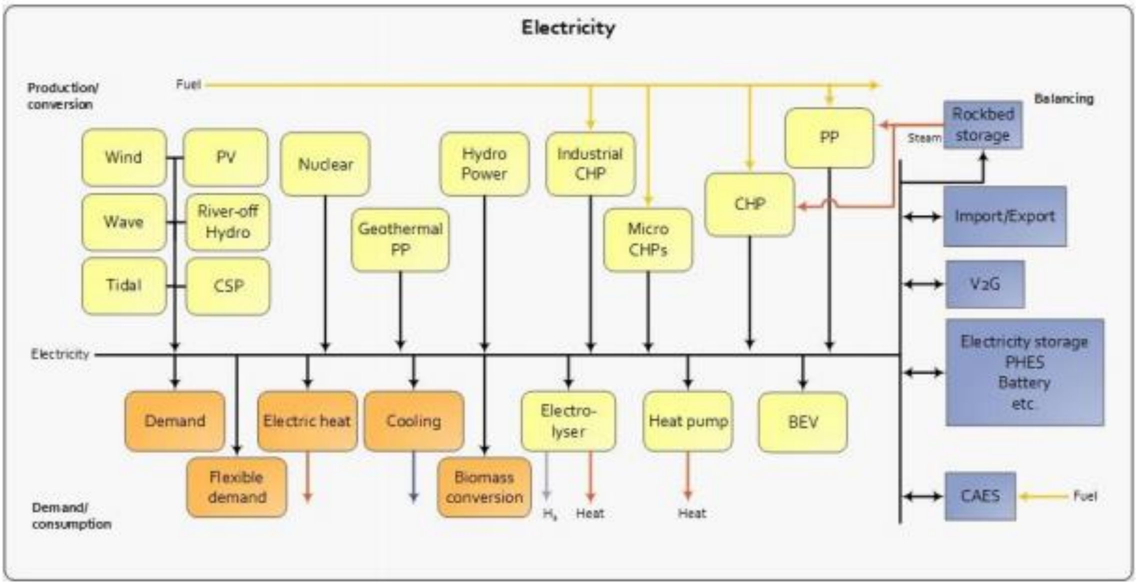


Fig 1-17 Future smart electricity grid [20]

A higher proportion of fluctuating renewable energy share from wind and solar will be fulfilled the supply of future smart electricity grid, as seen in Fig 1-17. One of the significant challenges is balancing the grid in the future smart energy system. The (IoT) Internet of things and ICT (Information and communication technologies) will play a significant role to interconnect consumers and generators.

B. Smart thermal grid: *"Smart thermal grids are defined as a network of pipes connecting the buildings in a neighbourhood, town centre, or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and cooling production units including individual contributions from the connected buildings*" [20]

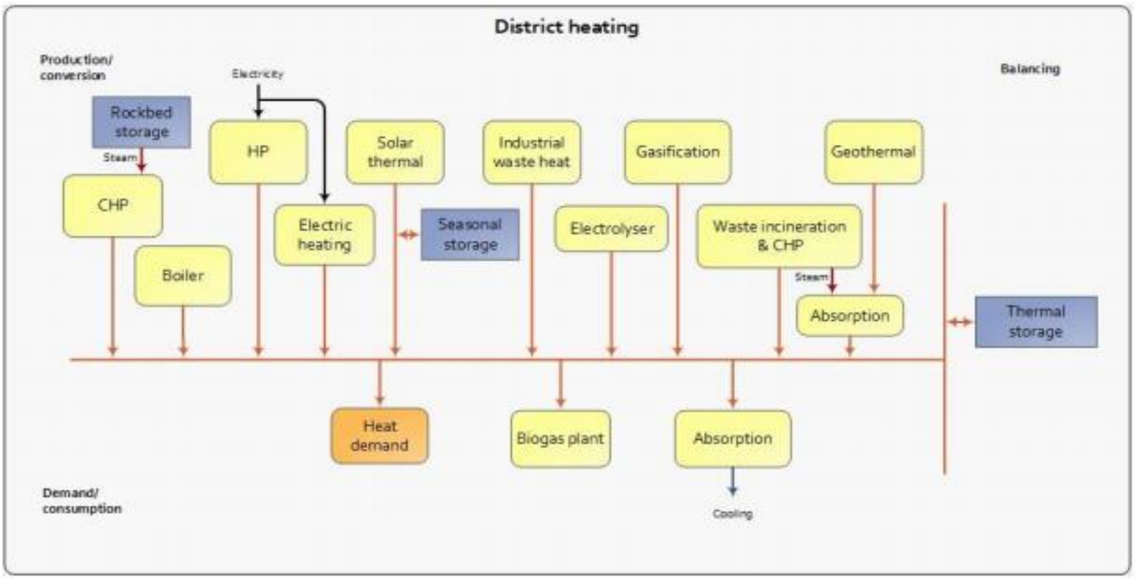


Fig 1-18 Future smart district heating grid [20]

District heating and cooling networks are the two main areas of the smart thermal grid, as seen in Fig 1-18 and Fig 1-19. Smart grids integrate and use a variety of sustainable energy resources such as CHP energy production, excess heating from industries, waste incineration plants, refineries, solar heating, geothermal, large heat pumps and electric boilers. Smart cooling grids operation has two techniques and first way supplied by heating, which is then converted to cooling in individual buildings by an absorption unit, and secondly through a centralized cooling network that harvests cold from rivers, seas or chiller units.

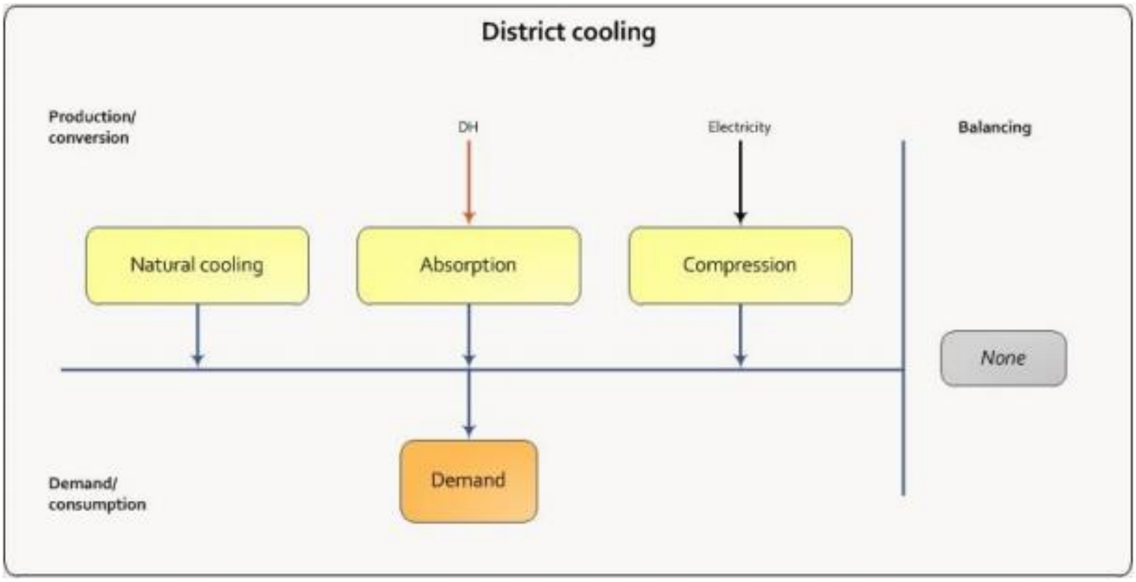


Fig 1-19Future smart cooling grid [20]

C. Smart gas grid: According to EnergyPLAN research group from Aalborg University "*Smart gas grids are defined as gas infrastructures that can intelligently integrate the actions of all users connected to it – suppliers, consumers, and those that do both – in order to efficiently deliver sustainable, economic, and secure gas supplies and storage*."

Future smart gas grids need to be ready to solve the challenge of converting from fossil-based natural gas to renewable gasses based on biogas, biomass and synthetic fuel. To achieve a better outcome from the above contest, the relation and integration with other girds should enhance, as illustrated in Fig1-20.

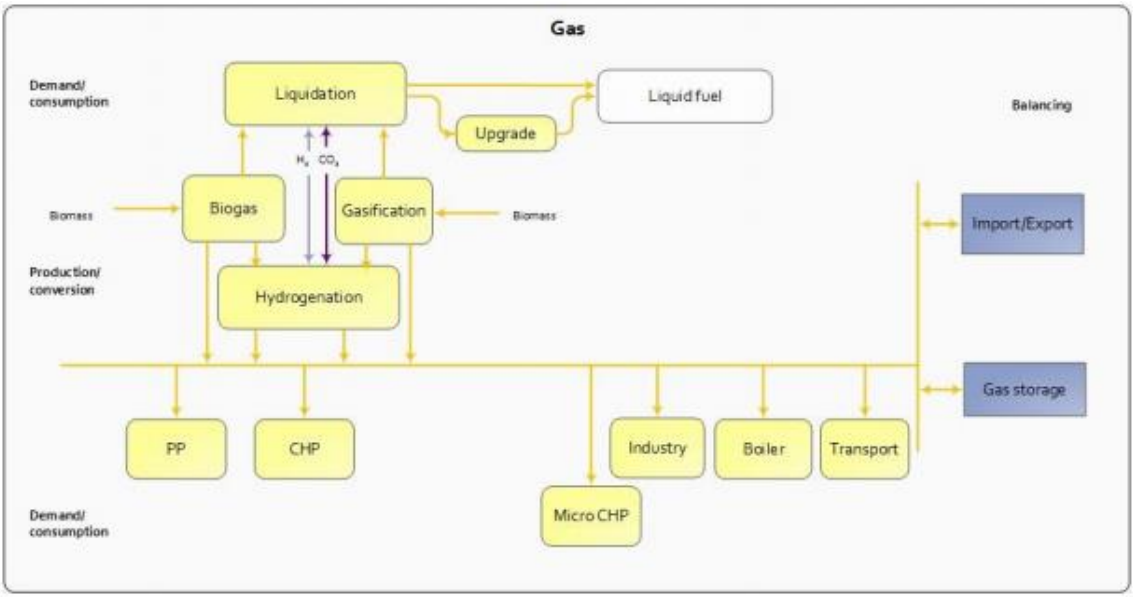


Fig 1-20 Future smart gas grid [20]

However, still, a different open question is remaining in the industry about the design of 100% renewable energy smart energy system because of the integration of all other sectors related to the primary energy system. As results, many different solutions have been proposed by researchers, academics and industry to highlights following undermentioned vital questions related to an energy system [19].

1. The technology mix required within the energy sectors
2. The future prioritizes energy carriers such as electrification, hydrogen, bioenergy in energy sectors.
3. The superior flexibility for a high share of variable renewable energy production
4. What kind of critical changes required in the existing system to convert future network infrastructure?
5. The types and role of energy storage in the future energy system
6. How to evaluate the energy cost?

1.7 Research aim, objectives and approach

This research aims to evaluate a feasibility study of the development and implementation of a smart energy system for 100% renewable energy and transport solutions in Sri Lanka. The research will investigate how critical components of multi renewable energy sources can be integrated into existing energy systems. The integration of RE will help sustain the transition to carbon neutrality and lead to sustainable transport solutions to achieving a greener Sri Lanka.

The following objectives will be carried out during the study.

- Assess the existing power and transport infrastructure system
- Investigate similar studies related to the EnergyPLAN.
- Develop appropriate models using EnergyPLAN in designing better energy models which utilise national power requirements of Sri Lanka
- Explore extended operation times for sustainable mechanisms: achieve more energy-efficient designs and create cheaper ways to integrate existing fossil fuel systems with new systems
- Simulate different studies using variable renewable energy for supplying electricity and for storing the excess in order to reduce dependence on fossil fuels
- Investigate efficiency in transport operation and technology, the possibility for a move to sustainable transport model share and management of transport demand
- Investigate advantages, disadvantages and barriers of development and implementation of multi renewable energy sources.

The subsequent methodological approaches are developed in connection with the objectives as mentioned above:

1) Assessment of the potential of renewable energy resources for power generation
2) Projection of the long-term electricity demand
3) Development of the EnergyPLAN-Sri Lanka model as an analytical planning tool for the Sri Lanka power sector
4) Development of future scenarios for the Sri Lanka power sector covering changes in resource constraints, cost factors, and technological development.

In this study, an EnergyPLAN model for the Sri Lanka power sector is developed to analyse alternative technological options for the next 30 years, considering the base year 2016 for addressing the challenges mentioned above.

1.8 Limitation of thesis

Primarily the thesis focuses on electricity energy and technologies which utilized fuels in the energy system. The investigation of energy system elements is reflected within the thesis but excluding the fuel refining.

The required data for this research is mainly obtained from the Ceylon Electricity Board (CEB) and Sustainable Energy Authority (SEA) in Sri Lanka. Some data did not offer due to the sensitivity of data and some data received partially after having a formal conversation with high ranking personal in CEB. One of the main burdens was to prepare annual generation profiles, and that data was not available within the authorities due to the private ownership of solar and wind farms.

The research main aim to find the technical feasibility only as did not find many related data to obtain the economic feasibility of 100% renewable smart energy system for Sri Lanka.

After designing the 100% renewable energy system infrastructure strategies in Sri Lanka, it is essential to consider the implementation process in the related surrounding society. When considering the implementation process, the following key area need to be analysed, and all key reasons should thus be a topic for future research

1. Energy market conditions and constraints.
2. Democratic decision processes.
3. Economic ability.

1.8.1 Resolution of thesis

The main idea behind the thesis was to find the 100% renewable smart energy system for Sri Lanka by summarising the findings and learnings from academia and industry. The following key areas have been analysed and contributed to new knowledge within the thesis:

1 Previous trends and solutions for designing 100% renewable energy smart systems.

2 Literature about energy planning tool type, purpose, features and results.

3 Applicable renewable energy technologies for Sri Lanka to obtain 100% renewable energy system

4 Possible way to apply smart energy concept and find ways to integrate renewable energy to the smart energy system.

1.9 Structure of the thesis

The overall structure of the thesis is visualized in Fig 1-21. This thesis initiates with an explanation of energy development and then discussed the energy sector challenges and solutions. Then thesis slowly moving the transition of 100% renewable energy system towards a smart energy system. These concepts are clearly explained through literature and evidently analysed energy planning tool to select the appropriate energy planning tool as described in chapter two.

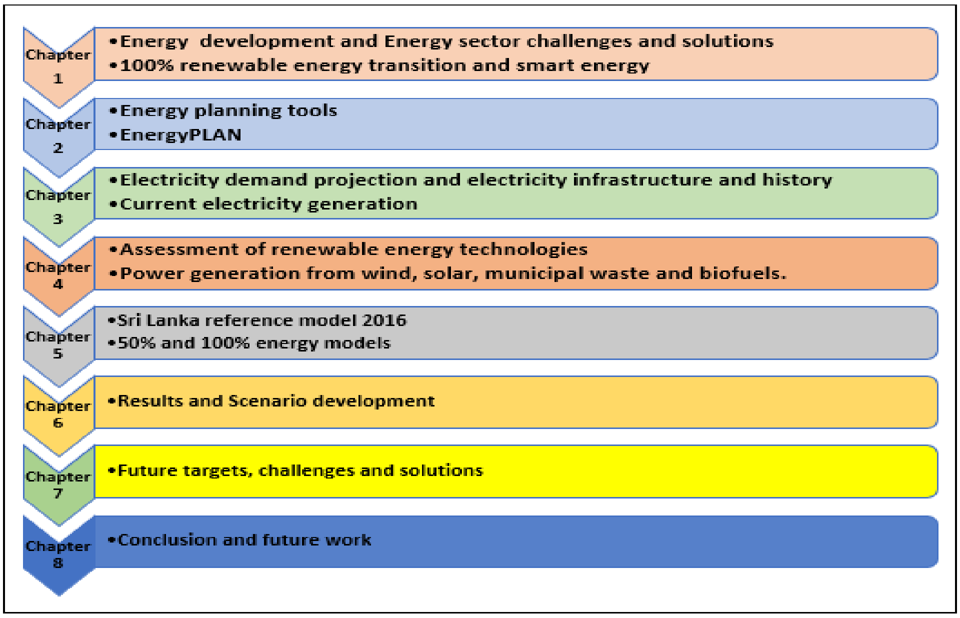


Fig 1-21Structure of the thesis

The energy demand projection, history of electricity infrastructure and current power generation of Sri Lanka describes in chapter three, while chapter four discusses the assessment of renewable energy resources. Within this section, renewable energy technologies such as wind, solar and biomass debate and the power generation from municipal waste management and energy from biofuels using anaerobic digester broadly discourse within this chapter.

Methodology leads to a presentation of the theoretical framework and methodologies used for design 2016 Sri Lankan reference model. That reference model is then modified to 2020-2045 energy models and after that created 50% renewable energy model. Secondly designed the 100% renewable energy solution for Sri Lanka as described in chapter five.

Finally, the results and discussion are condensed in chapter six, which is followed by a future targets, challenges and solutions in chapter seven while chapter eight is representing the conclusion of the research with future work. The thesis finally ends with a list of references as well as an appendix which included research results.

CHAPTER 2

2.TOOLS AND METHODS

This chapter presents the literature review conducted as a part of the thesis, including the search strategy of energy planning tools. Then followed by an overview of the current literature of EnergyPLAN tool purpose and applications. Finally, energy system analysis of the EnergyPLAN tool and similar studies related to EnergyPLAN discuss within this chapter

The structure of the tools and methods section illustrated in Fig 2-1.

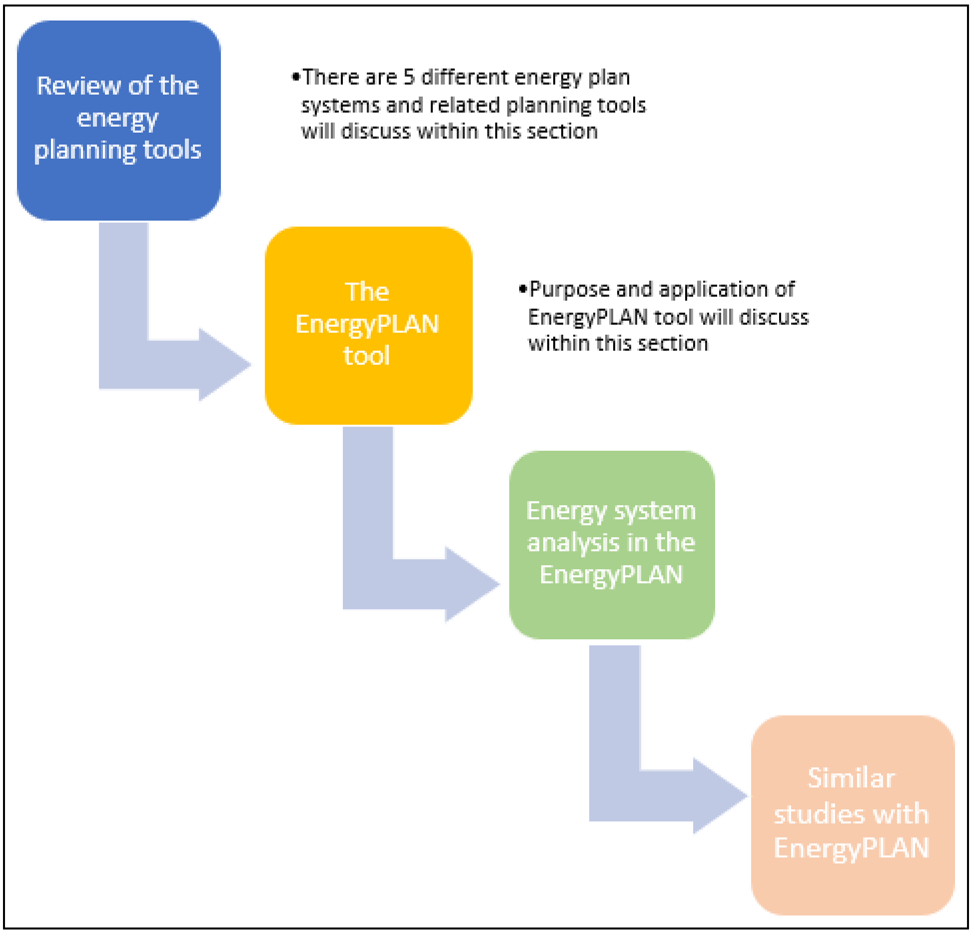


Fig 2-1 Structure of the tools and methods section

This chapter initiates with a review of the energy planning tools and there are five different energy systems has been discussed within this section. Thereafter discuss about EnergyPLAN tools including the purpose and application of this planning tool. Energy system analysis in EnergyPLAN tool is another important section and describes the way of calculations carried out in EnergyPLAN using appropriate inputs. Finally, this section finished with the similar studies carried out by EnergyPLAN in different countries.

2.1 Review of energy planning tools

Energy planning is a key parameter in the energy industry for both national governments and international agencies and organisations [21]. Energy planning support is needed to determine feasibility and decision making with respect to national and international development within the energy industry. The first energy planning study focussed on energy supply in 1960s [21]. Early stage planning practices were centred around security of energy supply, cost and environmental impact in the energy sector. Energy planning became more prominent especially for policy makers and environmental organisations after the energy crisis in the early 1970's. After this oil crisis, energy planning criteria was changed and more attention was given to the planning of long-term energy management, energy resources for coherent use and conservations, and critical assessment of fuel resources [22]. The country's social and environmental reflections, political aspects and historical data collected in previous energy plan mechanisms were being taking into account for the energy planning discipline of the country [23]. Current energy planning approaches are divided into three sections.

1. Planning by models
2. Planning by analogy
3. Planning by inquiry

The planning by model's methodology consists of two models such as optimisation and econometric. The optimisation method approach is used to find the best possible solution according to the aim and objectives of the case study. The econometric model generally uses a mathematical and statistical approach to implement the economics of a case study system [23].

In recent times, renewable energy is playing a major role in combatting more diverse challenges such as secure energy supply, climate changes and economic recession in modern society. To solve the above-mentioned issues, renewable energy can play a significant role by converting the energy system from a fossil fuel-based energy system to a renewable energy-based system. Therefore, identifying the renewable energy potential of an energy system has become a vital area of interest within energy planning in the energy industry [24]. Computer tools are used as a way of modelling an energy system in order to find the key technical aspects, implementation and effect of renewable energy, and its share within the energy system. Nonetheless, when implementing a feasibility study and discovering the potential of renewable energy within the energy system, it is still difficult to find the most appropriate energy planning tool even within a large amount of literature.

Consequently, it is important to understand the theory behind the selection of a suitable energy tool to model the Sri Lankan energy system. To understand the energy planning tools, it is necessary to make a detailed comparison for the investigation of renewable energy integration within different energy systems.

The key process parameters that need to be considered when selecting an energy planning tool for a relative case study are as follows [19].

1. Study or research purpose
2. General methods planning to apply
3. Applying tools and type
4. Geographical scope
5. Time horizon
6. Sectors planning to include
7. Propsing technologies or solutions
8. Main findings.

Due to different requirements, diverse zones, qualitative and quantitative factors of the research or case study, technologies and solutions use for the energy system, energy planning tools were divided into five different preliminary groups as illustrated in Fig 2-2 [25].

To obtain a detailed understanding of the energy planning tools, 37 simulation tools were analysed within the five groups as seen in Table 2-1. When investigating the energy planning tools, it was important, within the objective of this thesis, to identify tools to simulate a 100% renewable energy solution. The energy planning tools considered in this study were diverse in terms of their structure, operation and applications and there is a detailed description below about this energy planning tools.

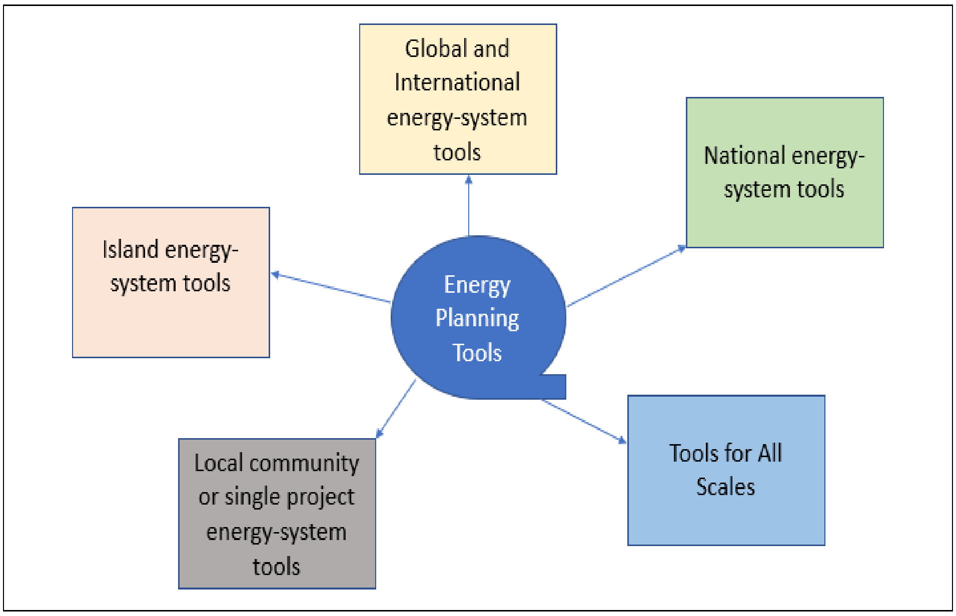


Fig 2-2 Different types of energy systems

When finding the best energy planning tool to design a 100% renewable energy solution, the outcomes of the following key questions were important to finalize the tool.

1. Number of users the tool has been used by - Need a clear idea about how many people have used it and in what capacity?

2. Background information of the tool- Understand the vision of the tool, who created it and for what purpose?

3. Properties of the tool- Basic characteristics of the tool to understand the type of the tool and ascertain its properties.

4. Tool applications- Need to know what applications can the tool be used for and what applications is it typically used for?

5. Case studies- Appreciate how the tool was used in previous case studies and research work. Was renewable energy identified as a specific focus?

6. Results achieved- Understand about the final outcomes and results gained from the above used tool. Is its partial solution or a comprehensive solution?

7. Further information- Assess and evaluate the use of the tool, identifying positive and negative features, reviews, general queries and problems faced during use of this software.

Table 2-1 Related energy planning tools used in different energy system

Global and International energy-system tools	National energy-system tools	Island energy-system tools	Local community or single project energy-system tools	Tools for All Scales
BALMOREL	AEOLIUS	H2RES	BCHP Screening Tool	RETScreen
EMPS	E4Cast		COMPOSE	
MESSAGE	EMCAS		energyPRO	
MiniCAM	EMINENT		HOMER	
PERSEUS	EnergyPLAN		HYDROGEMS	
RAMSES	ENPEP-BALANCE		TRNSYS 16	
WILMAR Planning Tool	GTMax			
	IKARUS			
	INFORSE			
	Invert			
	LEAP			
	MARKAL/ TIMES			
	Mesap PlaNet			
	NEMS			
	ORCED			
	PRIMES			
	ProdRisk			
	SimREN			
	SIVAEL			
	STREAM			
	UniSyD3.0			
	WASP			

2.1.1 Global and international energy system tools.

Seven energy planning tools were identified for the global and international energy system planning. Different aspects of each tool were discussed including several data sets such as description of a typical application and case study, tool information and the number of users, availability and invented times, type of each tool, energy mix, and renewable-energy penetrations simulated by each tool as noted in the Tables 2-2, 2-3, 2-4 and 2-5.

Table 2-2 Description of typical application and case studies of tools used in global and international energy system.

Tool	Description of typical applications	Case study
BALMOREL	Energy sector with electricity, CHP and the district heating [26].	Denmark, Norway, Estonia, Latvia, Lithuania, Germany, as well as in countries outside of Europe
EMPS	(EFI's Multi-Area Power market Simulator). Electricity sector only with an individual share of hydropower [27].	Nordic countries and Europe continental
MESSAGE	(Model for Energy Supply Strategy Alternatives and their General Environmental Impact). Medium to long-term energy systems, analysing climate change policies and developing scenario [28, 29].	Iran, China, Cuba and Baltic states
MiniCAM	Simulates long-term, large-scale global changes in the energy sector and agriculture sector. Economic activity, energy consumption, and energy and land-use change emissions in 15-year time steps from 1990 through 2095 [30, 31].	USA
PERSEUS	(Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading). Minimisation of all decision-relevant expenditure within the	Europe

	entire energy supply system. Comprises fuel supply and transport costs, transmission fees, fix and variable costs of the physical assets and investment costs for new plants [32].	
RAMSES	Electricity and district heating [33].	Denmark
WILMAR Planning Tool	Optimal operation of power systems treating wind power production forecasts and load forecasts [34, 35].	Nordic countries, Ireland

Table 2-3 Information, user capacity, availability and invented time of tools used in global and international energy system

Tool	Developer	User capacity	Availability	Created time
BALMOREL	Formulated in the GAMS modelling language and a GAMS license is needed to run the model.	N/A	Free to Download (Open Source)	2000
EMPS	Developed by SINTEF (Stiftelsen for industriell og teknisk forskning) Energy Research (previously EFI) in Norway	Medium	Commercial	1975
MESSAGE	Developed by the International Institute for Applied Systems Analysis (IIASA) in Austria	High	Free/Simulators must be purchased	1980
MiniCAM	Developed by the Pacific Northwest National Laboratory in the USA	N/A	Free to Download Once Contacted	1980
PERSEUS	Maintained by the Institute for Industrial Production at Universität Karlsruhe in Germany and the Chair for Energy Economics at the Brandenburgische Universität Cottbus (BTU)	Low	Commercial: only sold to large European utilities	N/A
RAMSES	Developed by Danish Energy Authority	Low	Projects completed for a fee	1990
WILMAR Planning Tool	Developed by an international consortium in the EU funded WILMAR project	N/A	Commercial	2006

Table 2-4 Characteristics of tools used in global and international energy system

Tool	Type					Optimisation	
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation	Investment
BALMOREL	Yes	Yes	Partial	No	Yes	Yes	Yes
EMPS	No	No	No	No	No	Yes	No
MESSAGE	No	Yes	Partial	No	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	No	No
PERSEUS	No	Yes	Yes	No	Yes	No	Yes
RAMSES	Yes	No	No	No	Yes	Yes	No
WILMAR	Yes	No	No	No	No	Yes	No

Table 2-5-Energy sector consideration and RE penetration of tools used in global and international energy system

Tool	Energy sectors considered			Renewable-energy penetrations			
	Electricity sector	Heat sector	Transport sector	100% electricity system	100% renewable energy system	Scenario timeframe	Time- setup
BALMOREL	Yes	Partly	No	No	No	50 years	Hourly
EMPS	Yes	No	No	Yes	Partly	25 years	Weekly
MESSAGE	Yes	Yes	Yes	No	No	50 + years	5 years
MiniCAM	Yes	Partly	Yes	Yes	Partly	50 + years	15 years
PERSEUS	Yes	Yes	Partly	Yes	No	50 years	36-72 days slots
RAMSES	Yes	Partly	No	No	No	30 years	Hourly
WILMAR	Yes	Partly	Partly	No	No	1 year	Hourly

2.1.2 National energy system tools

Twenty-two energy planning tools were identified for the national energy system planning. Different aspects of each tool were discussed including several data sets such as description of a typical application and case study, tool information and the number of users, availability and invented times, type of each tool, energy mix, and renewable-energy penetrations simulated by each tool as mentioned in the Tables 2-6, 2-7, 2-8 and 2-9.

Table 2-6 Description of typical application and case studies of tools used in national energy system.

Tool	Description of typical applications	Case study
AEOLIUS	Impact of higher penetration rates of fluctuating energy carriers (such as wind and PV) on the conventional power-plant systems [32].	Germany
E4Cast	Project Australia's long-term energy	Australia

	consumption, production and trade [36].	
EMCAS	(Electricity Market Complex Adaptive System) Operational and economic impacts of various external events on the electricity sector in an energy system [37].	USA, Central Europe, Croatia, Spain South Korea and the UK
EMINENT	New energy technologies and new energy solutions [38, 39].	Netherland
EnergyPLAN	Design of national or regional energy planning strategies based on technical and economic analyses of the consequences of implementing different energy systems and investments [40].	Denmark, Romania, Croatia, Portugal, Macedonia, Hungary, and Ireland
ENPEP-BALANCE	Matches the demand for energy with available resources and technologies [36]	Mexico, Turkey and Bulgaria
GTMax	(Generation and Transmission Maximisation Model) Simulates the dispatch of electric generating units and the economic trade of energy [37].	South-eastern Europe, Ethiopia, Kenya, Glen Canyon Dam and Grand Canyon National Park
IKARUS	Cost-optimization scenario model for national energy-systems [41].	Germany
INFORSE	(International Network for Sustainable Energy) Modelling energy production, energy demand, energy trends and energy policies. All thermal, renewable, hydrogen and transport technologies are considered [42].	Belarus, Bulgaria, Denmark, Latvia, Lithuania, Romania, Russia, Slovakia, Ukraine and the UK
Invert	All thermal generation except nuclear power, all renewable generation except wave and tidal, no storage and conversion technologies, and only biofuel transportation are simulated by the model [43].	Poland, Austria Germany United Kingdom, Greece and Denmark
LEAP	LEAP (Long-range Energy Alternatives	Korea, China and

	Planning) Track energy consumption, production and resource extraction in all sectors of an economy [44].	Greece
MARKAL/ TIMES	Energy, economic and environmental modelling [45, 46].	Europe, African countries and Asian Countries
Mesap PlaNet	Mesap (Modular Energy System Analysis and Planning Environment) and PlaNet (Planning Network). Analyse and simulate energy demand, supply, costs and environmental impacts for energy-systems [47].	Germany and Slovenia
NEMS	(National energy modelling system) Represents the behaviour of energy markets and their interactions with the U.S. economy on an annual basis up to the year 2030 [48].	USA
ORCED	ORCED (Oak Ridge Competitive Electricity Dispatch) Dispatches the power plants in a region to meet the electricity demands for any given year up to 2030 [49].	USA
PRIMES	Simulates a market equilibrium solution for energy supply and demand [50].	Europe
ProdRisk	Optimise and simulate of hydro-thermal systems [27].	Norway
SimREN	SimREN (Simulation of Renewable Energy Networks) Designs "close to reality" models of energy supply and demand systems following a "bottom-up" approach [51].	Spain and Japan
SIVAEL	Power system with related CHP areas developed by the Danish energy system [52].	Denmark
STREAM	A decision-making tool to complete energy system on both demand and supply side for national energy-systems [53].	Baltic sea region countries

UniSyD3.0	Modelling for national energy and economic systems [48].	New Zealand
WASP	WASP (Wien Automatic System Planning Package). Modelling to find optimal expansion plan for a power generating system over a long period [48].	Korea and Thailand

Table 2-7 Information, user capacity, availability and invented time of tools

Tool	Developer	User capacity	Availability	Created time
AEOLIUS	Developed by the Institute for Industrial Production at Universität Karlsruhe in Germany	Low	Commercial	N/A
E4Cast	Model of the Australian energy sector used by ABARE to project Australia's long term energy consumption, production and trade	N/A	Commercial	2000
EMCAS	Regularly updated and maintained by Argonne National Laboratory in the USA	Medium	Commercial	2002
EMINENT	Created during the EMINENT project by Netherlands Organisation for Applied Scientific Research (TNO) in The Netherlands	Low	Limited access	2005
EnergyPLAN	Developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark	High	Free to download	1999
ENPEP-BALANCE	Developed by Argonne National Laboratory in the USA	Medium	Free to download	1999
GTMax	Created by Argonne National Laboratory	Medium	Commercial	1995
IKARUS	Maintained by the Institute of Energy Research at Research Centre Jülich, Germany	Low	Commercial	N/A
INFORSE	Developed by INFORSE- Europe and it is one of the 7 regions of the international Network for the Sustainable Energy.	Low	Only for NGO's	2002
Invert	Developed by the Energy Economics Group (EEG) at Vienna University of Technology	High	Free to download	2003
LEAP	Developed by the Stockholm Environment Institute	Very high	Commercial/free for developing	N/A
MARKAL/ TIMES	Developed in a collaborative effort under the auspices of the International Energy Agency's Energy Technology Systems Analysis Programme	High	Commercial	1980 & 2000
Mesap PlaNet	Developed by the Institute for Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart	Low	Commercial	1997
NEMS	Developed by the Energy Information Administration (EIA)	Low	Free/Simulators must be	1993
ORCED	The Oak Ridge National Laboratory (ORNL) in the USA has developed	High	Free to download	1996
PRIMES	Developed by the National Technical University of Athens	Low	Projects completed for a	1994
ProdRisk	Developed by SINTEF	Low	Commercial	1994
SimREN	Developed by the Institute for Sustainable Solutions and Innovations (iSUSI)	N/A	Projects completed for a	1999
SIVAEL	Developed by the Danish TSO Energinet.dk	Low	Free to download	N/A
STREAM	The model is maintained by the Danish company Ea Energy Analyses	N/A	Free to Download Once Contacted	N/A
UniSyD3.0	Developed with system dynamics software by the Unitec Institute of Technology, New Zealand in	N/A	Free for students	2003
WASP	Maintained by the IAEA (International Atomic Energy Agency)	High	Commercial	N/A

Table 2-8 Characteristics of tools used in national energy system

Tool	Type					Optimisation	
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation	Investment
AEOLIUS	Yes	No	No	No	Yes	No	No
E4Cast	No	Yes	Yes	No	Yes	No	Yes
EMCAS	Yes	Yes	No	No	Yes	No	Yes
EMINENT	No	Yes	No	No	Yes	No	No
EnergyPLAN	Yes	Yes	No	No	Yes	Yes	Yes
ENPEP-BALANCE	No	Yes	Yes	Yes	No	No	No
GTMax	Yes	No	No	No	No	Yes	No
IKARUS	No	Yes	No	No	Yes	No	Yes
INFORSE	No	Yes	No	No	No	No	No
Invert	Yes	Yes	No	No	Yes	No	Yes
LEAP	Yes	Yes	No	Yes	Yes	No	No
MARKAL/ TIMES	No	Yes	Yes	Partly	Yes	No	Yes
Mesap PlaNet	No	Yes	No	No	Yes	No	No
NEMS	No	Yes	Yes	No	No	No	No
ORCED	Yes	Yes	Yes	No	Yes	Yes	Yes
PRIMES	No	No	Yes	No	No	No	No
ProdRisk	Yes	No	No	No	No	Yes	Yes
SimREN	No	No	No	No	No	No	No
SIVAEL	No	No	No	No	No	No	No
STREAM	Yes	No	No	No	No	No	No
UniSyD3.0	No	Yes	Yes	No	Yes	No	No
WASP	Yes	No	No	No	No	No	Yes

Table 2-9 Energy sector consideration and RE penetration of tools used in national energy system

Tool	Energy sectors considered			Renewable-energy penetrations		Scenario timeframe	Time- setup
	Electricity sector	Heat sector	Transport sector	100% electricity system	100% renewable energy system		
AEOLIUS	Yes	No	No	No	No	1 year	Minutes
E4Cast	Yes	Yes	Partly	No	No	50 years	Yearly
EMCAS	Yes	No	Partly	No	No	No limit	Hourly
EMINENT	Yes	Yes	No	No	No	1 year	None/Yearly
EnergyPLAN	Yes	Yes	Yes	Yes	Yes	1 year	Hourly
ENPEP-BALANCE	Yes	Yes	Yes	No	No	75 Years	Yearly
GTMax	Yes	Partly	No	No	No	No limit	Hourly
IKARUS	Yes	Yes	Yes	No	No	50 years	Yearly
INFORSE	Yes	Yes	Yes	Yes	Yes	50 + years	Yearly
Invert	Yes	Yes	Partly	Yes	Yes	50 years	Yearly
LEAP	Yes	Yes	Yes	Yes	Yes	No limit	Yearly
MARKAL/ TIMES	Yes	Yes	Yes	No	No	50 years	Hourly, daily&
Mesap PlaNet	Yes	Yes	Yes	Yes	Yes	No limit	Any
NEMS	Yes	Yes	Yes	No	No	50 years	Yearly
ORCED	Yes	No	Partly	No	No	1 year	Hourly
PRIMES	Yes	Yes	Yes	No	No	50 years	Yearly
ProdRisk	Yes	No	No	Yes	Partly	Multiple years	Hourly
SimREN	Yes	Yes	Partly	Yes	Yes	No limit	Minutes
SIVAEL	Yes	Partly	No	Yes	No	1 year	Hourly
STREAM	Yes	Yes	Partly	No	No	1 year	Hourly
UniSyD3.0	Yes	Partly	Yes	No	No	50 years	Weekly
WASP	Yes	No	No	No	No	50 years	12 load duration curves for a year

2.1.3 Island energy system tools

H2RES was identified as the Island energy system planning software. Different aspects of each tool were discussed in several data sets such as description of a typical application and case study, tool information and the number of users, availability and invented times, type of each tool, energy mix, and renewable-energy penetrations simulated by each tool as mentioned in the Tables 2-10, 2-11, 2-12 and 2-13.

Table 2-10 Description of typical application and case studies of uses in Island energy system

Tool	Description of typical applications	Case study
H2RES	Integration of renewable energy into energy systems [54].	Malta, Croatia and Portugal

Table 2-11 Information, user capacity, availability and invented time of tools used in Island energy system

Tool	Developer	User capacity	Availability	Created time
H2RES	Developed by the Instituto Superior Técnico, Lisbon and the Faculty of Mechanical Engineering and Naval Architecture at University of Zagreb, Croatia	N/A	Internal use only	2000

Table 2-12 Characteristics of tools used in Island energy system

Tool	Type					Optimisation	
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation	Investment
H2RES	Yes	Yes	No	No	Yes	Yes	No

Table 2-13 Energy sector consideration and RE penetration of tools used in Island energy system

Tool	Energy sectors considered			Renewable-energy penetrations		Scenario timeframe	Time- setup
	Electricity sector	Heat sector	Transport sector	100% electricity system	100% renewable energy system		
H2RES	Yes	Yes	Partly	Yes	Yes	No limit	hourly

2.1.4 Local community or single project energy-system tools

For the local community or single project energy system, six planning tools were recognised within the literature. Different aspects of each tool were discussed including several data sets such as description of a typical application and case study, tool information and the number of users in terms, availability and invented times, type of each tool, energy mix, and renewable-energy penetrations simulated by each tool as mentioned in the Tables 2-14, 2-15, 2-16 and 2-17.

Table 2-14 - Description of typical application and case studies of tools used in local community or single project energy system.

Tool	Description of typical applications	Case study
BCHP Screening Tool	Assessing the savings potential of combined cooling, heating, and power (CHP) systems [49].	USA
COMPOSE	COMPOSE (Compare Options for Sustainable Energy) is a techno-economic energy-project assessment model [48].	Denmark
energyPRO	Combined techno-economic design, analysis, and optimisation of both fossil and bio-fuelled cogeneration and trigeneration projects as well as wind power and other types of complex energy projects [55].	Denmark
HOMER	Simulates and optimises stand-alone and grid-connected power systems comprising any combination of wind turbines, PV arrays, run-of-river hydropower, biomass power, internal combustion engine generators, microturbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads [56].	Ethiopia, Saudi Arabia, Canada and the USA

HYDROGEMS	Suitable for simulation of integrated hydrogen energy systems; particularly renewable energy based stand-alone power systems [57].	Norway, Canada, Denmark and the UK
TRNSYS16	Simulates all energy sectors without the transport sector [57].	USA and France

Table 2-15 - Information, user capacity, availability and invented time of tools in local community or single project energy system

Tool	Organisation link	User capacity	Availability	Created time
BCHP Screening Tool	Developed by the Oak Ridge National Laboratory, USA	Very high	Free to download	2003
COMPOSE	Developed at Aalborg University in Denmark	Low	Free to download	2008
energyPRO	Developed and maintained by the company EMD International A/S in Denmark	Very high	Commercial	N/A
HOMER	Developed by the National Renewable Energy Agency in USA	Very high	Free to download	1992
HYDROGEMS	Developed at Institute for Energy Technology and later in various projects integrated into TRANSYS 15 & TRANSYS 16	N/A	Commercial/free for students	2002
TRNSYS 16	Maintained by an international collaboration from the United States (Thermal Energy System Specialists and the University of Wisconsin-Solar Energy Laboratory), France (Centre Scientifique et Technique du Bâtiment), and Germany (TRANSSOLAR Energietechnik)	High	Commercial	1975

Table 2-16 Characteristics of tools used in local community or single project energy system

Tool	Type					Optimisation	
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation	Investment
BCHP Screening Tool	Yes	No	No	No	Yes	Yes	No
COMPOSE	No	No	No	No	Yes	Yes	Yes
energyPRO	Yes	Yes	No	No	No	Yes	Yes
HOMER	Yes	No	No	No	Yes	Yes	Yes
HYDROGEMS	No	Yes	No	No	No	No	No
TRNSYS 16	Yes	Yes	No	No	Yes	Yes	yes

Table 2-17 Energy sector consideration and RE penetration of tools used in local community or single project energy system

Tool	Energy sectors considered			Renewable-energy penetrations		Scenario timeframe	Time-setup
	Electricity sector	Heat sector	Transport sector	100% electricity system	100% renewable energy system		
BCHP Screening Tool	No	No	No	No	No	1 year	Hourly
COMPOSE	Yes	Yes	Yes	No	No	No limit	Hourly
energyPRO	Yes	Partly	No	Yes	Partly	40 years	Minutes
HOMER	Yes	Yes	No	Yes	Partly	1 year	Minutes
HYDROGEMS	Yes	No	No	No	No	1 year	Minutes
TRNSYS 16	Yes	Yes	No	Yes	Partly	Multiple years	Seconds

2.1.5 All scales energy system tools

RET Screen was identified as the all scales system energy planning tool. The different aspects of this tool was discussed including several data sets such as description of a typical application and case study, tool information and the number of users in terms, availability and invented times, type of each tool, energy mix, and renewable-energy penetrations simulated by each tool as mentioned in the Tables 2-18, 2-19,2-20 and 2-21.

Table 2-18 Description of typical application and case studies of tool in all scale energy system tools

Tool	Description of typical applications	Case study
RETScreen	Evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs) [58].	Algeria, Lebanon and Egypt

Table 2-19 - Information, user capacity, availability and invented time of tools

Tool	Developer	User capacity	Availability	Created time
RETScreen	Developed with the contribution from government, industry, and academia by Natural Resources Canada	Very high	Free to download	1996

Table 2-20 Characteristics of tools used in all scale energy system

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
RETScreen	No	Yes	No	No	Yes	No	Yes

Table 2-21-Energy sector consideration and RE penetration of tools used in all scale energy system

Tool	Energy sectors considered			Renewable-energy penetrations simulated		Scenario timeframe	Time- setup
	Electricity sector	Heat sector	Transport sector	100% electricity simulated	100% renewable energy system		
RETScreen	Yes	Yes	No	Yes	Partly	50 years	Monthly

There are 37 simulation tools from nearly 40 energy planning tools [59,60] categorised within five different energy systems according to typical use, types, case studies and results. Finally, after concluding all the literature about energy tools, seven diverse tool types were identified as follows:

1. A simulation tool simulates the operation of a given energy-system to supply a given set of energy demands. Typically, a simulation tool is operated in hourly time-steps over a one-year time-period.

2. A scenario tool usually combines a series of years into a long-term scenario. Typically, scenario tools function in time-steps of 1 year and combine such annual results into a scenario of typically 20–50 years.

3. An equilibrium tool seeks to explain the behaviour of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets. It is often assumed that agents are price takers and that equilibrium can be identified.

4. A top-down tool is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demand. Typically, top-down tools are also equilibrium tools.

5. A bottom-up tool identifies and analyses specific energy technologies and thereby identifies investment options and alternatives.

6. Operation optimisation tools optimise the operation of a given energy-system. Typically, operation optimisation tools are also simulation tools optimising the operation of a given system.

7. Investment optimisation tools optimise the investments in an energy-system. Typically, optimisation tools are also scenario tools optimising investments in new energy stations and technologies.

2.2 The EnergyPLAN tool

After careful considerations of many energy planning tools in order to conduct an analysis for a 100% renewable energy system in Sri Lanka, it was decided to use the EnergyPLAN model. The EnergyPLAN computer model is the input/output tool used for analysing and designing national energy system in steps of one hour. As the EnergyPLAN is a very simple simulation process which takes up a very short time period, it is becoming very popular within scholars in academia and industry. Since 1999 this computer model has been developed and expanded on a continuous basis and it has the capacity to analyse results based on different technical simulation strategies, market-economic simulation strategies as well as feasibility strategies.

The analysis of different simulation strategies such as interaction between combined heat and power (CHP) production and fluctuating renewable energy sources was emphasised in the first version of EnergyPLAN. Added to this, the energy model has developed and expanded the whole energy system through various energy model versions by including a wide range of sectors such as electricity, heating, cooling and transport.

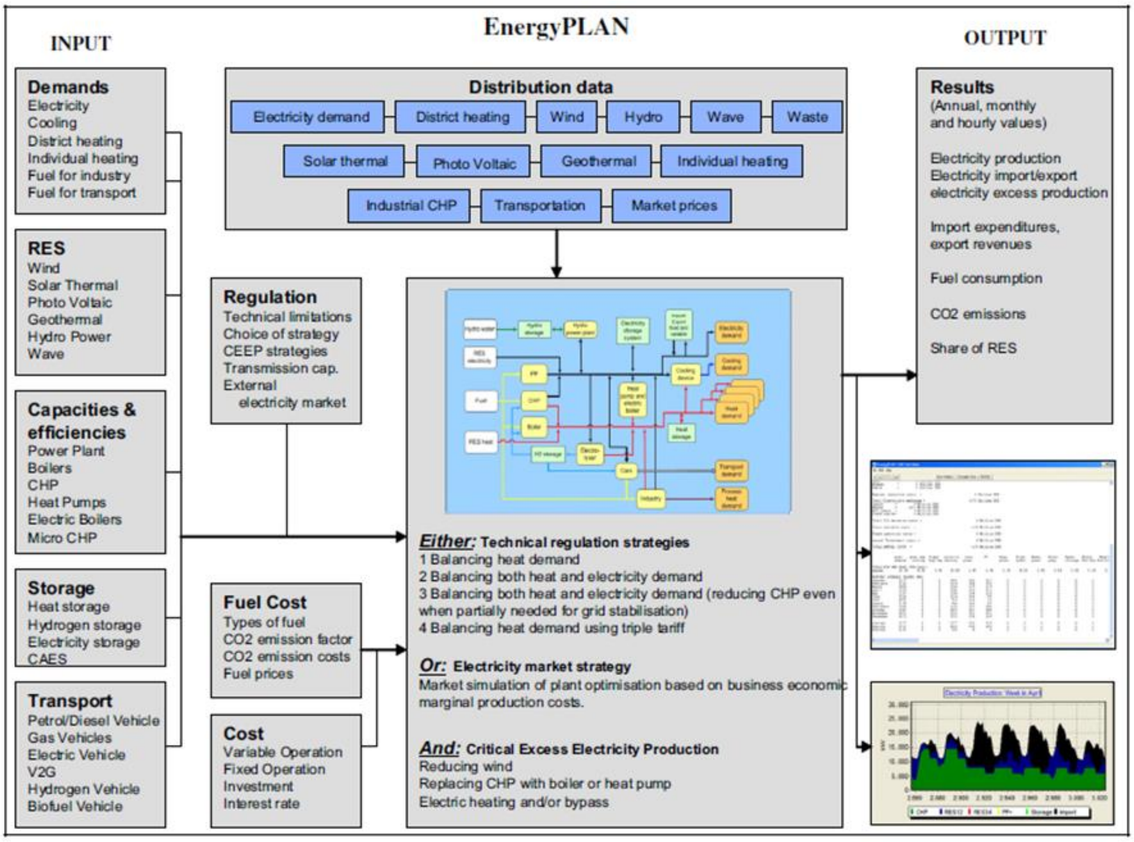


Fig 2-3 Schematic diagram of the EnergyPLAN model [25]

The output data represents supply and comprises of the following factors:

1. Annual, monthly and hourly values of electricity production
2. Electricity import/export
3. Import expenditures and export revenues
4. Fuel consumption
5. CO_2 emissions and
6. Share of RES.

To obtain the results of the simulation model, an hourly analysis of the annual distribution of demand series for electricity, district heating, individual heating, cooling and transport as well as hourly annual distribution curve with a supply sequence for wind, hydro, solar thermal, photo voltaic, geothermal and nuclear are required. A schematic diagram of the EnergyPLAN model is presented in Fig 2-3.

2.2.1 Purpose and application

The main purpose of the EnergyPLAN computer model is the technical and economic analysis of the consequences of different national energy systems and investments to assist in the design of national energy planning strategies. The model has also been applied to towns and/or municipalities within Europe.

The EnergyPLAN computer model uses analytic programming instead of iteration, and aggregated data inputs for the different units in various sectors to achieve an optimal solution for the energy system [61] and this tool is specialised in the following key areas.

1. Simulation of 100% renewable energy systems
2. Integration and optimal combination of large-scale renewables into the energy system [62- 64]
3. Implementation of combined heat and power plants (CHP) in the energy systems [65]
4. Implementation of transportation in the energy sector [66]
5. Identification of the most appropriate market auction settings for electricity in fossil free energy systems

Typical input data are demands and consists of the following parameters:

1. RES
2. Generation units' capacities
3. Storage capacities
4. Individual fuel consumption
5. Transport and industry sector
6. Fuel costs

7. Investment

8. Variable and fixed operation and maintenance costs of different units

9. CO_2 emissions factors of fuels

10. Different regulation strategies.

2.3 Energy systems analysis in the EnergyPLAN model

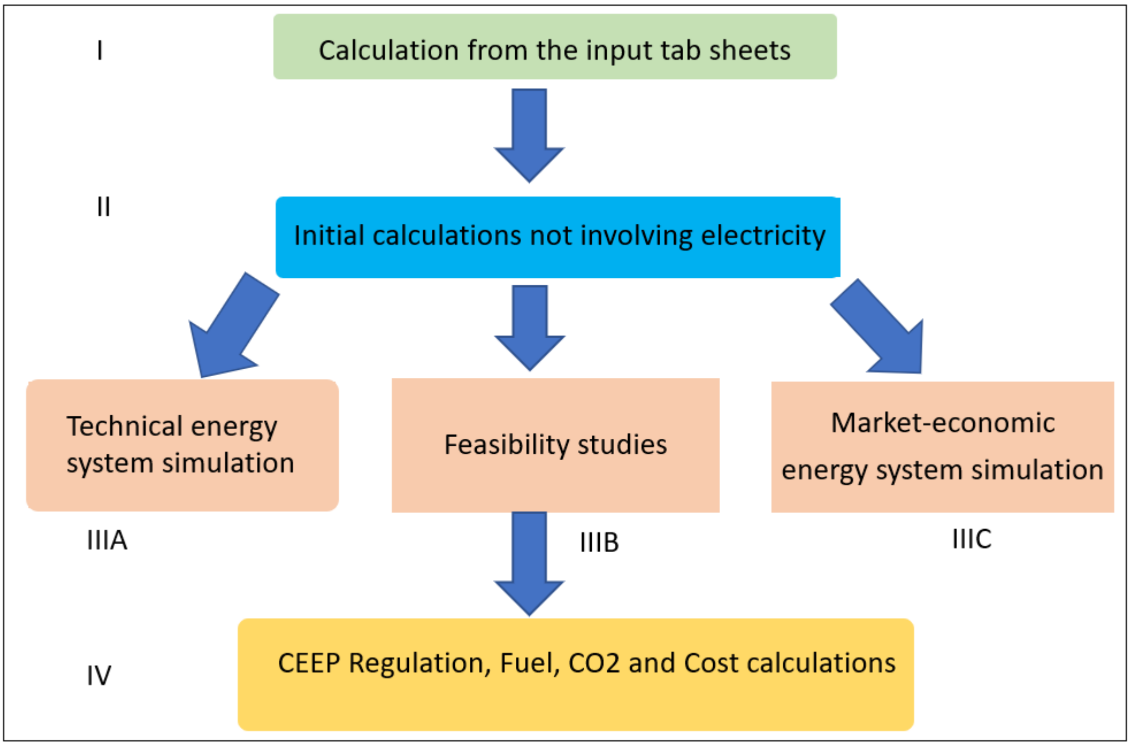


Fig 2-4 Procedure of the energy system analysis in EnergyPLAN

Fig 2-4 shows the procedure of the energy system analysis in the EnergyPLAN computer tool. The first part is a small calculation of input data consisting of input and cost tab sheets. The next step consists of some initial calculations, which do not involve electricity balancing. Then the procedure is divided into three sections such as technical simulation, market economic simulation and feasibility studies. Finally, the technical simulation minimises the import/export of electricity and seeks to identify the least fuel-consuming solution. On the other hand, the market-economic simulation identifies the least-cost solution based on the business-economic costs of each production unit. The combine solution forms the feasibility studies either technical or economic.

The following section describes the sequence of an energy system analysis with relative input and output tab sheets.

I. Calculation from the input tab sheets:

1. Electricity demand
2. Solar thermal
3. RES1, RES1, RES1 and RES4
4. Hydro Power
5. Nuclear Power or Geothermal Power
6. Hourly distribution between cooling produced from natural cooling and/or district heating and electricity
7. Individual solar thermal, boilers, CHPs and heat pumps
8. Biofuels for transport and CHP
9. Biogas, gasification and biofuel
10. Synthetic grid gas and biofuels.
11. Market prices of external market

II. Initial calculations not involving electricity balancing:

1. Fixed import/export of electricity specified in electricity demand
2. District heating demands including heating demands from absorption cooling
3. Industrial and Waste district heating and electricity productions
4. Fixed Boiler production subtracted from the district heating demand
5. Boiler production in district heating group 1

IIIA: Technical Energy System Analysis:

1. CHP, heat pumps and boilers in groups 2 and 3

2. Flexible electricity demand

3. CHP, heat pumps and boilers in groups 2 and 3

4. Hydro power

5. Individual CHP and heat pump systems

6. Electrolyser for micro CHP, transport, hydrogenation and CHP and Boilers in district heating group 2 and district heating group 3

7. Heat storage in groups 3 and 2

8. Transport (Smart charge and V2G)

9. Electricity storage

IIIB: Market-economic energy system analysis

1. Net Import and resulting external market price

2. Market economic simulation

3. CHP minimum production

4. Boilers and solar thermal in district heating

5. Hydrogen and electricity demands for electrolysis for transport, micro CHP and hydrogenation

6. Electricity consumption for heat pumps and electrolysers for hydrogen to CHP and boilers in district heating groups 2 and 3

7. Hydro Power

8. Electricity production from CHP and Power Plants

9. Electricity storage

IIIC: Feasibility studies

1. Total annual costs

2. Investment costs, fixed operational and maintenance costs

3. Electricity exchange costs and benefits

4. Possible CO_2 payments

IV: CEEP Regulation, Fuel, CO2 and Cost calculations:

1. Fixed boiler production is added to the boilers in groups 2 and 3
2. Critical Excess Regulation
3. Grid stabilisation
4. Heat balances in district heating systems
5. Fuel consumptions
6. CO_2 emissions
7. Balancing of Gas Grid
8. Share of Renewable Energy
9. Cost

The Fig 2-5 illustrates the pictorial view of the EnergyPLAN inputs which are needed to simulate the software and output parameters which can be obtained after the simulation results.

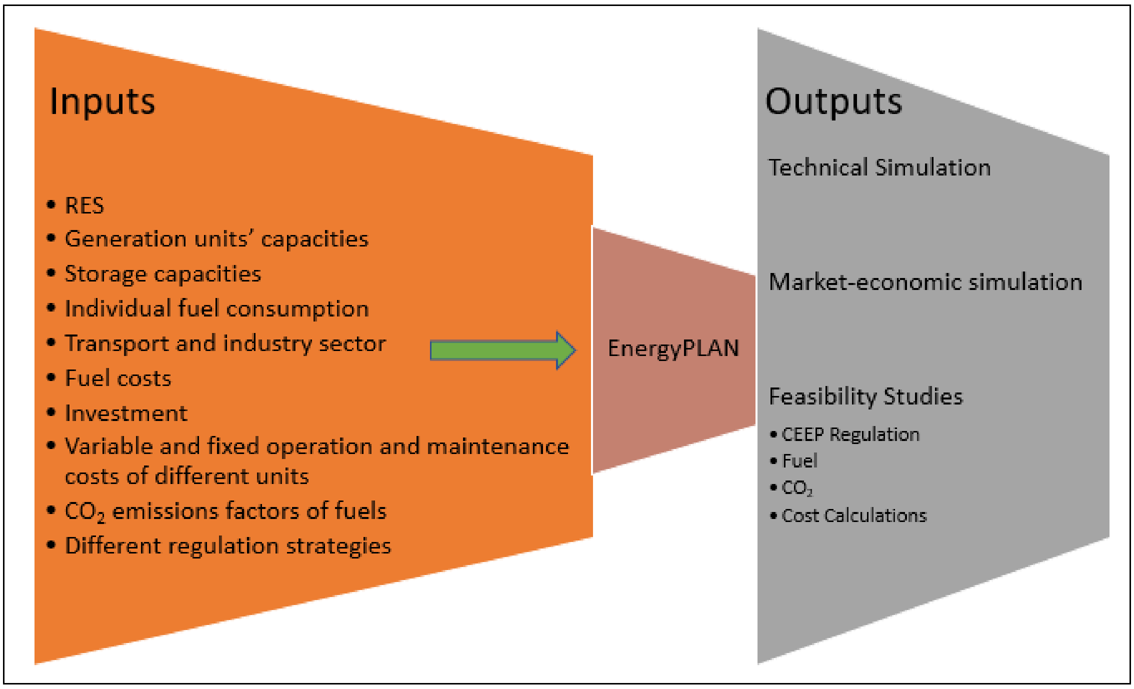


Fig 2-5 Pictorial veiw of relative inputs and outputs of EnergyPLAN

2.4 Similar Studies with EnergyPLAN

Globally many countries are conducting energy planning studies using various tools and practices. EnergyPLAN alone is being used in more than 30 countries with 15 different technologies. Table 2-22 illustrates a list of a few of such studies conducted in several countries.

Table 2-22 List of case studies

Country	Study
Austria	1. Heat Roadmap Europe 4 [67]. 2. The role of solar thermal in Future Energy Systems [68].
Croatia	1. Heat Roadmap Europe 2050 [67]. 2. A 100% renewable energy scenario for Croatia [69]. 3. A 100% renewable energy scenario for the Island of Mljet in Croatia [70].
Czech Republic	1. Heat Roadmap Europe 4 [67]. 2. Heat Roadmap Europe 2050 [67].
Denmark	1. The role of solar thermal in Future Energy Systems [68]. 2. The role of Photovoltaics towards 100% Renewable Energy Systems [71]. 3. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark [72]. 4. Copenhagen Energy Vision: A sustainable vision for bringing a Capital to 100% renewable energy [73].
Finland	1. The Impacts of High V2G Participation in a 100% Renewable Åland Energy System [74]. 2. Scenarios for a sustainable energy system in the Åland Islands in 2030 [75]. 3. Heat Roadmap Europe 4 [67].
France	1. Heat Roadmap Europe 4 (HRE4) [67].
Germany	1. Heat Roadmap Europe 4 [67]. 2. The role of solar thermal in Future Energy Systems [68].
Greece	1. Technical Optimisation of the Greek Interconnected

	Energy System of 2020 using the EnergyPLAN model [76].
Hong Kong	1. An energy system model for Hong Kong in 2020 [77].
Hungary	1. Heat Roadmap Europe 4 (HRE4) [67].
Ireland	1. The first step towards a 100% renewable energy system for Ireland (2011) [78]. 2. The Role of Electricity Storage for Integrating Wind Power in Ireland (2010) [79].
Italy	1. The role of solar thermal in Future Energy Systems [68]. 2. Energy Model of Italy and Penetration of Renewable Energy (2010) [80].

CHAPTER 3

3.ELECTRICITY DEMAND PROJECTION IN SRI LANKA

As illustrated in Fig 3-1, Chapter 3, initially, discusses the energy demand projection by considering electricity trend in Sri Lanka. Then, the history of electricity infrastructure discusses with the hydropower and thermal power infrastructural histories. Finally, this chapter discusses the current power generation, the economics of electricity, baseload and peak load plants and impact of current electricity generation in Sri Lanka.

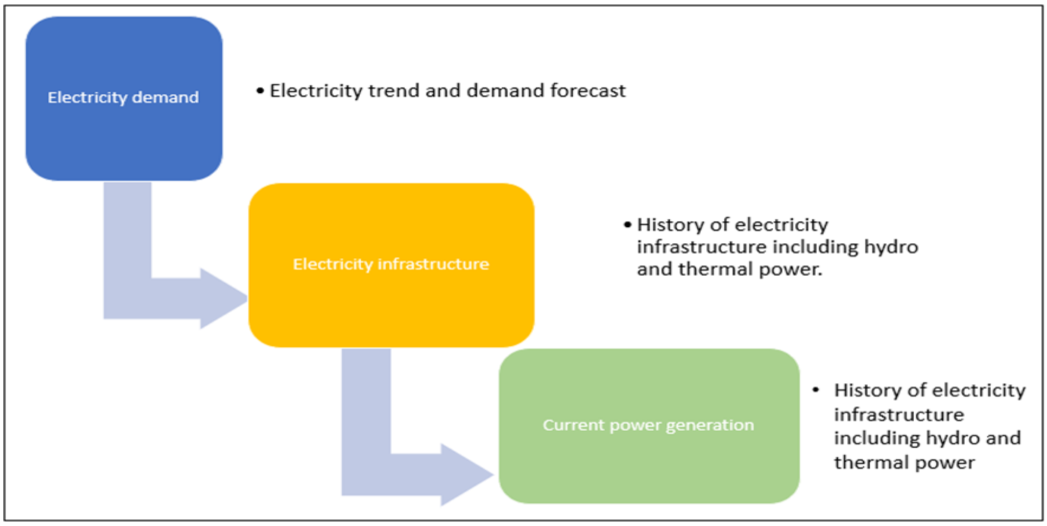


Fig 3-1 Structure of the electricity demand projection section

3.1 Electricity demand: Trend and projection

Electricity demand is divided into eight categories namely domestic, religious, general purpose, hotel, industry, government, street lighting and bulk supply to Lanka electricity company (LECO). Each of these sectors shows a typical trend with respect to the growth in energy demand. The detail description of energy demand in each sector will be presented later in Section 5.3.

According to the CEB long term generation plan (2020-2039) the future base load forecast [81] illustrated in Table 3-1. In addition, future electricity demand forecast graphically illustrated in Fig 3-2. Tab 3-1 consists of forecasted electricity demand, electricity generation and peak demand as well. The highlighted years and electricity demand in Tab 3-1 have been used for the EnergyPLAN simulations for different years for example 2025, 2030, 2040, 2045 and 2050 and clearly described in sections 5.4 to 5.6.

Table 3-1 Future baseload forecast

Year	Base Load Forecast				
	Demand		Net Generation		
	TWh	Growth Rate (%)	TWh	Growth Rate (%)	Peak Demand
2020	16.19	7.4	18.54	7.2	3050
2021	18.19	7.6	19.91	7.4	3254
2022	19.19	5.5	20.96	5.3	3403
2023	20.23	5.5	22.07	5.3	3561
2024	21.34	5.5	23.23	5.3	3728
2025	22.50	5.5	24.46	5.3	3903
2026	23.67	5.2	25.7	5.1	4079
2027	24.82	4.9	26.92	4.8	4241
2028	26.03	4.9	28.2	4.7	4444
2029	27.28	4.8	29.52	4.7	4655
2030	28.57	4.7	30.89	4.6	4872
2031	29.92	4.7	32.33	4.6	5101
2032	31.28	4.6	33.78	4.5	5332
2033	32.68	4.5	35.27	4.4	5569
2034	34.12	4.4	36.81	4.4	5814
2035	35.61	4.4	38.39	4.3	6067
2036	37.13	4.3	40.23	4.3	6328
2037	38.69	4.2	41.72	4.2	6597
2038	40.30	4.2	43.45	4.2	6873
2039	41.94	4.1	45.22	4.1	7155
2040	43.62	4	47.03	4.0	7445
2041	45.37	4	48.91	4.0	7745
2042	47.17	4	50.86	4.0	8054
2043	49.04	4	52.87	4.0	8376
2044	50.98	4	54.96	4.0	8706
2045	54.04	6	58.15	5.8	9150
2046	57.28	6	61.52	5.8	9617
2047	60.72	6	65.09	5.8	10107
2048	64.36	6	68.87	5.8	10623
2049	68.22	6	72.86	5.8	11164
2050	71.97	6	76.72	5.3	11700
10 Year Average Growth		5.5		5.3	4.8
20 Year Average Growth		4.9		4.8	4.6
25 Year Average Growth		4.7		4.6	4.5

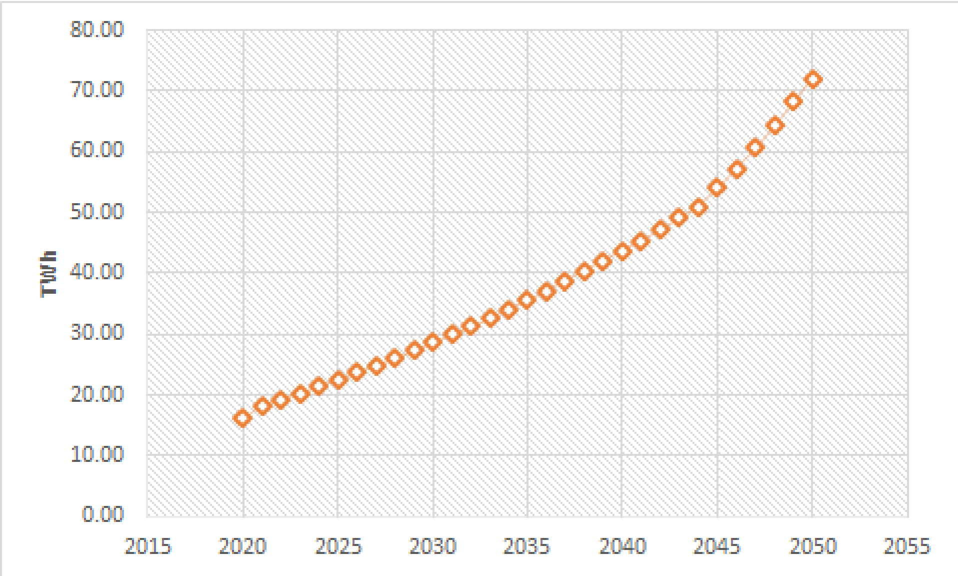


Fig 3-2 Future electricity demand forecast in Sri Lanka

3.2. Electricity infrastructure

Sri Lanka was a colony under the British Empire from 1815-1948 and in 1882 SS Helios ship which sailed to Colombo harbour was able to supply electricity to Colombo city.

3.2.1 History of electricity infrastructure

During 1860-1900, the hill country was mostly used for tea plantations. Initially they used small capacity waterfalls and Telton turbines to produce electricity, using individual direct current generators only for the lighting of their factories and bungalows. Fig 3-3 illustrated the Kataboola estate tea factory which use electricity for the first time for lighting and operations in old days [82].

Fig 3-3 Kataboola estate tea factory

3.2.2 History of hydropower

In 1912, the father of hydro-electricity in Sri Lanka, Engineer D J Wimalasurendra implemented the first small hydroelectricity plant in Blackpool, Nuwaraeliya, by using water from the Gregory river. Due to the non-availability of coal and considering the cost of fuel, the government decided to use the natural waterfalls to produce hydro energy. In 1950, as shown in Fig 3-4 the Laxapana was established as the first hydro power station with 25MW capacity to the national grid [82].

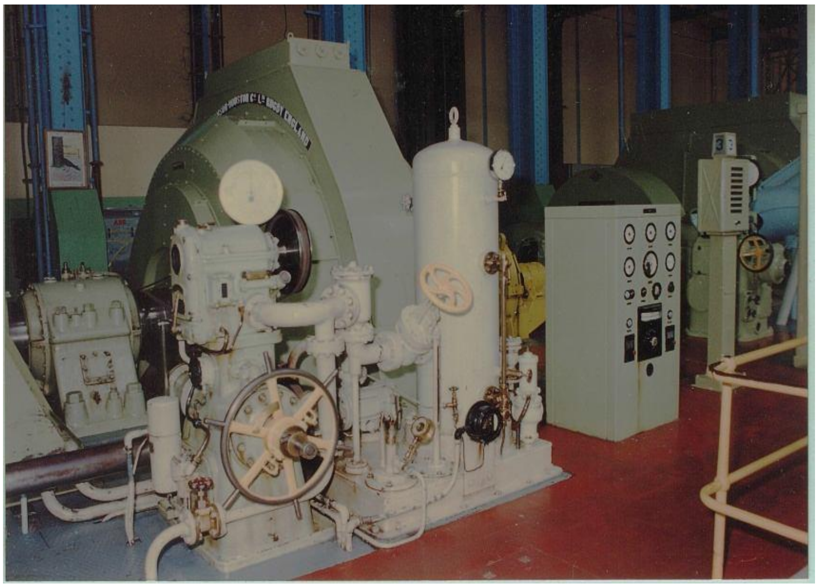


Fig 3-4 Laxapana first hydropower plant

3.2.3 History of thermal power

In 1890 at the billiard room in Bristol hotel Colombo Sri Lanka the first electric bulb was lit, and the power generated source was a diesel generator.

Fig 3-5 Kalanitissa Thermal power plant

In 1895 electricity was produced for the Colombo area at specific places by using the thermal power plant located at the Bristol building (Colombo), by the Boustead brothers. Then in 1902 this electricity infrastructure was implemented at Kandy by using a 500KW Diesel generator. A separate department for electricity established in 1926 and in order to meet the growing electricity demand the first thermal power plant was established in 1929 and was called Sir Herbert Stanley Power station with a 3MW capacity operated by steam [82].

In 2002, for the first time a combined cycle power plant with a capacity of 168MW was connected to the existing Kalanitissa power plant operating since 1962. In 2010, Sri Lanka's biggest combined cycle thermal power plant called Yugadanawi was implemented at Kerawalapitiya and this is commenced operations by generating 300 MW.

3.3 Current power generation

Table 3-2 illustrates the 2016 power generation sources in both CEB and private power plants (PPP) with related data [83].

Table 3-2 Power generation by source 2016

Ownership	**Source**	**Number of power plants**	**Installed capacity MW**	**Generation GWh**
CEB	Hydro	17	1384	3481
	Thermal oil	7	604	2297
	Thermal coal	1	900	5047
	Wind	1	3	2.1
PPP	Mini hydro	172	342	739
	Thermal oil	5	611	2164
	Wind	15	128.5	343
	Solar	5	21.4	4.3
	Biomass	9	24.1	72
Total		**232**	**4018**	**14149.4**

According to the power demand, the environmental impacts, the cost of fuel for thermal plants and considering the unit electricity price of hydroelectricity and thermal electricity the government have agreed to permit the construction and operation of only two coal power stations in the country. In future there are no coals power plants allowed for production.

Sri Lanka's power generation mostly rely on thermal power generation and it is 67% in 2016. Lakvijaya coal power plant is also known as Norochchole power plant is a large and only coal power plant located in Puttalm, Sri Lanka, and its construction began in 2006. Fig 3-6 shows the Norochchole thermal coal power plant and it comprises of 900MW and it concluded and commissioned in 2011 [82].

Fig 3-6 Norochchole thermal coal power plant

The plant exhausts are emitted through a 150m (492ft) tall chimney. Electricity is produced using a steam turbine and coal is used as the fuel in the purpose of producing steam that will then be used to rotate the turbine

State-run hydroelectric developments are categorised into three main geographic sectors: Laxapana hydro complex, Mahaweli hydro complex, and Samanala hydro complex [84].

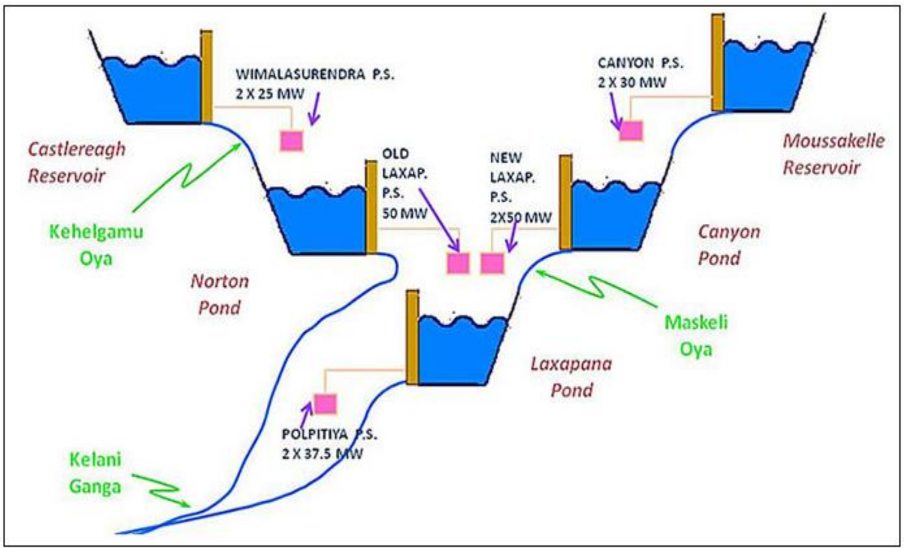


Fig 3-7 Setup mechanism for Laxapana hydro complex [84]

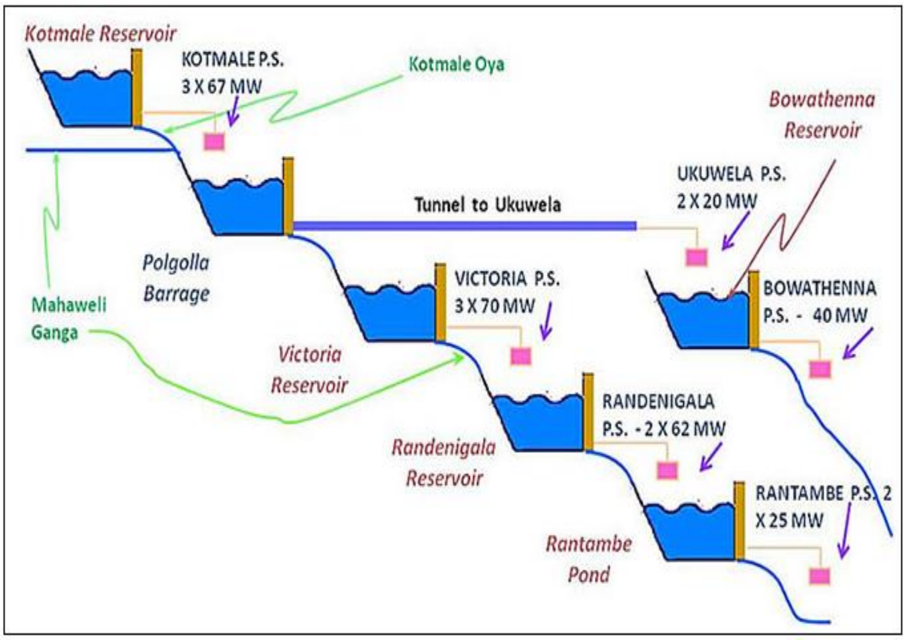


Fig 3-8 Setup mechanism for Mahaweli hydro complex [84]

Fig 3-7 and Fig 3-8 illustrated the setup mechanism for Laxapana and Mahaweli complex and Samanala hydro power complex consists of four water sources such as Samanala, Kukule gaga, Gal oya and Udawalawa. The Laxapana hydro complex contains six water resources but Fig 3-7 illustrated only five plants as Broadland plant is under construction and planned to be completed by 2020 with 35 MW installed capacity. The Mahaweli hydro complex is the biggest hydro power complex consists of ten power plants and the Uma oya power plant is still under construction as illustrated in Fig 3-8. Figs 3-9 and 3-10 illustrate the Victoria and Rantembe dams of Mahaweli complex. It is worth mentioning that most of the dams are very popular tourist destinations [82-84].

Fig 3-9 Victoria dam

Fig 3-10 Rantembe dam

The development of the small hydropower sector in Sri Lanka is widely considered to be a success story. The small hydro industry is typically characterised by projects with capacities less than 10 MW. The past 15 years have seen a growth in the non-conventional renewable energy industry. Most of these capacity additions are attributed to the growth in the small hydro power sector. In 2016, small hydro power contribution was 5.2% after the dammed hydro [85].

3.3.1 Economics of electricity

In Sri Lanka's the cost of electricity generation from hydroelectricity infrastructure is less than LKR 3 (0.02 US$) per unit. The hydropower electricity was popular in the past due to its low cost. But gradually increasing electricity demand proved that the generation was not enough and at that time the policy makers began believing in thermal power plants. In Sri Lanka, per unit cost of electricity by thermal power plants is between LKR 20-80 (0.15- 0.62 US$). The significant low rain capacity due the climate change caused the hydro reservoir storage level went down and resulted in regular power cuts in Sri Lankan energy sector during the peak hours. According to the above situation to reduce power cuts the government thought about coal plant-based electricity generation. This is much cheaper than thermal power and little higher than hydroelectricity. This coal plant electricity generation cost is nearly LKR 9 (0.07 US$) per unit [81,82,86].

In this situation, due to high electricity demand the future direction of generating electricity should be the renewables and nuclear. When considering renewable technologies this may be solar, wind, biomass, waste to energy or mini hydro mechanisms. This electricity generation cost from the renewables is nearly LKR 18 (0.14 US$) in Sri Lanka. By comparing the total capital cost, operation cost and maintenance cost with electricity production for long time period all these renewables have high payback time [87, 88].

Fig 3-11 Sri Lanka GDP profile from 2000 to 2016

By comparing Sri Lanka's unit electricity price with the international unit electricity price, Sri Lankan electricity unit price is low. To obtain a better picture of the electricity bills in Sri Lanka GDP growth profile need to be understood as illustrated in Fig 3-11.

The increased cost of living is causing people to be burdened even further with increasing electricity bills under the current economic condition in Sri Lanka [89].

3.3.2 Base load plant and peak plant

During the year 2016, maximum recorded electricity demand in Sri Lanka was 2453MW on 25th April and it was a 7.4% increase from 2,283 MW in the year 2015. Fig 3-12 illustrated the 25th of April 2016 daily load curve [83].

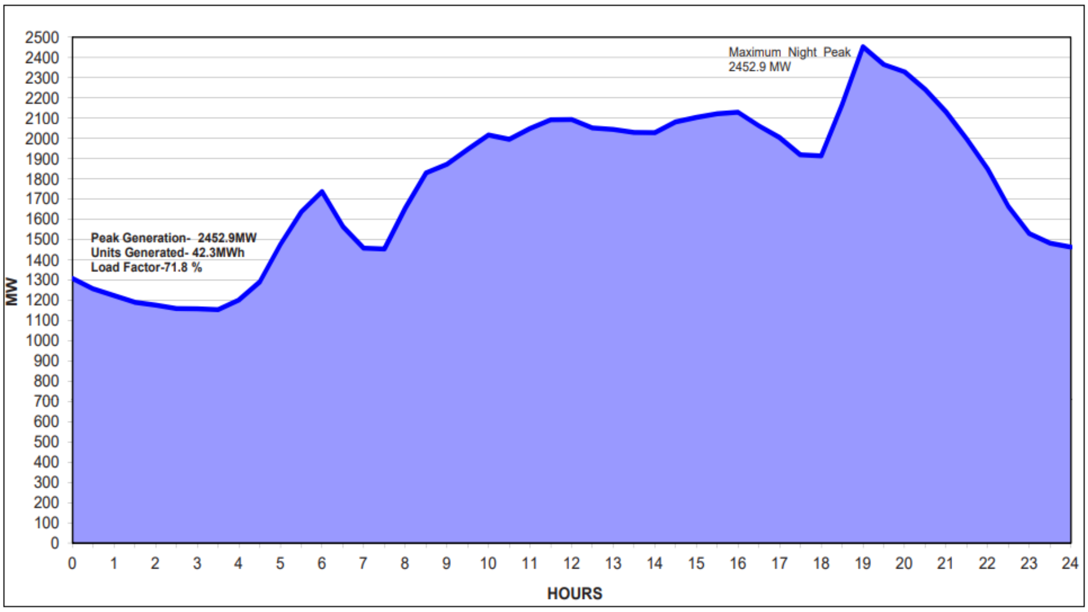


Fig 3-12 Daily load curve on 25th April 2016

According to the above graph, there are two peak times. They are 5am to 7am and 7pm to 9pm. This time requires a quick start power plant. That is called the peak plant. Mostly hydroelectricity plants are use as the peak plants. On the other times in a day consumption is lower than the peak and is called the base load. To provide the base load, the electricity providers use the plants that is called a base load plant. In Sri Lanka mostly coal, renewable energy and thermal power plants are used as base load plants.

3.3.3 Impacts of current electricity generation

Due to the environmental impact from hydroelectricity, thermal power and the coal power plants, high fuel cost for thermal power plants and high operational and maintenance cost for the coal power plants, the government electricity policy makers and stakeholders of the electrical and environment management system started thinking about non-conventional renewable technologies such as solar and wind power generation by taking advantage of the tropical climate and the island concept.

During the establishment of the Upper Kotmale plant, there were villages, schools, religion centres, hospitals demolished to fill the water and install the dam. In this case lot of tea plantations were demolished and impacted some natural water falls such as Devon Oya, Puna Oya, Ramboda Oya and St Andrews cascade waterfall etc.

The coal power plants impacted fisherman, carbon emissions, and high temperature vapour impacted rising temperature [85, 88, 89].

CHAPTER 4

4.ASSESSMENT OF RENEWABLE ENERGY RESOURCES

Renewable energy encompasses a broad range of energy resources. Sri Lanka is known to have a good potential for renewable energy, but so far, no systematic study has been done to quantify this potential for power generation. In this chapter, the potential of renewable energy for power generation in Sri Lanka is identified from the viewpoint of different promising available technologies.

The structure of the assessment of renewable energy resources section is illustrated in Fig 4-1

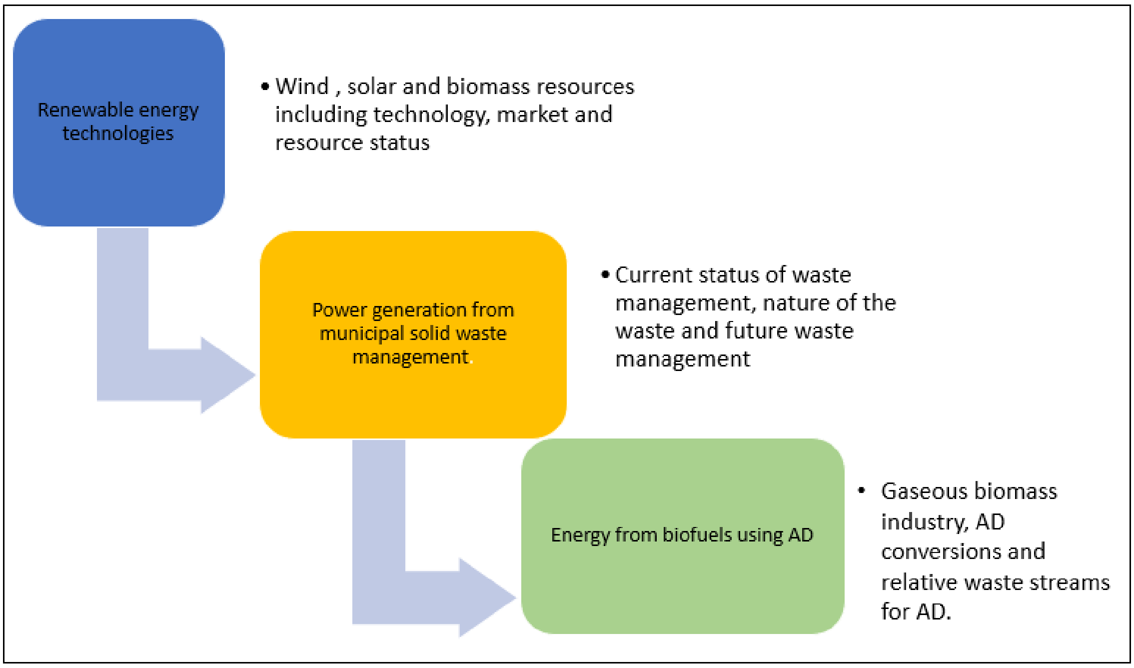


Fig 4-1 Structure of the assessment of renewable energy resources section

Chapter four discusses the assessment of renewable energy resources. Within this section initially, renewable energy technologies such as wind, solar and biomass are reviewed considering technology status, market status and resource status. Then the power generation from municipal waste management described considering the current status of waste management, nature of waste and future waste management using a hybrid system including anaerobic digester (AD) plant and incineration.

Finally, energy from biofuels using AD is broadly discussed within this chapter, including gaseous biomass industry, AD conversions and relative waste stream for AD plant industry in Sri Lanka.

4.1 Renewable energy technologies currently used in Sri Lanka.

This section describes wind, solar and biomass renewable energy resources which are currently used in Sri Lanka for electricity generation.

4.1.1 Wind energy

a. Technology Status.

A wind turbine consists of wind electricity generation systems (rotor blades, rotating shaft, gearbox and generator) and this unit converts wind energy into electricity. The kinetic energy of the wind initially turns into the mechanical energy by rotor, then converted into electrical energy via a generator [90].

Wind turbines' infrastructure consists of two basic categories:

1. Horizontal axis wind turbines
2. Vertical axis wind turbines

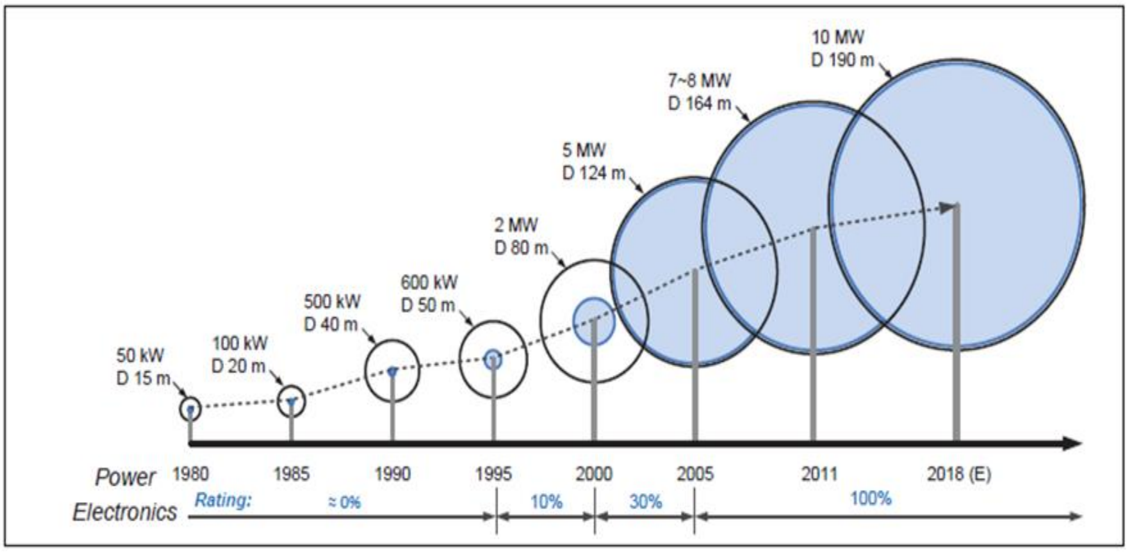


Fig 4-2 Development in wind turbine technology [91]

Globally the most generally used wind turbine is the horizontal axis wind turbine with three rotor blades. When wind passes through a swept area of the wind turbine, the aerofoil type rotor blades produce aerodynamic lift to rotate the blades which are connected to the rotating shaft. The rotating shaft of the wind turbine is connected to a gearbox, and this gearbox modifies the rotational speed of the wind blades to achieve a faster and more appropriate rotational speed to drive a generator to produce electricity.

The ideal operating wind speed is approximately 12–14 m/s enabling the maximum power output from the wind turbine [91]. The power ratings of the latest wind turbines vary from 50 kW to 10 MW. The rotor diameter of the modern wind turbines ranges from 15m to 190m with the integration of power electronics technology in wind turbine [91]. The combination of power electronics system will be more effective for supplying the national grid and application of advanced power electronics devices in the future renewable energy systems will enable a more reliable and flexible generation. Fig 4-2 shows the example of power electronic technology development in wind turbine application from 1980-2018.

Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be supplied, via the national grid. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine.

The wind power (P) defines as.

$P = \frac{1}{2}\rho A v^3$

Where.

$P = (MW)$ $\rho = Density\ of\ air\left(\frac{kg}{m^3}\right)$, $A = Swept\ area\ (m^2)$

$and\ v = Wind\ speed\ (\frac{m}{s})$

A German physicist Albert Betz concluded in 1919 that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. To this day, this is known as the Betz Limit or Betz' Law. The theoretical maximum power efficiency of any design of wind turbine is 0.59 (C_p = 0.59). The real-world limit is well below the Betz Limit with values of 0.35-0.45 common even in the best designed wind turbines.

Also, considering the gearbox, bearings, generator and so on - only 10-30% of the power of the wind is ever actually converted into usable electricity. Hence, the power coefficient needs to be factored in equation and the extractable power from the wind is given by:

$$P = \frac{1}{2}\rho A v^3 C_p$$

b. Market status

In 1999, the first pilot 3MW wind project established in Hambantota Sri Lanka was not a successful project. In 2015, after 16 years, Sri Lanka introduced an energy policy to promote electricity generation based on non-conventional renewable energy. CEB issued licenses to private sector investors, to develop Wind power plants. As of 2016, Sri Lanka had approximately 131.45 MW of installed wind capacity, consisting of 16 onshore wind energy sites [83]. Table 4-1 shows the wind farm details in Sri Lanka. After 2010, the Wind energy industry achieved extraordinary growth with an installed capacity of 128.45 MW. Currently, the cost of electricity generated from wind is less than the cost of electricity generated from fossil fuels but a little higher than the cost of electricity generated from mini-hydro [92]. In 2016, Independent Power Producers (IPP) sold 342.724 GWh wind power to the Ceylon Electricity Board (CEB) for a wholesale unit price of LKR 22.16 which is the highest generation cost from any renewable energy source [93 94].

CEB is a public sector institution and is the owner of the electricity infrastructure, including all major hydro, few mini hydro and limited thermal plants in Sri Lanka [83]. When considering the energy markets, CEB is selling electricity to consumers and one bulk electricity supplier called LECO. CEB is buying its power generation through Independent Power Plants (IPP) [88].

Table 4-1 Wind farms in Sri Lanka

Wind Farm	Install Capacity	Commissioned Year	Number of Wind Turbine	Size of each Wind Turbine
Hambantota	3.00 MW	1999	5	0.6 MW
Vidatamunai	9.6 MW	2010	12	0.8 MW
Mampuri 1	10.0 MW	2010	8	1.25 MW
Willpita	0.85 MW	2010	7	0.12 MW
Nirmalapura	10.5 MW	2011	7	1.5 MW
Madurankuliya	12 MW	2012	08	1.5 MW
Kalpitiya	10.2 MW	2012	12	0.85 MW
Ambewela	3.00 MW	2012	12	0.25 MW
Uppudaluwa	10.5 MW	2012	7	1.5 MW
Seguwantivu	10.4 MW	2012	13	0.8 MW
Nala Danavi	4.80 MW	2013	6	0.8 MW
Vallimunai	12.0 MW	2014	8	1.5 MW
Pollupalai	12.0 MW	2014	8	1.5 MW
Mampuri 11	10.5 MW	2014	5	2.1 MW
Mampuri 111	10.5 MW	2014	5	2.1 MW
Musalpetti	10.0 MW	2015	5	2.0 MW

The cost of wind electricity generation is dependent on several aspects such as location, wind speed and electrical grid connection availability, which changes from one place to another [93 94]. According to an energy generation report of 2016, published by the Public Utilities Commission of Sri Lanka, generation costs varied from 5.3 LKR per kWh (hydro energy) to 27.87 LKR per kWh (Thermal Independent Power

Plant). Table 4-2 shows the generation costs from different energy sources in 2016 [83-88].

Tab 4-2 Generation cost in Sri Lanka 2016

Source	**Annual Generation GWh**	**Average Unit Cost LKR per kWh**
Renewable	1208	16.71
All Hydro	3603	5.03
All CEB Thermal	7395	15.33
All IPP Thermal	2202	27.87
All Sources	14408	14.79

c. Resource Status

Sri Lanka is in the Indian Ocean facing a vast swathe of uninterrupted ocean, providing substantial wind energy potential [92]. The North East (NE) and South West (SW) monsoons are the most determined two Asian monsoons mostly consistent with Sri Lanka's wind climate [95]. According to historical data, there is a high wind potential from the SW monsoon, continuing from May to early October while potential wind from the NE monsoon lasts from December to February. The SW monsoon is the most energetic monsoon of both, and it touches the West coast and internal zones consisting of some mountainous areas of Sri Lanka [96]. The wind coming over the mountain areas is turbulent, incredibly location specific and seasonal to the SW monsoon. However, both monsoons bring steady wind over the plain landscapes such as the south-eastern and north-western coastal belts during that time [97].

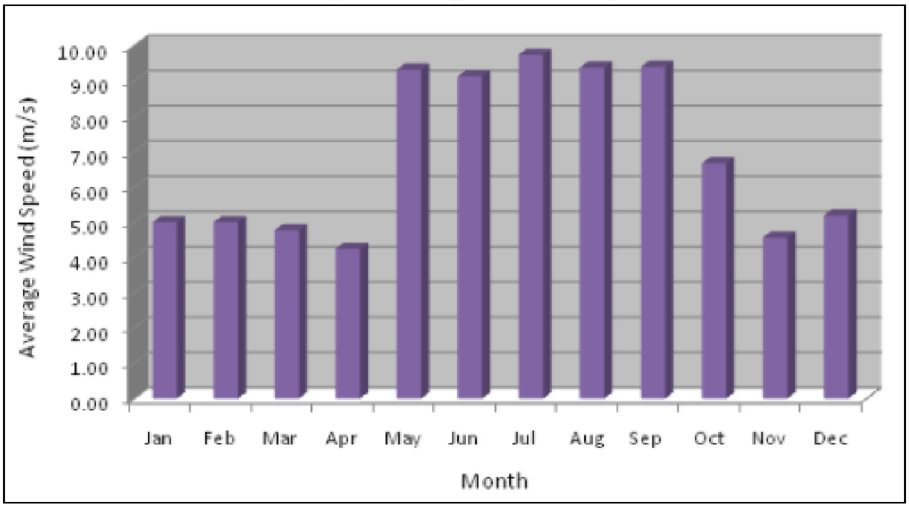


Fig 4-3 Monthly average wind speed in Puttalam district [96]

The Exploitable Technical wind power potential with wind power capacity density above 8 MW per square km is estimated as 5650 MW mainly in the North Western and Central regions [98]. According to the innovative research and development carried out by the National Renewable Energy Laboratory (NREL) of USA, the potential for wind power in Sri Lanka is 20,740 MW. The following areas were identified and evaluated following the screening criteria [95].

- Southeast Coast – Hambantota District
- West Coast – Puttalam District
- Northwest Coast – Mannar District
- North Coast – Jaffna District
- Central highlands in the interior of the country – largely in the Central Province
- Parts of the Sabaragamuwa and Uva Provinces

The wind regime at Puttalam region is a role model which follows the general monsoon wind climate pattern in most parts of Sri Lanka. Fig 4-3 shows the monthly average wind speed in Puttalam district and according to the data from the Sustainable Energy Authority, the average wind speed is nearly 7 m/s at an elevation of 50m.

4.1.2 Solar Energy

a. Technology Status

Energy from the sun is the most abundant and freely available energy on planet earth. Sunlight reaching the earth has the vast potential to be exploited and converted into electricity generation. Solar photovoltaic (PV) is modern technology which converts sunlight into direct current (DC) electricity. In PV cells semiconducting materials such as silicon are used. When sunlight hits a solar cell surface, the electrons become energized and move to the N-Type layer, and similarly, holes move to the P-Type layer. The electron movement from N-Type to P-Type causes the current flow in the load [95].

Due to high durability, no moving parts, low maintenance and no requirement for an additional resource (e.g., water and fuel), Solar PV is attractive, and is becoming more and more popular within the industry. Globally over the past years, the unit price of PV manufacturing and installation cost has dropped, and the solar PV efficiency is continuously improving. This situation is an added advantage for investment on an economic scale for a developing country like Sri Lanka [99].

b. Market status

Solar PV technology is mostly used to supply the rural electrical demand of non-electrified localities and rural households in Sri Lanka. It is a cost-effective mechanism providing a distributed source of electricity without connecting to the existing grid to fulfil remote area electrical requirements.

Tab 4-3 Solar farms in Sri Lanka

Solar Farm	**Install Capacity**	**Commissioned Year**
Gannoruwa I	0.737 MW	2011
Gannoruwa II	0.500 MW	2011
Thrippane	0.123 MW	2011
Saga Buruthukanda	10 MW	2016
Solar one Ceylon power	10 MW	2017

According to Table 4-3, there are five commercial type solar farms in Sri Lanka, and the current solar installed capacity is 21.36 MW. From the above five plants, three solar farms were commissioned in 2011 and the other two solar farms approved in October and December 2016, respectively [83].

The roof-top solar net metering system introduced in June 2010 meant that consumers connected to the grid as “micropower producers”. After that, two additional tariff-based options were introduced in September 2016 called net accounting, and net plus. Up to 2017, there were 8000 consumers engaged with these tariff options and this achieved 60MW installation capacity. Fig 4-4 illustrates the Rooftop solar PV number of connection and solar PV install capacity up to 2017.

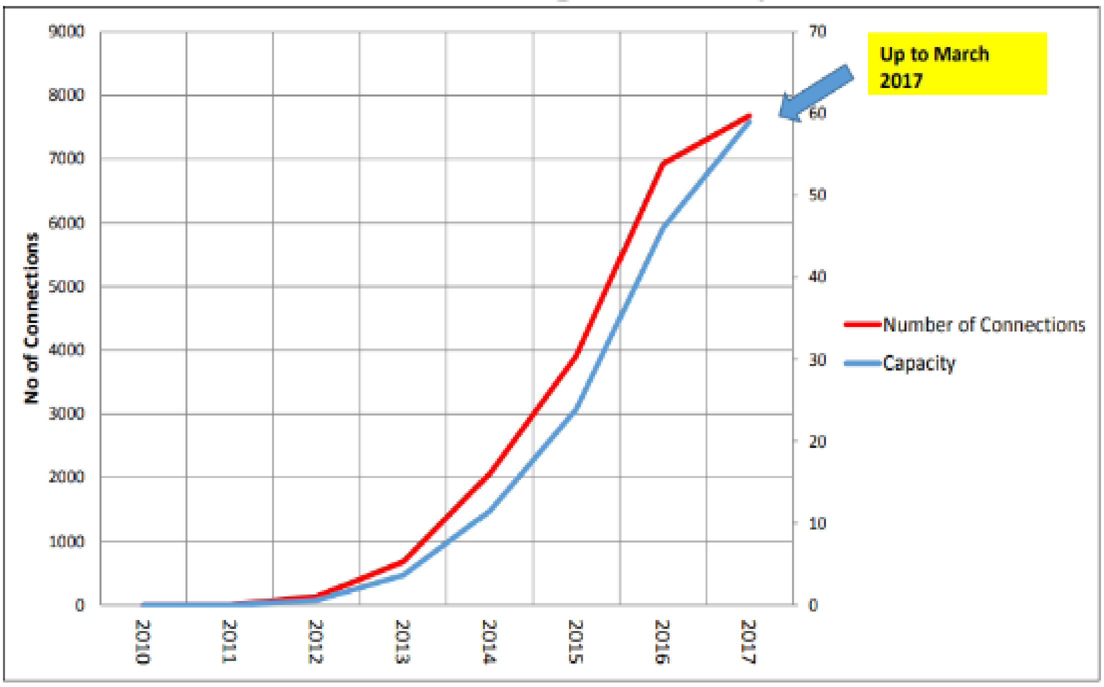


Fig 4-4 Solar PV rooftop number of consumers and capacity up to 2017.

Sri Lanka is situated close to the equator, therefore receives an abundant supply solar radiation year around. Solar radiation over the island does not show a marked seasonal variation, though significant spatial differentiation could be observed between the lowlands and mountain regions. When considering solar power generation in 2016, the CEB paid 95.141 Million LKR to produce 4.291GWh. This means that the average unit price of the solar power generation is 22.17 LKR ($ 0.12) which is not suitable for CEB who do not make a profit after selling to consumers [83,88,94].

c. Resource Status

As illustrates in Fig 4-5, there is a massive potential of solar radiation throughout the year due to the location of Sri Lanka within the equatorial belt and no seasonal variations for the solar radiations over the island [100]. According to the historical data record at several weather and agricultural stations throughout the country, it shows that the 4.2 to 5.6 kWh/m^2/day solar radiation can be expected across the country. There is a low level of solar radiation such as 2.0 – 3.5 kWh/m^2/day remaining in the hill country in the south-central region due to the significant cloud cover during most parts of the day [99 101].

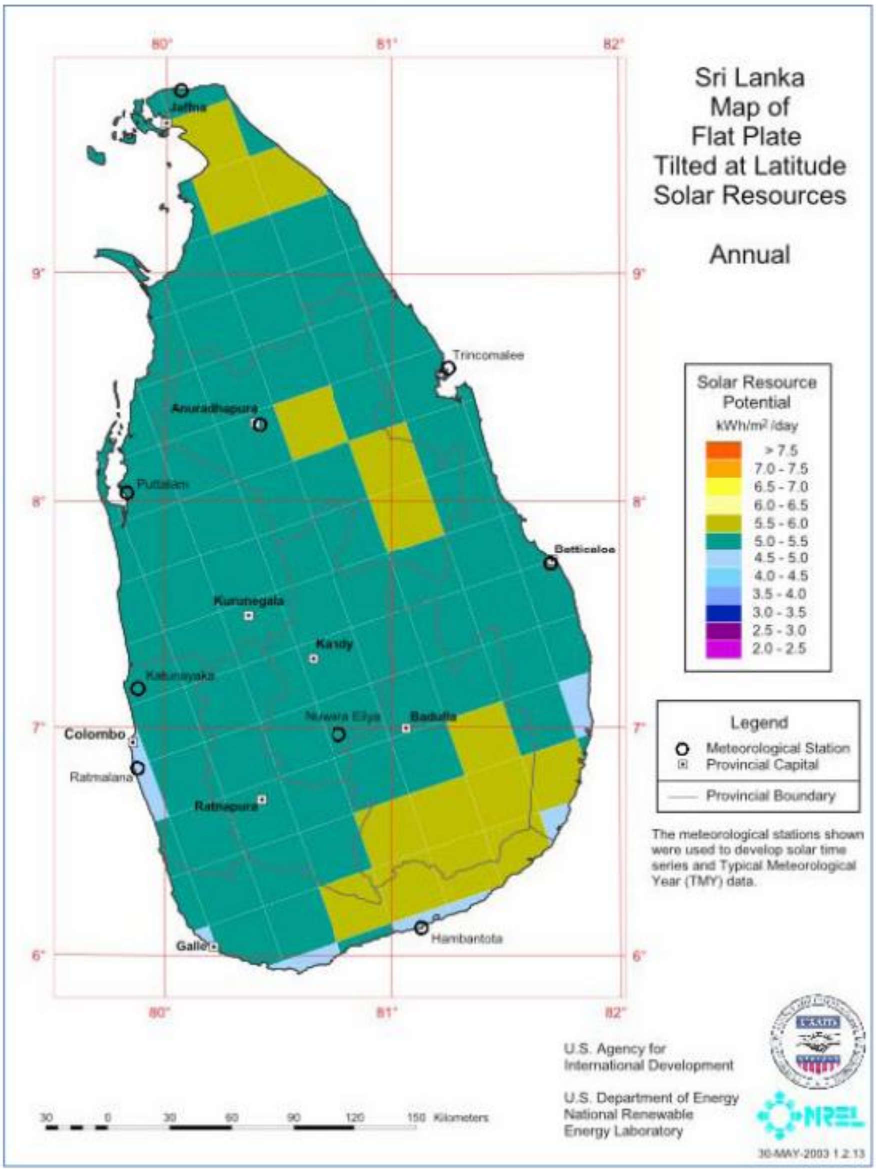


Fig 4-5 Annual solar resource potential in Sri Lanka [101]

4.1.3. Biomass

a. Technology status

Biomass is non-fossil material, and it consists of all kind of organic matters from fuelwood to marine vegetation. The biomass from rural households in most developing countries delivers the primary energy supply for cooking and heating.

To decrease dependence on combusting fossil fuels for energy generation biomass is an alternative solution and is becoming very popular. Worldwide, biomass is a much-explored prime energy source for power generation due to its significant environmental benefits and potential of low-cost supply as a fuel source. Apart from the above advantages, using biomass as a fuel source for power generation has socio-economic benefits such as local employment generation, mitigation of adverse impacts of climate change and potential carbon trading benefits [102].

Biomass can be separated into two main groups:

- Energy crops: Energy crops consist of three types of crop grown precisely for energy purpose.

  1. Fast growing trees with 8-20 years lifespan, used to produce wood fuel for energy production

  2. Annual crops for biomass production and use of traditional farming machinery for harvesting these crops.

  3. Liquid biofuel energy crops to produce transport fuel like biodiesel, bioethanol and bio-methanol by using several conversion techniques [92].

- Organic residues: Can be used to produce fuel for heat and power generation and biofuels (liquid, transport and gaseous). Organic residues include [103].

  1. Forest residues (branches and tree tops)

  2. Agricultural residues (slurry, manure, straw and chicken litter)

  3. Wood wastes (chippings, sawdust and bark)

  4. Waste vegetable oil (catering industry)

  5. Tallow (animal fat from food processing)

  6. Municipal solid waste (food processing waste)

  7. Industrial waste (wastewater and organic waste)

  8. Sewage sludge

  9. Seaweed

The organic material known as feedstock can be converted to fuel for different applications. The conversion technologies used to convert the feedstock to fuel for heat and power generation and biofuels are as follows [90].

1. Biochemical process (Hydrolysis, Fermentation and Anaerobic Digester)

2. Chemical process (Hydrogenation, Transesterification and catalysis)

3. Thermochemical process (Gasification, Pyrolysis and Combustion)

The biogas coming from the above conversion technologies can be used in standard or CHP applications. Landfill gas also formed by the organic components of the waste and CHP system remains is used to produce power generation in landfill sites. Currently, considering the waste management industry and waste to energy industry, CHP applications are the most cost-effective selection in terms of biopower using waste fuels.

b. Market status

When considering the biomass market in Sri Lanka, Dendro power generation is one kind of biomass technology currently being used in Sri Lanka. Dendro power is identified as a renewable energy harvesting technology from a short rotation energy crop called Gliricidia. The scientific name of this energy crop is Gliricidia sepium, also recognized as Ginisiriya, with many other local names such as Wetamara, Nanchi, Albesia and Ladap-pa [104].

Table 4-4 Dendro & biomass plants in Sri Lanka

Dendro Power	**Install Capacity**	**Commissioned Year**
Kottamurichchana	0.5 MW	2011
Embilipitiya	1.5 MW	2011
Bathalayaya	5.0 MW	2011
Batugammana	0.02 MW	2016
Loluwagoda	4.0 MW	2017
Biomass Plant	**Install Capacity**	**Commissioned Year**
Badalgama	1.00 MW	2005
Tokyo	10.0 MW	2008

Ninthahur	2.0 MW	2014
Dikkanda	0.080 MW	2015

Table 4-4 shows the Dendro and Biomass plants in Sri Lanka [83] and the total install capacity of biomass is 24.1 MW. In 2016, Dendro power sold 40.905 GWh of electricity to CEB for the unit price of 20.76 LKR ($ 0.11) which was not economical for either the CEB or consumer, while Biomass plants sold 31.051 GWh electricity to CEB for the unit price of 12.81 LKR ($ 0.07) which was excellent for the consumers [88,94].

c. Resources status

The availability of biomass resources in Sri Lanka is shown in Tab 4-5.

Table 4-5 Biomass availability in Sri Lanka

Type	**MT/Year**
Rice husk from commercial mills	175,149
Biomass from coconut plantations available for industrial use	1062,385
Sugar bagasse	283604
Biodegradable garbage	786,860
Sawdust	52,286
Off cuts from timber mills	47,938
Biomass from home gardens	505,880

By using the biomass resources shown in Table 4-5, it is estimated that the theoretical potential of biogas could achieve about 16 million-ton oil equivalents (mtoe) per annum.

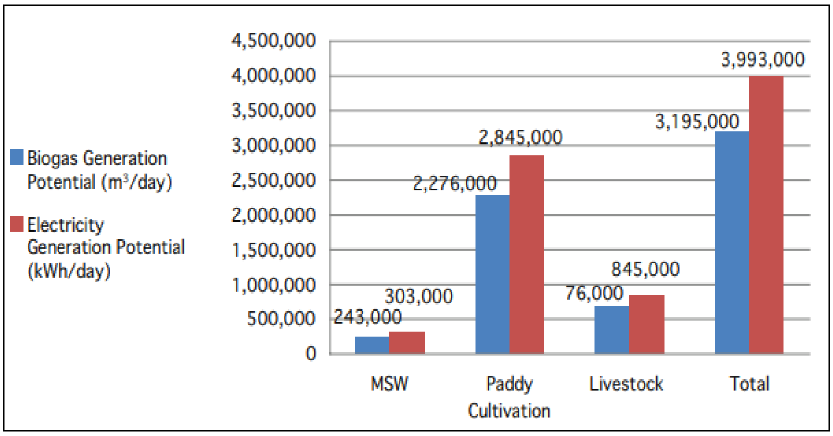


Fig 4-6 Potential power from biogas

Furthermore, Sri Lanka's Renewable Energy Master Plan indicates that the potential for electricity generation using grown biomass is 2,370 MW, out of which 1,319 MW will be from dedicated energy plantations, and the remaining 1,050 MW of capacity will be from mixed crops under various commercial plantations [92]. Fig 4-6 indicates the potential for the 4GWh/day power generation by using a variety of organic materials through biogas. It is known that rice paddies have the highest potential for biogas production. Fig 4-7 shows the forest and wildlife reserves in Sri Lanka [104].

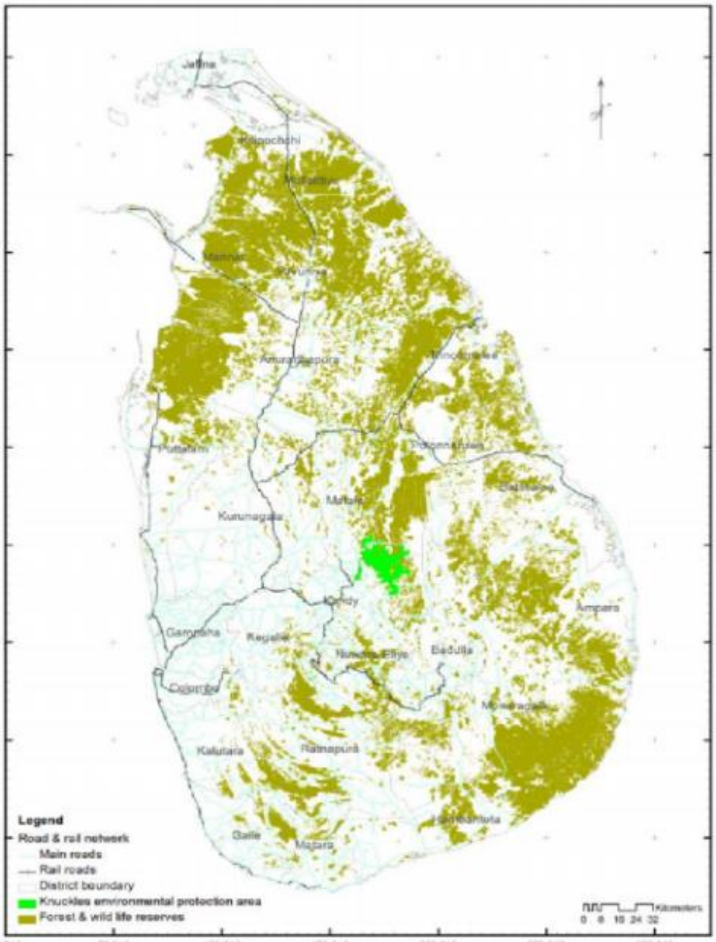


Fig 4-7 Forest and wildlife reserves in Sri Lanka [104]

The next two sections describe the different renewable energy technologies which can use for power generation to achieve a 100% renewable energy Sri Lanka. Biomass and municipal solid waste (MSW) are widely accepted as being crucial locally-available renewable energy sources offering low carbon dioxide (CO2) emissions.

Finding environmentally friendly methods related to sound municipal solid waste (MSW) management is of the highest priority in Sri Lanka. It is very important to study new approaches which can reduce waste generation and simultaneously enhance energy recovery.

Energy from Biofuels (EfBF) using Anaerobic Digester based stand-alone and grid-connected combined heat and power (CHP) systems is another possibility to produce electricity and biofuels in Sri Lanka. Energy crops, agricultural residues (slurry, manure, straw and chicken litter) and municipal solid waste (food waste) will be used as potential resources to produce methane gas to produce electricity.

4.2 Power Generation from Municipal Solid Waste Incineration Systems

The disposal of solid waste has become one of the most significant environmental issues in Sri Lanka. The dumping of municipal waste on roadsides and environmentally sensitive areas such as wetlands, marshy lands and river and stream reservations is a common practice that has been adopted by the public and even by some local authorities over the years. This waste dumping has been occurring mainly due to the attitudes that prevail among society concerning waste disposal and, in the case of local authorities, owing to their inability to adopt proper environmentally friendly methods of waste disposal. According to the Central Environmental Authority (CEA), the main issues faced by local authorities include the difficulty of finding suitable land for waste disposal, lack of technical knowledge in waste management, public objections to the development of sanitary landfill sites and financial restrictions. Open dumping and lack of hygienic and sustainable means of waste disposal and management have led to several detrimental environmental issues, especially in highly urbanized and populated areas of Sri Lanka [105].

Investigating the feasibility of power generation from Municipal Solid Waste (MSW) incineration system in Sri Lanka is very important and will help in the following ways by:

a) Creating a sustainable and effective waste disposal system for Sri Lanka

b) Maximizing the usage of renewable energy in meeting the energy needs of the country

According to waste generation and management procedures in Sri Lanka, it is imperative to implement a mechanism to minimize the socio-economic and environmental problems occurring from inadequate waste management systems. Power generation from a municipal solid waste incineration system in Sri Lanka will help to mitigate the above issues by generating electricity in a sustainable way. The grid-connected incinerator plant will use waste as a fuel to produce electricity during peak hours to generate electricity in peak demand duration [106,107].

4.2.1 Current Status of Waste Management

According to the Central Environmental Authority (CEA) in Sri Lanka, the current waste generation is 6400 tons and waste collection rate is 2683 tons per day. This shows that there is a significant amount of waste still to be collected and processed. This also demonstrates the lack of waste management practices in the country due to many reasons. Table 4-6 shows the per capita daily generation of solid waste within the local authorities [108].

Table 4-6 Per capita daily generation of solid waste [109]

Type of Local Authority	Per capita waste generation (Kg/day)
Colombo Municipal Council	0.75
Municipal Councils	0.70
Urban Councils	0.60
Divisional Council	0.40

Open waste dumping and open burning are the most common practices used in almost all local authority municipalities in Sri Lanka [109] with composting and land-filling also widely used in the waste management industry. The open dumping method is not an environmentally friendly nor is its best practice use in the waste management industry.

The use of outdated waste management practices has produced a giant garbage mountain, as shown in Fig 4-8. This man-made disaster can lead to tragic outcomes as exemplified by the recent loss of 35 lives and leaving more than 1,500 families homeless and displaced in April 2017 [110].

Fig 4-8 Meethotalmulla open garbage dump

Table 4-7 Solid waste collection rate by the province in 2018 [111]

Province	**Waste Collection rate**
Western Province	58.5%
Eastern Province	8.5%
Central Province	8%
Southern Province	7%
NW Province	6%
Northern Province	3.3%
Sabaragamuwa Province	3.2%
Uva Province	3%
NC Province	2.5%

However, most municipal councils and urban councils still have difficulties with the operation, maintenance, monitoring and evaluation activities in SWM, which lead to numerous solid waste management problems in urban areas in Sri Lanka [111]. Table 4-7 shows the difficulties facing local authorities in waste collection, and how it is essential to implement more effective strategies for establishing proper waste management methods very soon in order to minimize socio-economic and environment issues [109].

4.2.2 Nature of the Waste

Sri Lanka MSW consists of textiles, wood, yard wastes, ceramics, construction and demolition wastes, tyres, product packaging, bottles, food scraps, newspapers, cardboard, paint, treatment plant sludge, industrial solid waste, batteries and e-waste. [112] as illustrated in Fig 4-9 .

Fig 4-9 Typical MSW sample in Sri Lanka [11 2].

These are coming from residential homes, schools, hospitals, industries and businesses. However, hazardous waste, e-waste and infectious waste should be segregated at source to abide with the comprehensive environmental legislation of the country. Waste composition varies with waste type, socio-economic conditions of the collection area and seasonal variations [112].

Table 4-8 Waste composition in 2016 [112]

Category	**Composition Rate (%)**
Kitchen waste (Degradable)	52.55
Paper	13.56
Textile	4.32
Grass & Wood	14.06
Soft Plastic	9.15
Hard Plastic	1.37
Rubber & Leather	0.57

Incombustible	4.28
Others	0.14

Based on a recent data collection survey (2016) conducted by the Japan International Cooperation Agency (JICA) on solid waste management in Sri Lanka, physical composition data of the collected waste samples from the Colombo district is given in Table 4-8 [113].

There have been several studies previously carried out on MSW characterization. Findings of a research project carried out by the Sustainable Energy Authority in Sri Lanka (SEASL) and the Department of Civil Engineering, together with the Open University of Sri Lanka in 2015, to find solutions for selecting the right technology for treating Sri Lankan MSW issues, is relevant for the description of waste characterization. The report revealed that the previous MSW characterization had been conducted in 2004 by the CEA when the per capita Gross Domestic Production (GDP) was USD 1,035. Now the country's per capita GDP has changed with the lifestyle of the people (USD 2,135). Therefore, MSW characterization within the Colombo Municipality has drastically altered [108,114,113].

According to recent findings, the biodegradable percentage of MSW in Colombo has dropped from 65% to 54% between 2004 and 2015, while polythene and plastics percentages have increased to 14% from 5.4%. In addition, the paper and cardboard percentage has increased to 10% from 7%. The combustible share (paper, cardboard, textile, rubber and leather, wood and timber, polythene and plastics) of MSW shown in 2004 was only 17% while this share increased to 31% in this latest analysis done on the percentage composition of organic waste [106,112].

4.2.3 Future Waste Generation and Waste Management Practices -Sri Lanka

The available statistics show that the current generation of MSW in the Western Province (Districts of Colombo, Gampaha and Kalutara) is around 3,200 to 3,500 metric tons per day. The collection is around 2,400 metric tons, which is around 65% to 70 %. However, according to the University of Moratuwa, the current waste collection rate is estimated as 51%. Estimated future waste generation in the Colombo District based on a recent JICA study is as shown in Table 4-9 [113].

Tab 4-9 Estimated waste generation in Colombo district [113].

Year	Kg/Persons/Day	Tons/Day
2019	0.75	1812
2020	0.76	1845
2021	0.77	1885
2022	0.79	1922
2023	0.80	1961
2024	0.81	1999

Western Province Waste Management Authority (WMA) implements programmes enabling composting and recycling of waste but compared to the daily generation, this amount is negligible. The rest is disposed of through open dumping. The sanitary landfills in Karadiyana and Dompe as well as the Meethotamulla open dump site have been receiving MSW daily from the respective local authorities [109].

Disposing of MSW in Colombo has been a growing problem. Colombo, being the largest city and the central economic hub of Sri Lanka with a migratory population of over 2.3 million, is generating over 1000 tons of MSW per day. The Colombo Municipal Council (CMC) is the authority responsible for the daily collection and disposal of MSW from households and other sources [112].

The CMC has dumped MSW at the Meethotamulla site for the past few decades. With the collapse of the garbage mound recently, the CMC encountered several issues as to the disposal of MSW. Although the Government has now decided to remove the MSW collected from the CMC area to Karadiyana and Dompe landfills temporarily (and now even to the Muthurajawela marshes) a lasting solution to the disposal of MSW is now considered a national priority [113].

Table 4-10 shows the characteristics of the municipal solid waste brought from the four different dumping sites in the western province.

According to the above Table 4-10, the municipal solid waste at Viyangoda and Kolonnawa sites has low moister content compared to Karadiyana and Colombo MC sites. Based on studies carried out to identify the MSW nature, composition and characteristics at the above four sites, there are two types of Waste to Energy (W2E) solutions that can be proposed for proper waste management in the Western Province due to the high waste generation [114].

Table 4-10 Characteristics of the MSW [114].

Site	Moisture Content (%)	Calorific Value MJ/Kg	Combustible Ability (%)
Viyangoda	30.3	11.70	90.89
Kolonnawa	31.35	12.72	91.54
Karadiyana	48.7	9.01	95.29
Colombo MC	63	13.35	95.58

1. An incinerator plant generating electricity with mixed municipal solid waste (MSW) as the fuel.

The process is such that a thermal steam power plant continuously converts the energy stored in the fuels (MSW) into mechanical energy and ultimately into electrical power. Water is used as the working medium to carry energy released by fuels and converts the energy into mechanical energy through high pressure and high-temperature steam. A steam requirement for the turbine generator will be set through grate incinerations and boiler units. A steam turbine unit converts the thermal energy into mechanical energy whereas, an alternator unit converts mechanical energy into electrical power.

2. A hybrid system, Overall Process Technology consists of a thermal and biological dual process.

The thermal process consists of the incinerator plant generating electricity with mixed municipal solid waste (MSW) as the fuel.

Biological processing technology operates from the fresh organic waste received onto the site. The technology utilized is a proprietary waste feeding system that is coupled to a large controlled anaerobic digester. The biogas produced in the anaerobic digestion process is captured, cleaned and combusted in a commercial biogas engine. This is coupled to a generator or Combined Heat and Power (CHP) plant to produce electricity.

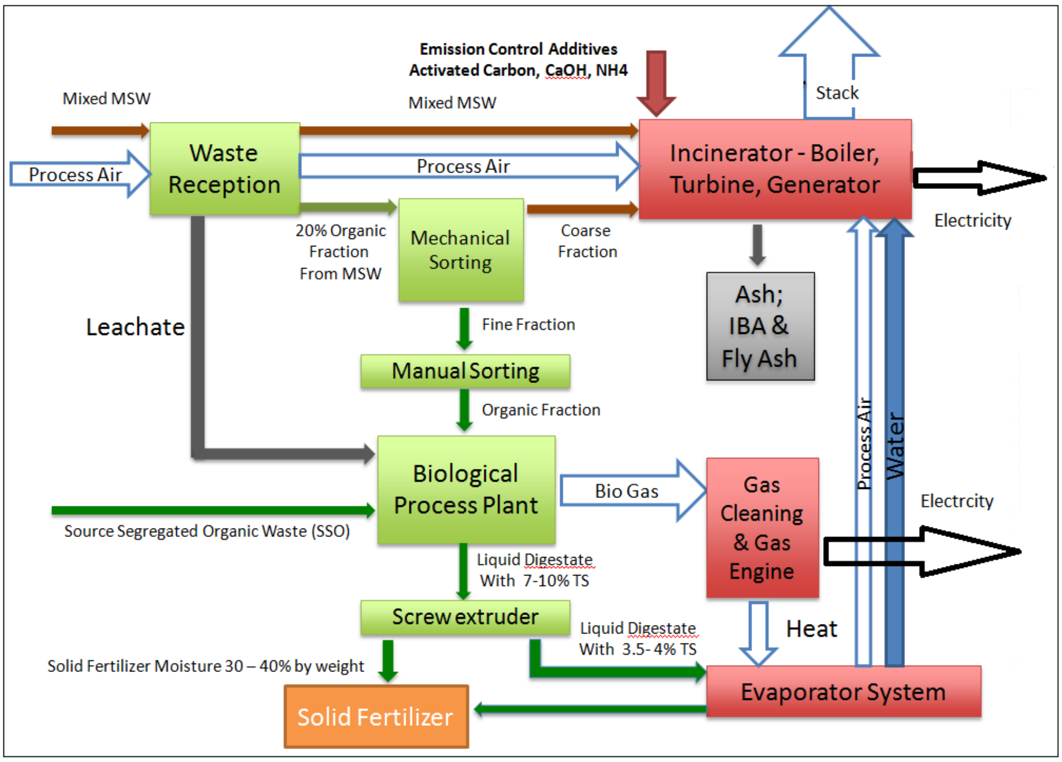


Fig 4-10 Hybrid system process flow chart for thermal and biological combi technologies.

Fig 4-10 represents the overall process flow chart of the proposed hybrid system considering the reliable waste parameters such as moisture content, calorific value and solid waste generation capacity within the western province. This kind of hybrid waste management system in urban areas helps to implement a sustainable waste management system and is a great asset to fulfil electricity demand for the populated area and prevents fossil fuel burning.

4.2.4 Waste Treatment Technologies

MSW can be managed in one of three ways, such as thermal treatment, biological treatment, or landfilling. The typical thermal treatment reduces the volume of waste, and consists of combustion (incineration), gasification, and pyrolysis. Biochemical treatment is an environmentally friendly method and consists of aerobic and anaerobic digestion systems. In the aerobic system, organic matter undergoes microbial action with the presence of oxygen. Whereas in the anaerobic digestion system, organic matter experiencing microbial action is absent of oxygen to produce methane (CH_4). The Landfill sites consist of non-recyclable waste, non-treated waste and waste residues gained through both thermal conversion and biological conversion within the waste management hierarchy. These waste treatment approaches and their products are illustrated in Fig 4-11.

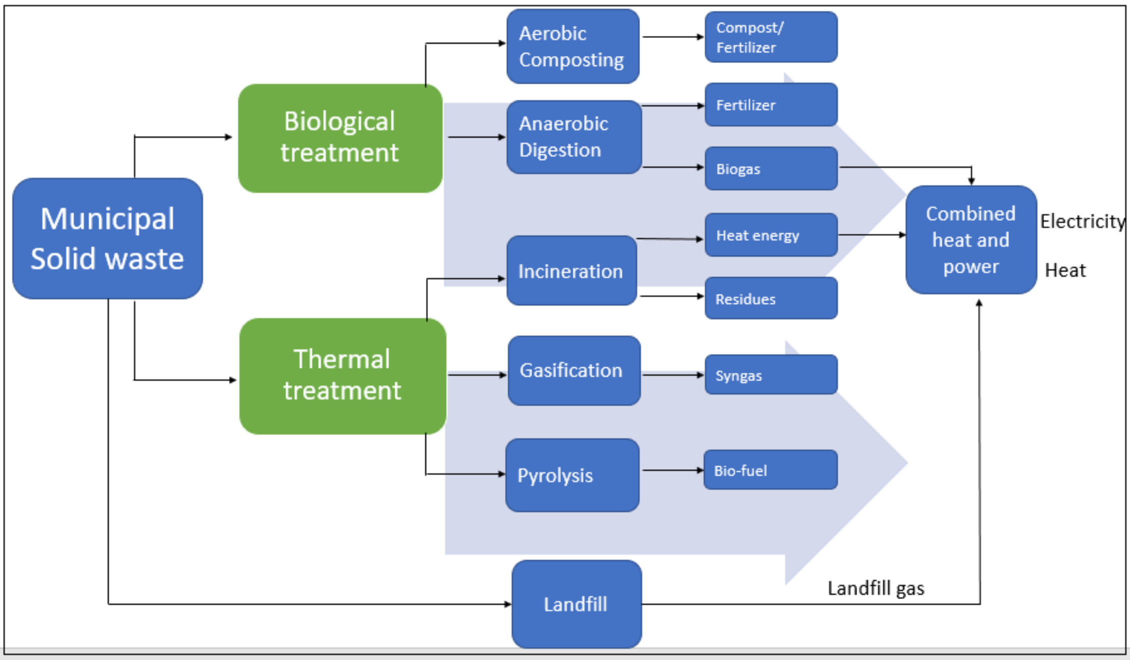


Fig 4-11Waste treatment technologies and their product

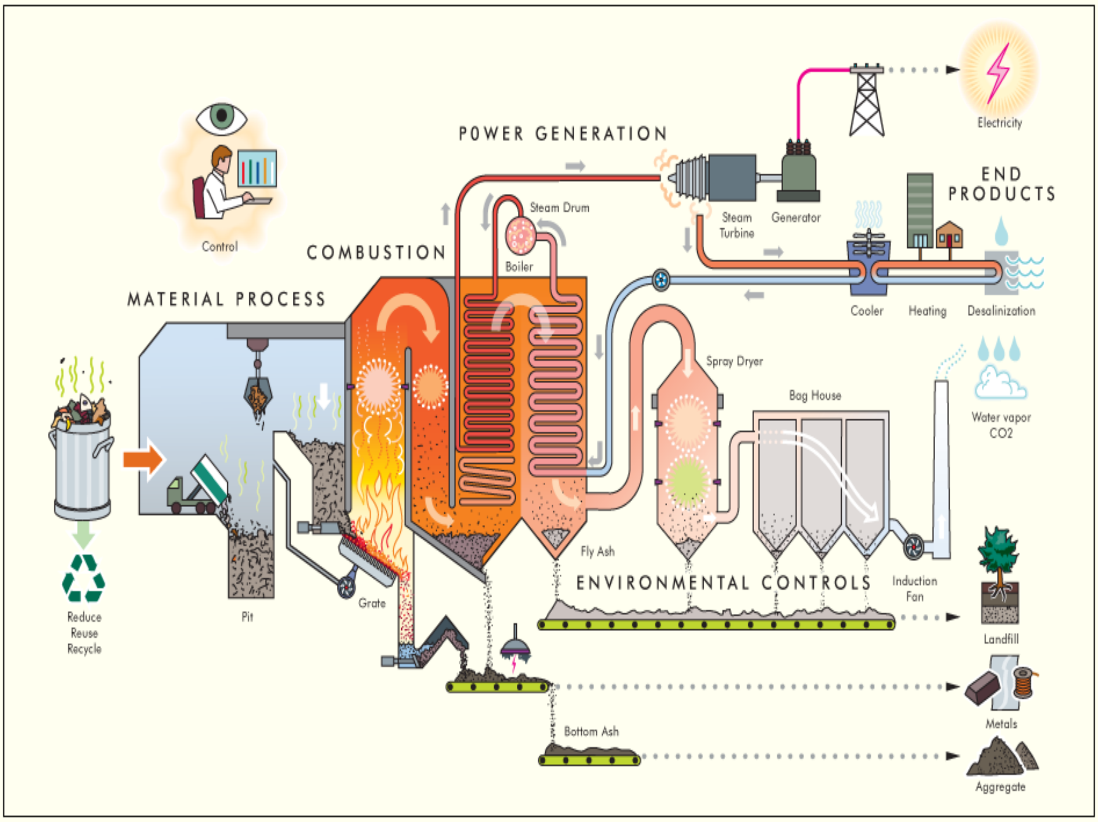


Fig 4-12 Pictorial view of the process flow diagram of incinerator [111]

MSW incineration plant consists of many technologies. Combustion of organic and non-organic substances contained in MSW is done at very high temperatures (around 850°C). The heat generated from waste incineration can be recovered and used as an energy source for electricity generation. Based on new technologies, incineration technology can be a group in four categories.

- Pre-treatment
- Combustion system
- Energy recovery
- Gas flue cleaning

The detailed view of the process flow diagram of the incineration system is illustrated in Fig 4-12. Fuel is fed into the feed hopper/feed chute and rammed directly into the combustion chamber/ furnace of the incineration through a ram feeder. Steam generated by a boiler is supplied to a steam turbine where part of the thermal energy available in the high-pressure steam is converted into mechanical energy. The steam turbine is coupled to a generator for converting mechanical energy into electrical energy and the power generator is connected to the grid for distribution to the national grid [111].

After using the thermal energy in the steam turbine, the high pressure & high-temperature steam converts less pressure and temperature steam with a lower amount of thermal energy. The final low-pressure steam is condensed in the condensing system and then pumped to the De-aerator. Condensate is re-circulated to the condensate storage tank through a level control operation.

A De-aerator removes all dissolved non-condensable gases and oxygen from makeup water, which affects boiler performance in the long run. The temperature of the makeup water also is raised in the De-aerator for better boiler efficiency using the steam taken from the turbine and then stored in the Feed Water Storage Tank. Inside the boiler, the feed water gets heated to form high pressure and high-temperature super-heated steam. Thus, the thermal cycle is completed [115].

Combustion gases after heat recovery in the boiler lead to the exhaust stack through the reaction chamber, fabric filter and induced draught fan. Ash generated in the Incinerator after burning the MSW is collected in ash hoppers located at the bottom of the furnace, economizer & fabric filter [116].

a. Incineration Advantages and Disadvantages

The possibility of the treatment of waste arising from the incineration process and the ability to contribute to energy production through such means has its own merits such as providing a lasting solution to the disposal of MSW and minimizing health risks (when open dumping is excessively practiced). The Western province is the most highly waste generation domain, and it is the centre of gravity of waste generation in Sri Lanka. Thus, incineration plants can be located near these areas to reduce the cost of waste transportation. Also, the location of plants helps to minimize the cost of systematizing electricity distribution due to the established electricity infrastructure in urban areas. The waste incinerators achieve 80-95% novel volume of combustible ability, and this helps to reduce the requirement for landfill sites because of an absence of suitable sites or extended transport costs. The output, such as ash from MSW incinerators can be used for environment-friendly construction work [115].

The investment cost of such ventures is high due to the modern technology involved. In addition, demerits exist such as residual air emissions, low options for the use of ash generated from the incineration process, possible contamination of water due to the disposal of sludge and effluents [116].

4.3 Energy from Biofuels (EfBF) using Anaerobic Digester based CHP

The solid material harvested or collected from biological organisms (plants) is referred to as biomass. Likewise, greater wealthy heterogeneous substantial waste such as husks, wood and plant stems are also included within the term of biomass. Furthermore, farm waste, animal manure, food waste and an organic portion of municipal and industrial waste also categorize as biomass. All these superior materials can be converted to an energy form such as power, heat and transport fuel [117].

Bioenergy derived from any renewable biological material, such as, plant matter, animal or organic waste and biomass produces bioenergy in several ways.

● Biofuels: Mainly produced by biochemical and thermochemical processes from a wide range of plant and animal materials and is used widely as liquid fuels for transport.

● Heat and power: This is a traditional form of bioenergy. Plant materials are burned to produce heat and then produce electricity.

● Biogas: Due to the biological reactions of biological materials in the anaerobic digester and landfill, the result is biogas which produces electricity and heat [118].

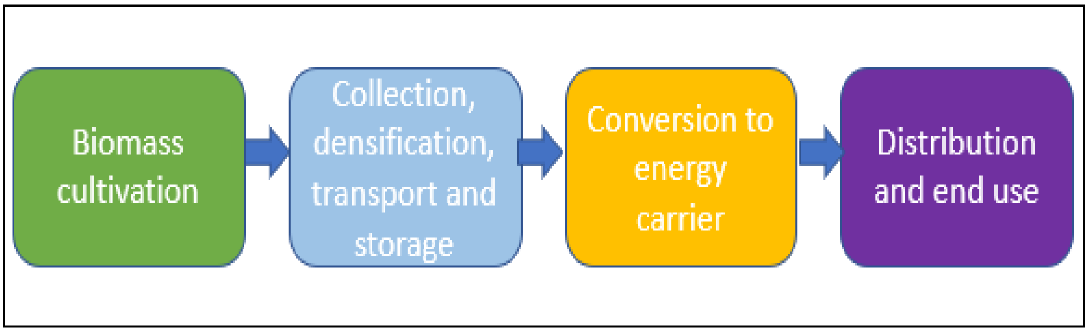


Fig 4-13 The production chain of bioenergy production

Fig 4-13 represents a pictorial view of the bioenergy production chain, and it consists of four main stages.

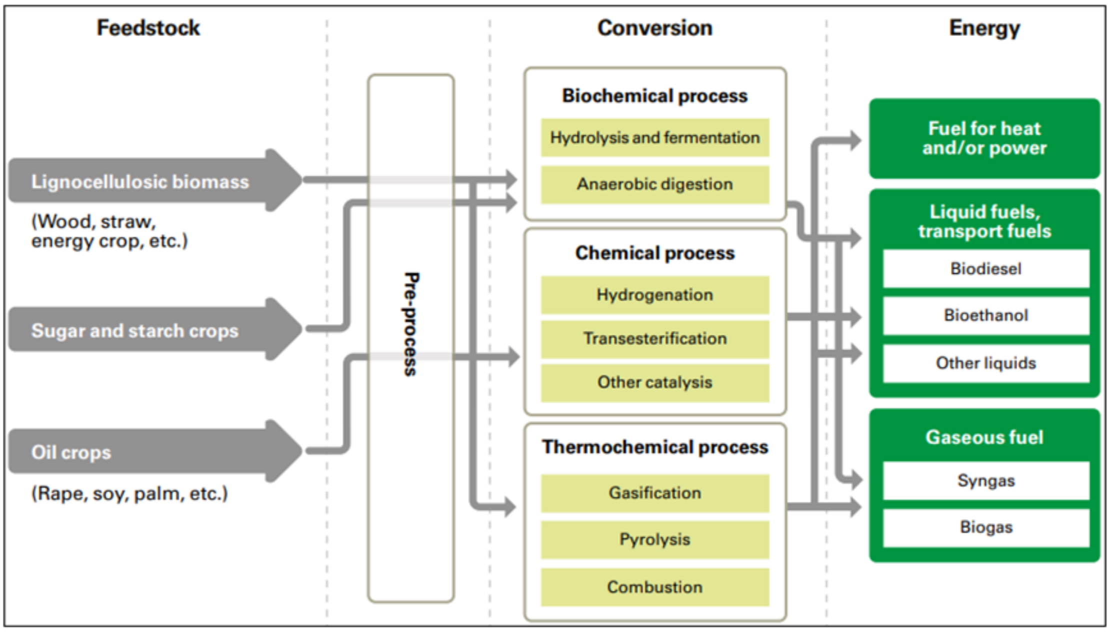


Fig 4-14 Schematic diagram of bioenergy production pathways

The wide range of practices used in conservative agriculture and forestry industry create biomass cultivations. They are then treated and selected for the transportable modes such as bales, chips, billets or pellets to be sent to the conversion facility. During this conversion process, biomass converts to alternative energy carriers such as electricity, heat, steam, liquid fuel or gas. From here, it is distributed and shared in the various forms to be used by the industrial, commercial, residential, and transport sectors of society [119].

Fig 4-14 is the schematic diagram of bioenergy production pathways and feedstock, transformed into solid, liquid or gaseous fuels via three different main processes such as the biochemical process, chemical process and thermochemical process [118,119].

4.3.1 Gaseous Biomass Industry- A. Anaerobic Digester

Anaerobic Digestion (AD) is the production of biogas by the digestion of organic material in the absence of oxygen. Biogas is a mixture of methane and CO_2. Anaerobic digestion produces biogas using a variety of biodegradable resources such as animal manure, farm waste, food waste, sewage, liquid industrial effluents, crops and organic fraction in MSW. Biogas also produced by the landfill sites can be used. Biogas can be used to produce electricity or supply a gas network (after removing the CO_2 and other gases) from the above-mentioned biogas resources, to reduce emissions of methane and potent greenhouse gas.

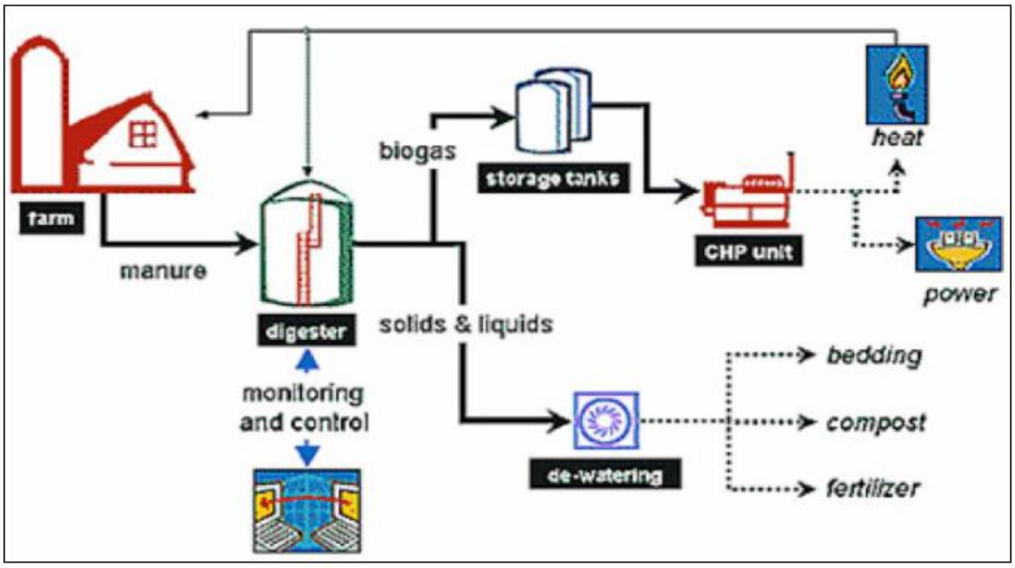


Fig 4-15 The typical anaerobic digestion facility

The biogas production from AD plants is becoming popular due to the positive outlook of businesses with agriculture residuals, food waste and with the businesses acknowledging the organic factor of municipal waste. The gas produced from the digestion of MSW was used for power generation. The AD plant facility produced fertilizer as a by-product. Fig 4-15 represents the typical anaerobic digestion facility [120].

4.3.2. Anaerobic Digestion Conversion Steps

Anaerobic biodegradation is the result of the co-operation of different groups of micro-organisms and Fig 4-16 illustrates the anaerobic conversion of organic matter [121]. The anaerobic conversion consists of hydrolysis, acidogenesis, acetogenesis and methanogenesis.

Hydrolysis and acidogenic breakdown of higher molecular weight constituents to oligo- and monomers, which are then fermented to fatty acids, alcohols, acetate, carbon dioxide and hydrogen. The initial hydrolysis is carried by exoenzymes that are excreted by the bacteria. The hydrolysis is often rate-limiting in the degradation of complex (organic) matter under anaerobic conditions. The hydrolysis rate is strongly influenced by the available surface area of the substrate. Therefore, decreasing the particle size of the substrate often results in higher degradation rates [122].

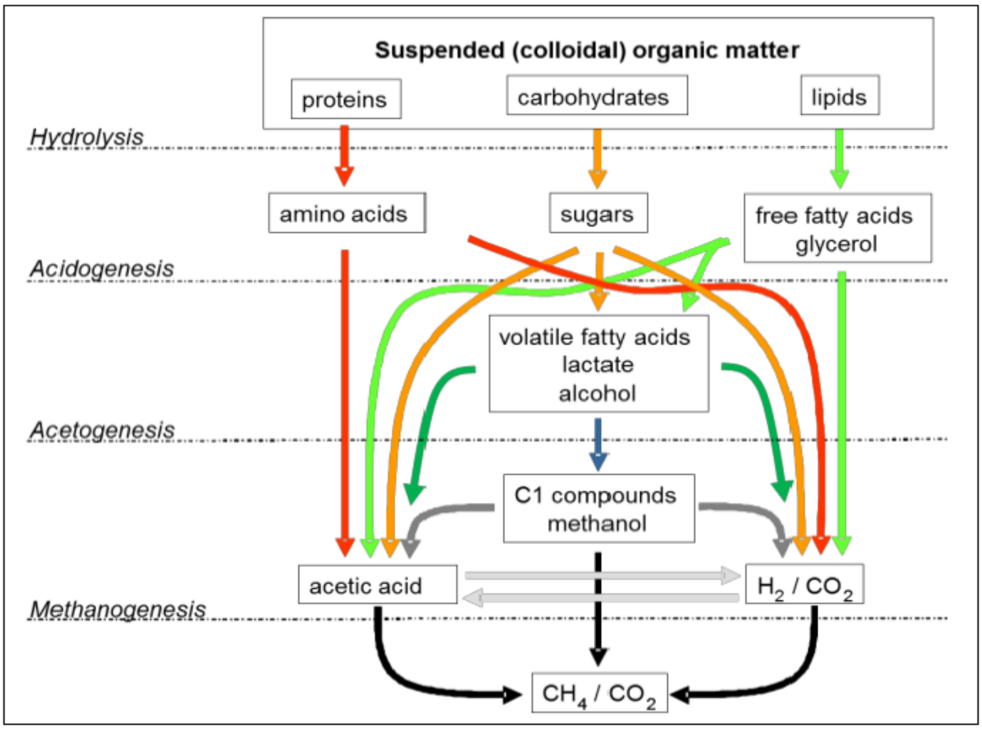


Fig 4-16 Anaerobic conversion of organic matter [121]

At the Acetogenic stage**,** volatile fatty acid, lactate and alcohol, fermentation to acetic acid, carbon dioxide and hydrogen via intermediates higher volatile fatty acids such as propionate and butyrate.

Methanogenesis stage**,** metabolization of a selected number of substrates, namely from acetic acid, H_2/CO_2, methylamines, methanol or other C compounds, to methane and carbon dioxide. Methanogens are often the slowest growing organisms in a digester. Therefore, methanogenesis is the most sensitive step in the anaerobic digestion process [122].

4.3.3. Relative Waste Streams for AD Systems

There are various suitable organic waste streams available in Sri Lanka for the anaerobic digestion operations. These originate from following industries.

- **Agriculture**
  - ✓ Animal manure

- ✓ Fruit, vegetable and pruning waste
- ✓ Field crops waste
- ✓ Energy crops
- ✓ Deadstock

• **Food processing industry**

- ✓ Dairies
- ✓ Slaughterhouse & meat packing plants
- ✓ Fish markets
- ✓ Markets (Fruits and Vegetables)
- ✓ Beverage industry

• **Residential, Commercial and Institutional**

- ✓ Commercial food waste (restaurants and hotel)
- ✓ Sewerage
- ✓ Organic fraction of the residential garbage bag
- ✓ Gardening waste (grass)
- ✓ Sewerage sludge

From the above-identified waste streams in Sri Lanka, there are a few places identified as critical places to implement a biogas project.

Fig 4-17 Vegetables and fruits open dumping near DDEC [123].

As an example, Dambulla Dedicated Economic Centre (DDEC) set up in 1999, enabled farmers in the area to market their produce even at night. DDEC at Dambulla, Sri Lanka, is closely connected with the lives of many farmers and agriculturists and is the hub of all agriculture-based economic activities in the region. The peak agricultural trade is estimated at 3,800 tons/day, and the average daily produce received at the centre is around 2750 tons/day [123].

Post-harvest losses of vegetables and fruits, especially from unplanned cultivation, improper transportation, handling and packaging are estimated to be between 10-30%. However, according to the vender's prediction, average daily waste generated is around 100 tons/day, and all waste is taken to the Dhigampathaha and Habaraththawala forest areas to be disposed of. Fruit and vegetable waste resulting from the above unethical behaviours and losses is a serious concern from both economic and environmental dimensions. Additionally, Farmers lose income from this untradeable behaviour. Unfortunately, this behaviour can be unintentional on the part of the farmers/vendors. Many do not have the means or finance to take their product to home and store, ready to return with it to market the following day. In addition, waste dumping causes a severe threat to the habitat and wildlife of the area of the above forest area. Since, elephants could get used to the taste of vegetables, which are not part of their usual diet, they may venture into neighbouring villages to find vegetables, causing damage to crop and homes, thus leading to human and elephant conflict.

A more critical aspect to this problem is the plastic and polythene which is included amongst the fruit and vegetable waste. This has a much more serious impact upon animals who eat it unwittingly and then are unable to digest the material and often die.

Fig 4-18 Vegetables and fruits thrown away after the market operations [124]

When considering the waste from hotels and restaurants in Sri Lanka, it is noted that about 40% of waste consists of food waste. Most food waste generated from Sri

Lankan hospitalities is used as animal food. Some hotels maintain their onsite digesters and composting site, but most hotels and restaurants are not following the standard methods to convert food waste into energy recovery.

All markets in Sri Lanka are another good food-waste source as all the small farmers and sellers leave their vegetables and fruits after-market hours due to transport cost. Also, every single fish market in Sri Lanka produces massive fish waste, and there is no proper waste collection method for either system to use effectively to produce energy from the waste [124].

One of the major environmental issues is that of small size farms situated nearby to communities. Most of the "small" farmers do not follow the correct mechanisms to store and produce gas from animal manure.

Municipal solid waste (MSW) management is one of the biggest social and environmental problems in Sri Lanka due to poor waste management. According to the central environmental authority (CEA) in Sri Lanka, the waste generation is 6400 tons and waste collection rate is 2683 tons per day. This identifies a lack of waste management practices in the country due to many reasons. Nearly 60% of the waste collection rate carried out in 2018 was by the Western province, which has the highest collection rate compared with other provinces. Table 4-11 shows the moisture content of each component contained in the MSW in the Western province. There are the possibilities of implementing AD plants to produce biogas due to the high moisture content available in this surplus waste [125,126].

Table 4-11 The moisture content of each component contained in the MSW in Western province

Component	**Average**	**Max**	**Min**
Vegetable waste	80%	83%	77%
Fruit waste	77%	81%	73%
Fish & Seafood waste	53%	66%	44%
Meat & Slaughterhouse waste	62%	64%	58%
Swill and Food waste	68%	70%	68%
Bones and Calcified organics	47%	53%	42%

CHAPTER 5

5.DATA COLLECTION AND DEVELOPMENT OF THE ENERGYPLAN MODEL FOR SRI LANKA

This chapter describes the methodology used to prepare a framework for the design of a 100% renewable energy system for Sri Lanka, including sectors such as energy, industry and transportation.

The structure of the chapter 5 illustrates in Fig 5-1. This chapter initiates with an energy system design and then discusses all related necessary data inputs to design Sri Lanka 2016 reference model.

Then, this chapter discusses about 2025, 2030 and 2040 simulation model carried out using EnergyPLAN tool. This section clearly describes both CEB and ADB scenarios concluding long term generation plan of CEB and 100% renewable electricity plan of ADB report. Finally, this chapter describes the simulation of 50% renewable energy solution by 2045 and 100% renewable energy solution by 2050 by adding appropriate renewable energy resources to the system.

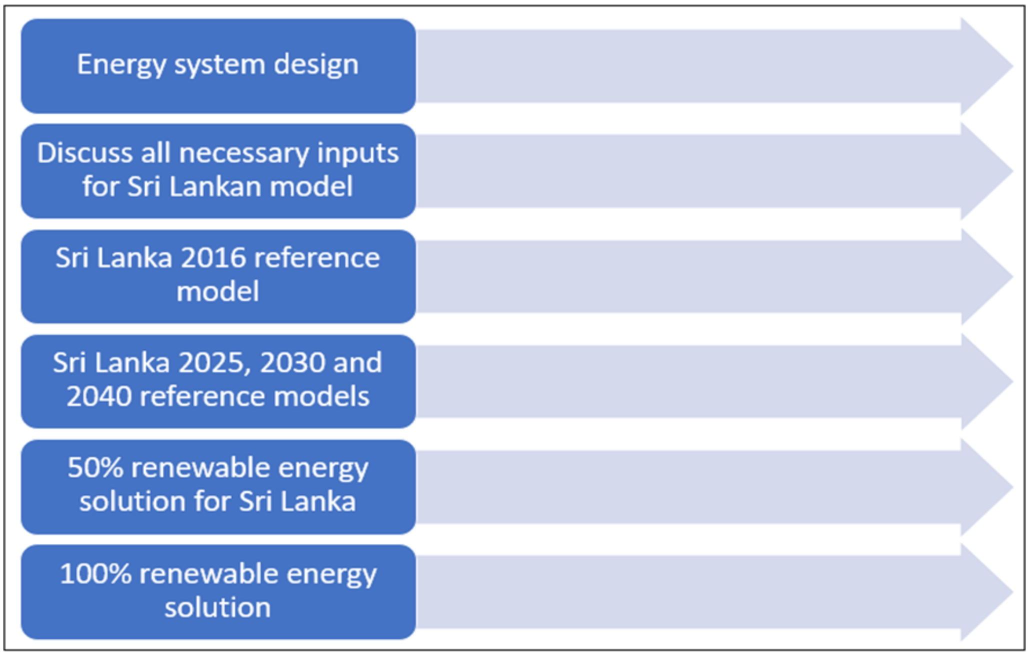


Fig 5-1 Structure of the development of the EnergyPLAN Sri Lanka model

5.1 Energy system design

The basic concept of designing a 100% renewable energy system is the integration of renewable energy sources with the existing energy system to obtain a possible result.

The complete ambition is to accomplish a 100% renewable energy solution in Sri Lanka by excluding nuclear power and carbon capture storage technologies as mentioned in section 1.2 [10]. One of the major plans is to use the biomass as it is assumed as CO_2 neutral according to the United Nations (UN), European Union (EU) and national definitions [127]. Also, planning to use other renewable energy sources such as solar, wind and tidal technologies in accordance with the geographical location and climate conditions is of interest of this thesis.

The country's energy plan design towards 2050 is a challenge under the current economic, political and social conditions in Sri Lanka. It is necessary to consider Sri Lanka's current energy policies, future energy markets and existing energy infrastructure system by allowing appropriate time to implement proposed measures to be introduced by the EnergyPLAN model. There is a critical need to change long existing electricity infrastructure to a more integrated smart energy system due to the current economic and environmental conditions that exist currently in Si Lanka.

Sri Lanka's energy generation primarily consists of a fossil fuel-based system and transformation from fossil fuel to a low carbon-based energy system is a huge challenge. The first step of this transformation design was creating a simulation model of the energy system for Sri Lanka and refer to it as a reference model. Also, choosing an appropriate energy planning tool to make the reference model is one of the critical obstacles within this research area. Due to the availability of a wide range of energy planning tools, the diversity of regions and countries analysed, and the objectives that energy planning tools fulfilled, it is difficult to find the appropriate energy planning tool.

Based on the information, data and reports gathered in the last few years, the 2016 reference model has been created. Based on the literature review and after careful consideration of nearly 40 simulation tools [24] the EnergyPLAN model was employed for the Sri Lankan case study for the following reasons.

1. EnergyPLAN tool is a user-friendly energy modelling tool consisting of a sequence of tab sheets for different energy parameters [25].
2. There is lots of literature about this tool, online training available from the website, and it is very straight forward. All the guidance supplied within the website enables researchers to quickly learn, understand and demonstrate the software [25].
3. The EnergyPLAN is free to download software [25].
4. The EnergyPLAN can consider three primary energy sectors such as electricity, heat and transport. The fluctuating renewable energy resources such as wind, solar and biomass are very prominent, and flexibility is a vital characteristic within the energy systems. The technologies such as combined heat and power (CHP) plants, heat pumps, electric vehicles, and hydrogen are the most promising methods of forming flexibility within the integration of electricity, heat and transport [25,128].
5. The EnergyPLAN modelling tool has been used previously for industry and academic case studies as follows
    a. Investigate the feasibility of a 100% RE system for Denmark [129], Ireland [24], Portugal [130] and Croatia [69].
    b. Analyse and simulate national energy system and municipal energy system of Denmark [131, 132], United Kingdom [133], Ireland [78 79], China [134], Romania [135], Macedonia [61], Hungarian [136] and Hong Kong [77].
    c. Analyse and observe the consequences of integration large-scale wind energy system into the existing energy systems [62, 63, 79, 137].
    d. Develop energy models for rural communities in islands such as the Island of Hvar [138] and the Island of Mljet [70].
    e. Analyse biomass integration limitations to the national energy systems [139].
    f. Optimize the RE electricity system combination of various fluctuating RE resources [64,140].
    g. Identify the benefits of integrating RE into the transport sector [141,142].

h. Analyse more literature and find solutions for specific technologies such as district heating and CHP technologies [65].
i. Find the possible energy saving technologies solutions for district heating [143].
j. Explore the advantages and importance of energy storage such as hydrogen storage mechanisms in high RE penetration systems [144].
k. Investigate energy markets and market structure's impact on wind power generation [145].
l. Finding related regulation strategies and subsidiary facilities in energy markets and energy industry [146].

6. After learning-related literature about energy planning tools and the use of energy planning tools to achieve 100% RE smart energy systems to Danish and Irish energy system, it was evident that similar research would benefit the Sri Lankan energy system. The EnergyPLAN Sri Lankan case study is the first research in the Asian continent to achieve 100% RE solution.

5.1.1 Collecting the Required Data

After choosing an appropriate energy simulation tool according to the research aim and objectives, it is necessary to collect all pertinent data to use as input for the EnergyPLAN. As mentioned in Chapter 2, the primary phase is to create a reference energy model for 2016. To develop this reference model, the energy data was obtained from 2016 because when starting the research, this was the latest available data.

This research is selected the 2016 Sri Lankan energy system as the first reference model called "2016 Sri Lankan Reference Model" and hereafter this report is mainly based on this model. To implement this reference model, the collection of the relevant data from Sri Lanka was the next challenge. Data was gathered by using several academic sources, using electronic sources to find energy-related data and a personal visit and collection of some information from energy authorities in Sri Lanka. Then, all data was collected and imported to the simulation tool as inputs data. However, some contributions were much discussed in detail and other inputs only briefly according to the availability of resources.

This chapter reflects the EnergyPLAN data and basically, this segment divides into two sections;

1. Technical Data

2. Economic Data

When simulating an energy system, the order of the input data method can be used as a typical modelling sequence. The reference energy model needs to simulate the energy system accurately in EnergyPLAN. There is no need for economic inputs for the reference model at the fundamental stage of simulation, as it regularly associated with the technical performance of the energy model initially. Once the reference energy model of Sri Lanka for the year of 2016 using technical inputs is completed, then socio-economic parameters of the energy system are analysed by using economic inputs such as fuel, investment and operation and maintenance (O&M). By following that kind of simulation sequences, therefore, substitutes for the energy system can be formed and compared concerning technical performance and annual operating costs of the energy system. Finally, market optimisation of the energy system can be accomplished in EnergyPLAN simulation by adding external electricity market costs to the system. It allows us to recognise the optimum performance of the entire energy system from a business-economic perspective, rather than a technical perspective. However, modifying the optimum business-economic scenario to the optimum socioeconomic scenario by adjusting taxes is more beneficial to society, and it is the most typical aim of the future alternatives in the energy system [10,147].

Nevertheless, this research has carried out the only technical outlook of the Sri Lankan energy system due to the lack of economic data collected during research time. Before reflecting the collected data, it is essential to understand and identify the characteristics of data that EnergyPLAN typically needs and two following energy parameters require for the successful the EnergyPLAN simulation:

1. Annual total supply/consumption.

2. Annual total supply/consumption as hourly annual distribution should include the following standards [10, 40, 147].

a. It should contain data from total hours in 2016 (24 hours x 366 days), which means 8784 data points for the entire year,

b. In the distribution file, the data points should be between 0 and 1,

c. Prepared distribution file saves as a text file in the “Distributions" folder.

5.2. Required technical data for Sri Lankan model

EnergyPLAN simulates a single year in hourly time-steps. To create an initial reference energy model, the year 2016 was chosen as it was the most recent year for gathering data for the research. This section explains where and what type of data was found as inputs for the EnergyPLAN software, furthermore, discusses each tab within the EnergyPLAN model separately.

The ‘Home’ tab, displayed in Fig 5-2 illustrates a flow diagram of the EnergyPLAN model, and represents how all the various sub-components of the energy system interconnect with one another. Fig 5-2 shows the version of the energy system analysis tool and the date published of this new version as well at the top right-hand corner of “Home” tab page [25].

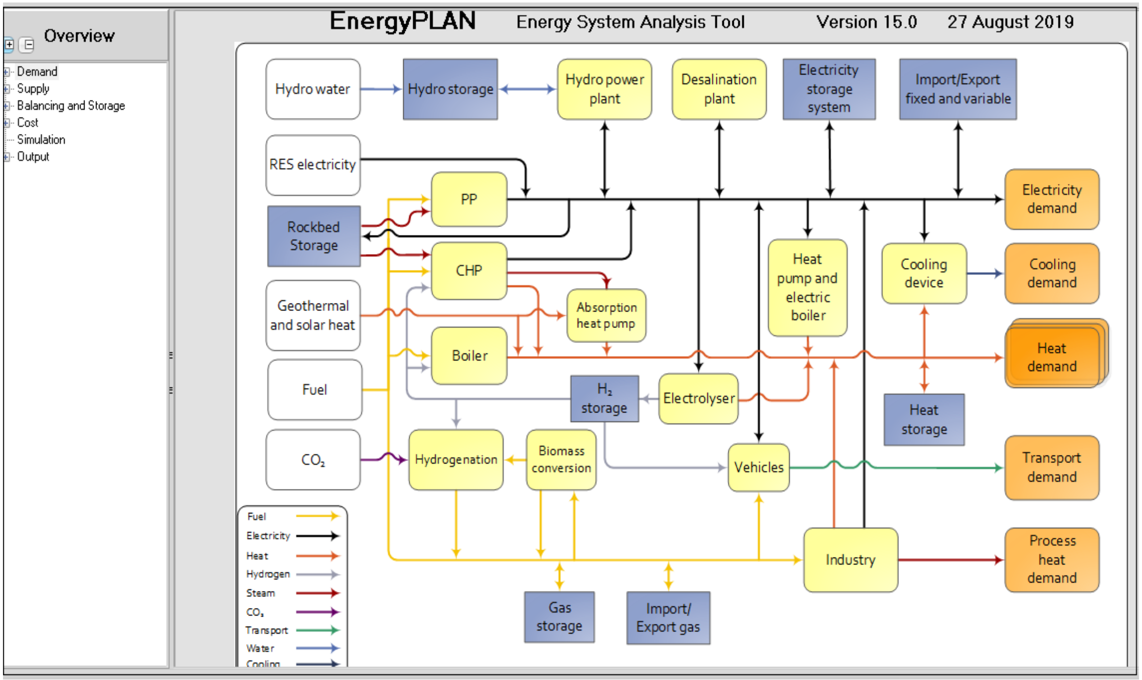


Fig 5-2 Home tab page of the EnergyPLAN tool

Fig 5-2 shows the principle of the EnergyPLAN model. According to the new EnergyPLAN "Home" tab under the overview sections, undermentioned five subcategories can be seen. From those subcategories there are four subcategories called as the input of the energy system and used to describe the parameters of the energy system in question. The last subcategory called output tab use to investigate results of the EnergyPLAN model as illustrated in Fig 5-3.[40, 147].

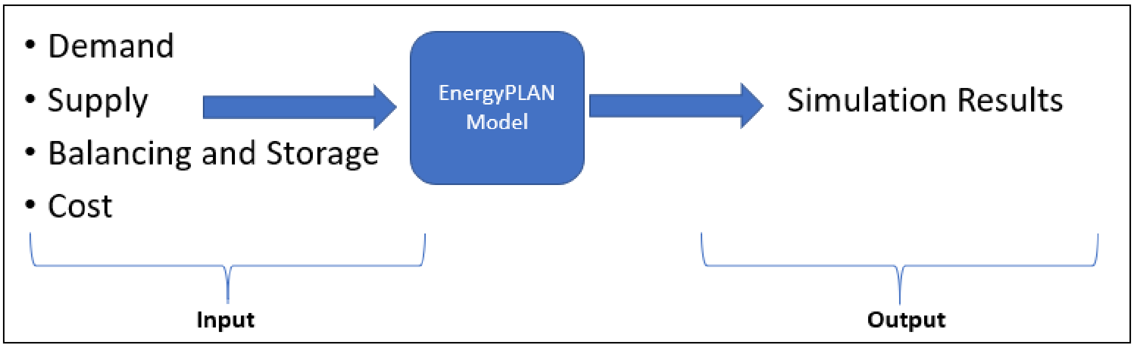


Fig 5-3 Related input and output data for EnergyPLAN tool

1. Demand (heat, electricity, transport, etc.)
2. Supply- Energy production units and resources for example, (wind turbines, power plants, oil boilers, storage, etc.) including energy conversion units such as electrolysers, biogas and gasification plants as well as hydrogenation units
3. Balancing and Storage
4. Cost- Used to input the costs associated with the energy system being investigated (Fuel costs, taxes, variable and fixed operational costs and investment costs)

   Under the 'Cost' tab, there is a simulation tab available, and it allows choosing a simulation strategy as 'Technical Simulation' or 'Market Economic Simulation'. Also, defining the simulation and operation of each plant and the system including technical limitations such as transmission capacity, etc.
5. Output- Used to analyse the results of the investigation.

Finally, the 'Settings' icon at the top of the quick access toolbar enables the user to change the scale of the units in the program.

Below is a brief description of the data used for 'Input' in the model. For above-mentioned input, data required for EnergyPLAN is usually generic data that can be obtained from few electronic sources such as International Energy Authority (IEA) [148], Census and Economic Information Centre (CEIC) [149] and The Organization for Economic Cooperation and Development (OECD) [150]. Also, for the Sri Lankan scenario, the sales and generation data were obtained from statistical digestion report from Sri Lanka Electricity Board [83] and another piece of information called Energy Balance from the source of Sustainable Energy Authority in Sri Lanka [151, 152]. The Sri Lankan Energy Balance was completed by the Sustainable Energy Authority of Sri Lanka.

The Energy Balance report published by Sri Lanka Sustainable Energy Authority indicates the energy consumed within each sector of the energy system as displayed in appendix 1. Energy Balance is one of the most critical documents proved to be the most useful source of data for research. However, it is vital to check the accuracy of the data in this document by cross-checking other related local energy data, as the figures can sometimes be based on estimates. By gathering all related data from Sri Lanka and the international sources, 'Data input for EnergyPLAN' document was finally produced as shown in appendix 2.

When predicting renewable energy production from fluctuating renewable energy sources such as wind, solar, and wave the historical meteorological data also proved to be very important. Sri Lanka meteorological data can usually be obtained from the Department of Meteorology [153]. Also, Sri Lanka weather data gained effectively from following online resources such as Weather- Forecast [154], world weather online[155] and windy.com [156].

However, a programme called 'Meteonorm' [157] is another excellent option to use for meteorological data of Sri Lanka related to research. From several meteorological stations around the world, this programme has gathered and stored data, which can be accessed using a very intuitive user interface. Before purchasing this programme there is a need to decide how vital meteorological data is for the proposed research to produce annual distribution related to EnergyPLAN as this program is not free. Even if planning to buy this package, it could be useful to compare and cross-check the data in the software to actual measurements from a weather station to ensure that the program is providing accurate data to produce final renewable energy distributions for the research.

To obtain final output such as simulation results needs input data to the EnergyPLAN tool as demand/ supply data. The input/demand data consists of electricity demand, heating/cooling demand, industry and fuel, transport and desalination. Also, the output/supply data contains heat and electricity, central power production, variable renewable electricity, heat only, fuel distribution, waste, liquid and gas fuel and CO_2 as describes section 5.2.1.

5.2.1. Electricity Demand

Electricity demand is divided into the following categories

1. Fixed demand
2. Three types of flexible demands, and
3. Fixed import/export if any.

Total electricity demand was obtained from the Ceylon Electricity Board (CEB) statistical reports. CEB reports, which provides a lot of useful detailed data about the production and consumption of electricity data in Sri Lanka. The data includes the following:

- Statistics
- Production Data
- Consumption Data
- Sales & Revenue Data
- Power Plant Data

According to the CEB, the annual electricity demand for 2016 was 12.785 TWh. The electricity demand (consumption) monthly details shows in Table 5-1. Also, Table 5-2 illustrates the electricity demand in Sri Lanka by sector. Sri Lanka energy demand consists of several sectors such as domestic, religious, industrial, general-purpose, hotel, government, bulk supply to LECO and street lightning. The sector with most energy consumption is the domestic sector followed by industrial and general-purpose sector.

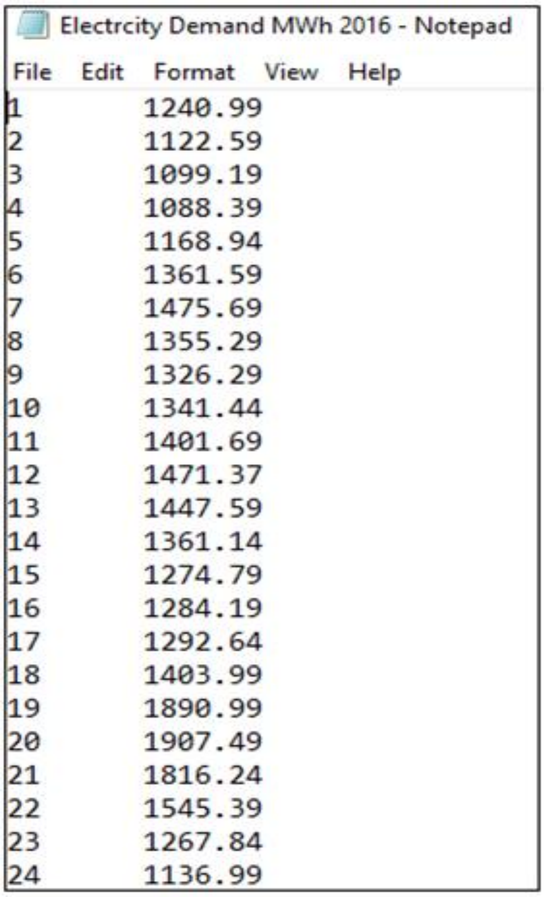
Table 5-1 Sri Lanka electricity demand in 2016

Month	Consumption/Demand (GWh)

January	1025.6
February	1005.0
March	1041.7
April	1048.8
May	1095.2
June	1060.9
July	1072.0
August	1112.1
September	1091.5
October	1097.5
November	1060.4
December	1074.9
Total	**12,785.6**

Table 5-2 Electricity demand in Sri Lanka by sector

Sector Tariff	Scale	Units in GWh -2016	Subtotal GWh
Domestic		4198.3	4198.3
Religious		74.1	74.1
Industrial	Small	330.3	
	Medium	1942.4	
	Large	1591.3	
Total			3864.1
General Purpose	Small	1480.2	
	Medium	798.7	
	Large	300.2	
Total			2579.111
Hotel	Small	2.5	
	Medium	159.7	
	Large	85.2	
Total			247.4
Government	Small	3.4	
	Medium	154.1	
	Large	2.9	
Total			160.4
Bulk Supply LECO		1553.2	1553.2
Street Lighting		108.7	108.7
Total			**12785.6**



Electrcity Demand MWh 2016 - Notepad

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1	1240.99
2	1122.59
3	1099.19
4	1088.39
5	1168.94
6	1361.59
7	1475.69
8	1355.29
9	1326.29
10	1341.44
11	1401.69
12	1471.37
13	1447.59
14	1361.14
15	1274.79
16	1284.19
17	1292.64
18	1403.99
19	1890.99
20	1907.49
21	1816.24
22	1545.39
23	1267.84
24	1136.99

Fig 5-4 Annual hourly electricity demand profile sample for one day

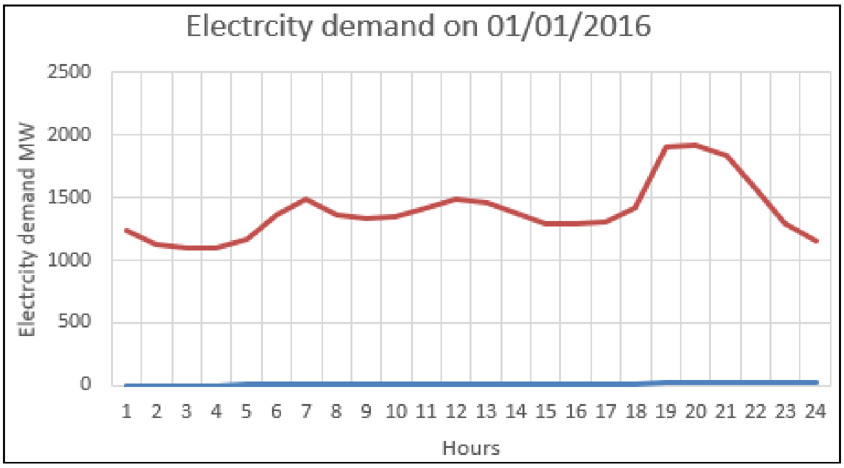

Fig 5-5 Electricity demand profile on 01/01/2016

As described in Chapter 2 under the EnergyPLAN literature, it is necessary to produce annual hourly electricity demand profiles for Sri Lanka as illustrates in Fig 5-4. According to the data abstract from the CEB statistical department, the annual hourly demand profile formed and simulate the software to achieve reference energy model. Also, Fig 5-5 illustrated the hourly electricity demand in Sir Lanka on 01/01/2016. The appendix 3 illustrates the actual simulation process of annual electricity demand.

Annual electricity demand = D_E

Hourly electricity demand = d_E, There for

$$D_E = \sum_{x=1}^{8784} d_E(x)$$

If the annual electricity demand contains an electric heating or electric cooling demand, such demand (D_{EH} and D_{EC}) can be defined and will be subtracted from the annual electricity demand:

Annual electric heating demand = D_{EH}

Hourly electric heating demand = d_{EH}

Annual electric cooling demand = D_{EC}

Hourly electric cooling demand = d_{EC}

$d_E' = d_E - d_{EH} - d_{EC}$

if $d_E' < 0$ then $d_E' = 0$

$D_E' = \Sigma\, d_E'$, There for

New annual electricity demand = D_E'

New hourly electricity demand = d_E'

5.2.2 Heating/Cooling Demand

Heating demand tab is also separated into

1. Total heat demand
2. Individual heating demand in decentralised CHP systems and
3. District heating demand in centralised CHP systems (Typically extraction plants or similar).

Cooling demand- is also divided into

1. Cooling based on electricity supply (air conditioning etc.)
2. Cooling based on heat supply from district heating from the three DH groups mentioned above (based on absorption technologies)
3. Contribution to district cooling from natural cooling

The initial EnergyPLAN model did not have to include any district heating, cooling and CHP as there are currently no largescale installations in Sri Lanka.

5.2.3 Industry and Fuel

Industry and Fuel tab in EnergyPLAN- divided into

1. Coal, oil, natural gas and biomass boilers

2. Micro CHP on either hydrogen, natural gas or biomass

The Industry and Other fuel consumption were obtained from the Energy Balance report published by Sustainable Energy Authority in Sri Lanka. This report consists of all relative quantities of energy sources used in Sri Lanka for Industry, Transport and other use. The report comprises of following details.

The Energy Balance report offers useful and practical information related to the energy industry in Sri Lanka and the following information extract from the report.

- Biomass data
- Coal & Fuel data
- Electricity data
- Grid Emission Factors
- Petroleum data

According to the 2016 Energy Balance report, the total Coal, Oil and Biomass consumption for all energy needs were 15.25, 59.55 and 54.16 TWh. The coal used for the industry is 0.57 TWh and the rest of 14.68 TWh used for electricity generation. The total oil consumption of 59.55 TWh consists of Transport 42.89 TWh, power plants for electricity generation 5.63 TWh, Industrial and other fuel consumption 11.03 TWh. Except the transport and power plant oil demands, the rest of oil demand is 11.03 TWh used as industry and other fuel consumption for this model. The total biomass demand for Sri Lanka is 54.16 TWh and 0.19 TWh biomass used for electricity generation and the rest of the biomass of 53.97 TWh used for Industry and other fuel consumption. From this 53.97 TWh biomass consumption purely 21.05 TWh used for industry and another respite 32.92 TWh used for general usage such as cooking. The appendix 4 illustrates the actual simulation process of energy and other industrial consumption.

Inputs to Industry are basically defined as fuel inputs since such figures are normally basic data in statistics.

Annual coal demands for Industry = $F_{I\text{-}Coal}$

Annual oil demands for Industry = $F_{I\text{-}Oil}$

Annual gas demands for Industry = $F_{I\text{-}Ngas}$

Annual biomass demands for Industry = $F_{I\text{-}bio}$

Annual hydrogen demands for Industry = $F_{i\text{-}hyd}$

Annual coal demands for various = $F_{V\text{-}Coal}$

Annual oil demands for various = $F_{V\text{-}Oil}$

Annual gas demands for various = $F_{V\text{-}Ngas}$

Annual biomass demands for various = $F_{V\text{-}bio}$

5.2.4 Transport

The energy used for transport separated into

1. Jet fuel, diesel, petrol, natural gas and biomass
2. NH_3 and hydrogen
3. Electric transport including smart charge and V2Gs (Vehicle to Grid)

The transport fuel consumption in 2016 was 42.89 TWh in Sri Lanka according to Energy Balance report. The total transport oil consumption consists of Diesel 24.29, Petrol 18.55, LPG 0.013, Aviation fuel 0.0331 and Aviation gas 0.0017 TWh. According to the EnergyPLAN, the total transport demand was 64 Billion km in 2016. Furthermore, the software represents the average efficiencies for the diesel, petrol, LPG, aviation fuel and gas 1.5 km/KWh. However, that average efficiency value is for H_2 based operation is 3km/KWh and for the electricity base transport, average efficiency is 5 km/KWh, which is good compared to fossil fuel efficiency. The appendix 5 illustrates the actual simulation process of transport.

The transport input tab sheet is designed to describe potential changes in the transport sector. The fuel inputs consist of fuel for cars and other transport units divided into jet petrol, diesel, petrol, natural gas, and LPG. For all these types of fuels, biofuels and electrofuels (if any) will be transferred from the waste, biomass conversion and electrofuel tab sheets and added to the sum.

Vehicles on hydrogen, hourly distribution which will be used to specify the demand for hydrogen administered in the Hydrogen tab sheet under the sub tab of liquid and gas fuels in supply tab.

Fuel demands

Annual jet fuel demand for transport = $F_{T\text{-}JF}$

Annual diesel demand for transport = $F_{T\text{-}Diesel}$

Annual petrol demand for transport = $F_{T\text{-}Petrol}$

Annual natural gas demand for transport = $F_{T\text{-}Ngas}$

Annual LPG demand for transport = $F_{T\text{-}LPG}$

Annual hydrogen fuel demand for transport = $F_{Transport\text{-}H2}$

A series of inputs describes battery electric vehicles (BEV). Basically, they are divided into dump cars and smart cars

Electricity demands

Electricity demand of Battery Electric Vehicles in TWh/year = D_{BEV}

Electricity demand of “V2G cars” and or “BEV smart charge” in TWh/year = D_{V2G}

The maximum share of cars which are driving during peak demand hour =$V_{2GMax\text{-}Share}$

The capacity of the grid to battery connection in MW = $C_{Charger}$

The share of parked V2G cars connected to the grid = $V_{2GConnection\text{-}Sh}$

The efficiency of the grid to battery connection (charger) = $\mu_{Charger}$

The capacity of the battery storage in GWh = $S_{V2G\text{-}Battery}$

The capacity of the battery to grid connection in MW = C_{Inv}

The efficiency of the battery to grid connection (inverter) = μ_{Inv}

5.2.5 Desalination

Desalination tab in the EnergyPLAN model consists of.

1. Freshwater demand from desalination and storage
2. Desalination plant including pumps
3. Pump hydro energy storage

The initial EnergyPLAN model did not have to include any Desalination data as there is currently no type of installations in Sri Lanka.

Once the demands have been defined, the next task is to design the supply side of the energy system. Within this supply-side there are different types of electricity, heat, cooling, and fuel production plants. Also, it can include the technical characteristics such as the capacities and efficiencies that are typically required for each plant, while in some cases, a predefined hourly distribution is also necessary.

5.2.6 Heat and Electricity

Heat and Electricity and it divided into

1. Boilers
2. Combined Heat and Power (CHP)
3. Industrial CHP

Basically, the initial EnergyPLAN model did not have to include any heating data as there is no heating demand at the demand side. Nevertheless, there is a 0.072 TWh biomass power generation coming from 24.1MW installed capacity biomass generation. This value has owed within Industrial CHP section Group 1 because electricity, as mentioned earlier capacity coming from generators running with biogas and not from CHP units.

Table 5-3 Overall biomass production in Sri Lanka

Month	**Dendro Generation- GWh**	**Biomass Generation GWh**
January	3.102	2.795
February	2.803	2.801
March	3.446	2.401
April	3.677	3.159
May	3.682	2.955
June	3.573	2.652
July	2.688	2.372
August	3.789	3.089
September	3.618	3.011
October	3.599	1.078
November	2.675	1.604
December	4.252	3.134
Total	40.904	31.051
Total	**71.955 GWh**	

The total installed capacity of biomass consists of 11.02 MW of Dendro power plants and 13.08 MW capacity from Biomass plants. The following Tab 5-3 represents the biomass generations during the year of 2016, and related data extracted from CEB reports. The appendix 6 illustrates the actual simulation process of biomass electricity generation under the heat and electricity tab.

Capacities and operation efficiencies of CHP units, power stations, boilers and heat pumps are defined as part of the input data. The size of heat storage capacities is also given here.

Energy production units

CHP capacity (MWe) in district heating group 2 $= C_{CHP2}$

Boiler capacity (MJ/s) in district heating group 2 $= T_{B2}$

CHP capacity (MWe) in district heating group 3 $= C_{CHP3}$

Boiler capacity (MJ/s) in district heating group 3 $= T_{B3}$

Power Plant capacity (MWe) $= C_{PP}$

Thermal efficiency, Boiler in district heating group 1 $=\rho_{B1}$

Electric efficiency, CHP in district heating group 2 $=\mu_{CHP2}$

Thermal efficiency, CHP in district heating group 2 $=\rho_{CHP2}$

Thermal efficiency, Boiler in district heating group 2 $= \rho_{B2}$

Electric efficiency, CHP in district heating group 3 $=\mu_{CHP3}$

Thermal efficiency, CHP in district heating group 3 $=\rho_{CHP3}$

Thermal efficiency, Boiler in district heating group 3 $=\rho_{B3}$

Electric efficiency, Power Plant $=\mu_{PP}$

Annual excess heat production from industry to district heating groups 1 to 3 $= Q_{I1}, \ldots. Q_{I3}$

Annual excess electricity production from industrial CHP (CSHP) $=E_{CSHP1},\ldots.E_{CSHP3}$

Heat storage

Capacity, Heat storage in district heating group 2 (GWh) $= S_{DH2}$

Capacity, Heat storage in district heating group 3 (GWh) $= S_{DH3}$

5.2.7 Central power production

Central power production- also separated into

1. Condensing power plants

2. Nuclear
3. Geothermal
4. Dammed hydropower
5. Transmission line capacity

For power plants, the first parameter required is the total capacity installed, which got from the CEB reports. If necessary, it is possible to divide the power plants into two categories: condensing and PP2.

In addition to the PP capacity, there is a need to find the total fuel consumed by the power plants, which is usually available in the energy balance report and CEB reports. For example, the Sri Lankan energy balance can be broken down into coal, oil, and biomass.

According to CEB reports, the coal power plant installed capacity is 900MW, and total Oil installed capacity is 1215MW, including state ownership and private power plants. The total installed capacity of 2115MW put within the condensing PP2. There is no possibility to introduce coal and oil installed capacity separately within this section. Once all the power plant capacity is put into the "condensing PP2" section, then all of the fuel consumption can define and split across rows under the "Fuel Distribution" section. The reason for putting all the coal and oil power plants installed capacity to "condensing PP2" is because those power plants are always used for electricity generation only.

In addition, the total installed capacity of Dammed hydro power in Sri Lanka in 2016 is 1384 MW and during this year 3.5 TWh hydropower generation achieved by Sri Lankan energy sector. The appendix 7 illustrates the actual simulation process of central power production. Table 5-4 illustrated the monthly dammed hydropower generation during the year of 2016.

Finally, also the efficiency of the condensing power plants and dammed hydropower plants are needed for the simulation. As mentioned, the total fuel consumption for each type of power plant can be obtained from the energy balance report. However, It was challenging to obtain the efficiencies of the individual condensing plant and Dammed hydro plants as it was "commercially sensitive information".

In this section, for the simulation, the efficiency of both coal and oil condensing power plants are considered as 0.45 and the efficiency of dammed hydropower is 0.60. According to this values, it is estimated that annual electricity production is 2.10 TWh. Nevertheless, in 2016, dammed hydropower generation achieved 3.5 TWh means there is a need to adjust the hydropower efficiency.

Table 5-4 Monthly dammed hydro power generation

Month	Dammed Hydro Generation GWh
January	417.065
February	337.289
March	297.293
April	234.423
May	347.532
June	455.714
July	334.206
August	240.596
September	173.697
October	215.114
November	237.869
December	207.925
Total	**3498.723**

The other important matter is developing annual hourly dammed hydropower generation for 2016. The related data obtained from CEB statistical branch has been made into annual hourly profile. Using above data created hourly distribution curve as described in Chapter 2 under the EnergyPLAN literature Fig 5-6 shown the sample of hourly dammed hydropower distribution chart and distribution file uploaded to the software. Fig 5-7 illustrated the 1st of January 2016 hydropower generation to cater the electricity demand in Sri Lanka.

Hydro Profile MWh 2016 - Notepad

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1	196.80
2	225.60
3	192.15
4	186.60
5	253.65
6	572.85
7	709.55
8	364.20
9	224.70
10	303.00
11	473.45
12	696.75
13	633.45
14	523.50
15	362.45
16	486.60
17	531.60
18	603.45
19	1630.87
20	1662.67
21	1308.82
22	822.00
23	281.25
24	207.75

Fig 5-6 Annual hourly hydro power generation

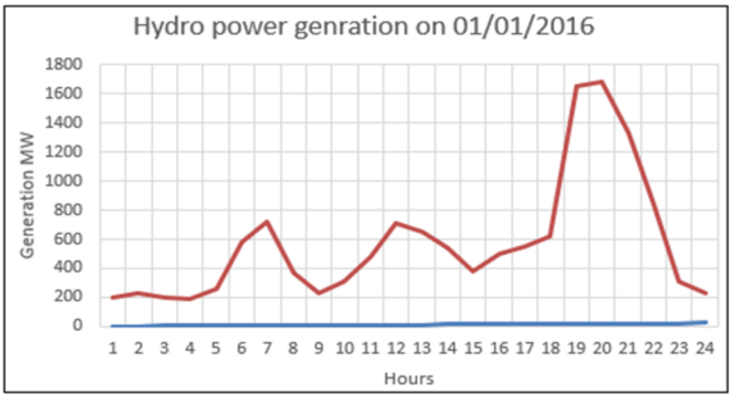

Fig 5-7 Dammed hydro generation profile on 01/01/2016

Condensing Power Plants

Power Plant capacity 2 (MWe) $= C_{PP2}$

Electric efficiency, Power Plant 2 $= \mu_{PP2}$

Nuclear

Capacity of the Nuclear Power Electricity Generator in MW $= C_{Nuclear}$

Efficiency of the Nuclear Power station $= \mu_{Nuclear}$

Distribution of the electricity production between 8784-hour values $= d_{Nuclear}$

Correction factor between production and capacity $= FAC_{Nuclear}$

Percent of the capacity that can be reduced. Works as a CEEP regulation $= PAR_{Nuclear}$

The nuclear unit is running as base load by default, and therefore, the power plant does not take part in the active regulation. The electricity production of the nuclear unit ($e_{Nuclear}$) is

$$e_{Nuclear} = FAC_{Nuclear} * C_{Nuclear} * d_{Nuclear} / Max(d_{Nuclear})$$

The correction factor is used to adjust differences between capacity and production. E.g. if the capacity factor is 0.8 then the maximum production will be 80% of the installed capacity.

The efficiency is used only for the calculation of the annual amount of fuel ($f_{Nuclear}$), which is calculated by applying the following formula:

$$f_{Nuclear} = e_{Nuclear} / \mu_{Nuclear}$$

Geothermal

Capacity of the Geothermal Power Electricity Generator in MW	$= C_{Geothermal}$
Efficiency of the Geothermal Power station	$=\mu_{Geothermal}$
Distribution of the electricity production between 8784-hour values	$= d_{Geothermal}$
Correction factor between production and capacity	$= FAC_{Geothermal}$

The geothermal power station is subject to the condition that it will always be involved in the task of maintaining grid stability. The geothermal unit is running as base load, and therefore, the power plant does not take part in the active regulation. The electricity production of the geothermal unit ($e_{Geothermal}$) is

$$e_{Geothermal} = FAC_{Geothermal} * C_{Geothermal} * d_{Geothermal} / Max(d_{Geothermal})$$

The correction factor is used to adjust differences between capacity and production. E.g. if the capacity factor is 0.8 then the maximum production will be 80% of the installed capacity.

The efficiency is used only for the calculation of the annual amount of fuel ($f_{Geothermal}$), which is calculated by applying the following formula:

$$f_{Geothermal} = e_{Geothermal} / \mu_{Geothermal}$$

Hydro power

Capacity of Electricity Generator in MW	$= C_{Hydro}$

Efficiency defined as the conversion from energy in the storage...

into electricity production $=\mu_{Hydro}$

Capacity of the storage in GWh $= S_{Hydro}$

Annual water supply to the storage in TWh/year $= W_{Hydro}$

Capacity of the Hydro Power Pump in MW $= C_{Hydro\text{-}Pump}$

Efficiency of Pump defined as the conversion from electricity…

to energy in the storage $= \alpha_{Hydro\text{-}Pump}$

Capacity of the lower water storage in GWh $= S_{Hydro\text{-}Pump}$

First, the average hydro electricity production ($e_{Hydro\text{-}ave}$) is calculated as the output of the average water supply (Annual water supply divided by 8784 hours/year):

$e_{Hydro\text{-}ave} = \mu Hydro * W_{Hydro} / 8784$

Then the program calculates the hourly modelling of the system, including the fluctuations in the storage content. Furthermore, the hydro power production (e_{Hydro}) is modified in accordance with the generator capacity, the distribution of the water supply, and the storage capacity in the following way:

Hydro storage content = Hydro storage content + w_{Hydro}

e_{Hydro} = MAX [e_{Hydro}-Ave, (Hydro storage content - S_{Hydro}) * μ_{Hydro}]

$e_{Hydro} <= C_{Hydro}$

Transmission line capacity:

Import/export transmission line capacity $= C_{Imp/exp}$

5.2.8 Variable renewable electricity

Variable renewable electricity divided into two sections

1. Variable renewable energy sources such as Wind, Photovoltaic Wave power, River hydro, Tidal and Wave power
2. Concentrated solar power (CSP).

To define the energy available from a variable renewable energy resource such as wind, offshore wind, photovoltaic, wave power, river hydro, tidal and CSP solar power (not stored) in the proposed energy system, there is a need to outline five major features:

1. The type of renewable energy source in question.
2. The installed capacity of renewable resource.
3. The distribution profile (hourly for one year).
4. The stabilisation share.
5. The correction factor.

Parameters 1-3 are reasonably intuitive and have been discussed in detail at the start of section 5.2. So, to repeat from the EnergyPLAN user manual [25], the stabilisation share is the percentage (between 0 and 1) of the installed capacity of the renewable resource that can contribute to grid stability, i.e. provide ancillary services such as voltage and frequency regulation on the electric grid. Present renewable energy technologies, except for hydro plants with storage, are not widely used for regulating the grid. Therefore, the stabilisation share will be set to 0 unless this changes in the future.

Also, from the EnergyPLAN user manual [25], the correction factor adjusts the hourly distribution inputted for the renewable resource. It does not change the power output at full-load hours or hours of zero output. However, it does increase the output at all other times and can be used for several different reasons. For example, future wind turbines may have higher capacity factors, and thus the same installed wind capacity will produce more power.

Onshore Wind

The installed wind capacity and monthly wind generation data obtained from CEB but CEB has no hourly data as all the wind energy farms are operated by private owners. By using average wind power speeds, wind power directions and monthly wind generation data 2016 hourly onshore wind distribution have designed for 131.5 MW installed capacity covering from fifteen onshore wind farms. The annual hourly wind distributions chart uploaded to the software to carry out the simulation process as illustrates in appendix 8.

Photovoltaic

The photovoltaic installed capacity of 52.92MW consists of 21.36MW from five solar parks and 31.56 MW net meter reading from household consumers. As mentioned earlier, monthly photovoltaic generation from solar parks is available in the reports but monthly generation for the net meter reading could not be found. However, CEB reports represent the data for the annual net meter reading generation. When considering the annual photovoltaic distribution, there was no way to find such data from solar parks owners, however, using irradiation data, monthly generation data and using historical data annual hourly photovoltaic distribution has been plotted and uploaded to the software for simulation processes as illustrates in appendix 8.

River hydro

All the related river hydro data has been obtained from CEB reports. The total river hydro installed capacity is 342MW covered by 172 mini-hydro projects. From the data obtained the monthly river hydro generation for the year 2016 can be abstracted but annual hourly river hydro generation could not be found. But considering all monthly generations, rainfall data, weather reports and related historical data annual hourly river hydro distribution has been plotted and uploaded to the software to finalise the simulation process as illustrates in appendix 8.

For all the above mentioned variable renewable energy resources the stabilisation factor was entered as 0 because wind power does not contribute to grid stabilisation. Also, the correction factor was entered as 0 because the installed wind capacity and the distribution used generated the expected annual wind energy. Otherwise, the correction factor would need to be adjusted until the wind production calculated by the model was the same as the actual annual production.

The input data set defines input from RES and hydro power. One can choose inputs from up to seven different renewable energy sources. Following specification can be attached to each RES:

- Wind
- Offshore Wind
- Photo Voltaic
- Wave Power
- River Hydro

- Tidal
- CSP Solar Power

Variable Renewable Electricity

Electricity generation	$= e_{Res}$
Electricity capacity from Renewable Energy Resources	$= C_{Res1}, ... C_{Res7}$
Share of RES capacity with grid stabilisation capabilities	$= Stab_{Res1}, ... Stab_{Res7}$
Correction factor of RES production¨	$= FAC_{Res1}, ... FAC_{Res7}$

Considering correction factor, new electricity generation e_{Res}' is

$$e_{Res}' = e_{Res} * 1 / [1 – FAC_{Res} * (1 – e_{Res})]$$

Concentrated solar power

Solar input	$= Q_{CSP}$
Storage capacity for CSP unit	$= S_{CSP}$
Loss in solar storage	$= LOSS_{CSP}$
Capacity of CSP plant	$= C_{CSP}$
Efficiency of CSP	$=\mu_{CSP}$
Share of CSP capacity with grid stabilisation capabilities	$= Stab_{CSP}$

First, the demand for solar thermal from the storage ($S_{CSP\text{-}demand}$) is defined based on the maximum production capacity:

$$S_{CSP\text{-}demand} = C_{CSP} / \mu_{Hydro}$$

Then the program calculates the maximum potential production from the CSP unit taking into consideration the storage losses in the following way:

If $Q_{CSP} > S_{CSP\text{-}demand},$ then $e_{CSP} = S_{CSP\text{-}demand} * \mu_{Hydro}$

If $Q_{CSP} < S_{CSP\text{-}demand},$ then $e_{CSP} = (Q_{CSP} + \text{storagecontent}) * \mu_{Hydro}$

If $e_{CSP} > C_{CSP}$ then $e_{CSP} = C_{CSP}$

Storagecontent(x)	$= \text{storagecontent}(x\text{-}1) + Q_{CSP} - C_{CSP} / \mu_{Hydro}$
Storageloss	$= \text{Storagecontent}(x) * LOSS_{CSP}/100.$
Storagecontent(x)	$= \text{storagecontent}(x) - \text{storageloss}$

If storagecontent > S_{CSP} then Storageloss = Storageloss + (Storagecontent(x) - S_{CSP})

5.2.9 Heat Only

Heat only separated into four segments

1. Solar thermal
2. Compression heat pumps
3. Geothermal from absorption heat pumps
4. Industrial excess heat.

The initial EnergyPLAN model did not have to include any heating supply as there is no demand for heat currently in Sri Lanka.

5.2.10 Fuel distribution

The quantity of each fuel-type consumed for electricity generation set under PP2 industry as PP2 condensing power plants are used for electricity generation only as illustrated in appendix 9.

5.2.11 Waste

The ‘Waste’ tab in the EnergyPLAN is split into two components

1. Waste incineration
2. Geothermal operated by absorption heat pump on steam from waste CHP plants.

The initial EnergyPLAN model did not have to include any waste energy supply as there is no “waste to energy projects” completed currently in Sri Lanka. However, currently, there are three “waste to energy projects started newly”.

5.2.12 Liquid and gas fuel

Liquid and gas fuel tab in EnergyPLAN software is divided into five sectors

1. Biofuel
2. Biogases
3. Hydrogen
4. Electrofuels

5. Gas to liquid

Nevertheless, currently, there is no energy supply producing from the above sectors, and currently, there are no inputs for the EnergyPLAN.

5.2.13 CO_2

CO_2 consists of two sectors

1. The CO_2 content in the fuel
2. Carbon capture storage (CCS) or Carbon capture recycling (CCR)

There is no input data for the EnergyPLAN related to CO_2. In this EnergyPLAN CO_2 emissions related to Sri Lankan case study only considered emissions associated with fossil fuel. The embodied carbon from solar panels, wind turbines and biomass plants not calculated and considered within this research.

In summary, by considering all the above input parameters following parameters has been used to develop Sri Lankan 2016 reference model.

1. Electricity demand
2. Industry and fuel
3. Transport
4. Heat and electricity
5. Central power production
6. Variable renewable electricity

5.3 Sri Lankan 2016 reference model

After studying the existing literature on the Sri Lankan energy system, it can be perceived that separate individual studies have been made for different renewable energy solutions and specific energy sectors. However, the above-mentioned renewable energy resources and energy sectors do not link to find the complete one energy solution and raise the problem of not having a model integrating the entire energy system.

The fundamental goal of this chapter is to develop and create a comprehensive reference model by gathering and including real and historical data from all energy sectors for the Sri Lankan energy system.

Once the data was gathered, the reference model was simulated with a sample time of 1 hour over one year. The input data such as the hourly distribution of the wind, hydro, river hydro, photovoltaic and electricity demand were obtained from the Sri Lankan Ceylon Electricity Board, and as for the fuel consumption, industry, transport, individual values and others, the Sustainable Energy Authority and the International Energy Agency (IEA) databases were used.

The first parameter to be taken into consideration was the electricity demand. The total amount of electricity demand for 2016 (12.785 TWh) as well as the distribution of the electricity demand over the year was simulated correctly in the model.

Then industry and other fuel demands, and transport demands were simulated in the model. The industry and other fuel demand consist of coal, oil, and biomass of 0.57, 11.03 and 53.98 TWh. The transport demand of Sri Lanka depends on 0.0348 TWh of jet fuel, 24.29 TWh of diesel, 18.55 TWh of petrol and 0.13 TWh of LPG.

The next step was to verify the electricity generated from various units from thermal (coal and oil), hydro (dammed and river), photovoltaic, biomass and wind power. In 2016 electricity generation from different sources was 14250 GWh consists of coal 5067 GWh, oil 2360 GWh, hydro dammed 3499 GWh, river hydro 739GWh, photovoltaic 4.3 GWh, biomass 72GWh and wind power 345 GWh. Finally, the correct coal, oil and biomass portions in the fuel distribution section was recognised. The all related data values were adequately simulated in the model and the simulated results described in Chapter 6 under the results and discussion and appendix 10 illustrates the results of EnergyPLAN 2016 reference model results.

The following Fig 5-8 illustrates the input/output parameters of EnergyPLAN model for the Sri Lankan 2016 reference model. The input parameters have been used to develop Sri Lankan 2016 reference model by using EnergyPLAN. When compared to European countries, there are fewer inputs available for the EnergyPLAN due to the smaller amount of resources, technology, and development of Sri Lankan energy sector.

After the simulation of the EnergyPLAN software using above inputs related to Sri Lanka, there are few output results achieved as mentioned below and all the results will be discussed under the results and discussion section in chapter 6.

1. Average monthly electricity demand
2. Annual electricity production
3. Annual fuel consumption
4. Annual CO_2 emission
5. Electricity balance
6. Renewable energy share

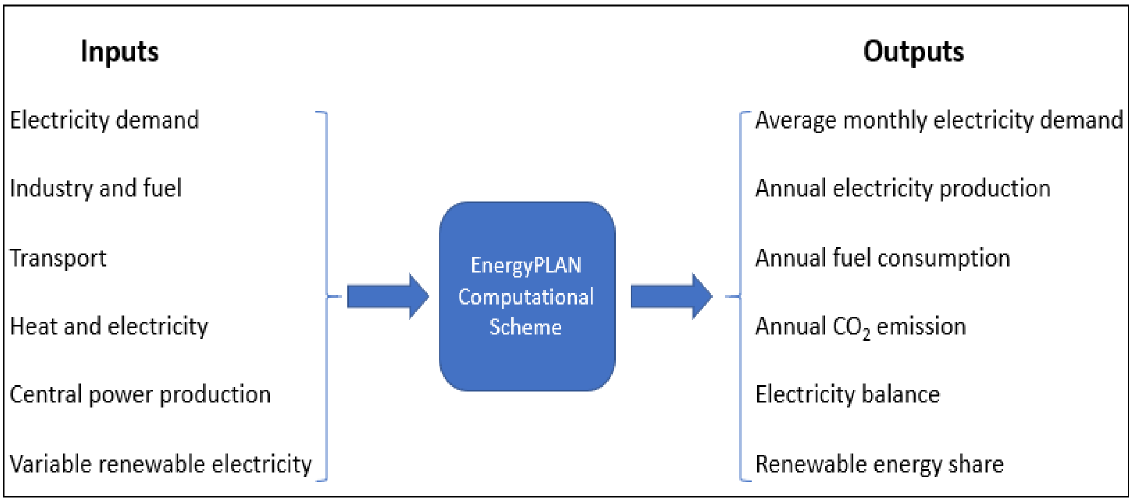

Fig 5-8 The input/output parameters of EnergyPLAN model for the Sri Lankan 2016 reference model.

5.4 Sri Lanka 2025, 2030 and 2040 models

The current Sri Lankan energy strategy is not directed towards the 100% renewable energy system for the entire energy system, but the usage of RES for the electricity generation is maximised in two official scenarios.

Table 5-5 CEB resource plan 2020-2039

Activitiy	Resource	2016	Addition Until 2025	2025 Final	Addition Until 2030	2030 Final	Addition Until 2039	2040 Final
Renewble Additions	Major Hydro	1384	227	1611	400 Pump Storage	1611/ 400PS	200 Pump Storage	1611/ 600PS
	Wind	131.5	490	621.5	185	806.5	500	1307
	R. Hydro	342	115	457	50	507	85	592
	Solar	21.4	420	441.4	480	921.4	1000	1921
	Biomass	24.1	30	54.1	25	79.1	45	124.1
Thermal Addition	Oil	1215	1488	1491	1356	2810	1500	3656
	Coal	900	0	900	0	900	0	900
Thermal Retirirement			-1212.4		-36		-654.79	

The "Long Term Generation Expansion 2020-2039" published by the Ceylon Electricity Board provides essential data such as a comprehensive view of the existing generating system, future electricity demand, future power generation options and expansion study results [81]. The above report describes individual renewable energy additions, thermal addition and thermal retirements for the period of 2020-2039 and the following Table 5-5 represents the CEB base resource plan for the period mentioned above.

The document published jointly by the Asian Development Bank and United Nations Development Project is another report about 100% renewable electricity generation in Sri Lanka. This report is a new study on the assessment of Sri Lanka's power sector – "100% Electricity Generation through Renewable Energy by 2050". This report introduced 100% renewable electricity generation by 2050 using different onsite renewable energy resources [158]. The following Table 5-6 represents Sri Lanka 2050 electricity generation mix for 100 % RE electricity generation. The "100% Electricity Generation through Renewable Energy by 2050" report is based on the Long-Term Generation Expansion 2018-2037 published by Sri Lanka Ceylon Electricity Board [159].

Table 5-6 Sri Lanka 2050 electricity generation mix for 100 % RE electricity generation

Sri Lanka 2050 Electricity Generation Mix: 100 % RE Electrcity Generation										
Year	Electrcity Generation Capacity									Total Install Capacity
	Gas Turbine	Combine Cycle	Oil	Coal	Large Hydro	Wind	River Hydro	Biomass	solar	
2022	218	594	96	825	1576	1073	458	129	721	5690
2023	105	594	61	825	1576	1356	473	134	798	5922
2024	105	594	61	1125	1576	1400	483	144	850	6338
2025	105	594	26	1125	1576	1449	493	149	900	6417
2026	105	594	26	1125	1576	1698	508	154	1279	7065
2027	105	594	26	1425	1576	1500	543	164	1060	6993
2028	105	594	26	1425	1576	1784	578	174	1356	7618
2029	105	594	26	1425	1576	2046	618	184	1639	8213
2030	105	594	26	1425	1576	2313	653	194	1950	8836
2031	105	594	26	1425	1576	2620	658	204	2284	9492
2032	105	594	26	1425	1576	2935	663	214	2628	10166
2033	105	270	26	1425	1576	3586	668	224	3362	11242
2034	105	270	26	1425	1576	3928	673	234	3736	11973
2035	105	270	26	1425	1576	4308	678	244	4156	12788
2036	105	270	26	1425	1576	4707	683	254	4598	13644
2037	105	270	26	1425	1576	5127	688	264	5063	14544
2038	105	270	26	1425	1576	5567	693	274	5552	15488
2039	105	270	26	1425	1576	6029	698	284	6066	16479
2040	105	270	26	1425	1576	6513	703	294	6608	17520
2041	105	270	26	1150	1576	7396	708	304	7612	19147
2042	105	270	26	1150	1576	7930	713	314	8210	20294
2043	105	270	26	875	1576	8863	718	324	9274	22031
2044	105	270	26	875	1576	9452	723	334	9936	23297
2045	105	270	26	600	1576	10442	728	344	11066	25157
2046	0	0	0	0	1576	12227	733	354	13122	28012
2047	0	0	0	0	1576	12907	738	364	13890	29475
2048	0	0	0	0	1576	13621	743	374	14698	31012
2049	0	0	0	0	1576	14370	748	384	15546	32624
2050	0	0	0	0	1576	15155	753	394	16438	34316

By considering data from both sources, the Asian Development Bank (ADB) and Ceylon Electricity Board (CEB), EnergyPLAN model is simulated for 2025, 2030 and 2040 to find the results for the following parameters for each year and compare the Sri Lankan official data with EnergyPLAN simulations.

1. CO_2 emission (Mt)
2. Renewable energy share (RES) of primary energy supply PES (%)
3. RES share of electricity production (%)
4. RES electricity production
5. Fuel consumption (total)
6. Fuel consumption (total) Fuel (including biomass and excluding RES
7. Fuel consumption including H_2
8. Fuel consumption
9. Coal consumption
10. Oil consumption

11. Natural gas consumption
12. Biomass consumption
13. Waste consumption

Table 5-7 illustrated all EnergyPLAN inputs for 2025, 2030 and 2040 energy simulations. All related data values were adequately simulated in the different models and the above results are described under the results and discussion section and with simulation results included in appendix 11 to 16.

Table 5-7 EnergyPLAN inputs for 2025, 2030 and 2040 for different ADB and CEB scenarios.

Parameter	Sector	Source	2025 ADB		2025 CEB		2030 ADB		2030 CEB		2040 ADB		2040 CEB	
			Installed Capacity MW	TWh	Installed Capacity MW	TWh	Installed Capacity MW	Value TWh	Installed Capacity MW	Output TWh	Installed Capacity MW	ValueT Wh	Installed Capacity MW	Output TWh
Demand	Electrcity			22.501		22.501		28.573		28.573		43.62		43.62
	Industry & Fuel	Coal		0.26		0.26		0.07		0.07		0		0
		Oil		15.37		15.37		18.33		18.33		24.16		24.16
		Biomass		47.98		47.98		44.43		44.43		37.33		37.33
	Transport	JF		0.037		0.037		0.03		0.03		0.03		0.03
		Diesel		33.09		33.09		37.74		37.74		47.02		47.02
		Biofuel(D)												
		Waste												
		Electrofuel												
		Petrol		14.7		14.7		16.84		16.84		21.12		21.12
		Biofuel(P)												
		Electrofuel												
		H2												
		LPG		0.03		0.03		0.03		0.03		0.05		0.05
Supply	Heat & Electricity	Biomass	149	0.435	54.1	0.158	194	0.6	79.1	0.23	249	0.86	124.1	0.36
	Central Power Production	Coal+Oil	1850	12.58	2390.6	14.75	2150	14.16	3710.6	20.86	1826	10.97	4556	20.86
	Variable Renewable	Hydro	1576	2.8	1611	2.8	1576	2.8	1611	2.8	1576	2.8	1611	2.8
		Pump Storage							400	0.02			600	0.03
		Wind	1449	4.09	621	1.75	2313	6.53	806	2.27	6513	18.37	1307	2.27
		Solar	900	1.74	441.4	0.85	1950	3.76	921.4	1.78	6608	12.74	1921	3.7
		River Hydro	493	2.28	457	2.12	653	3.02	507	2.35	703	3.25	592	2.35
	Waste													
	Liqid & Gas	Biofuels												
		Hydrogen												
		Electrofuels												

There is no plan with CEB for their future developments after 2039, but still, the ADB & UNDP joint report introduced a renewable energy electricity generation plan towards 2050. The following section presents scenarios for the renewable energy future of Sri Lanka based only on the RES used for the production of electricity, industry, transport and biofuels using EnergyPLAN simulations.

5.5 Sri Lanka 50% renewable energy model

The first model, the 50% renewable energy system, has been created for the year 2045 and represents the first step towards the 100% renewable energy future of Sri Lanka.

This 50% renewable energy model developed as three scenarios such as ADB model, EnergyPLAN (EP) model and EP enhanced (developed) models. Table 5-8 shows the input parameters for the EnergyPLAN 2045 model with different scenarios.

Table 5-8 Input parameters for the EnergyPLAN 2045 model with different scenarios.

Parameter	Sector	Source	2045 ADB		2045 EP 50% RES		2045 EP 50% Enhanced	
			Installed Capacity MW	Output TWh	Installed Capacity MW	Output TWh	Installed Capacity MW	Output TWh
Demand	Electrcity			54.04		54.04		48.64
	Industry & Fuel	Coal		0		0		
		Oil		27.07		27.07		13.535
		Biomass		33.78		33.78		67.56
	Transport	JF		0.03		0.03		0.03
		Biofeul (JF)						
		Diesel		51.66		38.76		29.07
		Biofuel(D)		0		12		15
		Waste		0		0.9		1.8
		Petrol		23.27		15.27		11.4525
		Biofuel(P)		0		8		10
		H2		0		1		2
		Dump Charge						
		Smart Charge						
		LPG		0.05		0.05		0.05
Supply	Heat & Electricity	Biomass	344	1	344	1	344	1
	Central Power Production	Coal+Oil	1001	5.65	500.5	4.4	500.5	4.4
	Variable Renewable	Hydro	1576	2.8	1576	2.8	1576	2.8
		Pump Storage						
		Wind	10442	29.46	3820	10.78	3800	10.78
		Solar	11066	21.34	5600	10.8	5600	10.8
		River Hydro	728	3.37	728	3.37	728	3.37
	Waste				1 TWh	0.9	2 TWh	1.8
	Liqid & Gas fuel	Biofuels			37.12 TWh	20	46.4TWh	25
		Hydrogen			350 MW	1	700 MW	2
		Electrofuels						

According to the ADB report, the renewable energy plan towards 2045 comprises some significant variations towards renewable electricity generation. The wind power capacity will reach the value of 10442 MW; solar size rises to 11066 MW the river hydro capacity will increase to 728 MW while dammed hydro 1576 MW installed capacity is remaining the same according to ADB data with the EnergyPLAN simulation.

Nevertheless, the EnergyPLAN simulation scenario uses less wind and solar installed capacities compared to waste and liquid and gas fuel such as biofuel and hydrogen.

The third scenario is an enhanced scenario with some excellent energy management technologies and ethical practices within society. In this scenario, the following assumptions have been introduced to the simulations to achieve more than 50% of RES for the entire energy system.

1. 10% of electricity reduction from total electricity demand by introducing energy saving strategies
2. 50% of oil reduction in the industry
3. 50% of biomass increase in the industry
4. 25% of diesel usage reduction in the transport sector.
5. 25% of petrol usage reduction in the transport sector.
6. 25% of biofuel increase as biodiesel.
7. 25% of biofuel increase as bio petrol.
8. Double the supply of waste to energy power.
9. Double the H_2 fuel supply

The all related data values were adequately simulated in the different models and the above results are described under the results and discussion section and with simulation results included in appendix 17, 18 and 19.

5.6 Planning of the Sri Lankan energy system

The 100% renewable energy solution for the year 2050 is created by expanding the 2016 reference model and 2020 to 2045 EnergyPLAN simulation models. The 2050 solution also assumed the rise in demand for electricity, agricultural, forest, commercial, industrial, transport and residential sectors according to the literature.

Sri Lankan electricity requirement is expected to rise from 12.78 TWh in 2016 to 71.97 TWh in 2050, equal to an annual rise of 5.04%. Furthermore, the final energy demand in Sri Lanka is expected to rise from 406.9 PJ in 2016 to 625.59 PJ with the highest increase in household and commercial sectors, followed by transport and industry sectors. In industry, transport, commercial and household energy savings, fuel mixes and long-term energy demand projections have been taken into consideration to design 100% renewable energy solution in 2050.

The renewable energy scenarios for the years 2045 and 2050 are based on substantial energy savings through the introduction of new technologies and the phasing out of old ones, and on high penetration of RES in combination with storage technologies. These changes are introduced in the 2045 & 2050 models such as waste to energy generation, biofuels H_2 and dump charging systems.

5.6.1 Sri Lanka 100% renewable energy model

The final model has been designed for the 100% renewable energy system based only on the RES in the year 2050. This final simulation also consists of two scenarios such as the ADB 100% electricity generation model and the EnergyPLAN 100% renewable energy model. Table 5-9 illustrates the input parameters for the EnergyPLAN 2050 model for both simulation scenarios. The 100% ADB model was designed using the data from the ADB report, which was targeted to obtain a 100% electricity generation in 2050.

The 100% EnergyPLAN model was designed using the ADB report, Sri Lankan energy balance and future energy data forecasting. To obtain 100% renewable energy solution for Sri Lanka, there are a few assumptions introduced to the EnergyPLAN model.

There is no coal and oil use for industry, and other fuel requirements and biomass usage has tripled for the industry. The jet fuel is replaced by biofuel (JF), diesel replaced by biofuel and waste. The petrol necessity is fulfilled by biofuels and H_2. The dump charge covered the other part of transport demand. When considering the supply side, the 1.15 TWh electricity comes from 394MW installed capacity of biomass plants. There are no thermal power plants added to the design while the hydro dammed power plant produces 2.8 TWh per year from the 1576 MW installed capacity. The other fluctuating renewable energy resources such as wind, solar and river hydro produced 40.71 TWh, 30.8 TWh and 3.49 TWh electricity generations using 14430MW, 15600 MW and 753 MW installed capacities, respectively.

The 3 TWh of waste input is converted to the biofuels to replace 2.7 TWh diesel. 143.15 TWh of biofuels input is formed to the 83TWh diesel and petrol biofuels.

Finally, 700MW installed capacity of transport and electro-fuel with 25 GWh hydrogen storage produces 2 TWh H_2.

The above results are described under the results and discussion section and with simulation results included in appendix 20 and 21.

Table 5-9 Input parameters for the EnergyPLAN 2050 model with different scenarios

Parameter	Sector	Source	2050 ADB 100 %		2050 EP 100% RE	
			Installed Capacity MW	Output TWh	Installed Capacity MW	Output TWh
Demand	Electrcity			71.97		71.97
	Industry & Fuel	Coal				0
		Oil		29.99		0
		Biomass		30.23		90.24
	Transport	JF		0.03		0
		Biofeul (JF)				0.03
		Diesel		56.31		0
		Biofuel(D)				57
		Waste				2.7
		Petrol		25.41		0
		Biofuel(P)				26
		H2				2
		Dump Charge				2
		Smart Charge				0
		LPG		0.05		0
Supply	Heat & Electricity	Biomass	394	1.15	394	1.15
	Central Power Production	Coal+Oil	0	0	0	0
	Variable Renewable	Hydro	1576	2.8	1576	2.8
		Pump Storage				
		Wind	15155	42.76	14430	40.71
		Solar	16438	10.67	15600	30.08
		River Hydro	753	3.49	753	3.49
	Waste				3 TWh	2.7
	Liqid & Gas fuel	Biofuels			143.15 TWI	83
		Hydrogen			700MW	2
		Electrofuels				

Also, the following technologies are available within the EnergyPLAN to simulate better and combined results to achieve 100% renewable energy solutions for Sri Lanka.

1. Electricity (smart charge)
2. Combined heat and power plant

3. Geothermal
4. Wave power
5. Tidal
6. Biomass conversion plants
7. Electrofuels production

CHAPTER 6

6.RESULTS AND SCENARIO DEVELOPMENT

This chapter describes the results and scenario development of thesis concluding all scenarios such as 2016 reference model, 2025-2040 models, 2045 model and finally 2050 model.

The structure of Chapter 6 illustrates in Fig 6-1 and this chapter consists of results and scenario development. This section initiates with 2016 reference model validation comparing actual results and EnergyPLAN simulation results and then moved to discuss all related results for 2025-2040 energy models.

After that, Chapter 6 discusses the results of 2045 and 2050 energy models to achieve 50% and 100% renewable energy solutions respectively by using simulated results.

Finally, this chapter describes the scenario development of industry, transport and electricity sectors, by developing a pictorial view of final EnergyPLAN output presenting 2016 reference model, 50% RES EnergyPLAN model and 100% RES EnergyPLAN energy balance.

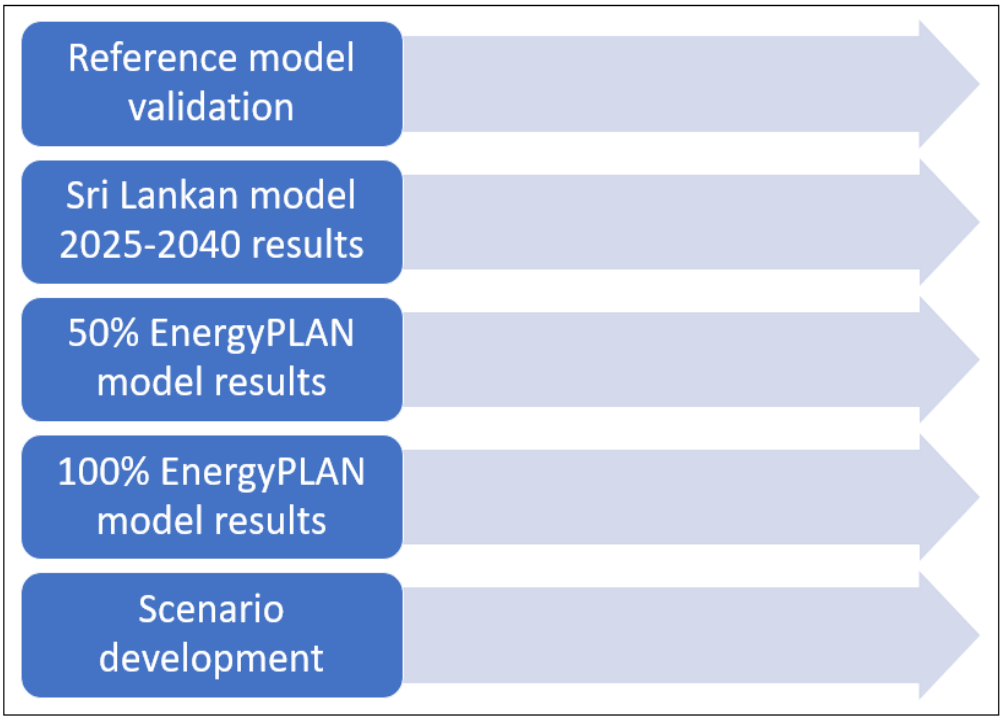

Fig 6-1 Structure of the results and scenario development section.

6.2 Reference Model Development and Validation

Different types of input data were used in order to develop the Sri Lankan 2016 reference energy model. All related input data from the year 2016, because of the statistical data available and used for the validation of the model are from 2016. The input data used in the reference model was as follows

1. Electricity demand
2. Industry and other energy demands
3. Transport demands
4. Power plant electricity generation
5. Dammed hydropower generation
6. Renewable energy sources and their hourly distribution (8784 values for each distribution file for the year 2016)

After the simulation process was carried out, the model is validated by comparing the results from the EnergyPLAN tool with the official statistical data. This process was essential to ensure that the results generated by EnergyPLAN were accurate for future simulation models. The detailed results sheet attached to appendix 10.

Table 6-1 Comparison of average monthly electricity demand from actual statistical and EnergyPLAN data

Month	Average monthly electricity demand (MW)		Difference MW	Difference (%)
	Actual 2016	EnergyPLAN 2016 model		
January	1401	1378	23	1.64
February	1373	1444	-71	-5.17
March	1423	1400	23	1.62
April	1433	1457	-24	-1.67
May	1496	1472	24	1.60
June	1449	1473	-24	-1.66
July	1465	1441	24	1.64
August	1519	1495	24	1.58
September	1491	1516	-25	-1.68
October	1499	1475	24	1.60
November	1449	1473	-24	-1.66
December	1468	1445	23	1.57

The total amount of electricity demand for 2016 (12.785 TWh), as well as the distribution of electricity demand over the year, was simulated correctly in the model. Table 6-1 shows the comparison of average monthly electricity demand from actual statistical and EnergyPLAN data. According to the simulated results from the EnergyPLAN software can obtain graphical pictures from the output tab. Fig 6-2 illustrates the electricity demand throughout January.

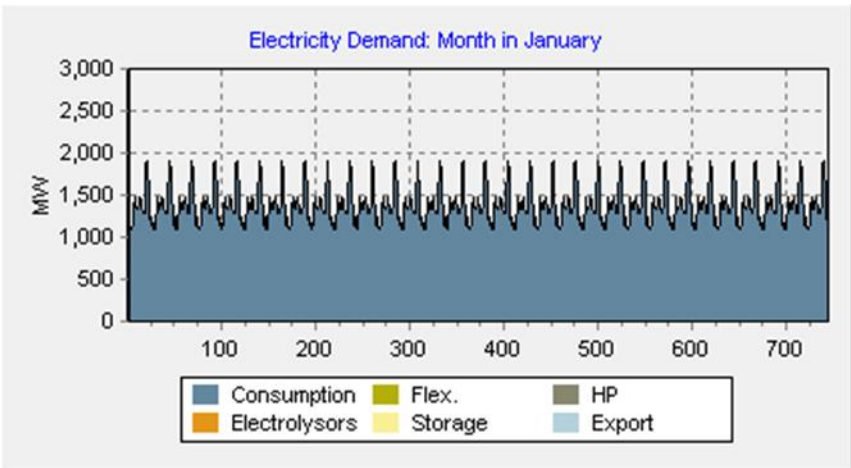

Fig 6-2 Electricity demand profile January 2016.

The next step was to verify the electricity produced by various units. As seen in Table 6-2, the annual total amount of electricity generated from the various production units of the reference model and EnergyPLAN model are illustrated below. In the case of power plants (PP), the oil and coal plants data could not be obtained separately.

Tab 6-2 Comparison of annual electricity production by source in two different scenarios

Source	Annual electricity production TWh		Difference TWh	Difference (%)
	Actual 2016	EnergyPLAN 2016 model		
Hydro	3.5	2.8	0.7	20.00
Biomass	0.07	0.072	-0.002	-2.86
Wind	0.34	0.37	-0.03	-8.82
Solar	0.0043	0.03	-0.0257	-597.67
River Hydro	0.74	1.58	-0.84	-113.51
PP	7.43	7.86	-0.43	-5.79

According to the above table, there is a huge difference in the percentage of solar and river hydroelectricity production. The reason for the difference between the actual data and model results for solar production are unavailability of correct meter readings from solar farms, reading and reporting differences submitted to CEB, full solar installed capacity not functioning and net meter reading household generation not being counted within the system. However, in EnergyPLAN, solar generation was calculated to the 2016 fully installed capacity of 56.2 MW as described in the Section 5.1, there was also a significant difference within the EnergyPLAN reading as well. To obtain the correct value of output generation, the plant factor of the solar farms needs to be changed to 0.865.

With regard to river hydro, the EnergyPLAN value is correct when compared with the plant factor of the overall river hydro generation. The difference between the actual value and EnergyPLAN value has many reasons such as not obtaining the correct generation data from the plants, reading and reporting differences to CEB, full installed capacity not functioning at that time and no direct relation to checking the generation data from river hydro to the central monitoring point. Nevertheless, the EnergyPLAN value was obtained through full installed capacity and annual data distribution of the river hydro plant.

According to the simulation results obtained from EnergyPLAN software, Fig 6-3 illustrates the electricity production during January 2016.

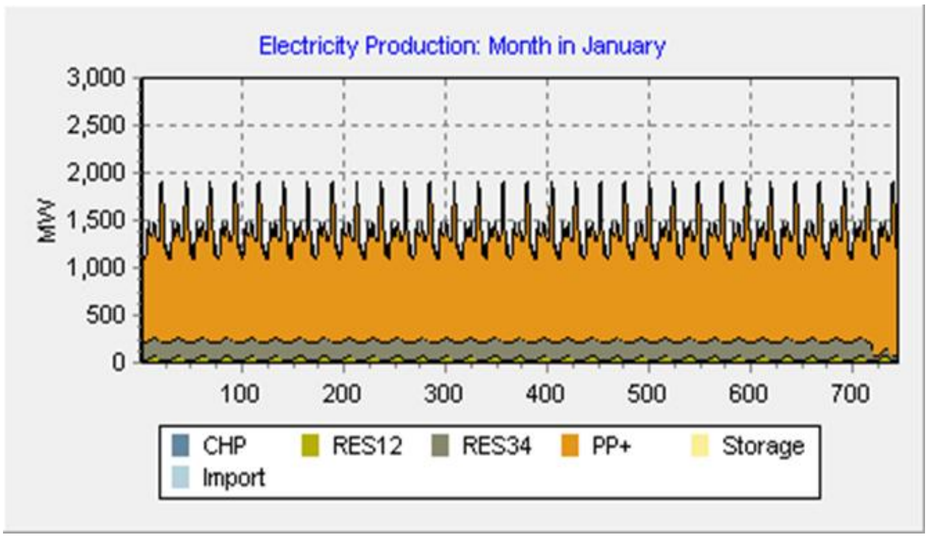

Fig 6-3 Electricity production January 2016.

After the electricity sector was analysed, the figures of the other sectors were compared with the actual 2016 data.

Table 6-3 Comparison of annual fuel consumption by source in two different scenarios

Source	Annual fuel consumption TWh		Difference TWh	Difference (%)
	Actual 2016	EnergyPLAN 2016 model		
Coal	15.25	14.1	1.15	7.54
Oil	59.55	57.65	1.9	3.19
Biomass	54.16	54.16	0	0.00
Renewable	3.5	4.86	-1.36	-38.86

The total fuel consumption within the Sri Lankan energy system was compared with the values calculated by EnergyPLAN. As seen in Table 6-3, the simulated values correspond to the actual data from 2016; the most significant relative difference being 7.5% for coal.

Finally, the CO_2 emissions for Sri Lanka were compared with EnergyPLAN. The total CO_2 emissions for Sri Lanka in 2016 according to the energy balance report published by the sustainable energy authority in Sri Lanka was 18.22 Mt, as seen in Table 6-4. In comparison, EnergyPLAN calculated the CO_2 emissions for Sri Lanka in 2016 at 20.21 Mt. The difference between the figures is -1.99 Mt (-9.8%); thus, indicating that the reference model provides an accurate representation of the Sri Lankan energy system.

After completing this comparison, it was concluded that the model was accurate and appropriate for the analysis of future models, as presented in this chapter.

Table 6-4 Comparison of CO_2 emissions in different scenarios.

	CO2 emission Mt		Difference Mt	Difference (%)
	Actual 2016	EnergyPLAN 2016 model		
CO2	18.22	20.21	-1.99	-10.92

When discussing the results obtained from EnergyPLAN, energy balance was also another vital parameter and it consisted of four sub-components such as import electricity, export electricity, Critical Excess Electricity Production (CEEP) and Exportable Excess Electricity Production (EEEP). This energy balance value was 0 for the reference model. Renewable electricity generation achieved to 38% in this reference model and the total Renewable Energy Share (RES) from primary energy supply was 45.1%.

6.3 Sri Lankan reference models 2025, 2030 and 2040

Having implemented the 2016 reference model, 2025, 2030 and 2040 reference models were simulated. The data obtained from the ADB 100% renewable electricity generation report and the CEB long term generation plan from 2020-2039 report was used to develop the above reference scenarios. Actual and precise figures from both of the above-mentioned reports were used in the EnergyPLAN software. Furthermore, different EnergyPLAN models were simulated for future years for both ADB and CEB scenarios. All related simulation results attached in appendix 11-16.

Table 6-5 Comparison of average monthly electricity demand for all three scenarios

Month	Average monthly electricity demand (MW)		
	2025	2030	2040
	ADB & CEB	ADB & CEB	ADB & CEB
January	2426	3081	4703
February	2541	3227	4927
March	2464	3129	4777
April	2564	3255	4970
May	2591	3290	5022
June	2593	3293	5027
July	2536	3220	4916
August	2631	3341	5100
September	2667	3387	5171
October	2596	3297	5033
November	2592	3291	5025
December	2543	3229	4929

According to the official projected statistics for 2025, 2030 and 2040, the total electricity demand forecast is 22.50 TWh, 28.57 TWh and 43.62 TWh, respectively. The total amount of electricity demand and distribution of electricity demand over the year were simulated correctly in the model. Table 6-5 shows the comparison of average monthly electricity demand for all three scenarios in each year. According to the above results, the average, maximum and minimum electricity demand for Sri Lanka is illustrated in Table 6-6 for different scenarios in each year.

Table 6-6 Average, maximum and minimum electricity demand in three scenarios

Demand MW	2025	2030	2040
	ADB & CEB	ADB & CEB	ADB & CEB
Average	2562	3253	4966
Maximum	3597	4568	6974
Minimum	1915	2432	3713

The electricity produced in different scenarios varies due to diverse resources installed capacities. As seen in Table 6-7, the total amount of electricity generated from the various production units of each reference model in different years is illustrated. In the case of the Power Plant (PP), oil and coal plants data could not be obtained separately.

Table 6-7 Annual electricity production by source in different scenarios

Source	Annual electricity production TWh					
	2025		2030		2040	
	ADB	CEB	ADB	CEB	ADB	CEB
Hydro	2.8	2.8	2.8	2.8	2.8	2.8
Biomass	0.43	0.16	0.6	0.23	0.86	0.36
Wind	4.09	1.75	6.53	2.27	18.37	3.69
Solar	1.74	0.85	3.76	1.78	12.74	3.7
River Hydro	2.28	2.12	3.02	2.35	3.25	2.74
PP	10.94	14.75	11.46	19.13	8.03	29.35

The information in Table 6-7 is represented in graph form in Fig 6-4.

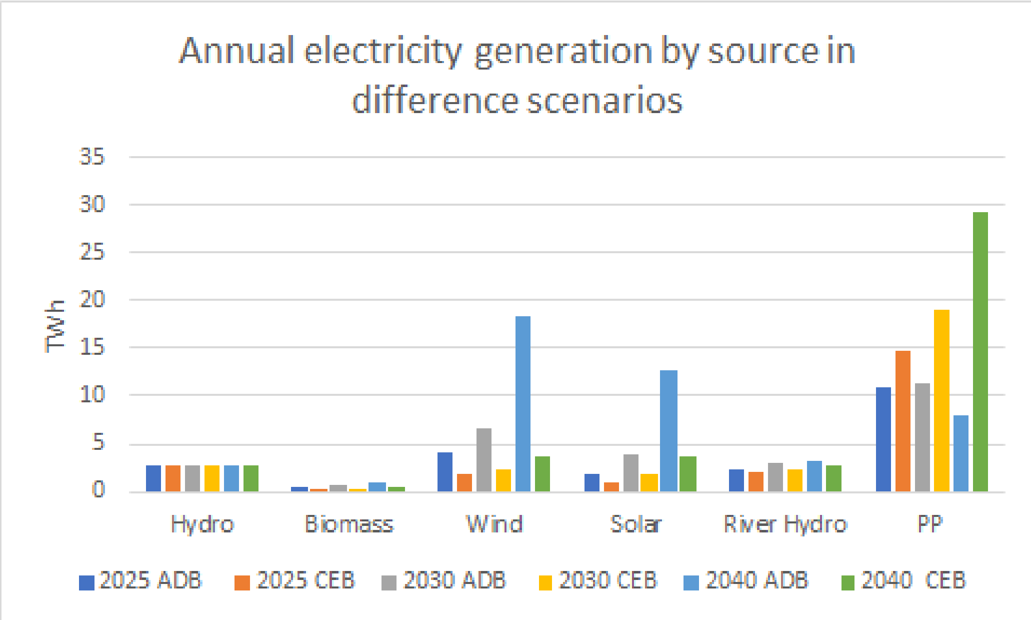

Fig 6-4 Annual electricity generation by source in different scenarios.

On the whole, hydro generation figures do not change until 2040 due to less opportunities in adding future hydro development to the electricity infrastructure in Sri Lanka. This is determined by the current socio-economic situation in the country and assuming that this situation does not change.

When considering biomass development, the ADB report has very little influence on biomass and the CEB report has no intention of generating electricity using biomass. This technology is not currently accessible in Sri Lanka, but there is a vast potential to achieve biomass generation due to the environment and weather patterns in Sri Lanka.

Chapter 4 (4.2 and 4.3) discusses the possibility of implementing biomass generation in Sri Lanka in detail.

Wind power is the most reputable renewable energy source to use in an ADB scenario, but unfortunately the CEB commitment to wind development is minimal compared to ADB. Also, ADB plans to develop solar energy gradually and still CEB reports demonstrate very few development opportunities for solar power.

Finally, ADB is gradually decreasing the Power Plants (PP) installed capacity, according to the 100% renewable energy electricity generation plan in alignment with global climate requirements. However, CEB plans to keep increasing the number of power plants needed for the electricity infrastructure to ensure dependence on thermal energy for electricity generation.

The total fuel consumption within the Sri Lankan energy system is compared with the values calculated by EnergyPLAN for ADB and CEB scenarios, as seen in Tab 6-8.

Table 6-8 Annual fuel consumption by source in different scenarios

Source	Annual fuel consumption TWh					
	2025		2030		2040	
	ADB	CEB	ADB	CEB	ADB	CEB
Coal	8.37	11.19	8.56	14.24	5.94	21.74
Oil	71.37	74.16	81.46	87.14	98.32	114.07
Biomass	56.09	58.91	52.92	58.6	43.27	59.07
Renewable	10.91	7.52	16.11	9.2	37.17	12.93

Table 6-8 is graphically represented in the Fig 6-5. Coal consumption for energy generation is decreasing in the ADB scenario. However, coal consumption is gradually increasing in CEB scenarios.

Oil consumption is gradually increasing within both scenarios to fulfil the energy demand in Sri Lanka due to high transport growth. However, biomass consumption has low development in the ADB scenario while the CEB intention to biomass as fuel to fulfil final energy demand remains constant. The renewable energy share for the final energy consumption in Sri Lanka is increasing in both scenarios, but the ADB scenario shows more rapid renewable energy development than the CEB.

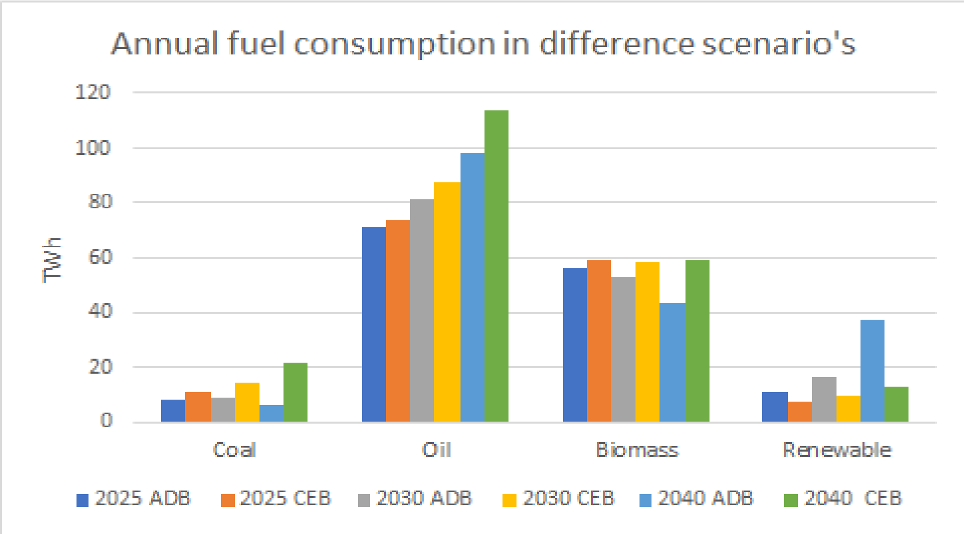

Fig 6-5 Annual fuel consumption by source in different scenarios.

The CO_2 emission is also one of the key results found from the simulation and the CO_2 emissions for Sri Lanka were compared with different scenarios in 2025, 2030 and 2040, as seen in Table 6-9.

Table 6-9 Annual CO_2 emissions in different scenarios

CO2	CO2 emission Mt					
	2025		2030		2040	
	ADB	CEB	ADB	CEB	ADB	CEB
	21.87	23.58	24.63	28.06	28.22	37.84

When discussing electricity balance, the following Table 6-10 represents the critical parameters of import electricity, export electricity, Critical Excess Electricity Production (CEEP) and Exportable Excess Electricity Production (EEEP).

Table 6-10 Electricity balance in different scenarios.

Parameter	Electricity Balance TWh					
	2025		2030		2040	
	ADB	CEB	ADB	CEB	ADB	CEB
Import	0.23	0.07	0.56	0.01	3.85	0.98
Export	0.02	0	0.15	0	6.29	0
CEEP	0.02	0	0.15	0	6.29	0
EEEP	0	0	0	0	0	0

According to the Table 6-10, the CEB scenarios for 2025, 2030 and 2040 not generating excess electricity to export. The CEB has low import capacity, and that means if the intermittent renewable energy generation has changed, the CEB need to import only spare energy capacity to recover electricity demand. In the ADB scenario, as in 2040 there are relatively high export and CEEP values which mean that excess electricity is being produced using renewable energy sources.

In this situation, Sri Lanka needs an electricity infrastructure to export electricity to nearby countries. Alternatively, on the other hand, if intermittent renewable energy is not providing the necessary generation to Sri Lanka, it will be necessary to import high value of electricity to meet the demand.

Table 6-11 Renewable energy share in different scenarios.

	Renewable Energy Share (%)					
	2025		2030		2040	
	ADB	CEB	ADB	CEB	ADB	CEB
Primary Energy Supply(PES)	45.7	43.8	43.4	40.1	43.6	34.6
Electricity Generation	48.5	33.4	56.4	32.2	85.2	29.6

Finally, the renewable energy share of the primary energy supply and electricity generation is a significant factor in the simulation results. The Renewable Energy Share (RES) of the primary energy supply and renewable energy share for electricity generation are also shown in Table 6-11. As identified, ADB determines the development of renewable energy share within the electricity generation in Sri Lanka and CEB aspirations for renewable energy share for both primary energy supply and electricity generation have no promising development.

6.4 Sri Lankan 50% renewable energy model by 2045.

After implementing the simulation models for 2025, 2030 and 2040, then the 2045 model was simulated with EnergyPLAN. This 2045 model consisted of three different scenarios; ADB model, 50% RES EnergyPLAN model and 50% RES Energy plan enhanced model. For the design of the ADB model, the data was obtained from ADB 100% renewable electricity generation report as CEB has no long-term generation plan beyond 2039. The EP 50% model was designed by using data from the above report and the supply parameters were changed to obtain the 50% renewable electricity generation and 50% renewable power supply. The final energy model has been designed and included assumptions such as reduced fossil fuels usage, increased biomass and biofuel usage and lower electricity demand as described in Section 5.4. All related simulation results attached in appendix 17, 18 and 19.

Table 6-12 Comparison of average monthly electricity demand for all three scenarios in 2045.

Month	Average monthly electricity demand (MW) 2045		
	ADB	EP 50% RES	EP 50% Enhanced
January	5826	5852	5276
February	6104	6129	5525
March	5918	5943	5358
April	6157	6182	5573
May	6222	6247	5631
June	6228	6253	5637
July	6090	6115	5513
August	6318	6343	5718
September	6406	6431	5797
October	6235	6260	5643
November	6225	6250	5634
December	6106	6132	5528

According to the official predicted statistics for 2045, the total electricity demand forecast is 54.04 TWh and the total amount of electricity demand and distribution of electricity demand over this year were simulated correctly within the ADB model. The EnergyPLAN (EP) 50% RES model consumes 0.22 TWh of additional electricity demand for biomass conversions and the total electricity demand is 54.26 TWh. The EP 50% amended version model assumes a 10% reduction in electricity demand by utilising energy saving strategies which is 48.64 TWh, and it consists of 0.27 TWh electricity demand again for biomass conversions.

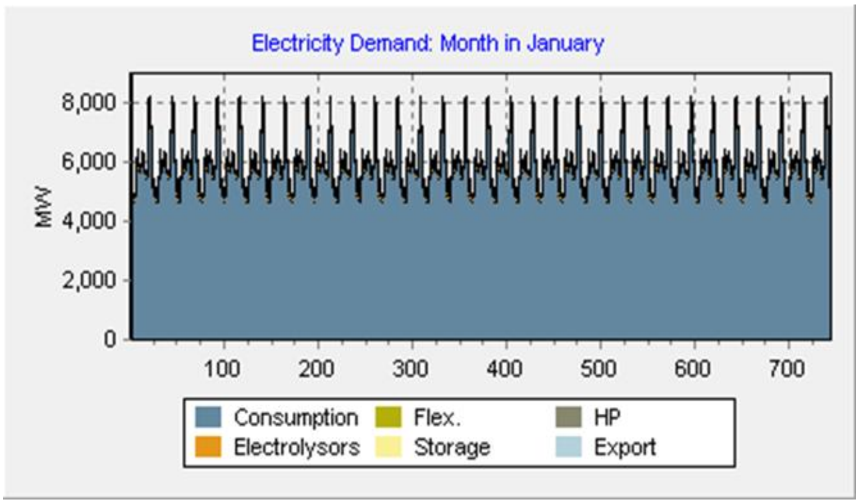

Fig 6-6 Electricity demand for January 2045 for EP 50% model

Table 6-12 shows the comparison of average monthly electricity demand for all three scenarios in 2045 and Fig three represents the electricity demand through January for EP 50% model.

Due to the introduction of diverse installed capacities from both ADB official statistics and EnergyPLAN, electricity production has varied in each scenario. The total amount of electricity generated from the various production units of each model in 2045 is seen in Table 6-13. In the case of Power Plants (PP), oil and coal plants data could not be obtained separately.

Table 6-13 Annual electricity production by source in different scenarios

Source	Annual electricity production TWh		
	2045		
	ADB	EP 50% RES	EP 50% Enhanced
Hydro	2.8	2.8	2.8
Biomass	1	1	1
Wind	29.46	10.78	10.78
Solar	21.34	10.8	10.8
River Hydro	3.37	3.37	3.37
PP	3.98	4.01	3.81
Electrolysers	0	1.18	2.35

According to the Table 6-13, dammed hydro, biomass, river hydro and Power Plants (PP) annual electricity production is similar in different scenarios. The most important factor is that the ADB scenario has used much more wind and solar installed capacity to obtain renewable electricity generation. The EnergyPLAN scenarios have used balance resources such as wind, solar, biomass and H_2 which were produced by electrolysers to minimise the excess electricity production from the energy system.

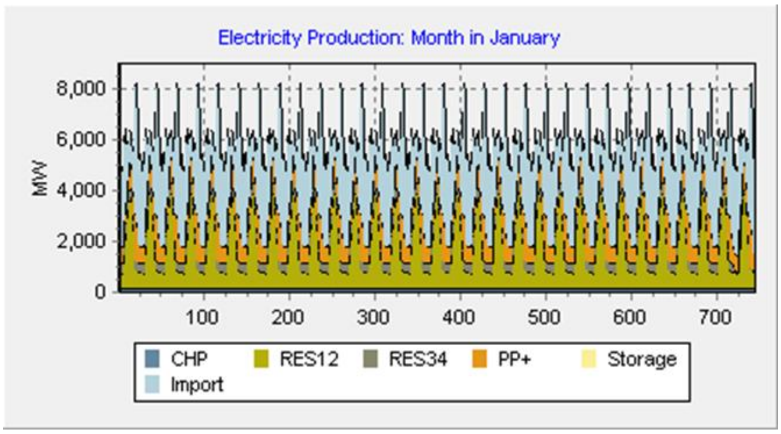

Fig 6-7 Electricity production during January 2045

According to the simulation results obtained from EnergyPLAN software, Fig 6-7 illustrates the electricity production during January 2045.

The Table 6-13, illustrated in graphic form in Fig 6-8, is explaining the annual electricity generation in 2045 from different sources in three different scenarios.

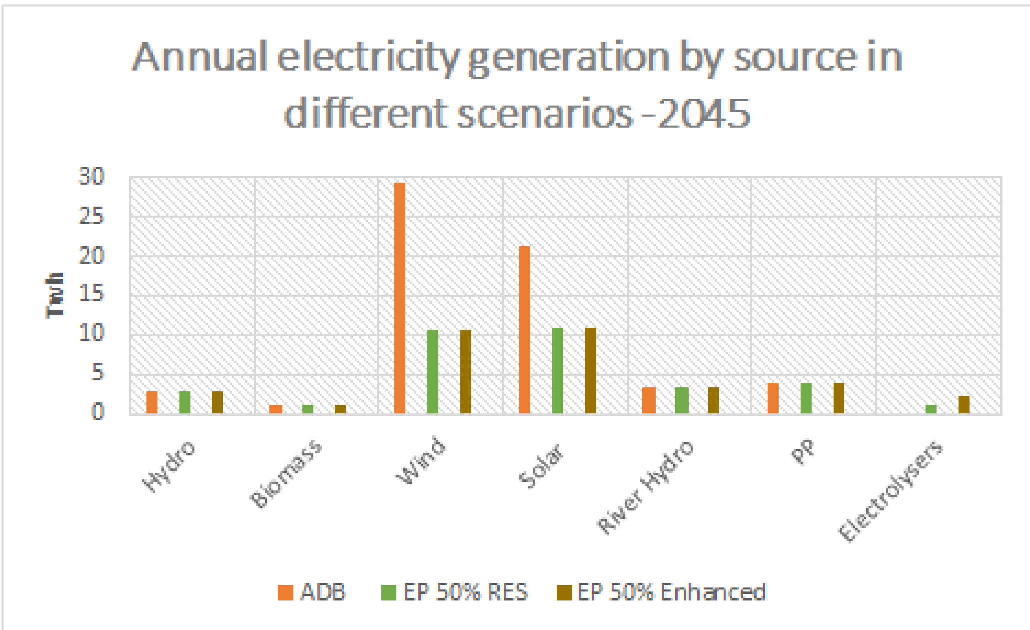

Fig 6-8 Annual electricity generation by source in different scenarios -2045

According to the Table 6-13 and Fig 6-8, wind and solar resources have been used in the ADB scenario solely for electricity generation, and both these resources indicated excess electricity which is available for export. Nevertheless, there is no such current infrastructure available to handle that kind of massive electricity export as Sri Lanka's electricity infrastructure is isolated from other Asian countries.

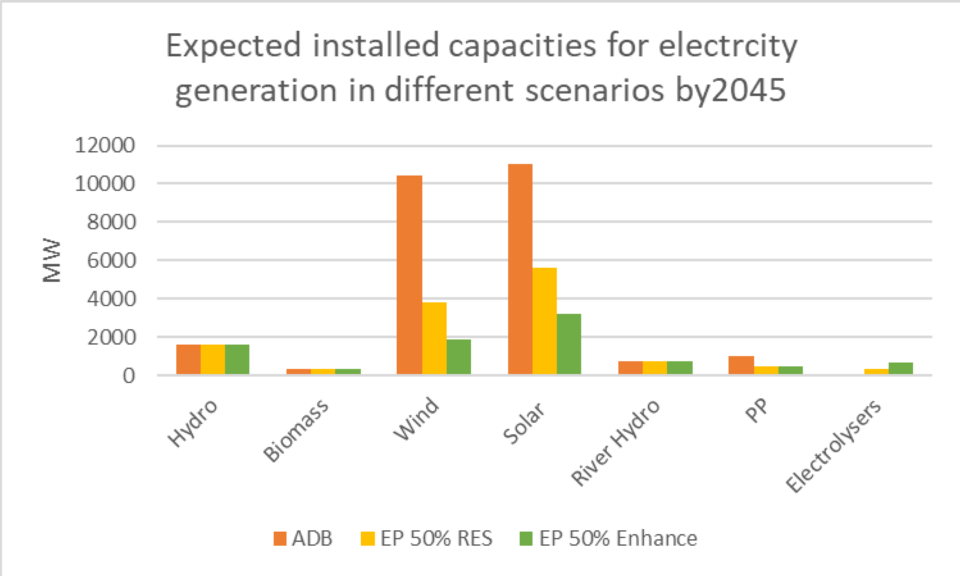

Fig 6-9 Installed capacities used for electricity generation in the different scenarios

Fig 6-9 illustrated the installed capacities used for electricity generation in the different scenarios. Within all three scenarios hydro, biomass and river hydro, the installed capacity is 1576 MW, 344 MW and 728 MW. Power Plant (PP) installed capacity is 1001 MW in the ADB scenario, and the other two EnergyPLAN scenarios have used 500.5 MW. Electrolysers installed capacities are 350 MW and 700 MW in both EnergyPLAN models. Wind and solar power installed capacities are 10442 MW and 11066 MW in ADB model. Wind and solar installed capacities are 3820 MW and 5600 MW respectively in both EnergyPLAN models and this is lower than the ADB model.

The total fuel consumption in the Sri Lankan energy system is compared with the values calculated by EnergyPLAN for ADB, EnergyPLAN 50% RES and EnergyPLAN 50% Enhanced scenarios as seen in Tab 6-14.

Table 6-14 Annual fuel consumption by source in different scenarios

Source	Annual fuel consumption TWh		
	2045		
	ADB	EP 50% RES	EP 50% Enhanced
Coal	2.95	0	0
Oil	105.03	85.64	58.37
Biomass	36.73	66.36	107.69
Renewable	59.67	27.75	27.75

Table 6-14 is represented in graph form in Fig 6-10. The ADB scenario has a higher oil and renewable energy share than biomass share for the final energy consumption. Both EnergyPLAN scenarios have no coal consumption and oil consumption is reducing gradually. The biomass consumption as fuel is increasing in both EnergyPLAN scenarios while renewable energy consumption keeps constant.

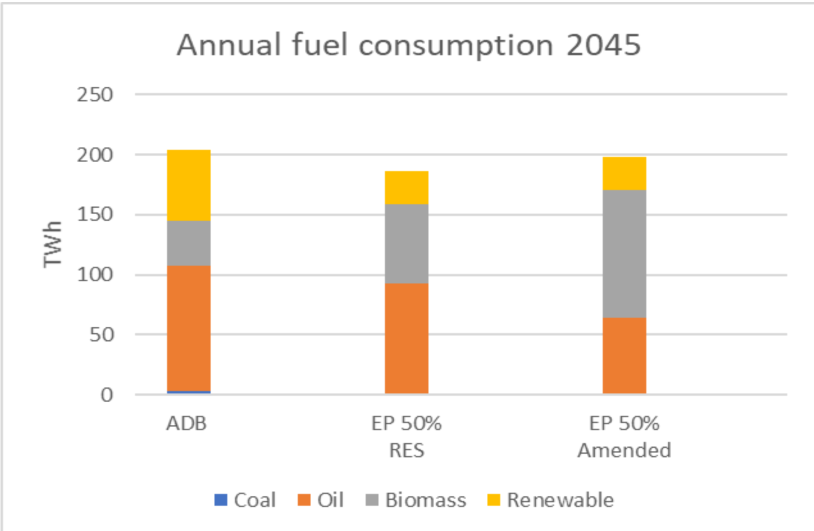

Fig 6-10 Annual fuel consumption by source

According to the Fig 6-10, oil consumption is gradually reducing in both EnergyPLAN scenarios and coal is no longer used for electricity generation in Si Lanka. In both EnergyPLAN scenarios, biomass has been used for industry and other energy needs while biofuels have been used to fulfil the transport fuel demand in Sri Lanka due to high transport growth.

The CO_2 emission results found from the simulation and the CO_2 emissions for Sri Lanka were compared within different scenarios in 2045, as seen in Table 6-15.

Table 6-15 Annual CO_2 emissions in different scenarios

CO2	CO2 emission Mt		
	2045		
	ADB	EP 50% RES	EP 50% Enhanced
	28.98	22.81	15.55

The CO_2 emissions are 24.81 Mt, and 17.05 Mt in both EnergyPLAN scenarios and that is relatively is lower than the ADB scenario due to the high biomass share and low oil share.

The Table 6-16 describes the electricity balance in these three scenarios. In the ADB scenario, the 15.71 TWh export/CEEP value is comparatively high for export and need more energy storage facilities to cater to that value. However, import electricity share is 7.8 TWh, meaning that if fluctuating renewable energy is not supplying Sri Lanka's electricity needs, the necessary supplementary electricity must be imported from elsewhere e.g. nearest country to recover the electricity demand. However, the EnergyPLAN scenarios represent high import value and less export and CEEP values which are relatively positive due to the low chance of electricity export.

Table 6-16 Electricity balance in different scenarios

Parameter	Electricity Balance TWh		
	2045		
	ADB	EP 50% RES	EP 50% Enhanced
Import	7.8	22.97	19.36
Export	15.71	0.28	0.64
CEEP	15.71	0.28	0.64
EEEP	0	0	0

Fig 6-11 graphically represents the electricity balance in 50% EP scenario for January 2045.

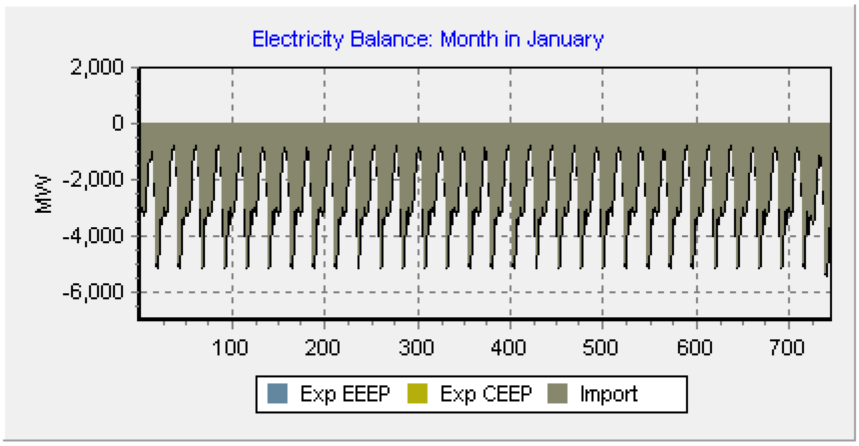

Fig 6-11 Electricity balance January 2045 for 50% EP model.

Table 6-17 illustrates the renewable energy share of the primary energy supply and electricity generation. ADB has 105.4% renewable electricity generation due to the high use of wind and solar power share. The EnergyPLAN 50% RES scenario design, using optimal resources is described in the section 5.4 and achieves 50% renewable energy of the primary energy supply and 50% of electricity generation. Furthermore, the EnergyPLAN 50% amended version design uses more biomass, biofuels and electrolysers. In addition, the reduction of electricity demand and saving of oil for industry and transport are also contributing factors in the success of the EnergyPLAN 50% amended version as described in section 5.4. The final EnergyPLAN design has a 67.7% renewable energy share of primary energy supply if the country's renewable energy concept implements this design.

Table 6-17 Renewable energy share in different scenarios

Parameter	**Renewable Energy Share -RES (%)**		
	2045		
	ADB	**EP 50% RES**	**EP 50% Enhanced**
Primary Energy Supply(PES)	46.5	52	69.9
Electricity Generation	105.4	50	54.1

6.5 Sri Lankan 100% Renewable energy model

Finally, a 100% renewable energy simulation model for 2050 was designed by reflecting on the 2025, 2030, 2040 and 2045 simulation models. As described in

Chapter 5, the 2050 model involved two different model scenarios, utilising the ADB 100% model and the EnergyPLAN 100% RES model. The ADB model design used data from ADB 100% renewable electricity generation. The EP 100% model was designed in relation to the 2045 EP 50% RES model. The related simulation results attached in appendix 20 and 21.

Tab 6-18 Average monthly electricity demand

Month	Average monthly electricity demand (MW) 2050	
	ADB 100%	EP 100% RES
January	7759	7841
February	8129	8211
March	7881	7963
April	8200	8282
May	8286	8368
June	8294	8376
July	8111	8193
August	8415	8496
September	8532	8613
October	8304	8386
November	8290	8372
December	8132	8214

According to the official statistics for 2050, the total electricity demand forecast is 71.97 TWh. The ADB 100% model used both the identified projected value and the distribution of the electricity demand over the year to simulate the above design. The EnergyPLAN (EP) 100% RES model consumes 0.55 TWh additional electricity demand for the biomass conversions and transportation and 1 TWh for the dump charging system. Table 6-18 shows the comparison of average monthly electricity demand for two scenarios in 2050.

According to the simulated results from the EnergyPLAN software can obtain graphical pictures from the output tab. Fig 6-12 illustrates the electricity demand throughout January 2050.

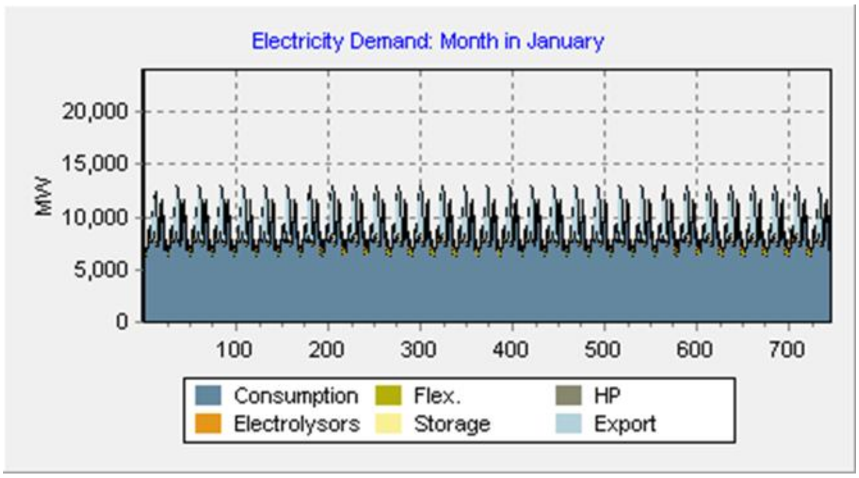

Fig 6-12 Electricity demand month of January 2050 for 100% EP model

The electricity produced from various resources such as hydro, biomass wind-solar, river hydro, power plant and electrolysers were different in each scenario.

Table 6-19 Annual electricity demand by source in different scenarios.

Source	Annual electricity production TWh	
	2050	
	ADB 100%	EP 100% RES
Hydro	2.8	2.8
Biomass	1.15	1.15
Wind	42.76	40.71
Solar	31.7	30.8
River Hydro	3.49	3.49
PP	0	0
Electrolysers	0	2.35

The ADB 100% model was targeted to achieve 100% renewable electricity generation and the EP 100% RES model is demonstrated a comprehensive energy solution for electricity, industry and transport sectors. Tab 6-19 represents the total amount of electricity generated from the various resources of each model in 2050.

According to the Table 6-19, renewable energy resources used in both scenarios look to achieve 100% renewable electricity generation. The ADB scenario produced more wind and solar energy than the EP 100% scenario, but the EP scenario used electrolysers to produce H_2. According to the simulation results obtained from EnergyPLAN software, Fig 6-13 illustrates the electricity production during January 2016.

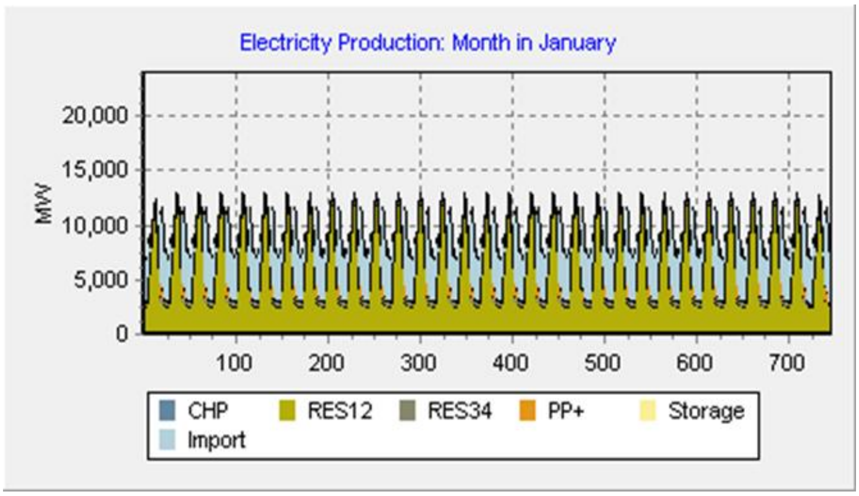

Fig 6-13 Electricity production January 2050 100% EP model

Fig 6-14 shows the installed capacities used for electricity generation in different scenarios. Both scenarios have used the same installed capacities for hydro, biomass and river hydro i.e. 1576 MW, 394 MW and 753 MW respectively, as there is no development for future dammed hydro and river hydro. However, there is less biomass share used for electricity generation in the EnergyPLAN scenario because more biomass and waste have been used as biofuel to fulfil the transport demand in the energy and industry sectors. Both scenarios have used wind and solar massively to achieve 100% renewable electricity generation. Electrolyser installed capacity is 700 MW in EnergyPLAN model.

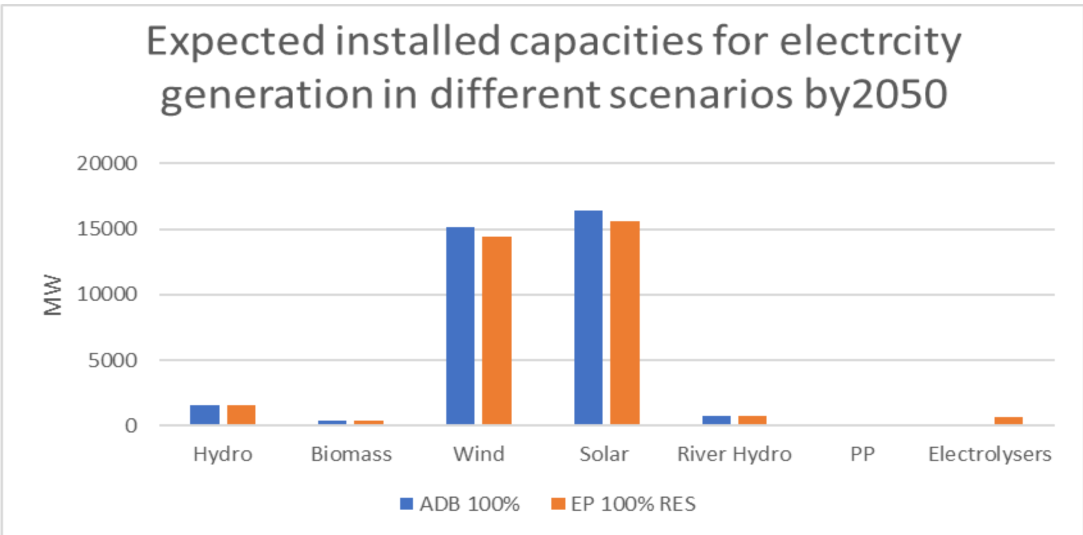

Fig 6-14 Total installed capacity for electricity generation by 2050 in different scenarios.

The total fuel consumption in Sri Lankan energy system for 2050 as identified in the ADB 100% and EnergyPLAN 100% RES scenarios as seen in Tab 6-20.

Table 6-20 Annual fuel consumption in different scenarios

Source	Annual fuel consumption TWh 2050	
	ADB 100%	EP 100% RES
Coal	0	0
Oil	111.8	0
Biomass	30.23	203.94
Renewable	80.74	77.08

Table 6-20 is represented below in graph form as seen in Fig 6-15. The ADB scenario shows a higher oil and renewable energy share than biomass share for the final energy consumption. Both EnergyPLAN scenarios have no coal consumption, and oil consumption has reduced gradually to zero. Biomass consumption as fuel has a low share in the ADB scenario but the biomass share is higher in EP scenario. The ADB scenario shows that the renewable energy share is higher than the EP scenario.

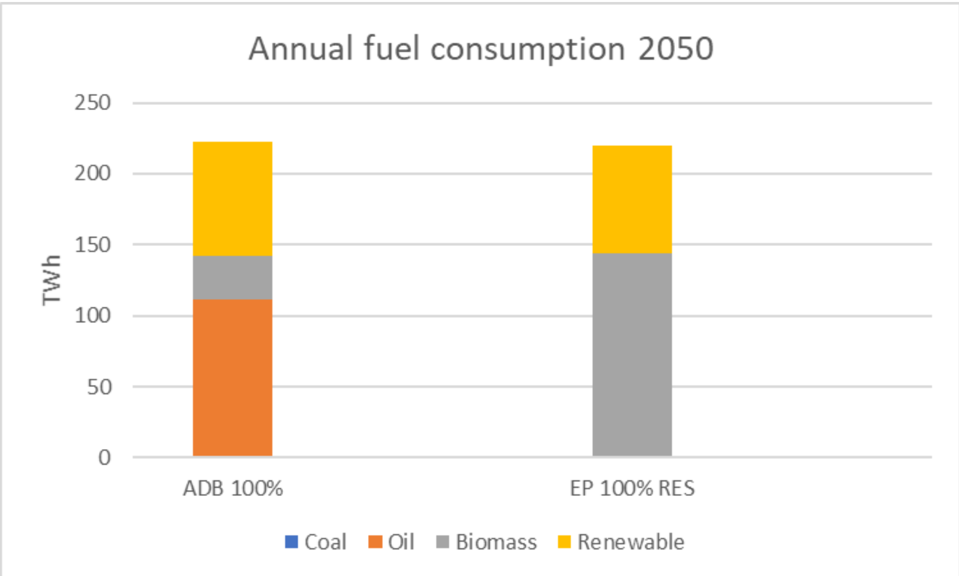

Fig 6-15 Annual fuel consumption by source in different scenarios.

EnergyPLAN scenarios used biomass and renewable energy to fulfil the entire energy demand in Sri Lanka.

The CO_2 emission results found from the simulation and the CO_2 emissions for Sri Lanka were compared within different scenarios in 2050, as seen in Table 6-21.

Table 6-21 Annual CO_2 emissions

CO2	CO2 emission Mt	
	2050	
	ADB 100%	EP 100% RES
	29.78	0

The CO_2 emissions were 29.78 Mt in the ADB scenario, and 0% in the EnergyPLAN scenario due to the use of biomass and renewable energy to fulfil the entire energy demand in Sri Lanka.

Table 6-22 describes the electricity balance of these two scenarios. In the ADB scenario, 25.17 TWh export/CEEP figure is relatively high, allowing for export and /or the need of energy storage facilities to cater for that value. Nevertheless, import electricity share is 15.25 TWh meaning that if fluctuating renewable energy is not supplying Sri Lanka's electricity needs, additional electricity must be imported from elsewhere to recover the electricity demand. However, EnergyPLAN scenarios represent low import value and high export and CEEP values and to balance that excess energy, storage facilities must be available.

Table 6-22 Electricity balance

Parameter	Electricity balance TWh	
	2050	
	ADB 100%	EP 100% RES
Import	15.25	19.44
Export	25.17	20.63
CEEP	25.17	20.63
EEEP	0	0

Fig 6-23 graphically represents the electricity balance in 100% EP scenario for January 2050.

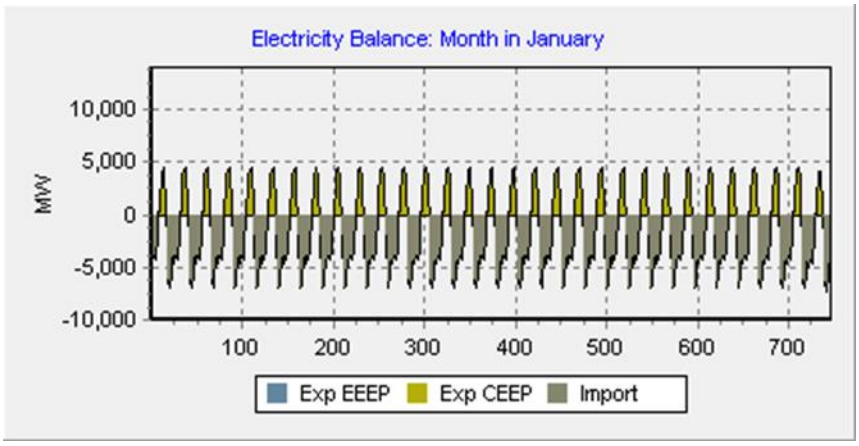

Fig 6-16 Electricity balance January 2050 for 100% EP model

Table 6-23 illustrates the renewable energy share of the primary energy supply and electricity generation. The ADB model achieved 49.8% renewable energy share from the primary energy supply and reached 112.2% renewable electricity generation due to the high use of wind and solar power share. The EnergyPLAN 100% RES scenario design achieved 100% renewable energy share for both primary energy supply and electricity generation.

Table 6-23 Renewable energy share

Parameter	Renewable Energy Share- RES (%)	
	2050	
	ADB	EP 50% RES
Primary Energy Supply(PES)	49.8	100
Electricity Generation	112.2	100

The Sri Lankan CEB grid development plan for 2040 contains some significant modifications for the electrcitity infastructure system [83]. The ADB [158] report also provides electricity infrastructure changes to achieve 100% renewable electricity generation. The EnergyPLAN simulation has been completed by designing a 100% renewable energy solution for the entire energy system. In this design, the official data has been obtained from both CEB and ADB reports along with the energy balance predictions from the Sustainable Energy Authority [15].

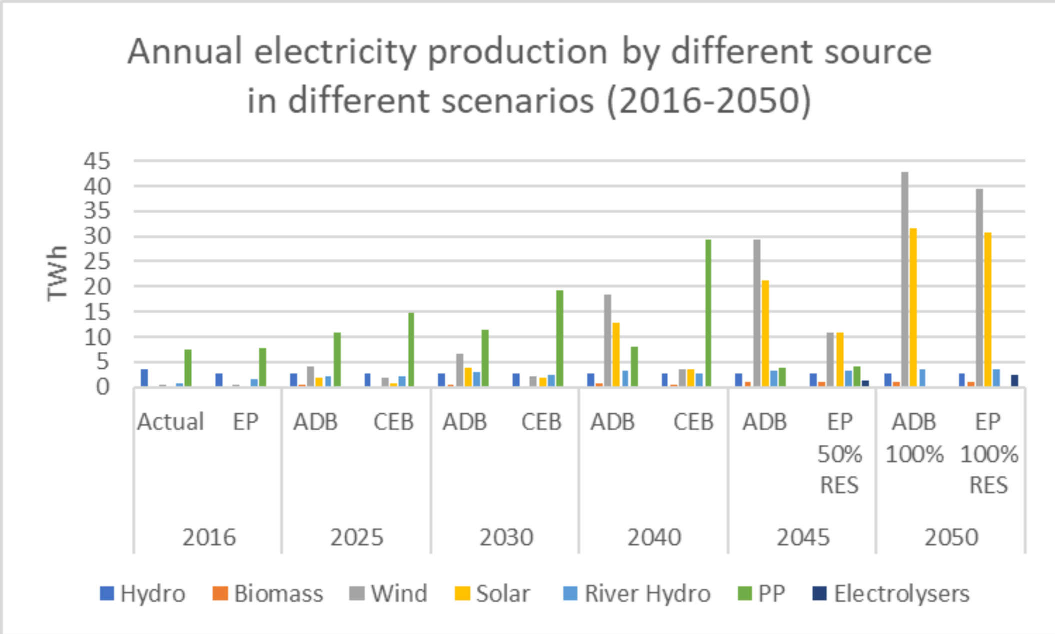

Fig 6-17 Annual electricity production by source in different scenarios from 2016-2050.

Fig 6-17 illustrates the annual electricity generation in different scenarios from 2016 to 2050 by source. There is a massive increase in renewable energy production due to the higher share of wind and solar energy. Until 2050 the dammed hydro and river hydro generation does not change and there is a minimal development of biomass for electricity generation in this energy scenario.

In the 2050 ADB and EP scenarios, wind power capacity will reach the value of 15155 MW and 14430 MW from 131.5 MW in 2016. Also, solar power capacity will increase to 16438 MW and 15600 MW respectively from 21.4 MW in 2016. The reason for the above massive increase in the installed wind and solar capacities is the decrease in energy production of power plants in achieving zero carbon emissions. There are no significant changes in hydro, river hydro and biomass developments and the Fig 6-18 illustrates the total installed capacities for electricity generation by sources from 2016 to 2050.

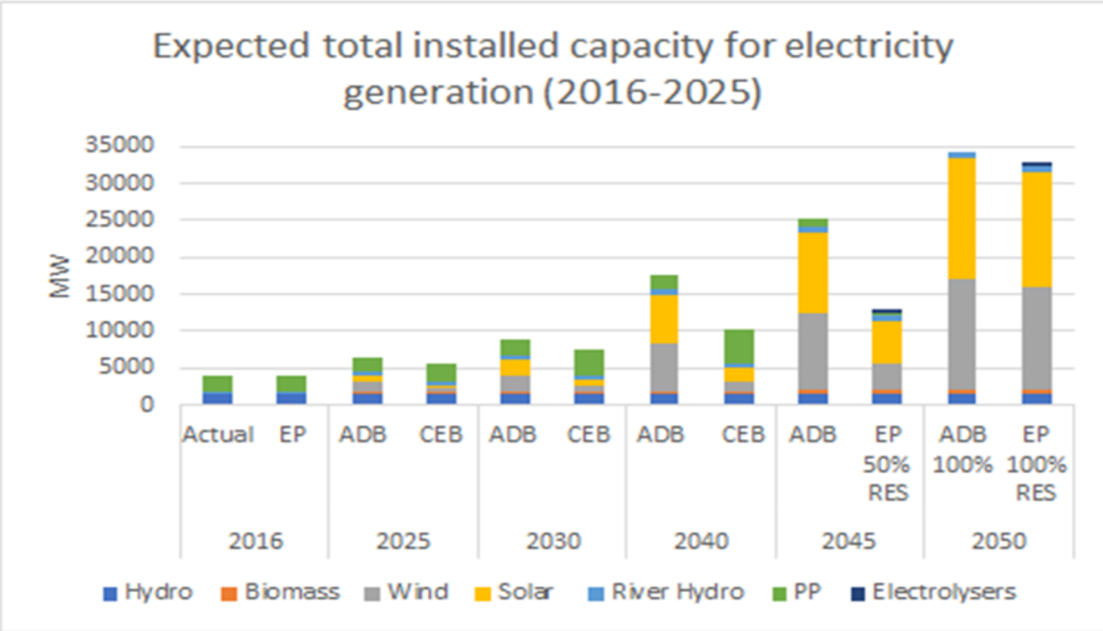

Fig 6-18 Installed capacities for electricity generation in different scenarios from 2016-2050.

The Fig 6-19 represents the annual fuel consumption in Sri Lanka. Coal consumption decreases from 15.25 TWh in 2016 to 0.00 TWh in the 2045 and 2050 EnergyPLAN models. The biomass shares of 54.16 TWh increases to 65.44 TWh and 143.6 TWh respectively in 2045 and 2050. It shows an 83.3% increase of biomass in 2045 and a 45.6% biomass share increase in 2050. The 2045 and 2050 renewable energy shares are 27.69 TWh and 75.86 TWh respectively, and this is an increase from 4.86 TWh in 2016.

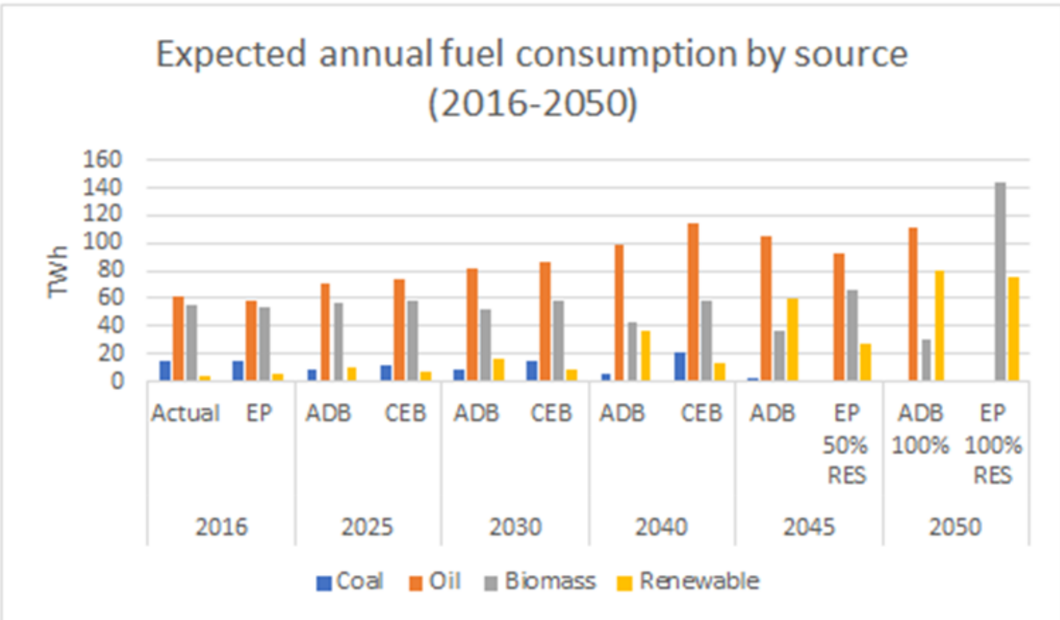

Fig 6-19 Annual fuel consumption by source from 2016-2050.

The renewable energy production of the power plants will contribute to a decrease in CO_2 emissions. As seen in Fig 6-20, the CO_2 emissions in 2016 are 20.21 Mt and in 2045; the CO_2 emissions are 22.81 Mt. According to the figure, across all time scales, the ADB scenarios have less CO_2 emissions than CEB scenarios due to the introduction of renewable energy share in every year.

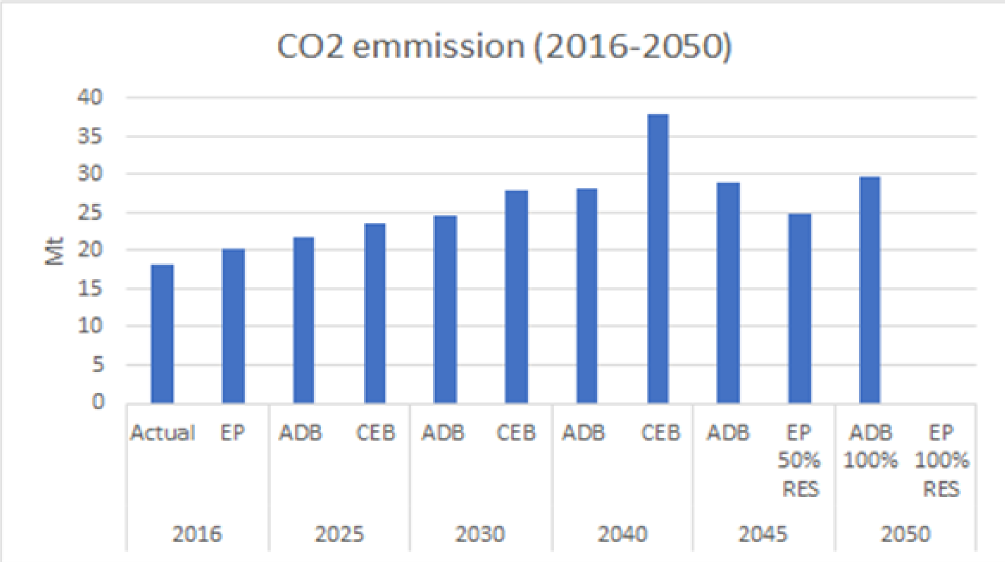

Fig 6-20 CO_2 emissions in different scenarios from 2016-2050.

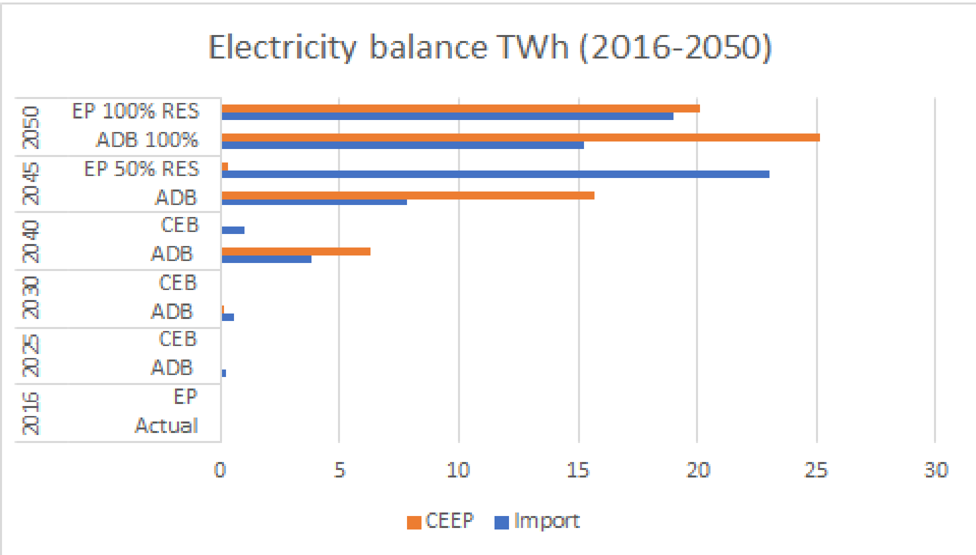

Fig 6-21 Electricity balance

The analyses in the EnergyPLAN model are conducted for the closed energy system, which means that the total electricity demand, albeit industry, transport or other demands demand is provided by local/national generation. In some cases, a Critical Excess of Electricity (CEEP) can occur. CEEP cannot be used in the energy system as it is the amount of excess electricity produced from the energy generation system. This excess is the result of the mismatch between supply and demand, and the inability of the energy system to absorb the extra electricity. Fig 6-21 illustrates the electricity balance in different scenarios from 2016-2050.

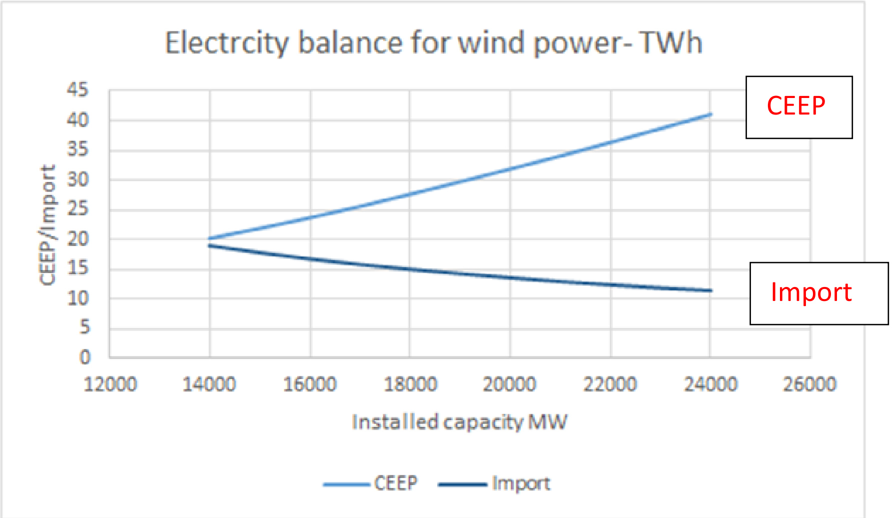

Fig 6-22 Electricity balance for wind power

The increased wind energy production will also lead to a massive increase of CEEP and decrease of import. The Fig 6-22 shows electricity balance for wind power when the installed capacity increases from 14000MW to 24000MW.

Furthermore, for 100% renewable energy solutions, the Sri Lankan energy system must come from power units capable of supplying ancillary services needed for grid stability and energy storage. Also, there will be a need for some more back up power plants to manage the imported electricity.

6.6 Scenario development

Scenarios are like storylines to predict the future within a possible range of existence. Researchers agree to the fact that future events related to technological development or economic growth cannot be predicted accurately. These are usually associated with some uncertainty due to unpredicted events or landmarks that decide a path of growth for future techno-economic scenes. However, significant possibilities are usually known and should be incorporated in any future planning. Therefore, the scope of this study has also been to cover significant possibilities in the form of different scenarios. These scenarios represent those factors most likely to affect the future development of renewable energy technologies in the Sri Lanka power sector.

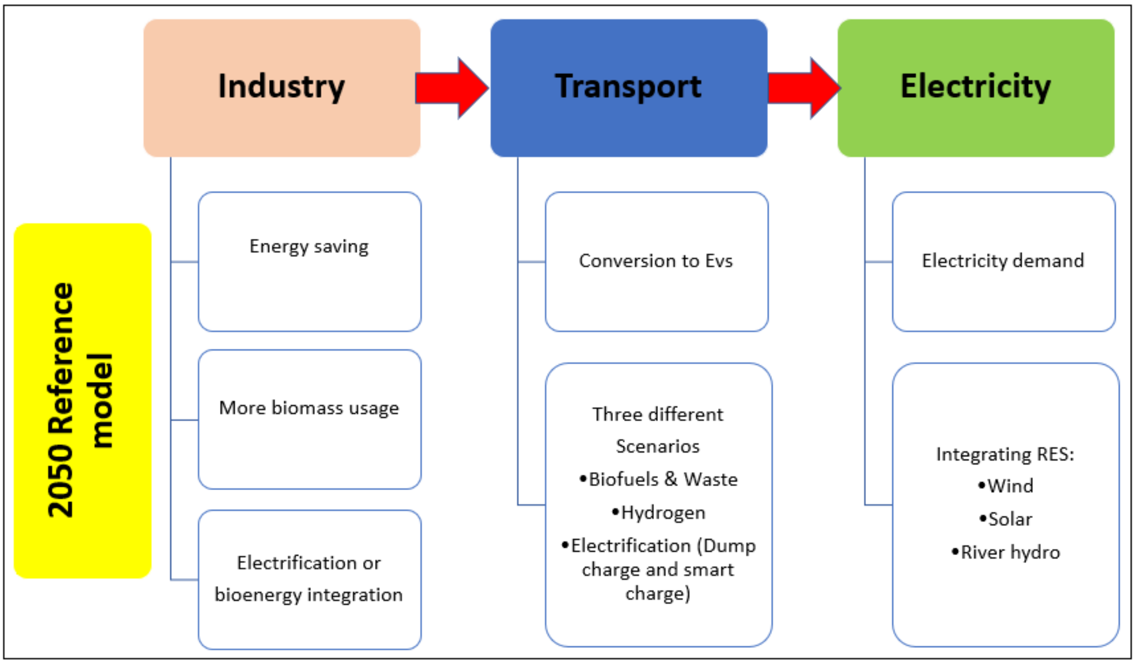

Fig 6-23 Different scenarios and factors for future energy system.

The overall ambition of the scenarios is to achieve a 100% renewable Sri Lanka energy system in 2050. Scenarios, including proposals for new renewable energy resources and technologies, are developed with a view towards 2050 by using the CEB long term generation plan and the ADB 100% electricity generation reports.

A reference model of the Sri Lanka 2016 was created initially. Using recent data from the Sri Lanka energy sector, 2050 model was created which includes development improvements for renewable energy technologies for industry, transport and electricity sectors as illustrated in Fig 6-23.

6.6.1 Industry

For the industrial sector, three scenarios are proposed for developing and converting towards 100% renewable energy. The first scenario is primarily focusing on energy-saving measures within the industry, while the second scenario focuses on more biomass use for industry operations. Alternatively, bioenergy integration and electrification is the third scenario proposed for the industry sector to achieve 100% renewable energy.

Through implementing improvements in industrial energy intensity and by using correct saving potentials, there will be lower fuel demand. Fuel demand for the industry will be supplied through a high share of biomass usage. The third scenario measures are implemented for bioenergy and electrification integration, and in the bioenergy scenario, all remaining fuel consumption is converted to solid biomass, corresponding to a biomass demand of 90.24 TWh/year.

6.6.2 Transport

The transport sector scenarios continue from two groups of scenarios that are developed within the transport sector for converting to renewable energy. The first scenario consists of significant conversion to electric vehicles (cars and vans). The next group consists of three alternatives to convert the remaining cars and vans as well as heavy-duty transport (air, sea, rail, trucks and busses) to use renewable energy.

The groups of scenarios are:

1. Conversion of cars and vans to electric vehicles (EVs)
2. Conversion of the rest of the transport demand to:
    - 2nd generation biofuels
    - Hydrogen
    - Electricity (dump and smart charging)

The EV conversion scenario assumes that all transport fuel demand that was previously based on oil-based products can be converted to electricity-powered transport in cars and vans. The remaining transport demands are supplied from fossil fuel sources replaced by 2nd generation biofuels, Hydrogen, Bio-electrofuels, CO2-electrofuels and Electricity (dump and smart charging).

However, this approach indicates which technologies are preferable for converting towards 100% renewable energy in the transport sector. The biofuel scenario converts all remaining oil consumption to 2nd generation biofuel products if diesel vehicles are converted to biodiesel, petrol vehicles to bioethanol while aviation is converted to bio-jet fuel. Also, biofuel transportation requirement is fulfilled from the waste as well. Vehicle efficiencies are unchanged in this scenario compared to the previous fossil fuel scenarios in the hydrogen scenario; all remaining transport demand is converted to transport modes supplied by hydrogen via fuel cell powertrain technologies.

In the dump charge system, one charging station is assumed per electric vehicle. A dump charging system can be achieved from the solar power systems in many different sites related to home or work base locations.

According to the 2050 EnergyPLAN model, diesel, petrol and jet fuel requirements are fulfilled by biodiesel, methanol and bio-jet fuel. The demand for those sections are 57, 26 and 0.03 TWh respectively and the 2.7 TWh biofuel demand is gained from waste to achieve full transport demand. The H_2 demand is 2 TWh and 2 TWh of dump charge system which also contributes to fulfilling the annual 145 Billion km transport demand in Sri Lanka by 2050.

Fig 6-24 Illustrates of components of H_2 energy system and interactions with other parts of the whole system. In the model, Hydrogen is calculated as three separate systems:

1. One for CHP and Power plants
2. one for micro CHPs, and
3. a joint system for the production of hydrogen for transportation and hydrogenation

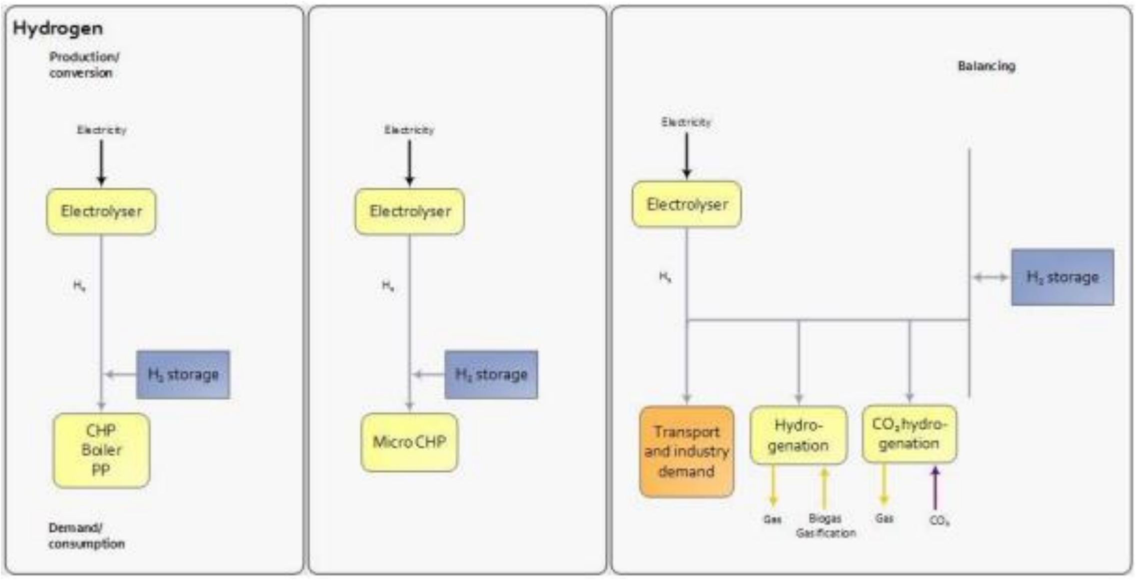

Fig 6-24 Components of H_2 energy system [20]

6.6.3 Electricity

The non-renewable primary energy remaining in the system at this stage is within the electricity sector, which is the final sector to be converted. The following measures are taken for converting to 100% renewable energy in Sri Lanka:

1. Energy savings in the current electricity demand
2. Variable renewable sources integration such as wind, PV, dammed hydro and river hydro.

The total electricity considered through simulation is 73.52 TWh, including electricity for biomass conversions and electricity for transportation as well. The above-mentioned electricity demand is obtained from 14430MW wind, 15600MW solar, 1576 MW major hydro and 753 river hydro.

6.6.4 2016 Reference EnergyPLAN model

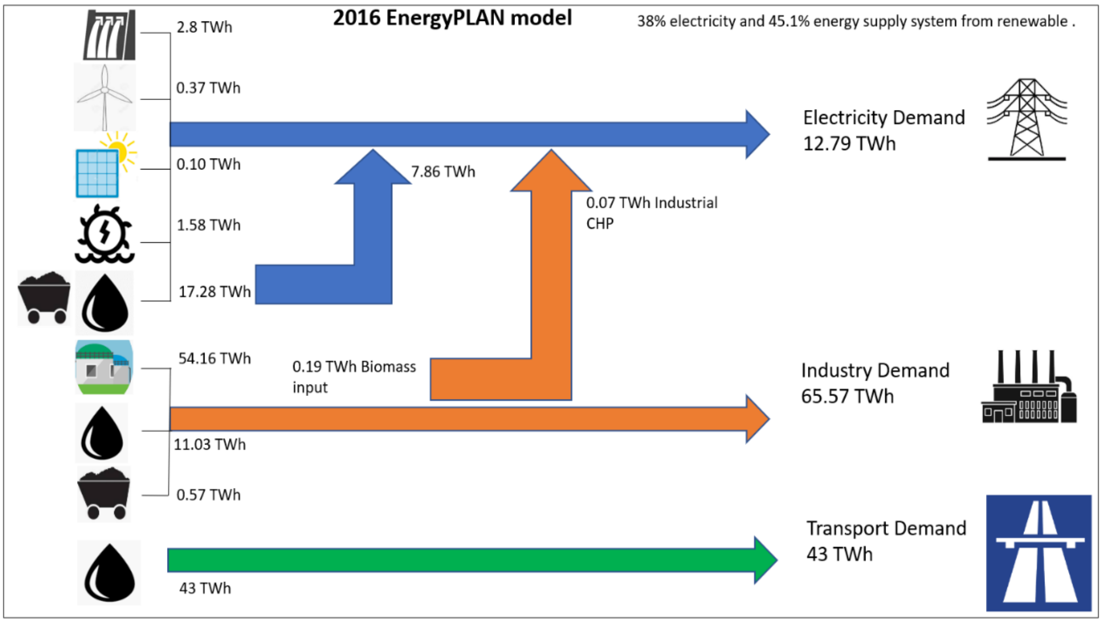

Fig 6-25 Energy flow chart for 2016 reference energy model

The reference energy model in Sri Lanka 2016 is based on measures which can be realised with current technology. In this model, electricity demand consists of the following components: dammed hydro, river hydro, wind, solar and oil. A high share of biomass, oil and a little percentage of coal fulfils the industry energy demand while only oil satisfies the transport demand in Sri Lanka as illustrates in Fig 6-25 energy flow chart.

6.6.5 2045 EnergyPLAN model

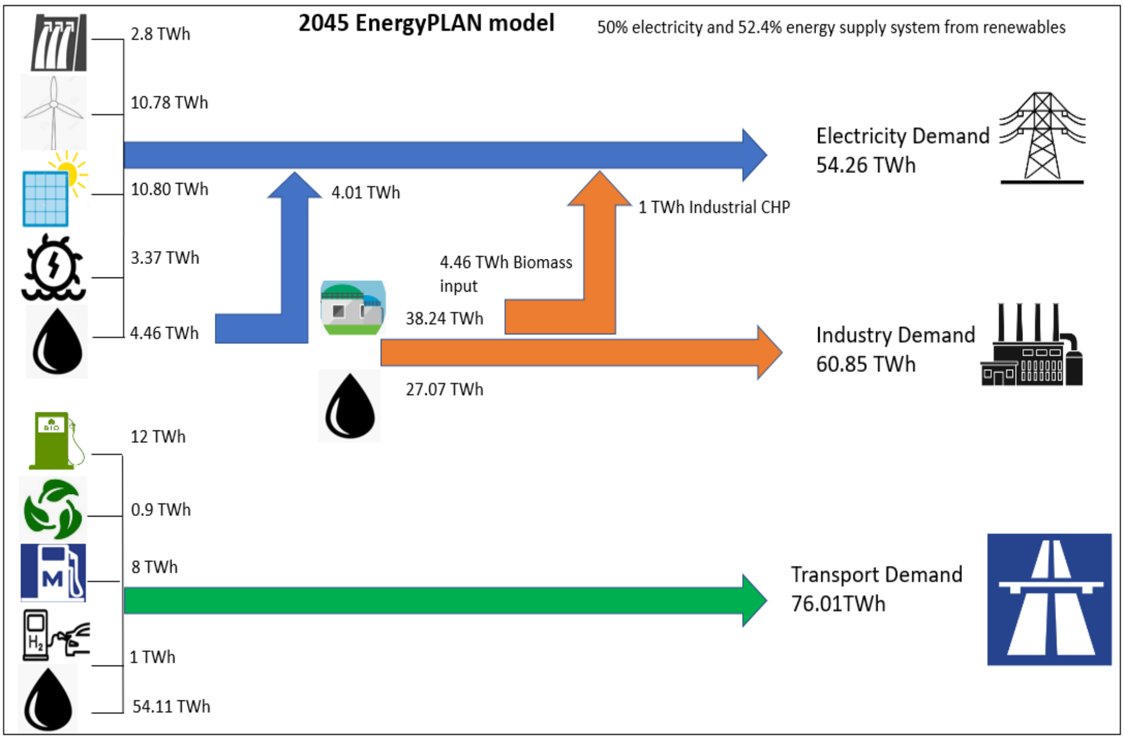

Fig 6-26 Energy flow chart for 50% RES model.

In the 2045 energy model, more efficient power plants, more mature and new renewable energy technologies are introduced, and further energy savings implemented. In general, large parts of fossil fuel consumption are replaced by new renewable technologies in electricity demand and more biomass is introduced for the industry energy demand. Specifically, within transport, biodiesel, methanol, biofuels from waste, H2 technology, battery electric vehicles and electrically powered trains have been presented in this model to achieve a 50% renewable energy system. Fig 6-26 illustrates the energy flow chart for 50% RES system including electricity, industry and transport sectors.

6.6.6 2050 EnergyPLAN model

In 2050, an energy system is designed, which is based on 100% renewable energy, starting from the initiatives proposed in the 2016 reference model and including all suggestions from energy models up to and including 2045. The high growth of electricity demand is achieved by a high share of wind and solar, dammed hydro and river hydro. The industry energy demand is covered fully by biomass with incorporating supreme energy-saving approaches and technologies. The transport sectors have achieved radical changes by converting to a high share of biodiesel and methanol, bio-jet fuel, H2 and by implementing a dump charging system as well. Fig 6-27 illustrate the 100% RES model including electricity, industry and transport sectors.

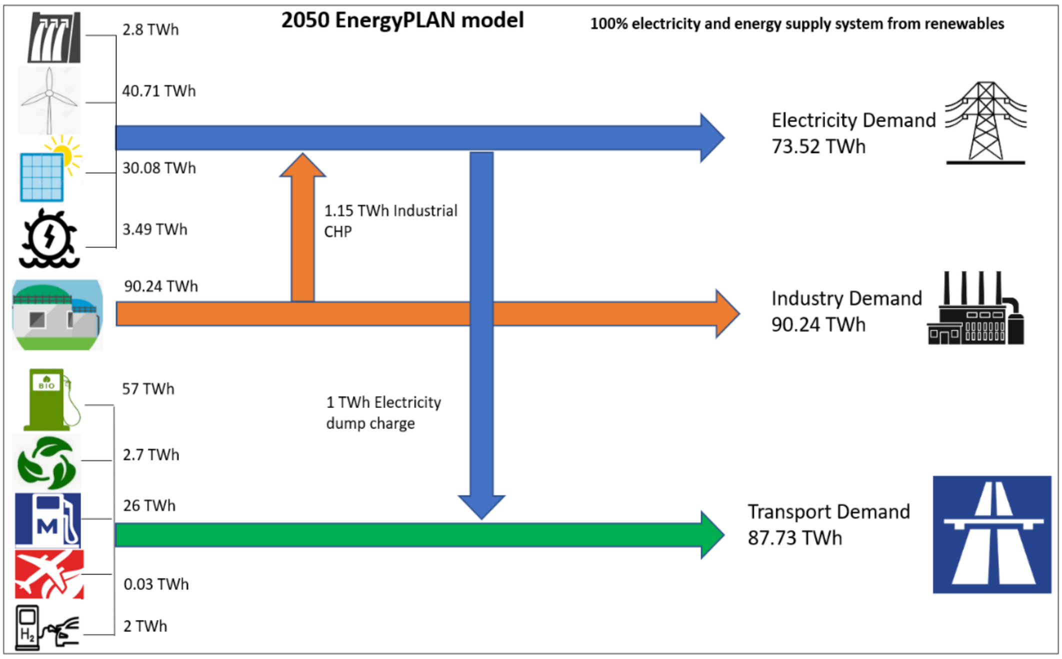

Fig 6-27 Energy flow chart for 100% RES model

Total electricity consumption was 12.79 TWh in 2016 and is projected to increase 5.7 times to 73.52 TWh by 2050. The consumption of electricity in the residential sector increases significantly, as less use of biomass for cooking and other residential use.

In the industrial sector, electricity consumption is projected to increase and biomass and fuel usage predictable to decrease. In 2005, total industry demand was 65.57 TWh and 90.24 TWh and increases about 1.4 times by 2050.

Transport sector demand is projected to increase heavily and need deep-seated changes to develop public transport service in Sri Lanka to reduce personal usage of vehicles especially during busy work hours. The transport demand fulfils by a high share of biodiesel, methanol, bio-jet fuel, H2 and a dump charging system.

6.6.7 Scenario development results

1) The total electricity generation capacity is expected to increase from 4.05 GW in 2016 base reference scenario to 32 GW in 100% renewable energy 2050, i.e., at an average growth rate of 0.8 %.

2) The share of thermal-based power plants for electricity reduces from 0.5 GW in 2045 to 0.0 GW in 2050.

3) The share of industry fuel demand reduces from 11.06 TWh in 2016 to 0.0 TWh in 2050, while biomass share increases from 54.16 TWh in 2016 to 90.24 TWh in 2050.

4) The transport fuel switch from diesel, petrol, LPG and Jet fuel to biofuel, methanol, waste to biofuel, jet biofuel, H2 and dump charge technologies. Diesel consumption decrease from 27.07 TWh in 2045 to 0.0 TWh in 2050 while biodiesel production increases from 12 TWh in 2045 to 57 TWh in 2050. Also, biodiesel from waste increases to 2.7 TWh in 2050 from 0.9 TWh in 2045.

Petrol consumption for transport decreases from 15.27 TWh in 2045 to 0.0 TWh in 2050 while bio methanol production increases from 8Twh in 2045 to 26 TWh in 2050. Jet biofuel production of 0.03 TWh achieves in 2050. H2 scenario developed to 2 TWh in 2050 from 1 TWh in 2045 while dump charge system deploys to transport system with 2 TWh capacity in 2050.

5) The cumulative CO_2 emission from the entire energy system decreases from 20.21 Mt in 2016 to 0.0 Mt in 2050.

6) In the renewable target production and null fossil-based fuel import scenarios, wind and solar PV plays a vital role in the generation of electricity, and the capacity is expected to grow by 14.43 GW and 15.6 GW, respectively, by 2050. Other renewable energies reach their allowed maximum capacity levels within the limitations of developments.

7) The capacity share of renewable technologies (biomass and renewable energy) in total fuel consumption (fuel balance) rises 59.2 TWh in 2016 to 94.11 TWh in 2045 and 281.02 TWh in 2050. Most of the biomass between 2045 and 2050 converted to biofuels to fulfil the transport demand in Sri Lanka.

8) Electricity Generation from renewable technologies increases from 4.86 TWh in the base scenario 2016 to 27.75 TWh in 50% renewable energy scenario and, 77.08 TWh in 100% renewable scenario 2050.

9) The share of renewable energy technologies in electricity generation increases from 38% in 2016 to 50% in 2045 and 100% in 2050. The share of renewable energy in primary energy supply increases from 45.1% in 2016 to 52% in 2045 and 100% in 2050.

CHAPTER 7

7.FUTURE TARGETS, CHALLENGES AND SOLUTIONS

This chapter discusses the future targets, challenges and solutions, Sri Lanka facing in the energy industry.

The structure of chapter 7 illustrates in Fig 7-1, and this chapter consists of Sri Lanka's future energy targets, significant challenges in Sri Lanka energy sector and appropriate solutions for Sri Lankan energy sector.

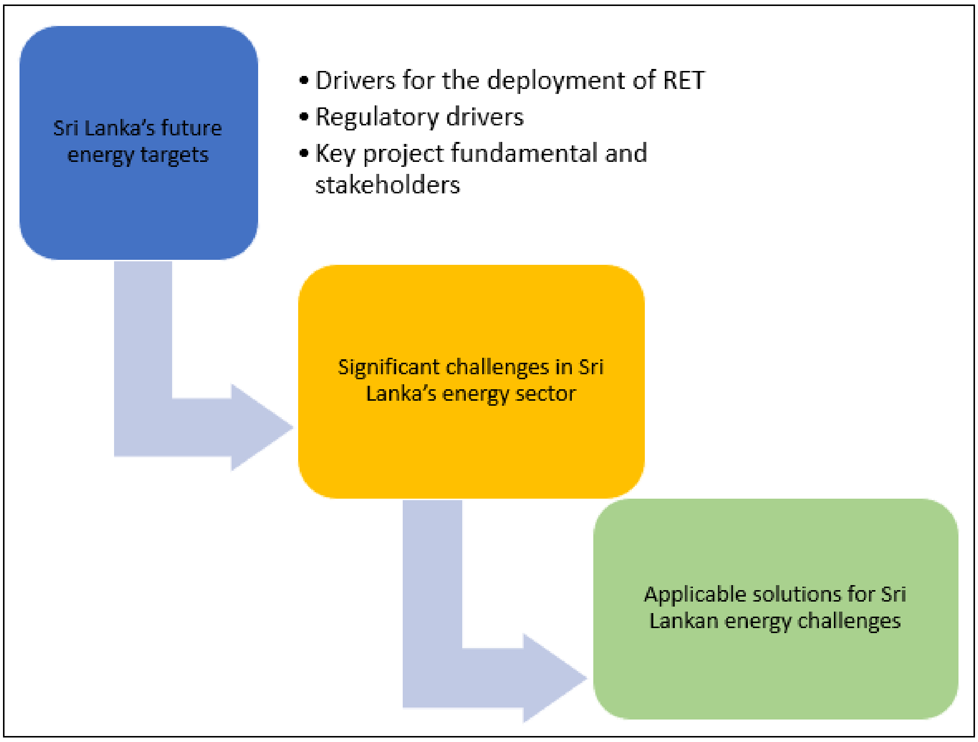

Fig 7-1 Structure of the future targets, challenges and solutions section.

Drivers of the deployment of renewable energy technologies in Sri Lanka, regulatory drivers and critical project fundamental and vital stakeholders to implement renewable energy project in Sri Lanka discuss within the first part of this section.

7.1 Sri Lanka's future energy targets

In 2016, Sri Lanka's electricity generation through fossil fuels was 67%. Indigenous fossil fuel resources are giving a negative impact on the environment, society and economy. The fossil fuel used for electricity generation is imported, and it is a significant part of Sri Lanka's import expenditure. As a developing country, Sri Lanka's demand for electricity is going to increase in the future. It is imperative, therefore, for Sri Lanka to secure its energy future by focusing on the development and adoption of indigenous, renewable sources of energy to meet this growing demand and reduce the economic burden of imports [158].

Sri Lanka pledged to practice only renewable energy electricity generation by 2050 in the Climate Vulnerable Forum at 22nd UNFCCC Conference in Marrakesh, Morocco, November 2016. According to the joint study of 'Assessment of Sri Lanka's Power Sector -100 per cent Electricity Generation through Renewable [14] Energy by 2050' by the United Nations Development Programme (UNDP) and the Asian Development Bank (ADB), the country's installed capacity will increase to about 34,000 MW from the current 4018 MW in 2016. The total installed capacity will be provided by solar, wind and biomass-based power plants respectively 47%, 44% and 9% [158,159].

Sri Lanka's government energy action plan includes the following parameters to achieve a 100% renewable energy in electricity generation by 2050:

1. Motivations to ensure the secured energy supply.
2. Motivations to encourage sustainable energy supply and practice.
3. Motivations to improve the attractiveness of energy supply.

While committed to 100% renewable energy electricity generation by using a reasonable generation mix, it is a challenge to overcome numerous technical and economic problems such as renewable energy integration difficulties and financial interferences required for Sri Lanka’s power sector [159].

7.1.1 Drivers for the deployment of renewable energy technologies in Sri Lanka

There are some abundant drivers and motivations available to achieve the successful deployment of renewable energy technologies in Sri Lanka. Some of the drivers include [160]:

1. Security of energy supply
2. Environmental concerns
3. High and fluctuating fossil fuel prices
4. Technology development and business perspectives

5. Agricultural, rural and social issues
6. Modern energy recovery technologies
7. Renewable energy integrations.

7.1.2. Regulatory drivers

When considering the modern renewable energy industry such as incineration, biomass and biofuel projects in Sri Lanka, it is necessary to understand the associate major regulatory drivers forcing the development as mentioned in Fig 7-1.

1. Greenhouse gas (GHG) policies
2. Renewable energy policies
3. Recycling policies

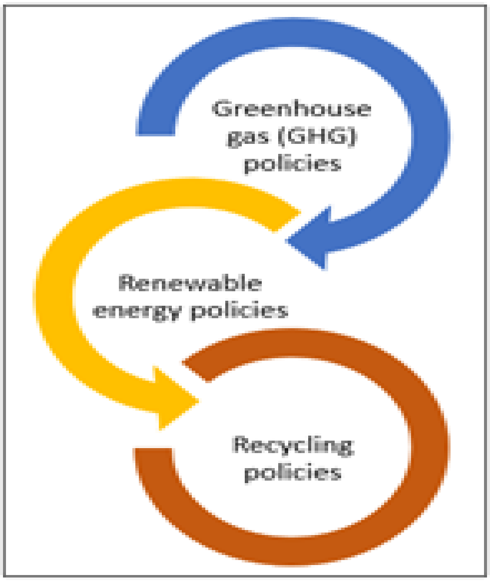

Fig 7-2 Regulatory drivers of modern renewable energy development

Due to open garbage dumping, a significant amount of methane is sent into the atmosphere as part of greenhouse gas emissions. Minimize this environmental issue; need to implement proper waste management systems and recycling policies whereby waste should be reduced, reused and recycled (3Rs) before final disposal. By encouraging GHG and recycling policies in Sri Lanka, this would lead to minimizing organic landfilling by compelling aerobic (composting) and anaerobic digestion of organic waste. By establishing renewable energy policies in Sri Lanka, the energy authorities could produce a certain percentage of energy from renewable sources. Biogas is one of the key renewable energy sources that utilities could use consistently.

7.1.3 Key project fundamental and stakeholders.

Technical aspects and related project fundamentals are the key features for small scale or large-scale renewable energy development projects. Technology is the main character of the mechanism, and feedstock/ fuel source, energy, output material and stakeholders are the other related aspects to the project development

The feedstock quantity and composition are two of the dominant parameters in a biogas project and need a proper mechanism in place to utilize biogas in an efficient way to produce energy. The energy produced from the project and then sold to the National Grid is the critical task within this project, and there should be a proper infrastructure to feed the energy to the National Grid.

In the biogas process, a biomass plant transforms 10% of the mass into the biogas, and the remaining 90% fed into the digester comes out as fertilizer or digestate. It is essential to find the most inexpensive outlet way for the digestate to be shared and used in communities, and it would be a way of securing the project's success. Finally, the project needs a secure financing system which should manage investment costs, operational cost and revenue effectively, to reach a successful project operation outcome.

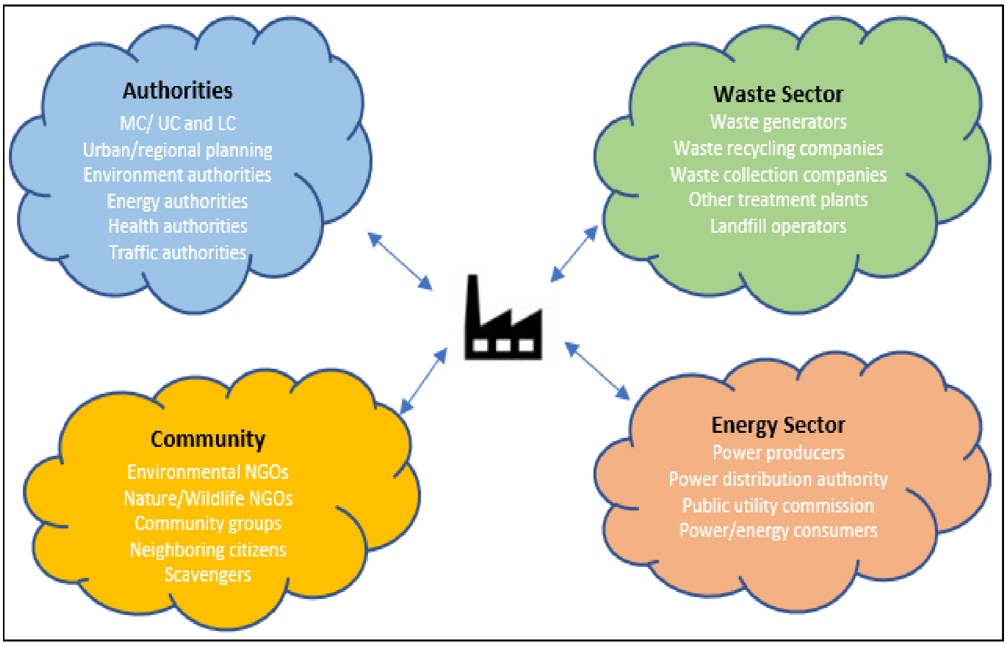

Fig 7-3 Waste management industry-relevant stakeholder

The attitudes of relative stakeholders, legislation and institutional framework of the waste management institute are the most critical parameters for the success or failure of incineration projects. Globally, having different interests between virtual stakeholders is a common problem in the MSW incineration industry, and it is necessary to have a durable agreement regulating the supply of waste, the sale of energy and the price-setting within the key stakeholders. Fig 7-2 shows the necessary stakeholders needed to avoid environmental, institutional, or financial differences in the solid waste management industry [115,116].

7.2 Significant challenges in Sri Lanka's energy sector

There are some significant challenges can be identified within the Sri Lankan energy sector, and those are [115,116,160];

1. Lack of local capacity development, research and technology
2. Traditional institutional setup not geared to meet emerging energy sector challenges
3. Unsustainable consumption patterns
4. Energy wastage and losses
5. The need for significant investment needs for infrastructure development in the power & energy sectors.
6. Renewable energy integration technology issues
7. Week supply chain management for successful project operations.
8. Connection limitations from the renewable energy power plant to the national grid
9. Limitations of power connection facilities for the infrastructure facilities for the connection of the national grid.
10. Low interests from developers and investor's on investments for the new renewable energy projects due to market instability.
11. Weak transport mechanisms.
12. Government's weak proposal for the attractive incentives and offers on reasonable subsidies for developers and investors
13. Government's short attention of giving assurance to developers to protect them from investment risks
14. Unavailability of the guaranteed short-term power purchase price for the generated power until the pioneer ventures stabilize

15. Lack of encouragement and education for all relative stakeholders to understand the basic principles of renewable energy power generation
16. Absence of reasonable tariff policies for the purchase of renewable energy power to the national grid
17. Lack of community engagement for the operation and maintenance of renewable energy projects to eliminate operation costs and other related costs.

7.3 Applicable solutions for Sri Lankan energy challenges

Many solutions can be taken to increase the use of renewable energy in Sri Lanka [115,116,160].

1. Build solar panel parks on buildings, schools, public areas, and wherever it is feasible and applicable.
2. Encourage domestic solar panel installations. People should be educated to use smart meter process and produce electricity to the national grid and could earn income.
3. Since putting up, solar panels incur a start-up cost, interest-free or low-interest loans could be provided for individuals and companies who are interested in contributing to producing electricity. These could be written off against the income generated by producing power or utility bills.
4. Building wind farms (like solar parks)
5. Encouraged investors and small business owners to start biomass projects.
6. People should be encouraged to build mini-hydro power plants, either as individuals or companies. The same encouragement in the form of awareness and loans could be provided.
7. The general public should be made aware of using more renewable energy sources and saving electricity as much as possible.
8. Encourage people for the sustainable waste management system and state participation for the waste to energy projects.
9. The rules and regulations of the country should be changed; thus, people are strictly bound by legislation to use more renewable energy resources and provide rewards for producing energy and providing them to the national grid.

10. Promoting research and development on renewable energy technologies, introducing collaboration opportunities with other countries to learn and deliver related energy projects.
11. Addressing the possibilities and benefits of renewable energy projects in the community and creating a positive path for the recycling of waste.
12. Promoting attendance at conference and workshops for farmers, community leaders, investors and developers to learn about how renewable energy produces power.
13. Organizing exhibitions to gather together all the relative stakeholders and community members to learn about the new technologies and advantages of developing renewable energy projects.

CHAPTER 8

8.CONCLUSIONS AND FUTURE WORK.

8.1 Summary methodology

This research aims to evaluate a feasibility study of the development and implementation of a smart energy system for 100% renewable energy and transport solutions in Sri Lanka with a particular focus on renewable energy technologies.

To fulfil one of the broad research objectives, the EnergyPLAN model was selected and adapted to the Sri Lankan power sector. As EnergyPLAN requires exogenous electricity demand, the CEB long term generation plan and Energy balance reports were used to calculate the future demand for different energy sectors such as electricity, industry and transport. The following methodologies were applied during the research work:

1) Assessment of the potential of renewable energy resources for power generation: Renewable energy sources such as sun and wind are widely available, but renewable energy does not exist in ready-to-use forms for power generation. The theoretical potential of renewable energy resources is relatively high. However, in the course of exploitation, constraints such as land use, geographical area and climate are encountered. To deploy these resources, suitable sites need to be identified, which also must guarantee minimum disturbance to the surroundings. In the case of wind power, these conditions mean that wind turbines should be located within a certain distance from residential areas to reduce noise and shadow effects. In the case of solar photovoltaic (PV) however, these constraints do not apply because this technology causes almost no noise or pollution. Therefore, different methodologies need to be developed for each renewable-energy-based power generation.
2) Development of the EnergyPLAN-SRI LANKA model: The exogenous parameters of power generation used for the development of the EnergyPLAN-SRI LANKA model can be grouped into three broad categories, namely:

a. Power or energy demand,
b. Availability of energy resources
c. Conversion technologies.

Modelling with EnergyPLAN requires the establishment of relationships between technologies, activities and energy flows. The Sri Lanka power sector was taken as the reference energy system and represented the activities and technologies in an energy system. This research can be used as a role model by other Asian countries to develop and achieve 100% renewable energy scenarios.

3) Modelling the Sri Lankan power sector with particular focus on renewable energy technologies: Like other energy planning models, the EnergyPLAN model was initially designed, applied and developed to find the technical feasibility for the 100% renewable energy solution.

   Issues like the market price of energy, fuel prices, investment costs etc., operation and maintenance cost of the power plant and other related costs are the significant reasons for not developing economic feasibility for the 100% renewable energy solution. There is a considerable problem in collecting data in the energy industry to address the above-mentioned issues. There is a separate data tab sheet to handle economic parameters in the model. However, the Sri Lankan model does not provide parameters that can be applied to specify the energy markets and energy economics. Therefore, the economic feasibility of renewable energy technologies does not represent the central focus of this EnergyPLAN model.

4) Scenario development: In the EnergyPLAN model, several scenarios were developed to determine future power supply options for electricity, industry and transport sectors in Sri Lanka. Furthermore, the energy flow diagram for the 2016 reference model, 2045 EnergyPLAN model and 2050 EnergyPLAN model illustrates the energy flow of each scenario and highlights energy production for each sector energy demand.

8.2 Interpretation of results

The results of this study reveal that Sri Lanka has a good potential of renewable energy resources for electricity generation. Based on the four investigated resources, i.e., solar, wind, biomass dammed hydro and river hydro energy, solar energy appears to be the most promising source to achieve 100RE transition due higher technical potential of solar PV (15600 MW). Solar PV technologies are experiencing significant improvements in technologies and cost reduction in global energy economics.

The potential install capacity of wind, biomass, dammed hydro, and river hydro are estimated at 14430 MW, 394MW, 1576 MW and753 MW, respectively. Furthermore, Sri Lanka has a good potential of renewable energy resources for power generation in the industry and transport sectors. Based on the research, 90.24 TWh Biomass capacity will fulfil the industry energy necessity by using appropriate conversion technologies. A total of 143.15 TWH biomass input provides 83 TWh biofuel while 3 TWh waste input provides 2.7 TWh transport fuel to fulfil transport demand. H_2 technology provides the 2 TWh energy supply with 700 MW installed capacity electrolysers with 25 MWh storage facility while dump charging technology provides 2 TWh energy generation to fulfil the balance of transport demand.

8.3 Conclusion

Chronic power shortages due to increasing demands, increasing incapacitation of hydro-power due to global warming, rising costs of imported fossil fuels and difficulties in nuclear alternatives are evident. The current power hike may have been precipitated due to past mismanagement and corruption, but it is inevitable in the best of circumstances.

The demand for energy is snowballing in Sri Lanka. In order to meet demand and at the same time achieve sustainable development objectives on a global scale, conventional approaches to meet energy requirements must be re-orientated toward energy systems based on renewable energy and energy efficiency, which will make it possible to address social, economic, and environmental concerns simultaneously.

In the region, energy infrastructure development lags energy demand growth, due to lack of access in financing. Innovative financing needs to achieve the required investment levels and reduce the high dependency on imported fossil fuel. To this end, the countries in the region have to find alternative energy supply options, including new and renewable energy resources, along with the adoption of more aggressive energy conservation and efficiency policies that will militate against growing GHGs and other pollutants. The region needs a paradigm shift in energy policies and strategies correspondingly in Sri Lanka. There is a growing understanding of the close coupling between secure and sustainable energy supplies and sustainable socio-economic development.

Sri Lanka has the vast potential to use various renewable energy resources for power generation due to the high incidence of solar, wind, rainfall and tidal power. When considering the market status of the above resources, there is a considerable mismatch between the wholesale market and consumer selling price. The private sector owns all renewable energy power plants, and it is necessary to consider the wholesale unit electricity price according to the selling price. There is a lack of introducing new renewable energy projects in Sri Lanka, and the related energy authorities need to reconsider their importance by encouraging people to participate in new renewable energy project investments.

Currently, electricity power cuts in Sri Lanka are influencing the economy of the country, and it is essential to consider new policies, regulations and special incentives applied to investors and consumers for attracting attitudes towards new renewable energy projects. As a tropical country and beautiful island, it is essential to take maximum advantage by using renewable energy in Sri Lanka. Surrounded by the beautiful ocean, the position of the country gives the land the best climate and an abundance of natural resources. Due to its location in the equatorial belt, Sri Lanka receives year-round solar energy potential. By the end of 2017, the UK total solar installed capacity was 12800 MW even though the solar irradiation is 900-1300 KWh/m^2. When comparing the UK with Sri Lanka, Sri Lanka’s total solar installed capacity was 21.36 MW by 2016 and the country has a solar irradiation of 1240 KWh/m2-2110 KWh/m2 which is higher compared to the UK. This figure reflects the lack of government policies, low levels of finance and poor political decisions to achieve sustainable energy future. . Incredible wind energy can also be achieved due to the location of the ocean and tropical temperatures. Due to rainfall, solar energy and environmental conditions, there is high biomass potential. Besides, there are abundant resources from which technologies are available globally to harness the full potential of renewable energy by using the above-mentioned renewable energy technologies.

Power Generation from the Municipal Solid Waste Incineration System in Sri Lanka can contribute to the economic development of the country by two principal means.

1. Transitioning to sustainable municipal solid waste management
2. Contributing to transitioning to 100% RE goals as per Renewable Energy (NCRE) targets as identified in terms of the energy policy of Sri Lanka.

In 2018, the Energy from Waste (EfW) operational capacity was 12 Mt of waste and operated by 43 plants over the UK. The average of 536 KWh/t generated per tonne of waste in the UK in and the total power exported by Energy from Waste in the UK was 6153 GWh approximately 1.9% of entire UK generation in 2018. But Sri Lanka is currently at the early stage of implementing the Energy from Waste projects to handle the waste management system. The adequate disposal of MSW has been a long-lasting issue which has seen a severe tragedy in recent times with the collapse of the Meethotamulla waste dump mountain. Responsible agencies are exploring ways for using MSW for more productive purposes rather than open dumping throughout and Waste to Energy projects have been encouraged. The environmental and social acceptability of these projects has been established previously by other investigators and studies conducted by responsible agencies. However, the situation has remained unchanged over the last few years.

Assessing the environmental and social impact provides a better justification for the implementation of a Waste to Energy project in the Western province in Sri Lanka. Rapid waste generation, poor waste management, waste transportation and the grid infrastructure system make it even more critical to implement Waste to Energy projects.

The operation of a power plant is required throughout the day to handle that massive daily waste quantity, and therefore the waste collection bins of the plant should have required buffer stocks to face any contingency situations.

The other major issue is how to handle ash, which is the major residual from the operation of the project. The highest amount (which is 85.5%) constitutes bottom ash, and the quantity depends on how much MSW is incinerated per day. There is no proven method yet developed in Sri Lanka, but there are some positive motivations and research ongoing to find the best possible solution to use bottom ash for construction work.

Currently, Sri Lanka is experiencing many substantial waste management problems, and there are many socio-economic and environmental issues related to them. Most of the waste generation and collection can be seen in the Western province of Sri Lanka, and the main fraction of the waste produced (47–80%) is organic. This organic amount is ideal for anaerobic digestion processes and composting in order to produce biogas and fertiliser.

Globally, the magnitude of solid waste management is becoming more crucial for communities and the environment, and modern research aims to introduce a resource recovery solid waste management system. The new arrangement is to establish a plant to produce biogas through using solid waste and subsequently generate electricity using the biogas produced. Also, another advantage is producing fertiliser as a by-product. Benefits of the project include the recovery of energy in the form of biogas, reduction of substantial waste quantity, production of organic fertiliser and environmental protection.

The UK generated 34,758 GWh of electricity and heat from biomass from 205 biomass plants with the installed capacity amounted to 10,225 MW as of December 2018. But under the current economic situation, Sri Lanka has biomass installed capacity of 24.1 MW which is very low related to the resources available.

Sources of waste for the Western province plants are markets, slaughterhouses, fish markets, hotels, industries and households from urban areas. The estimated biodegradable waste generation can be more than 60 t/d of waste, and it should be an absolute priority to initiate a new AD plant.

Before establishing the project, there are supplementary non-technical and technical measures, such as legal aspects and collection, sorting, storage, and transportation of the waste, which need to be addressed. Also, any AD plant established in an urban area will minimise the electricity infrastructure cost of connection to the National Grid. It will also help to cover peak demand by shutting down coal and diesel plants in the busy hours.

As the solar potential is relatively very high, the mission for the next 30 years should be to make Sri Lanka a solar energy country. Such a national solar energy mission should be a significant issue of the government of Sri Lanka to promote ecologically sustainable growth while addressing the country's energy security challenge. This kind of energy mission would also constitute a significant contribution by Sri Lanka to the global effort to meet the challenges of climate change.

Achieving these promising objectives will require vision, strong policy support and the recognition that the higher near-term investment costs will be paid back in the long run with significantly lower costs for imported fuels, cleaner air and reasonable energy security for Sri Lanka.

By using the above-mentioned renewable energy resources, implementing energy-saving methods and deploying related rules, regulation and policies Sri Lanka can develop and implement smart energy system for 50% and 100% renewable energy and transport solution by 2045 and 2050 respectively.

The overall conclusion of the analysis in this thesis is that the design of 100% renewable energy systems for Sri Lanka is possible. Various 100% renewable energy system substitutes were designed for all European countries and the Sri Lankan reference model can be used as a sample or research model to extend the 100% renewable energy solution concept for other countries as well.

Future 100% renewable energy systems will be more efficient in terms of primary energy supply compared to existing systems due to energy savings and the integration of technologies with fewer energy losses.

8.4 Contribution to the field.

In the 21st Century, Sri Lanka must have a vision for integrating more renewable energy into its energy system. All the necessary resources are on-site, and the technology and expertise is available to implement these new energy saving systems. The integration of renewable energy into the entire Sri Lankan energy-system has never been comprehensively analysed before, and this is the first research investigating an entire energy system in Sri Lanka. The outcome of this research can be used as a renewable energy development roadmap for the Sri Lankan energy sector.

In addition, within the Asian continent, no single country has carried out a study of the technical feasibility for a 100% renewable energy system for an entire energy system and this research fulfils the literature gap relating to a 100% renewable energy system. Again, this is the first research in Asia so far, to achieve a comprehensive energy solution using renewable energy for a country. The outcomes of this thesis can be used in any country in Asia to develop a model achieving a 100% renewable energy system.

Finally, the EnergyPLAN has also never been used before in Asia or Africa to design a 100% renewable energy system. This thesis provides an important contribution to the field of renewable energy and can be used as a case study for countries in the above-mentioned continents to achieve a 100% renewable energy solution.

8.5 Recommendations for Future Work

Points unearthed in this research for future work are as follows;

1. Economic feasibility for 100% renewable energy system.

   Future work needs to include the carrying out of an economic feasibility study towards achieving a 100% renewable energy system after obtaining the related data regarding energy markets and energy economics.

2. Additional parameters for the EnergyPLAN application.

   The overall EnergyPLAN simulation target for European countries focusses more precisely on heating, cooling and transport demand. However, when this EnergyPLAN software is implemented for the African and Asian continents, there are some specific parameters that should be added to the EnergyPLAN software.

3. Further refinement of data inputs

   A large portion of the data used in EnergyPLAN training, including costs, efficiencies and future technology development comes from Danish references. However, it would be relevant to investigate other data, such as labour costs, energy management mechanisms, economic status of operation and maintenance costs, and renewable sources generation profiles.

4. Saving potentials for industries and electricity

   The savings potentials for the industrial, electricity and transport sectors need to be analysed thoroughly. This kind of research would also provide further details about costs for these types of measures.

5. Further analysis of the transport sector measures

   This research analysis is to achieve 100% renewable energy within the transport system only. However, future work is needed to investigate biofuel technologies and other H_2 technologies developments, including creating a sustainable transport system in Sri Lanka.

6. Further analysis in the cooling sector

   The cooling demand currently calculated through electricity demand and future works requires to ascertain cooling demand separately as the industry sector will grow in the near future.

7. Further analysis of grid constraints

   Due to the lack of focus on grid constraints in the EnergyPLAN tool, it could be interesting to analyse this aspect using other tools that are better suited to the task. This kind of research would provide further insights into future energy grids.

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APPENDICES

Appendix 1; Sri Lanka energy balance 2016

Sri Lanka Energy Balance 2016 (in original units)

	Renewable Energy (GWh)	Electricity (GWh)	LPG (000't)	Petrol (000't)	Naphtha (000't)	Aviation gas (000't)	Kerosene (000't)	Jet A1 (000't)	Diesel (000't)	Fuel oil (000't)	Residual oil (000't)	Solvents (000't)	Coal (000't)	Bagasse (000't)	Fuel wood (000't)	Charcoal (000't)	Crude oil (000't)
Supply																	
Primary Energy	4660.66													241.07	11956.36		
Imports			345	956.684		0.106		337.043	1574.444	349.551			2404.57				1685.025
Direct Exports					-33.541					-55.668						0	
Foreign Bunkers						0		-523.378	0	-593.953							
Stock Change	70.66		2.19	340.56	69.26	0.03	68.14	41.51	243.37	524.52	199.28	1.16	-322.65	118.01			173.9
Total Energy Supply	4731.32		347.19	1297.24	35.72	0.14	68.14	-144.82	1817.81	224.45	199.28	1.16	2081.92	359.08	11956.36		1858.93
Energy Conversion																	
Petroleum Refinery			8.84	165.82	144.24		104.24	147.53	583.42	478.72		0.63					-1746.18
Conventional Hydro Power	-3481.94	3481.94															
Thermal Power Plants		9630.01			-179.96				-389.78	-327.39	-199.28		-2004.02				
Small Hydro Power	-738.84	738.84															
Wind Power Plants	-344.857	344.857															
Biomass Power Plants	-71.96	71.96												-118.014			
Solar Power	-4.291	4.291															
Waste Heat	0																
Net-metered Power Plants	-70.665	70.665															
Self generation by customers																	
Off-grid Conventional																	
Off Grid Non Conventional	-18.77	18.77															
Charcoal Production																32.32	
Own Use		-631.3349															
Conversion Losses																	-112.75
Losses in Transport and Distribution		-997.413															
Consumption for Non Energy Use												-1.793				-32.32	
Total Energy Conversion	-4731.32	12732.59	8.84	165.82	-35.72		104.24	147.53	193.64	151.33	-199.28	-1.16	-2004.02	-118.01			-1858.93
Use																	
Agriculture									0.57	0.2							
Industries		4148.91	70.2				5.67		21.66	375.58			77.9	241.07	4510.39		
Transport			1.06	1463.06		0.14		2.71	1989.22								
Household, Commercial and Other		8566.06	284.77				166.71								7445.97		
Total Energy Use		12714.97	356.03	1463.06		0.14	172.38	2.71	2011.45	375.78			77.9	241.07	11956.36		

Sri Lanka Energy Balance 2016 (in thousand toe)

	Renewable Energy	Electricity	LPG	Gasoline	Naphtha	AV.Gas	Kerosene	Avtur	Diesel	F.Oil	Residual	Solvents	Coal	Baggase	F.Wood	Charcoal	Crude Oil	Total
Supply																		
Primary Energy	1118.56													96.43	4543.42			5758.41
Imports			365.7	1042.79		0.11		353.9	1653.17	342.56			1514.88				1735.58	7008.69
Direct Exports					-36.56					-54.55						0		-91.11
Foreign Bunkers						0		-549.55	0	-582.07								-1131.62
Stock Change	16.96		2.32	371.21	75.49	0.03	71.55	43.59	255.54	514.03	195.29	1.03	-203.27	47.2			179.12	1570.09
Total Energy Supply	1135.52		368.02	1414	38.93	0.14	71.55	-152.06	1908.71	219.97	195.29	1.03	1311.61	143.63	4543.42		1914.7	13114.46
Energy Conversion																		
Petroleum Refinery			9.37	180.74	157.22		109.45	154.91	612.59	469.15		0.56					-1798.57	-104.58
Conventional Hydro Power	-835.67	299.45																-536.22
Thermal Power Plants		828.18			-196.16				-409.27	-320.84	-195.29		-1262.53					-1555.91
Small Hydro Power	-177.3216	63.54024																-113.781
Wind Power Plants	-82.77	29.66																-53.11
Biomass Power Plants	-17.27	6.19												-47.21				-58.29
Solar Power	-1.02984	0.369026																-0.66081
Waste Heat	0																	
Net-metered Power Plants	-16.9596	6.07719																-10.8824
Self generation by customers																		
Off-grid Conventional	0																	
Off Grid Non Conventional	-4.5	1.61																-2.89
Charcoal Production																21.01		21.01
Own Use		-54.29																-54.29
Conversion Losses																	-116.13	-116.13
Losses in Transport and Distribution		-85.78																-85.78
Consumption for Non Energy Use												-1.6				-21.01		-22.61
Total Energy Conversion	-1118.56	1088.93	9.37	180.74	-38.94		109.45	154.91	203.32	148.31	-195.29	-1.04	-1262.53	-47.21			-1914.7	-2683.24
Use																		
Agriculture									0.6	0.2								0.8
Industries		356.81	74.41				5.95		22.74	368.07			49.08	96.43	1713.95			2687.44
Transport			1.12	1594.74		0.15		2.85	2088.68									3687.54
Household, Commercial and Other		736.68	301.86				175.05								2829.47			4043.06
Total Energy Use		1093.49	377.39	1594.74		0.15	181	2.85	2112.02	368.26			49.08	96.43	4543.42			10418.83

Sri Lanka Energy Balance 2016 (in Tera Joules)

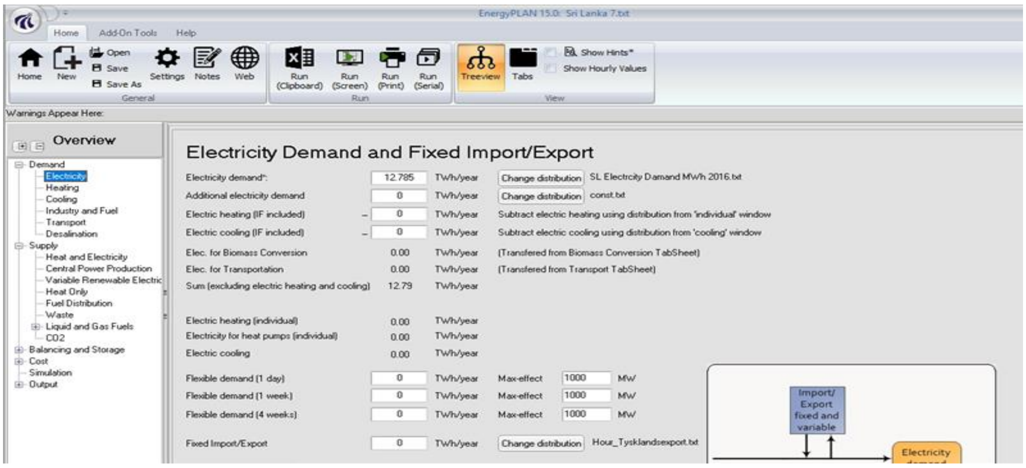
	Renewable Energy	Electricity	LPG	Gasoline	Naphtha	AV.Gas	Kerosene	Avtur	Diesel	F.Oil	Residual	Solvents	Coal	Baggase	F.Wood	Charcoal	Crude Oil	Total
Supply																		
Primary Energy	46831.87													4037.33	190223.9			241093.1
Imports			15311.13	43659.53		4.61		14817.09	69214.92	14342.3			63425				72665.26	293439.8
Direct Exports					-1530.69					-2283.9						0		-3814.59
Foreign Bunkers						0		-23008.6	0	-24370.1								-47378.7
Stock Change	710.08128		97.13376	15541.82	3160.615	1.25604	2995.655	1825.026	10698.95	21521.41	8176.402	43.12404	-8510.51	1976.17			7499.396	65736.53
Total Energy Supply	47541.95		15408.26	59201.35	1629.93	5.87	2995.66	-6366.44	79913.87	9209.7	8176.4	43.12	54914.49	6013.5	190223.9		80164.66	549076.2
Energy Conversion																		
Petroleum Refinery			392.3	7567.22	6582.49		4582.45	6485.77	25647.92	19642.37		23.45					-75302.5	-4378.56
Conventional Hydro Power	-34987.83	12537.37																-22450.5
Thermal Power Plants		34674.24			-8212.83				-17135.3	-13432.9	-8176.4		-52859.6					-65142.9
Small Hydro Power	-7424.100749	2660.3028																5320.606
Wind Power Plants	-3465.41	1241.8																-2223.61
Biomass Power Plants	-723.06	259.16												-1976.59				-2440.49
Solar Power	-43.11734112	15.450381																-27.667
Waste Heat	0																	
Net-metered Power Plants	-710.0645328	254.43979																-455.625
Self generation by customer	0																	
Off-grid Conventional																		
Off Grid Non Conventional	-188.41	67.41																-121
Charcoal Production																879.65		879.65
Own Use		-2273.01																-2273.01
Conversion Losses																	-4862.13	-4862.13
Losses in Transport and Distribution		-3591.44																-3591.44
Consumption for Non Energy Use												-66.99				-879.65		-946.64
Total Energy Conversion	-46831.93	45591.28	392.3	7567.22	-1630.34		4582.45	6485.77	8512.6	6209.44	-8176.4	-43.54	-52859.6	-1976.59			-80164.7	-102258
Use																		
Agriculture									25.12	8.37								33.49
Industries		14938.92	3115.4				249.11		952.08	15410.35			2054.88	4037.33	71759.66			112517.7
Transport			46.89	66768.57		6.28		119.32	87448.85									154389.9
Household, Commercial and Other		30843.32	12638.27				7328.99								118464.3			169274.8
Total Energy Use		45782.24	15800.56	66768.57		6.28	7578.11	119.32	88426.05	15418.31			2054.88	4037.33	190223.9			436215.6

Appendix 2; Sri Lanka data input of EnergyPLAN 2016 reference model

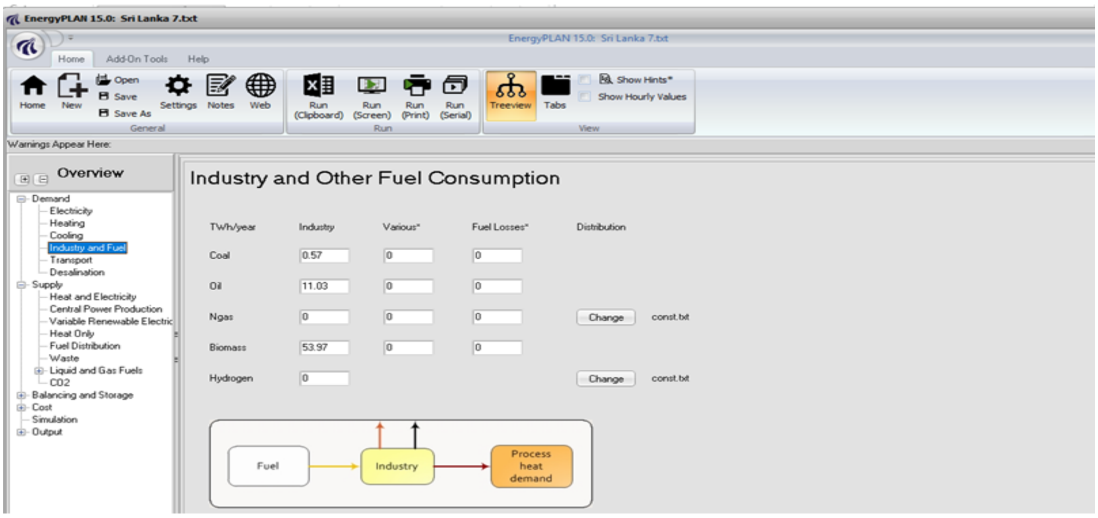
Important
Less important

Data inputs for EnergyPLAN			Model 1	Model 2	Model x
Data category	Technology	Unit	2014	2015	2016
Primary Energy demand	Total	TWh/year			121.255
	Fuels	TWh/year			
	Coal				0.58
	Petrolium				53.92
	Biomass				53.97
	Electrcity				12.785
	Hydro				
	New Renewable Energy				
	Statistical differences	TWh/year			
Primary energy supply	Total	TWh/year	135.28	145.31	152.32
	Fuels	TWh/year			
	Coal		10.71	14.41	15.25
	Petrolium		53.81	56.9	69.55
	Biomass		57.12	56.16	54.51
	Electrcity				
	Hydro		10.19	13.69	9.72
	New Renewable Energy		3.45	4.15	3.29
	Statistical differences	TWh/year			
Electricity production	Total	TWh/year	12.85	13.3	14.31
	Thermal-Oil	TWh/year	1.76	1.08	2.36
	Thermal coal	TWh/year	3.5	4.5	5.07
	New Renewable Energy	TWh/year	0.31	0.4	
	Micro Power Production-IPP-Thermal	TWh/year	2.67	1.28	2.16
	Net Meterd-Solar	TWh/year	0.02	0.04	0.07
	Off Grid - Non Conventional	TWh/year	0.018	0.018	
	Offshore wind	TWh/year			
	Onshore wind	TWh/year			0.34
	Onshore wind	TWh/year	0.002	0.001	0.002
	Solar PV	TWh/year			0.004
	CSP solar power	TWh/year			
	Biomass	TWh/year			0.072
	Hydro Total	TWh/year	4.55	5.96	4.23
	-hydro Major-CEB	TWh/year	3.62	4.82	3.43
	-Hydro Samll-CEB	TWh/year	0.03	0.08	0.06
	Hydri-IPP	TWh/year	0.90	1.06	0.74
	-Hydro Pumped	TWh/year			
	Geothermal	TWh/year			
	Nuclear	TWh/year			
	Wave power	TWh/year			
	Tidal power	TWh/year			
	Thermal production	TWh/year			
	-CHP	TWh/year			
	-PP	TWh/year			
	Industrial (CHP + power only)	TWh/year			
	Waste	TWh/year			
	Import	TWh/year			
	Export	TWh/year			
Electricity Demand	Total	TWh/year	11	11.74	12.71
	Individual electric heating	TWh/year			
	Individual Heat pumps	TWh/year			
	Electric cooling	TWh/year			
	Centralised electric boilers	TWh/year			
	Centralised heat pump	TWh/year			
	Transport: Electric Cars	TWh/year			
	Transport: Rail	TWh/year			
	Transport: Other	TWh/year			
	PHES pump	TWh/year			
	Losses (including own use)	TWh/year			
	CCS	TWh/year			
	Bioenergy production	TWh/year			
	Electrolysers	TWh/year			
	Desalination electricity	kWh/m3 water			
	Other Flexible Electricity Demands	TWh/year			
	Other Electricity Demands	TWh/year			
Electricity production capacities	Thermal	MWe	2213	2088	2064
	Coal- CEB	MWe	900	900	900
	Oil-CEB	MWe	544	544	520
	Fuel-IPP	MWe	769	644	644
	Hydro total	MWe	1664.48	1683.62	1721.77
	Hydro (Major)-CEB	MWe	1356.5	1356.5	1363.4
	Hydro (small)-CEB	MWe	20.45	20.45	20.45
	Hydro-IPP	MWe	287.53	306.67	337.92
	Hydro (run-of-river)	MWe			
	Hydro (pump)	MWe			
	Solar	MWe	1.36	1.36	21.36
	Solar Net Meter Project	MWe	13.27	27.71	31.56
	CSP solar power	MWe			
	Wind onshore- CEB	MWe	3	3	3
	Wind onshore-IPP	MWe	128.45	123.85	128.45
	Wind offshore	MWe			
	Geothermal	MWe			
	Biomass	MWe	20	20.1	24.1
	Wave power	MWe			
	Tidal power	MWe			
	Nuclear	MWe			
	Electrolysers	MWe			
	Interconnections	MWe			
	Elecricity grid	MWe	2151.7	2283.4	2452.9
Heating demand	Total	TWh/year			
	Individual	TWh/year			
	District heating	TWh/year			
District Heating production capacities	CHP	MWe			
	CHP	MWth			
	Boiler	MW			
	Heat Pumps	MWe			
	Others?	?			
Individual Heating Capacities					
Heating production	Total	TWh/year			
	Individual boilers	TWh/year			
	- coal	TWh/year			
	- oil	TWh/year			
	- Ngas	TWh/year			
	- biomass	TWh/year			
	Individual Electric heating	TWh/year			
	Individual HP	TWh/year			
	CHP District heating	TWh/year			
	Boiler District heating	TWh/year			
	Heat pump District heating	TWh/year			
	Electric boilers	TWh/year			
	Waste	TWh/year			
	Geothermal heating	TWh/year			
	Industrial DH	TWh/year			
	Solar thermal	TWh/year			
	Micro-CHP	TWh/year			
	- H2	TWh/year			
	- Ngas	TWh/year			
	- Biomass	TWh/year			
	District heating own use	TWh/year			
	District heating losses	TWh/year			
Thermal production efficiencies	Condensing power plants	%			
	Centralised DH boilers	%			
	CHP - thermal	%			
	CHP - electric	%			
	Individual heat pumps	%			
	Individual boilers	%			
	- coal	%			
	- oil	%			
	- Ngas	%			
	- biomass	%			
	Micro-CHP (electric and thermal)	%			
	- H2	%			
	- Ngas	%			
	- Biomass	%			
	Electrolysers	%			
Fuel input distributions	Thermal production	-			
Cooling demand & production	Individual cooling demand	TWh/year			
	District cooling	TWh/year			
	Cooling COP	%			
	District cooling network losses	%			
Storage	Thermal storage	GWh			
	DH Solar thermal storage	GWh			
	Individual Solar thermal storage	GWh			
	Cold storage	GWh			
	Oil storage	GWh			
	Gas storage	GWh			
	Pumped Hydro Pump	MWe			
	Pumped Hydro Turbine	MWe			
	Hydro pumped storage	GWh			
	Dam hydro storage	GWh			1259
	Hydrogen	GWh			
Industry energy demand	Total	TWh/year			
	- coal	TWh/year	0.72	0.63	0.57
	- oil	TWh/year	2.71	9.93	11.03
	- Ngas	TWh/year			
	- biomass	TWh/year	20.3	20.94	53.97
	Electricity	TWh/year	3.76	3.88	12.72
	Various/non-energy use	TWh/year			
	- coal	TWh/year			
	- oil	TWh/year			
	- Ngas	TWh/year			
	- biomass	TWh/year			
Transport	Total	TWh/year			42.89
	-LPG	TWh/year	0.015	0.015	0.013
	- Petrol	TWh/year	10.6	10.6	18.55
	Aviation Gas	TWh/year	0.0017	0.0017	0.0017
	-Aviation fuel	TWh/year	0.0362	0.0294	0.0331
	-Diesel	TWh/year	20.27	22.72	24.29
	Fuel Oil	TWh/year	0.32		
	-Navigation (sea) fuel	TWh/year			
	-Biodiesel	TWh/year			
	-Biopetrol	TWh/year			
	-Electricity rail	TWh/year			
	-Electricity EVs	TWh/year			
	-Hydrogen	TWh/year			
Desalination	Desalination Capacity	1000 m3 fresh water/hour			
Biogas	Biogas production	TWh/year			
CO2 (Do we need Biomass burning CO2 mmision as well? If not why?	Total emission	Mt	1.35E+10	1.75E+10	1.82E+10
	- Coal	kg/GJ	3.65E+09	4.91E+09	5.19E+09
	- Fuel oil/Diesel/petrol	kg/GJ	9.18E+09	1.16E+10	1.30E+10
	- Ngas	kg/GJ			
	- LPG	kg/GJ	6.48E+08	9.40E+08	9.97E+08
	- Waste	kg/GJ			
	CO2 captured by CCS	Mt			
Costs?					

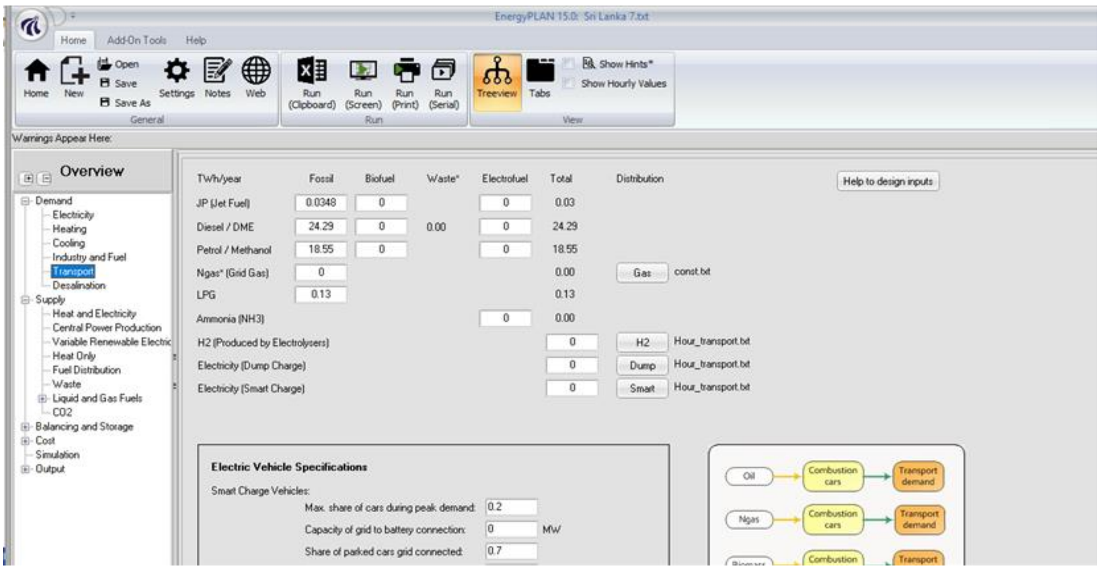
Appendix 3; Actual simulation process of annual electricity demand



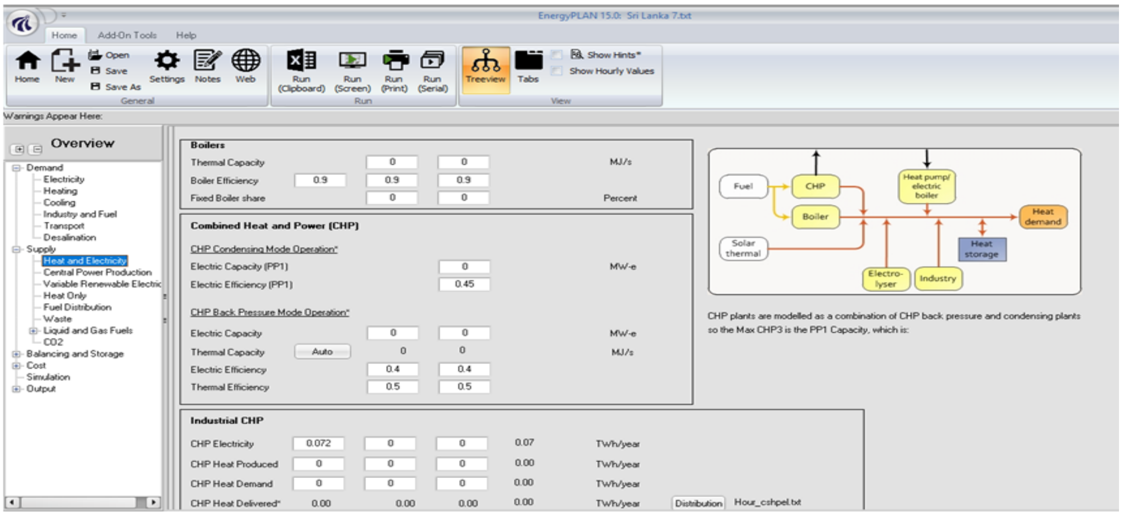
Appendix 4; Actual simulation process of industrial and other consumption



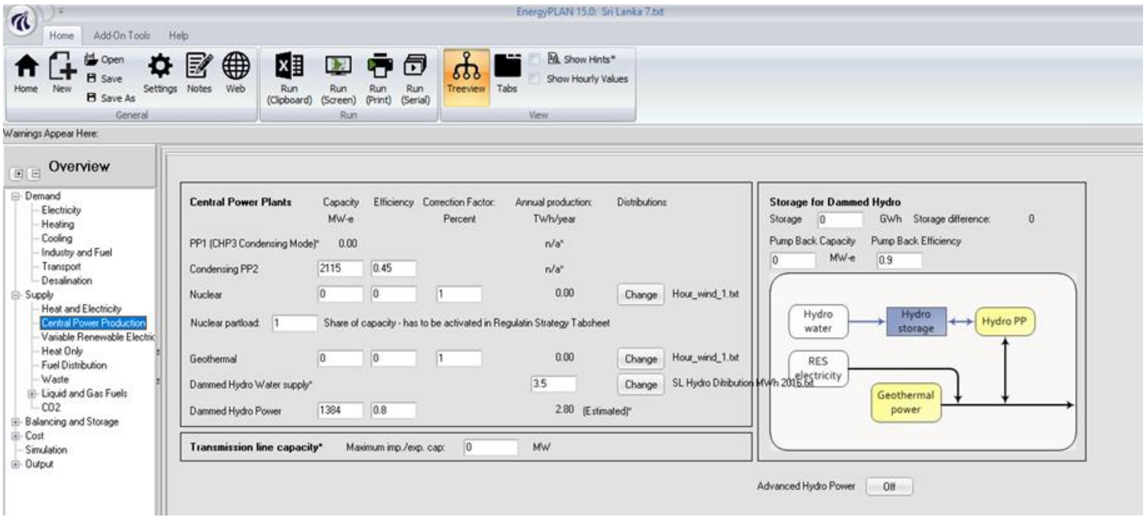
Appendix 5; Actual simulation process of transport demand



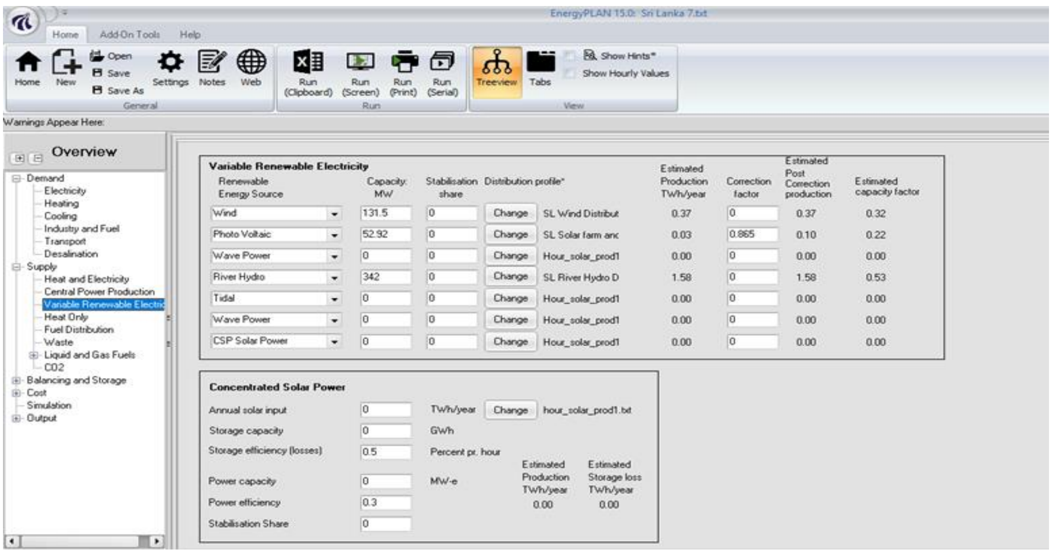
Appendix 6; Actual simulation process of biomass electricity generation



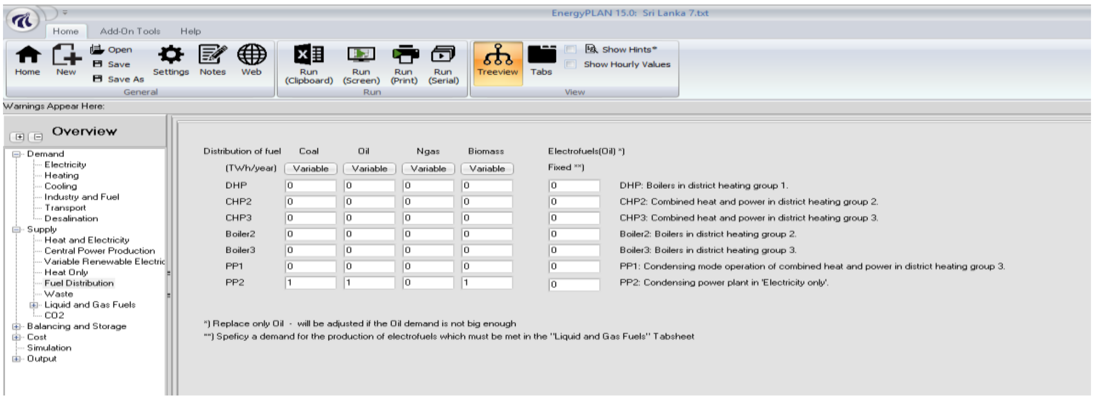
Appendix 7; Actual simulation process of central power production supply



Appendix 8; Actual simulation process of variable renewable electricity supply



Appendix 9; Actual simulation process of fuel distribution



Appendix 10; Results of EnergyPLAN 2016 reference model

Input Sri Lanka 7.txt — The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	12.79	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	12.79

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	132 MW	0.37	TWh/year	0.00	Grid
Photo Voltaic	53 MW	0.1	TWh/year	0.00	stabil-
Wave Power	0 MW	0	TWh/year	0.00	sation
River Hydro	342 MW	1.58	TWh/year	0.00	share
Hydro Power	1384 MW	2.8	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.07	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW
Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	DKK/MWh
Multiplication factor	2.00	
Dependency factor	0.00	DKK/MWh pr. MW
Average Market Price	227	DKK/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:	0.000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	42.87	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.57	11.03	0.00	53.97
Various	0.00	0.00	0.00	0.00

Output

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million DKK	Exp
January	0	0	0	0	0	0	0	0	0	0	1378	0	0	0	0	0	0	222	449	0	8	0	699	100	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	1444	0	0	0	0	0	0	139	388	0	8	0	909	100	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	1400	0	0	0	0	0	0	90	320	0	8	0	982	100	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	1457	0	0	0	0	0	0	141	261	0	8	0	1047	100	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	1472	0	0	0	0	0	0	400	374	0	8	0	690	100	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	1473	0	0	0	0	0	0	423	506	0	8	0	536	100	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	1441	0	0	0	0	0	0	272	359	0	8	0	802	100	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	1495	0	0	0	0	0	0	252	259	0	8	0	976	100	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	1516	0	0	0	0	0	0	221	193	0	8	0	1094	100	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	1475	0	0	0	0	0	0	189	231	0	8	0	1046	100	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	1473	0	0	0	0	0	0	300	264	0	8	0	901	100	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	1445	0	0	0	0	0	0	159	224	0	8	0	1053	100	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	1455	0	0	0	0	0	0	234	319	0	8	0	894	100	0	0	0	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	2044	0	0	0	0	0	0	484	1384	0	8	0	1407	100	0	0	0	0	(DKK/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	1088	0	0	0	0	0	0	63	21	0	8	0	200	100	0	0	0	0	218	228
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.79	0.00	0.00	0.00	0.00	0.00	0.00	2.06	2.80	0.00	0.07	0.00	7.86		0.00	0.00	0.00	0.00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	13.53	-	-	-	-	-	-	-	-	-	-	-	-	-	0.57	14.10	0.00	14.10	4.82	4.82
Oil	-	-	-	-	-	3.75	-	-	-	-	-	-	-	-	-	-	-	42.87	-	11.03	57.65	0.00	57.65	15.36	15.36
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.13	-	-	0.13	0.00	0.13	0.03	0.05
Biomass	-	-	-	-	-	0.19	-	-	-	-	-	-	-	-	-	-	-	-	-	53.97	54.16	0.00	54.16	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	0.37	0.10	-	4.38	-	-	-	-	4.86	0.00	4.86	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	17.46	-	2.80	-	-	-	-	0.37	0.10	-	4.38	-	43.00	-	65.57	130.89	0.00	130.89	20.21	20.23

14-October-2019 [14:25]

Appendix 11; Results of EnergyPLAN 2025 ADB model

Input   Sri Lanka 8A 2025 ADB.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	22.50	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	22.50

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	1449 MW	4.09	TWh/year	0.00	Grid
Photo Voltaic	900 MW	1.74	TWh/year	0.00	stabili-
Offshore Wind	0 MW	0	TWh/year	0.00	sation
River Hydro	493 MW	2.28	TWh/year	0.00	share
Hydro Power	1576 MW	2.8	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.43	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:	0.000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	47.82	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.26	15.41	0.00	47.98
Various	0.00	0.00	0.00	0.00

Output   WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million USD	Exp Million USD
January	0	0	0	0	0	0	0	0	0	0	2426	0	0	0	0	0	0	725	449	0	50	0	1203	100	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	2541	0	0	0	0	0	0	522	388	0	50	0	1579	100	3	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	2464	0	0	0	0	0	0	407	320	0	50	0	1667	100	21	0	0	0	3	0
April	0	0	0	0	0	0	0	0	0	0	2564	0	0	0	0	0	0	478	261	0	50	0	1691	100	84	0	0	0	14	0
May	0	0	0	0	0	0	0	0	0	0	2591	0	0	0	0	0	0	1177	374	0	50	0	990	100	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	2593	0	0	0	0	0	0	1538	507	0	50	0	520	100	0	21	21	0	0	5
July	0	0	0	0	0	0	0	0	0	0	2536	0	0	0	0	0	0	1195	359	0	50	0	932	100	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	2631	0	0	0	0	0	0	1146	259	0	50	0	1173	100	3	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	2667	0	0	0	0	0	0	1175	193	0	50	0	1218	100	32	0	0	0	6	0
October	0	0	0	0	0	0	0	0	0	0	2596	0	0	0	0	0	0	914	231	0	50	0	1355	100	46	0	0	0	9	0
November	0	0	0	0	0	0	0	0	0	0	2592	0	0	0	0	0	0	913	264	0	50	0	1314	100	51	0	0	0	9	0
December	0	0	0	0	0	0	0	0	0	0	2543	0	0	0	0	0	0	870	224	0	50	0	1322	100	78	0	0	0	15	0
Average	0	0	0	0	0	0	0	0	0	0	2562	0	0	0	0	0	0	923	319	0	50	0	1246	100	26	2	2	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	3597	0	0	0	0	0	0	2288	1389	0	50	0	1850	100	641	252	252	0	(USD/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	1915	0	0	0	0	0	0	216	21	0	50	0	0	100	0	0	0	0	242	319
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.50	0.00	0.00	0.00	0.00	0.00	0.00	8.11	2.80	0.00	0.43	0.00	10.94		0.23	0.02	0.02	0.00	56	5

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	8.11	-	-	-	-	-	-	-	-	-	-	-	-	-	0.26	8.37	0.00	8.37	2.86	2.86
Oil	-	-	-	-	-	8.11	-	-	-	-	-	-	-	-	-	-	-	47.82	-	15.41	71.34	0.00	71.34	19.00	19.00
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	-	-	0.03	0.00	0.03	0.01	0.01
Biomass	-	-	-	-	-	8.11	-	-	-	-	-	-	-	-	-	-	-	-	-	47.98	56.09	0.00	56.09	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	4.09	1.74	-	5.08	-	-	-	-	10.91	0.00	10.91	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	24.32	-	2.80	-	-	-	-	4.09	1.74	-	5.08	-	47.85	-	63.65	146.72	0.48	147.21	21.87	21.88

12-October-2019 [15:22]

Appendix 12; Results of EnergyPLAN 2025 CEB model

Input Sri Lanka 8B 2025 CEB.txt — The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	22.50	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	22.50

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	621	MW	1.75	TWh/year	0.00	Grid
Photo Voltaic	441	MW	0.85	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	457	MW	2.12	TWh/year	0.00	share
Hydro Power	1611	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.16	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	47.83	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.26	15.37	0.00	47.98
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (3) PP/Import problem

	District Heating Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW	Electricity Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Electricity Production: Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million USD	Exp
January	0	0	0	0	0	0	0	0	0	0	2426	0	0	0	0	0	0	454	449	0	18	0	1505	100	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	2541	0	0	0	0	0	0	313	388	0	18	0	1823	100	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	2464	0	0	0	0	0	0	232	320	0	18	0	1894	100	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	2564	0	0	0	0	0	0	299	261	0	18	0	1966	100	20	0	0	0	3	0
May	0	0	0	0	0	0	0	0	0	0	2591	0	0	0	0	0	0	758	374	0	18	0	1440	100	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	2593	0	0	0	0	0	0	907	507	0	18	0	1162	100	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	2536	0	0	0	0	0	0	661	359	0	18	0	1497	100	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	2631	0	0	0	0	0	0	625	259	0	18	0	1729	100	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	2667	0	0	0	0	0	0	611	193	0	18	0	1820	100	26	0	0	0	5	0
October	0	0	0	0	0	0	0	0	0	0	2596	0	0	0	0	0	0	498	231	0	18	0	1830	100	18	0	0	0	4	0
November	0	0	0	0	0	0	0	0	0	0	2592	0	0	0	0	0	0	605	264	0	18	0	1702	100	3	0	0	0	1	0
December	0	0	0	0	0	0	0	0	0	0	2543	0	0	0	0	0	0	477	224	0	18	0	1795	100	29	0	0	0	5	0
Average	0	0	0	0	0	0	0	0	0	0	2562	0	0	0	0	0	0	537	319	0	18	0	1680	100	8	0	0	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	3597	0	0	0	0	0	0	1241	1389	0	18	0	2391	100	289	0	0	0	(USD/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	1915	0	0	0	0	0	0	141	21	0	18	0	826	100	0	0	0	0	252	219
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.50	0.00	0.00	0.00	0.00	0.00	0.00	4.72	2.80	0.00	0.16	0.00	14.75		0.07	0.00	0.00	0.00	18	0

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	10.93	-	-	-	-	-	-	-	-	-	-	-	-	-	0.26	11.19	0.00	11.19	3.83	3.83
Oil	-	-	-	-	-	10.93	-	-	-	-	-	-	-	-	-	-	-	47.83	-	15.37	74.13	0.00	74.13	19.75	19.75
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	-	-	0.03	0.00	0.03	0.01	0.01
Biomass	-	-	-	-	-	10.93	-	-	-	-	-	-	-	-	-	-	-	-	-	47.98	58.91	0.00	58.91	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	1.75	0.85	-	4.92	-	-	-	-	7.52	0.00	7.52	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	32.79	-	2.80	-	-	-	-	1.75	0.85	-	4.92	-	47.86	-	63.61	151.77	0.16	151.93	23.58	23.59

12-October-2019 [16:45]

Appendix 13; Results of EnergyPLAN 2030 ADB model

Input Sri Lanka 9A 2030 ADB.txt — **The EnergyPLAN model 14.1**

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	28.57	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	28.57

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

					Grid stabilisation share
Wind	2313	MW	6.53	TWh/year	0.00
Photo Voltaic	1950	MW	3.76	TWh/year	0.00
Offshore Wind	0	MW	0	TWh/year	0.00
River Hydro	653	MW	3.02	TWh/year	0.00
Hydro Power	1576	MW	2.8	TWh/year	
Geothermal/Nuclear	0	MW	0	TWh/year	

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.60	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:	0.000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	54.61	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.07	18.33	0.00	44.43
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production							Balance						Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Balance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Electrolyser MW	EH MW	Hydro Pump MW	Turbine MW	RES MW	Hydro MW	Geothermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million USD	Exp Million USD
January	0	0	0	0	0	0	0	0	0	0	3081	0	0	0	0	0	0	1174	449	0	68	0	1389	100	1	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	3227	0	0	0	0	0	0	875	388	0	68	0	1824	100	72	0	0	0	12	0
March	0	0	0	0	0	0	0	0	0	0	3129	0	0	0	0	0	0	711	320	0	68	0	1920	100	109	0	0	0	17	0
April	0	0	0	0	0	0	0	0	0	0	3255	0	0	0	0	0	0	803	261	0	68	0	1944	100	180	0	0	0	30	0
May	0	0	0	0	0	0	0	0	0	0	3290	0	0	0	0	0	0	1822	374	0	68	0	1026	100	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	3293	0	0	0	0	0	0	2411	507	0	68	0	490	100	0	184	184	0	0	38
July	0	0	0	0	0	0	0	0	0	0	3220	0	0	0	0	0	0	1923	359	0	68	0	895	100	0	25	25	0	0	4
August	0	0	0	0	0	0	0	0	0	0	3341	0	0	0	0	0	0	1840	259	0	68	0	1158	100	17	1	1	0	3	0
September	0	0	0	0	0	0	0	0	0	0	3387	0	0	0	0	0	0	1905	193	0	68	0	1179	100	46	3	3	0	9	1
October	0	0	0	0	0	0	0	0	0	0	3297	0	0	0	0	0	0	1530	231	0	68	0	1383	100	85	0	0	0	16	0
November	0	0	0	0	0	0	0	0	0	0	3291	0	0	0	0	0	0	1575	264	0	68	0	1270	100	114	0	0	0	20	0
December	0	0	0	0	0	0	0	0	0	0	3229	0	0	0	0	0	0	1591	224	0	68	0	1200	100	145	0	0	0	27	0
Average	0	0	0	0	0	0	0	0	0	0	3253	0	0	0	0	0	0	1515	319	0	68	0	1305	100	64	18	18	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	4568	0	0	0	0	0	0	3727	1389	0	68	0	2150	100	1102	1019	1019	0	(USD/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	2432	0	0	0	0	0	0	319	21	0	68	0	0	100	0	0	0	0	236	277
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	28.57	0.00	0.00	0.00	0.00	0.00	0.00	13.31	2.80	0.00	0.60	0.00	11.46		0.56	0.15	0.15	0.00	132	43

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	-	-	-	8.49	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	8.56	0.00	8.56	2.93	2.93
Oil	-	-	-	-	-	8.49	-	-	-	-	-	-	-	-	-	-	-	54.61	-	18.33	81.43	0.00	81.43	21.69	21.69
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	-	-	0.03	0.00	0.03	0.01	0.01
Biomass	-	-	-	-	-	8.49	-	-	-	-	-	-	-	-	-	-	-	-	-	44.43	52.92	0.00	52.92	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	6.53	3.76	-	5.82	-	-	-	-	16.11	0.00	16.11	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	25.46	-	2.80	-	-	-	-	6.53	3.76	-	5.82	-	54.64	-	62.83	159.04	0.90	159.94	24.63	24.63

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Appendix 14; Results of EnergyPLAN 2030 CEB model

Input   Sri Lanka 9B 2030 CEB.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	28.57	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	28.57

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	806	MW	2.27	TWh/year	0.00	Grid
Photo Voltaic	921	MW	1.78	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	507	MW	2.35	TWh/year	0.00	share
Hydro Power	1611	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.23	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW
Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	54.61	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.07	18.33	0.00	44.43
Various	0.00	0.00	0.00	0.00

Output   WARNING!!: (3) PP/Import problem

	District Heating Demand: Distr. heating MW	DH Production: Solar MW	Waste+CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Electricity Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Electricity Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million USD	Exp Million USD
January	0	0	0	0	0	0	0	0	0	0	3081	0	0	0	0	0	0	603	428	0	26	0	2023	100	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	3227	0	0	0	0	0	0	435	368	0	26	0	2377	100	1	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	3129	0	0	0	0	0	0	344	320	0	26	0	2434	100	5	0	0	0	1	0
April	0	0	0	0	0	0	0	0	0	0	3255	0	0	0	0	0	0	417	280	0	26	0	2523	100	9	0	0	0	1	0
May	0	0	0	0	0	0	0	0	0	0	3290	0	0	0	0	0	0	950	355	0	26	0	1959	100	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	3293	0	0	0	0	0	0	1152	506	0	26	0	1608	100	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	3220	0	0	0	0	0	0	871	360	0	26	0	1963	100	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	3341	0	0	0	0	0	0	821	278	0	26	0	2215	100	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	3387	0	0	0	0	0	0	815	194	0	26	0	2352	100	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	3297	0	0	0	0	0	0	696	231	0	26	0	2343	100	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	3291	0	0	0	0	0	0	868	264	0	26	0	2134	100	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	3229	0	0	0	0	0	0	759	224	0	26	0	2217	100	2	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	3253	0	0	0	0	0	0	728	319	0	26	0	2178	100	1	0	0	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	4568	0	0	0	0	0	0	1667	1389	0	26	0	3711	100	128	0	0	0	(USD/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	2432	0	0	0	0	0	0	166	21	0	26	0	1083	100	0	0	0	0	252	224
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	28.57	0.00	0.00	0.00	0.00	0.00	0.00	6.40	2.80	0.00	0.23	0.00	19.13		0.01	0.00	0.00	0.00	3	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	14.17	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	14.24	0.00	14.24	4.87	4.87
Oil	-	-	-	-	-	14.17	-	-	-	-	-	-	-	-	-	-	-	54.61	-	18.33	87.11	0.00	87.11	23.21	23.21
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	-	-	0.03	0.00	0.03	0.01	0.01
Biomass	-	-	-	-	-	14.17	-	-	-	-	-	-	-	-	-	-	-	-	-	44.43	58.60	0.00	58.60	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	2.27	1.78	-	5.15	-	-	-	-	9.20	0.00	9.20	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	42.52	-	2.80	-	-	-	-	2.27	1.78	-	5.15	-	54.64	-	62.83	169.19	0.03	169.21	28.08	28.09

18-October-2019 [14:13]

Appendix 15; Results of EnergyPLAN 2040 ADB model

Input Sri Lanka 10A 2040 ADB.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	43.62	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	43.62

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	6513	MW	18.37	TWh/year	0.00	Grid
Photo Voltaic	6608	MW	12.74	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	703	MW	3.25	TWh/year	0.00	share
Hydro Power	1576	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.86	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities	Storage	Efficiencies	
	MW-e	GWh	elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	68.17	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	24.16	0.00	37.33
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million USD	Exp
January	0	0	0	0	0	0	0	0	0	0	4703	0	0	0	0	0	0	2882	449	0	98	0	1135	100	365	226	226	0	63	52
February	0	0	0	0	0	0	0	0	0	0	4927	0	0	0	0	0	0	2278	388	0	98	0	1380	100	797	14	14	0	116	2
March	0	0	0	0	0	0	0	0	0	0	4777	0	0	0	0	0	0	1973	320	0	98	0	1448	100	938	0	0	0	134	0
April	0	0	0	0	0	0	0	0	0	0	4970	0	0	0	0	0	0	2059	261	0	98	0	1499	100	1053	0	0	0	161	0
May	0	0	0	0	0	0	0	0	0	0	5022	0	0	0	0	0	0	4160	374	0	98	0	840	100	86	537	537	0	15	133
June	0	0	0	0	0	0	0	0	0	0	5027	0	0	0	0	0	0	5877	507	0	98	0	160	100	0	1615	1615	0	0	322
July	0	0	0	0	0	0	0	0	0	0	4916	0	0	0	0	0	0	4969	359	0	98	0	543	100	6	1059	1059	0	1	164
August	0	0	0	0	0	0	0	0	0	0	5100	0	0	0	0	0	0	4772	259	0	98	0	700	100	91	819	819	0	15	143
September	0	0	0	0	0	0	0	0	0	0	5171	0	0	0	0	0	0	5091	193	0	98	0	663	100	99	974	974	0	19	178
October	0	0	0	0	0	0	0	0	0	0	5033	0	0	0	0	0	0	4141	231	0	98	0	935	100	333	705	705	0	62	130
November	0	0	0	0	0	0	0	0	0	0	5025	0	0	0	0	0	0	4038	264	0	98	0	837	100	819	1032	1032	0	134	175
December	0	0	0	0	0	0	0	0	0	0	4929	0	0	0	0	0	0	4655	224	0	98	0	837	100	707	1592	1592	0	122	311
Average	0	0	0	0	0	0	0	0	0	0	4966	0	0	0	0	0	0	3913	319	0	98	0	914	100	439	716	716	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	6974	0	0	0	0	0	0	9841	1389	0	98	0	1826	100	3306	5449	5449	0	(USD/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	3713	0	0	0	0	0	0	675	21	0	98	0	0	100	0	0	0	0	218	256
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	43.62	0.00	0.00	0.00	0.00	0.00	0.00	34.37	2.80	0.00	0.86	0.00	8.03		3.85	6.29	6.29	0.00	840	1611

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	5.94	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.94	0.00	5.94	2.03	2.03
Oil	-	-	-	-	-	5.94	-	-	-	-	-	-	-	-	-	-	-	68.17	-	24.16	98.27	0.00	98.27	26.18	26.18
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.05	0.00	0.05	0.01	0.02
Biomass	-	-	-	-	-	5.94	-	-	-	-	-	-	-	-	-	-	-	-	-	37.33	43.27	0.00	43.27	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	18.37	12.74	-	6.05	-	-	-	-	37.17	0.00	37.17	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	17.83	-	2.80	-	-	-	-	18.37	12.74	-	6.05	-	68.22	-	61.49	184.72	-5.41	179.30	28.22	28.23

12-October-2019 [15:49]

Appendix 16; Results of EnergyPLAN 2040 CEB model

Input Sri Lanka 10B 2040 CEB.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	43.62	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	43.62

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	1307	MW	3.69	TWh/year	0.00	Grid
Photo Voltaic	1921	MW	3.7	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	592	MW	2.74	TWh/year	0.00	share
Hydro Power	1611	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.36	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	68.17	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	24.16	0.00	37.33
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (3) PP/Import problem

District Heating / Electricity / Exchange

	DH Demand: Distr. heating MW	DH Prod.: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW	Elec. Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Elec. Production: Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million USD	Exp Million USD
January	0	0	0	0	0	0	0	0	0	0	4703	0	0	0	0	0	0	927	417	0	41	0	3291	100	27	0	0	0	5	0
February	0	0	0	0	0	0	0	0	0	0	4927	0	0	0	0	0	0	701	388	0	41	0	3690	100	107	0	0	0	22	0
March	0	0	0	0	0	0	0	0	0	0	4777	0	0	0	0	0	0	587	320	0	41	0	3660	100	169	0	0	0	29	0
April	0	0	0	0	0	0	0	0	0	0	4970	0	0	0	0	0	0	669	292	0	41	0	3780	100	188	0	0	0	32	0
May	0	0	0	0	0	0	0	0	0	0	5022	0	0	0	0	0	0	1374	343	0	41	0	3191	100	72	0	0	0	14	0
June	0	0	0	0	0	0	0	0	0	0	5027	0	0	0	0	0	0	1717	506	0	41	0	2763	100	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	4916	0	0	0	0	0	0	1357	360	0	41	0	3096	100	62	0	0	0	8	0
August	0	0	0	0	0	0	0	0	0	0	5100	0	0	0	0	0	0	1280	289	0	41	0	3373	100	116	0	0	0	19	0
September	0	0	0	0	0	0	0	0	0	0	5171	0	0	0	0	0	0	1298	194	0	41	0	3513	100	125	0	0	0	23	0
October	0	0	0	0	0	0	0	0	0	0	5033	0	0	0	0	0	0	1143	231	0	41	0	3472	100	146	0	0	0	28	0
November	0	0	0	0	0	0	0	0	0	0	5025	0	0	0	0	0	0	1413	264	0	41	0	3151	100	156	0	0	0	27	0
December	0	0	0	0	0	0	0	0	0	0	4929	0	0	0	0	0	0	1361	224	0	41	0	3136	100	166	0	0	0	31	0
Average	0	0	0	0	0	0	0	0	0	0	4966	0	0	0	0	0	0	1153	319	0	41	0	3342	100	111	0	0	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	6974	0	0	0	0	0	0	2650	1389	0	41	0	4556	100	1526	0	0	0	(USD/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	3713	0	0	0	0	0	0	224	21	0	41	0	1797	100	0	0	0	0	243	224
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	43.62	0.00	0.00	0.00	0.00	0.00	0.00	10.13	2.80	0.00	0.36	0.00	29.35		0.98	0.00	0.00	0.00	237	0

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	-	-	-	21.74	-	-	-	-	-	-	-	-	-	-	-	-	-	-	21.74	0.00	21.74	7.44	7.44
Oil	-	-	-	-	-	21.74	-	-	-	-	-	-	-	-	-	-	-	68.17	-	24.16	114.07	0.00	114.07	30.39	30.39
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.05	0.00	0.05	0.01	0.02
Biomass	-	-	-	-	-	21.74	-	-	-	-	-	-	-	-	-	-	-	-	-	37.33	59.07	0.00	59.07	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	3.69	3.70	-	5.54	-	-	-	-	12.93	0.00	12.93	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	65.23	-	2.80	-	-	-	-	3.69	3.70	-	5.54	-	68.22	-	61.49	207.87	2.17	210.04	37.84	37.85

12-October-2019 [15:55]

Appendix 17; Results of EnergyPLAN 2045 ADB model

Input Sri Lanka 11A 2045 ADB.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	54.04	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	54.04

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	10442	MW	29.46	TWh/year	0.00	Grid
Photo Voltaic	11066	MW	21.34	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	728	MW	3.37	TWh/year	0.00	share
Hydro Power	1576	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	1.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy: Technical regulation no. 2
CEEP regulation 000000000
Minimum Stabilisation share 0.00
Stabilisation share of CHP 0.00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0.50
Maximum import/export 0 MW

Distr. Name : Hour_nordpool.txt
Addition factor 0.00 USD/MWh
Multiplication factor 2.00
Dependency factor 0.00 USD/MWh pr. MW
Average Market Price 227 USD/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	

CAES fuel ratio: 0.000

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	74.96	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	27.07	0.00	33.78
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

District Heating

	Demand: Distr. heating MW	Production: Solar MW	Waste+CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW
January	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Electricity

	Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million USD	Exp Million USD
January	5826	0	0	0	0	0	0	4485	449	0	114	0	592	100	990	804	804	0	162	192
February	6104	0	0	0	0	0	0	3600	388	0	114	0	700	100	1602	301	301	0	230	48
March	5918	0	0	0	0	0	0	3167	320	0	114	0	723	100	1829	234	234	0	258	48
April	6157	0	0	0	0	0	0	3243	261	0	114	0	747	100	1973	180	180	0	299	38
May	6222	0	0	0	0	0	0	6341	374	0	114	0	488	100	306	1402	1402	0	52	346
June	6228	0	0	0	0	0	0	9114	507	0	114	0	25	100	0	3532	3532	0	0	675
July	6090	0	0	0	0	0	0	7824	359	0	114	0	225	100	60	2493	2493	0	7	373
August	6318	0	0	0	0	0	0	7519	259	0	114	0	314	100	173	2061	2061	0	28	359
September	6406	0	0	0	0	0	0	8079	193	0	114	0	236	100	154	2369	2369	0	29	433
October	6235	0	0	0	0	0	0	6598	231	0	114	0	470	100	717	1895	1895	0	129	351
November	6225	0	0	0	0	0	0	6369	264	0	114	0	459	100	1582	2564	2564	0	257	434
December	6106	0	0	0	0	0	0	7562	224	0	114	0	459	100	1322	3574	3574	0	223	697
Average	6152	0	0	0	0	0	0	6167	319	0	114	0	453	100	888	1788	1788	0	Average price	
Maximum	8640	0	0	0	0	0	0	15579	1389	0	114	0	1001	100	5342	10017	10017	0	(USD/MWh)	
Minimum	4600	0	0	0	0	0	0	1004	21	0	114	0	0	100	0	0	0	0	214	254
TWh/year	54.04	0.00	0.00	0.00	0.00	0.00	0.00	54.17	2.80	0.00	1.00	0.00	3.98		7.80	15.71	15.71	0.00	1673	3993

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	2.95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.95	0.00	2.95	1.01	1.01
Oil	-	-	-	-	-	2.95	-	-	-	-	-	-	-	-	-	-	-	74.96	-	27.07	104.98	0.00	104.98	27.97	27.97
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.05	0.00	0.05	0.01	0.02
Biomass	-	-	-	-	-	2.95	-	-	-	-	-	-	-	-	-	-	-	-	-	33.78	36.73	0.00	36.73	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	29.46	21.34	-	6.17	-	-	-	-	56.97	0.00	56.97	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	8.84	-	2.80	-	-	-	-	29.46	21.34	-	6.17	-	75.01	-	60.85	201.67	-17.57	184.10	28.98	28.99

12-October-2019 [16:04]

Appendix 18; Results of EnergyPLAN 2045 model for 50% RES

Input Sri Lanka 11B 2045 EP 50%.txt — The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	54.26	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	54.26

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	3820	MW	10.78	TWh/year	0.00	Grid
Photo Voltaic	5600	MW	10.8	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	728	MW	3.37	TWh/year	0.00	share
Hydro Power	1576	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	1.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW
Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	350	13	0.85	
Ely. MicroCHP:	0	0	0.00	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	54.06	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	27.07	0.00	33.78
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

District Heating

	Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW
January	0	0	252	0	0	0	0	0	0	-252
February	0	0	252	0	0	0	0	0	0	-252
March	0	0	252	0	0	0	0	0	0	-252
April	0	0	252	0	0	0	0	0	0	-252
May	0	0	252	0	0	0	0	0	0	-252
June	0	0	252	0	0	0	0	0	0	-252
July	0	0	252	0	0	0	0	0	0	-252
August	0	0	252	0	0	0	0	0	0	-252
September	0	0	252	0	0	0	0	0	0	-252
October	0	0	252	0	0	0	0	0	0	-252
November	0	0	252	0	0	0	0	0	0	-252
December	0	0	252	0	0	0	0	0	0	-252
Average	0	0	252	0	0	0	0	0	0	-252
Maximum	0	0	252	0	0	0	0	0	0	-252
Minimum	0	0	252	0	0	0	0	0	0	-252
TWh/year	0.00	0.00	2.21	0.00	0.00	0.00	0.00	0.00	0.00	-2.21

Electricity and Exchange

	Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million USD	Exp Million USD
January	5852	0	0	134	0	0	0	2161	449	0	114	0	500	100	2761	0	0	0	508	0
February	6129	0	0	134	0	0	0	1721	388	0	114	0	500	100	3539	0	0	0	525	0
March	5943	0	0	134	0	0	0	1516	320	0	114	0	500	100	3627	0	0	0	561	0
April	6182	0	0	134	0	0	0	1607	261	0	114	0	500	100	3635	0	0	0	632	0
May	6247	0	0	134	0	0	0	3013	374	0	114	0	500	100	2380	0	0	0	399	0
June	6253	0	0	134	0	0	0	4044	507	0	114	0	378	100	1476	130	130	0	194	29
July	6115	0	0	134	0	0	0	3398	359	0	114	0	442	100	1947	11	11	0	190	2
August	6343	0	0	134	0	0	0	3227	259	0	114	0	496	100	2382	0	0	0	372	0
September	6431	0	0	134	0	0	0	3392	193	0	114	0	490	100	2377	0	0	0	413	0
October	6260	0	0	134	0	0	0	2955	231	0	114	0	500	100	2593	0	0	0	462	0
November	6250	0	0	134	0	0	0	3352	264	0	114	0	376	100	2293	15	15	0	371	2
December	6132	0	0	134	0	0	0	3654	224	0	114	0	296	100	2210	232	232	0	369	45
Average	6177	0	0	134	0	0	0	2840	319	0	114	0	457	100	2615	32	32	0	Average price	
Maximum	8665	0	0	134	0	0	0	6898	1389	0	114	0	500	100	6646	1048	1048	0	(USD/MWh)	
Minimum	4626	0	0	134	0	0	0	458	21	0	114	0	0	100	0	0	0	0	217	272
TWh/year	54.26	0.00	0.00	1.18	0.00	0.00	0.00	24.95	2.80	0.00	1.00	0.00	4.01		22.97	0.28	0.28	0.00	4994	78

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	-	-	-	4.46	-	-	-	-	-	-	-	-	-	-	-	54.06	-	27.07	85.59	0.00	85.59	22.80	22.80
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.05	0.00	0.05	0.01	0.02
Biomass	-	-	-	-	-	4.46	-	-	1.00	-	27.12	-	-	-	-	-	-	-	-	33.78	66.36	0.00	66.36	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	10.78	10.80	-	6.17	-	-	-	-	27.75	0.00	27.75	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-1.00	-	-	-	-	-	-	-	1.00	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-0.90	-	-20.00	-	-	-	-	-	-	20.90	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	8.91	-	2.80	0.10	-1.00	7.12	-	10.78	10.80	-	6.17	-	76.01	-	60.85	179.74	50.41	230.15	22.81	22.82

01-December-2019 [19:53]

Appendix 19; Results of EnergyPLAN 2045 enhanced model

Input Sri Lanka 11C 2045 EP 50% Amended.txt — **The EnergyPLAN model 14.1**

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	48.92	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	48.92

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	3820 MW	10.78 TWh/year	0.00	Grid
Photo Voltaic	5600 MW	10.8 TWh/year	0.00	stabili-
Offshore Wind	0 MW	0 TWh/year	0.00	sation
River Hydro	728 MW	3.37 TWh/year	0.00	share
Hydro Power	1576 MW	2.8 TWh/year		
Geothermal/Nuclear	0 MW	0 TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	1.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2
CEEP regulation	000000000
Minimum Stabilisation share	0.00
Stabilisation share of CHP	0.00
Minimum CHP gr 3 load	0 MW
Minimum PP	0 MW
Heat Pump maximum share	0.50
Maximum import/export	0 MW
Distr. Name :	Hour_nordpool.txt
Addition factor	0.00 USD/MWh
Multiplication factor	2.00
Dependency factor	0.00 USD/MWh pr. MW
Average Market Price	227 USD/MWh
Gas Storage	0 GWh
Syngas capacity	0 MW
Biogas max to grid	0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	700	25	0.85	
Ely. MicroCHP:	0	0	0.00	
CAES fuel ratio:	0.000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	40.55	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	13.54	0.00	67.56
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating Demand	District Heating Production									Electricity Consumption						Electricity Production							Electricity Balance					Exchange Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million USD	Exp Million USD
January	0	0	315	0	0	0	0	0	0	-315	5276	0	0	268	0	0	0	2161	449	0	114	0	500	100	2319	0	0	0	419	0
February	0	0	315	0	0	0	0	0	0	-315	5525	0	0	268	0	0	0	1721	388	0	114	0	500	100	3070	0	0	0	453	0
March	0	0	315	0	0	0	0	0	0	-315	5358	0	0	268	0	0	0	1516	320	0	114	0	500	100	3176	0	0	0	487	0
April	0	0	315	0	0	0	0	0	0	-315	5573	0	0	268	0	0	0	1607	261	0	114	0	500	100	3359	0	0	0	550	0
May	0	0	315	0	0	0	0	0	0	-315	5631	0	0	268	0	0	0	3013	374	0	114	0	488	100	1911	0	0	0	311	0
June	0	0	315	0	0	0	0	0	0	-315	5637	0	0	268	0	0	0	4044	507	0	114	0	347	100	1142	248	248	0	148	53
July	0	0	315	0	0	0	0	0	0	-315	5513	0	0	268	0	0	0	3398	359	0	114	0	400	100	1575	64	64	0	150	10
August	0	0	315	0	0	0	0	0	0	-315	5718	0	0	268	0	0	0	3227	259	0	114	0	460	100	1931	4	4	0	299	1
September	0	0	315	0	0	0	0	0	0	-315	5797	0	0	268	0	0	0	3392	193	0	114	0	441	100	1936	11	11	0	335	2
October	0	0	315	0	0	0	0	0	0	-315	5643	0	0	268	0	0	0	2955	231	0	114	0	462	100	2148	0	0	0	381	0
November	0	0	315	0	0	0	0	0	0	-315	5634	0	0	268	0	0	0	3352	264	0	114	0	306	100	1997	131	131	0	322	22
December	0	0	315	0	0	0	0	0	0	-315	5528	0	0	268	0	0	0	3654	224	0	114	0	292	100	1932	420	420	0	322	82
Average	0	0	315	0	0	0	0	0	0	-315	5569	0	0	268	0	0	0	2840	319	0	114	0	433	100	2204	73	73	0	Average price	
Maximum	0	0	315	0	0	0	0	0	0	-315	7808	0	0	268	0	0	0	6898	1389	0	114	0	500	100	5948	1522	1522	0	(USD/MWh)	
Minimum	0	0	315	0	0	0	0	0	0	-315	4172	0	0	268	0	0	0	458	21	0	114	0	0	100	0	0	0	0	216	264
TWh/year	0.00	0.00	2.77	0.00	0.00	0.00	0.00	0.00	0.00	-2.77	48.92	0.00	0.00	2.35	0.00	0.00	0.00	24.95	2.80	0.00	1.00	0.00	3.81		19.36	0.64	0.64	0.00	4178	170

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	-	-	-	4.23	-	-	-	-	-	-	-	-	-	-	-	40.55	-	13.54	58.32	0.00	58.32	15.54	15.54
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.05	0.00	0.05	0.01	0.02
Biomass	-	-	-	-	-	4.23	-	-	2.00	-	33.90	-	-	-	-	-	-	-	-	67.56	107.69	0.00	107.69	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	10.78	10.80	-	6.17	-	-	-	-	27.75	0.00	27.75	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-2.00	-	-	-	-	-	-	-	2.00	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-1.80	-	-25.00	-	-	-	-	-	-	26.80	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	8.46	-	2.80	0.20	-2.00	8.90	-	10.78	10.80	-	6.17	-	69.40	-	81.10	193.81	41.60	235.40	15.55	15.56

01-December-2019 [21:48]

Appendix 20; Results of EnergyPLAN 2050 ADB model.

Input Sri Lanka 12B 2050 ADB 100% electricity.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	71.97	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	0.00	Total	71.97

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	15155 MW	42.76 TWh/year	0.00	Grid
Photo Voltaic	16438 MW	31.7 TWh/year	0.00	stabili-
Offshore Wind	0 MW	0 TWh/year	0.00	sation
River Hydro	753 MW	3.49 TWh/year	0.00	share
Hydro Power	1576 MW	2.8 TWh/year		
Geothermal/Nuclear	0 MW	0 TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	1.15	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities	Storage	Efficiencies	
	MW-e	GWh	elec.	Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.85	
Ely. MicroCHP:	0	0	0.00	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	81.75	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	29.99	0.00	30.23
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

District Heating (MW)

	Demand: Distr. heating	Production: Solar	Waste+ CSHP	DHP	CHP	HP	ELT	Boiler	EH	Ba- lance
January	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Electricity and Exchange

	Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Production: Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million USD	Exp Million USD
January	7759	0	0	0	0	0	0	6410	449	0	131	0	0	100	2116	1347	1347	0	346	323
February	8129	0	0	0	0	0	0	5189	388	0	131	0	0	100	3029	608	608	0	435	97
March	7881	0	0	0	0	0	0	4602	320	0	131	0	0	100	3334	505	505	0	472	103
April	8200	0	0	0	0	0	0	4665	261	0	131	0	0	100	3555	412	412	0	541	88
May	8286	0	0	0	0	0	0	8956	374	0	131	0	0	100	1030	2205	2205	0	157	544
June	8294	0	0	0	0	0	0	12997	507	0	131	0	0	100	29	5369	5369	0	4	1021
July	8111	0	0	0	0	0	0	11250	359	0	131	0	0	100	313	3943	3943	0	35	583
August	8415	0	0	0	0	0	0	10816	259	0	131	0	0	100	500	3291	3291	0	79	572
September	8532	0	0	0	0	0	0	11666	193	0	131	0	0	100	384	3842	3842	0	71	700
October	8304	0	0	0	0	0	0	9550	231	0	131	0	0	100	1474	3083	3083	0	262	571
November	8290	0	0	0	0	0	0	9172	264	0	131	0	0	100	2794	4071	4071	0	452	688
December	8132	0	0	0	0	0	0	11059	224	0	131	0	0	100	2350	5632	5632	0	393	1097
Average	8193	0	0	0	0	0	0	8873	319	0	131	0	0	100	1736	2865	2865	0	Average price	
Maximum	11506	0	0	0	0	0	0	22467	1389	0	131	0	0	100	8642	14881	14881	0	(USD/MWh)	
Minimum	6127	0	0	0	0	0	0	1397	21	0	131	0	0	100	0	0	0	0	213	254
TWh/year	71.97	0.00	0.00	0.00	0.00	0.00	0.00	77.94	2.80	0.00	1.15	0.00	0.00		15.25	25.17	25.17	0.00	3247	6388

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	81.75	-	29.99	111.74	0.00	111.74	29.77	29.77
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.06	-	-	0.06	0.00	0.06	0.01	0.03
Biomass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	30.23	30.23	0.00	30.23	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	42.76	31.70	-	6.29	-	-	-	-	80.74	0.00	80.74	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	-	-	2.80	-	-	-	-	42.76	31.70	-	6.29	-	81.81	-	60.22	222.77	-22.04	200.73	29.78	29.79

20-October-2019 [17:37]

Appendix 21; Results of EnergyPLAN 2050 model for 100% RES.

Input Sri Lanka 12C 2050 EP 100% RES.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	72.69	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	2.00
Electric cooling	0.00	Total	74.69

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	14430	MW	40.71	TWh/year	0.00	Grid
Photo Voltaic	15600	MW	30.08	TWh/year	0.00	stabili-
Offshore Wind	0	MW	0	TWh/year	0.00	sation
River Hydro	753	MW	3.49	TWh/year	0.00	share
Hydro Power	1576	MW	2.8	TWh/year		
Geothermal/Nuclear	0	MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	0		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	1.15	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	000000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0.50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	USD/MWh
Multiplication factor	2.00	
Dependency factor	0.00	USD/MWh pr. MW
Average Market Price	227	USD/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	700	50	0.85	
Ely. MicroCHP:	0	0	0.00	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	0.00	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	0.00	0.00	90.24
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

District Heating / Electricity Consumption

	Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Balance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Electrolyser MW	EH MW	Hydro Pump MW
January	0	0	820	0	0	0	0	0	0	-820	7841	228	0	268	0	0
February	0	0	820	0	0	0	0	0	0	-820	8211	228	0	268	0	0
March	0	0	820	0	0	0	0	0	0	-820	7963	228	0	268	0	0
April	0	0	820	0	0	0	0	0	0	-820	8282	228	0	268	0	0
May	0	0	820	0	0	0	0	0	0	-820	8368	228	0	268	0	0
June	0	0	820	0	0	0	0	0	0	-820	8376	228	0	268	0	0
July	0	0	820	0	0	0	0	0	0	-820	8193	228	0	268	0	0
August	0	0	820	0	0	0	0	0	0	-820	8496	228	0	268	0	0
September	0	0	820	0	0	0	0	0	0	-820	8613	228	0	268	0	0
October	0	0	820	0	0	0	0	0	0	-820	8386	228	0	268	0	0
November	0	0	820	0	0	0	0	0	0	-820	8372	228	0	268	0	0
December	0	0	820	0	0	0	0	0	0	-820	8214	228	0	268	0	0
Average	0	0	820	0	0	0	0	0	0	-820	8275	228	0	268	0	0
Maximum	0	0	820	0	0	0	0	0	0	-820	11588	455	0	268	0	0
Minimum	0	0	820	0	0	0	0	0	0	-820	6209	0	0	268	0	0
TWh/year	0.00	0.00	7.20	0.00	0.00	0.00	0.00	0.00	0.00	-7.20	72.69	2.00	0.00	2.35	0.00	0.00

Electricity Production / Balance / Exchange

	Turbine MW	RES MW	Hydro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Payment Imp Million USD	Payment Exp Million USD
January	0	6114	449	0	131	0	0	100	2663	1020	1020	0	433	242
February	0	4944	388	0	131	0	0	100	3621	377	377	0	516	61
March	0	4380	320	0	131	0	0	100	3928	299	299	0	556	61
April	0	4446	261	0	131	0	0	100	4161	221	221	0	634	47
May	0	8556	374	0	131	0	0	100	1581	1778	1778	0	234	440
June	0	12401	507	0	131	0	0	100	184	4351	4351	0	25	857
July	0	10723	359	0	131	0	0	100	747	3272	3272	0	73	496
August	0	10309	259	0	131	0	0	100	1017	2724	2724	0	157	475
September	0	11114	193	0	131	0	0	100	837	3165	3165	0	149	580
October	0	9095	231	0	131	0	0	100	1971	2547	2547	0	348	472
November	0	8739	264	0	131	0	0	100	3173	3439	3439	0	512	582
December	0	10517	224	0	131	0	0	100	2755	4916	4916	0	458	960
Average	0	8456	319	0	131	0	0	100	2214	2348	2348	0	Average price	
Maximum	0	21406	1389	0	131	0	0	100	9518	13471	13471	0	(USD/MWh)	
Minimum	0	1338	21	0	131	0	0	100	0	0	0	0	211	256
TWh/year	0.00	74.28	2.80	0.00	1.15	0.00	0.00		19.44	20.63	20.63	0.00	4094	5273

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biomass	-	-	-	-	-	-	-	-	3.00	-	110.70	-	-	-	-	-	-	-	-	90.24	203.94	0.00	203.94	0.00	0.00
Renewable	-	-	-	-	-	-	-	2.80	-	-	-	-	40.71	30.08	-	6.29	-	-	-	-	77.08	0.00	77.08	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-2.00	-	-	-	-	-	-	-	2.00	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-2.70	-	-83.03	-	-	-	-	-	-	85.73	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	-	-	-	-	-	2.80	0.30	-2.00	27.67	-	40.71	30.08	-	6.29	-	87.73	-	90.24	281.02	-2.63	278.38	0.00	0.00

01-December-2019 [22:20]