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Evaluating the Energy Metabolic System in Sri Lanka

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Abstract

Fast growing economy of Sri Lanka with an annual GDP growth rate of 5% has significantly increased demand for energy. As energy supply must grow in a sustainable way to meet the demand, concern over the environmental impact of energy flows have been gaining attention during policy development and implementation. Therefore, there is a need of comprehensively evaluating energy metabolic system in Sri Lanka to identify resource dependencies of the country that must be addressed to increase the sustainability.

A conceptual energy metabolic model was developed identifying economic, social and demographic variables affecting energy demand, transformation and supply and GHG emissions in Sri Lanka. Developed model was used to evaluate the current energy flows and forecast the behaviour of energy metabolism while assessing the sustainability of the energy system using number of sustainability indicators.

Developed model indicates an average annual growth rate of 4.06% in energy demand, 4.17% in non-renewable energy supply and 3.36% in GHG emissions. Transport sector has the highest GHG emissions percentage of 73%. Sustainability evaluation of the energy metabolic system shows that Sri Lanka is becoming more efficient and less energy intensive over the years. However, increase in GHG emissions per capita and emission intensity has a negative impact on the environmental sustainability while increase renewable energy share in total energy supply can be considered positive. The findings of the research give new insights to the energy system of Sri Lanka which enable energy planners to implement policies to transition towards a more secure and sustainable energy system.

Keywords: energy metabolism, energy modelling, GHG emissions, sustainability indicators, sustainability evaluation

1. Introduction

Similar to human metabolism or cyclical mechanisms of natural ecosystem, the physical and biological systems of a city require fluxes of materials and energy for transforming products, services, and subsequently generating wastes (Huang & Hsu, 2003). Urban metabolism is a multi-disciplinary concept that examines material and energy flows in the cities shaped by various social, economic and environmental forces (Holmes et al., 2012). According to Hoornweg et al. (2012), it represents a comprehensive framework that helps monitor the transformation occurring in cities, as well as their contributions to sustainable development. In urban energy metabolic processes, energy produced by the energy exploitation sector is considered the primary energy source; it consequently provides energy for both the transformation i.e. oil refining, power generation and co-generation and terminal consumption sectors which includes both industries and households (Kuznecova et al., 2014).

Most studies focussing on energy structure, energy use intensity or energy forecasting models have modelled urban energy system as a black box. And compartmentalization of components within urban system, energy metabolism processes and flows between these components, have seldom been investigated (Facchini et al, 2016). According to Pincetl et al. (2012) the expansion of urban metabolism to a wider systems-oriented approach requires the collaboration of different disciplines in the analysis of a city’s metabolism, in matching energy and waste flows to land uses and social-demographic variables, in evaluation of the socioeconomic and policy drivers that govern the flows and patterns, as well as life cycle assessment of the various processes and materials that make up a city’s metabolism.

Developing economies play a major role in the overall energy scenario of the world, and this role is only expected to increase. As main goal of developing communities is only socioeconomic development, protection of the environment is not a priority and often considered as an obstacle on the path of development. Sri Lanka is a developing country with population of 20 million and a mid-range annual GDP per capita. Following a 30-year civil war, Sri Lanka's economy has grown at an average rate of 6.4% between 2010 and 2015, with GDP per capita rising from US$ 2,014 in 2008 to US$ 3,837 in 2015 (ADB & UNDP, 2017). The country's economy is based on the service sector which has contributed 59% to the GDP with the industrial and agricultural sectors contributing 29% and 12%, respectively (Ministry of Environment, 2011).

When considering the energy consumption 56% of total energy consumption is from indigenous sources while balance fossil fuels are imported. With compared to other South Asian countries like Bangladesh, India, and the Maldives, Sri Lanka has a higher share of renewable energy supply (mainly biomass and hydropower) along with Bhutan and Nepal (Shrestha et al., 2012). The annual total electricity demand of 10,500 GWh includes 38% from domestic consumers, 39% from industries and 20% from commercial enterprises, with the balance coming from other sectors such as religious organizations and street lighting. The overall annual demand for electricity is expected to increase by around 4-6 %, a number constrained by high prices (Ministry of Power and Energy Sri Lanka, 2015).

Although currently Sri Lanka is amongst the lowest GHG emitters in the world (ranked 194th out of a total 251 countries) as well as in South Asia (0.8 $mtCO_2e$/capita in 2015), increased dependence on fossil fuels has led to an increase in Sri Lanka's GHG emissions (ADB & UNDP, 2017). Total GHG emissions of energy using activities across South Asia increased by 98.2% during 1990–2005, while global emissions increased by only 30.8%. Of the increase, Nepal had the highest (233.3%), and India the lowest (95.5%). The region's contribution to global GHG emissions from energy-using activities increased from 2.9% in 1990 to 3.7% in 1995 and 4.4% in 2005 (Shrestha et al., 2012). Steady growth in Sri Lanka's GHG emissions (from 0.5 $mtCO_2e$/capita in 2000) is dominated by the energy sector (41%), waste (26%), Land Use Change and Forestry (LUCF) (14%) and agriculture (12%) sectors in 2016 (ADB and UNDP, 2017).

In order to control the growth in GHG emissions Sri Lanka is in need of formulating energy policies focusing on GHG reductions via energy savings and encouraging renewable energy sources. Under the United Nations Framework Convention of Climate Change (UNFCCC) reduction of GHG emissions has become a share goal for its member countries. Therefore, adhering to Paris Agreement submitted intended nationally determined contributions by Sri Lankan government in 2015 aims to reduce the GHG emissions against BAU scenario by 20% in energy sector which is highest emitter of GHGs. To achieve set GHG emissions reduction targets and sustainability targets, it is necessary to develop feasible energy policies monitoring the progress of the energy metabolism towards sustainability, within the overall economic, social and environmental framework. Thus, this research aims to develop an energy metabolic model to evaluate current status and sustainability of energy metabolic flows. The first part of the paper discusses the literature background to energy metabolism followed by development process of energy metabolic model. Third section of the paper discusses the results of the data analysis followed by conclusions of the paper.

2. Development of Urban Energy Metabolic Model

2.1 Urban Energy Modelling

An urban energy model is a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area (Keirsteada et al., 2012). Energy models are used to project the future energy demand and supply of a country or a region. They are mostly used in an exploratory manner assuming certain developments of boundary conditions such as the development of economic activities, demographic development, or energy prices on world markets (Herbst et al., 2012). They are also used to simulate policy and technology choices that may influence future energy demand and supply, and hence investments in energy systems, including energy efficiency policies. Herbst et al. (2012) further states that energy models represent a more or less simplified picture of the real energy system and the real economy.

Modelling is not novel when it comes to policy development as many policy makers over the years have been dependant on models designed to estimate and predict energy demand/supply and GHG emissions. According to (IPCC, 1996), out of widely used types of energy modelling techniques top-down energy models are focussed on the aggregate relationships based on historical data while bottom-up energy models determine the financially cheapest way to achieve a given target based on the best available technologies and processes. Top-down energy models include computational general equilibrium models, econometric models, input/output models, and system dynamics models that treat the energy system as a part of the macro-economy (Unger, 2010). Further they depict the economy as a whole on a national or regional level and to assess the aggregated effects of energy and climate change policies in monetary units (Herbst et al., 2012). Therefore, according to UNFCCC (2005), top down models are important when general impact of GHG mitigation is examined, GHG emissions mitigation will cause substantial changes to an economy and when typically, macroeconomic variables are examined. Thus, this study has combined top down approach with system dynamics concept to identify the subsystems, analyse their interactions to provide a wholistic understanding of the energy metabolic system in Sri Lanka. Section 2.3 elaborates the development process of energy metabolic model of this study.

2.2 Model Development

The model is constructed to evaluate the energy metabolism in Sri Lanka by analysing energy demand, energy supply and GHG emissions. Figure 1 elaborates the development process of energy metabolic model. Various economic and social demographic parameters such as population, GDP, income and energy price have been used as main input variables to evaluate the energy demand and GHG emission in Sri Lanka. In the case of energy price, the historical data of average crude oil products price has been used. In general, the recorded data from 2000-2015 (Refer Appendix A) is applied to evaluate the current behaviour of energy flows and have been further extrapolated to evaluate the energy metabolism of the future period time of 2016-2030.

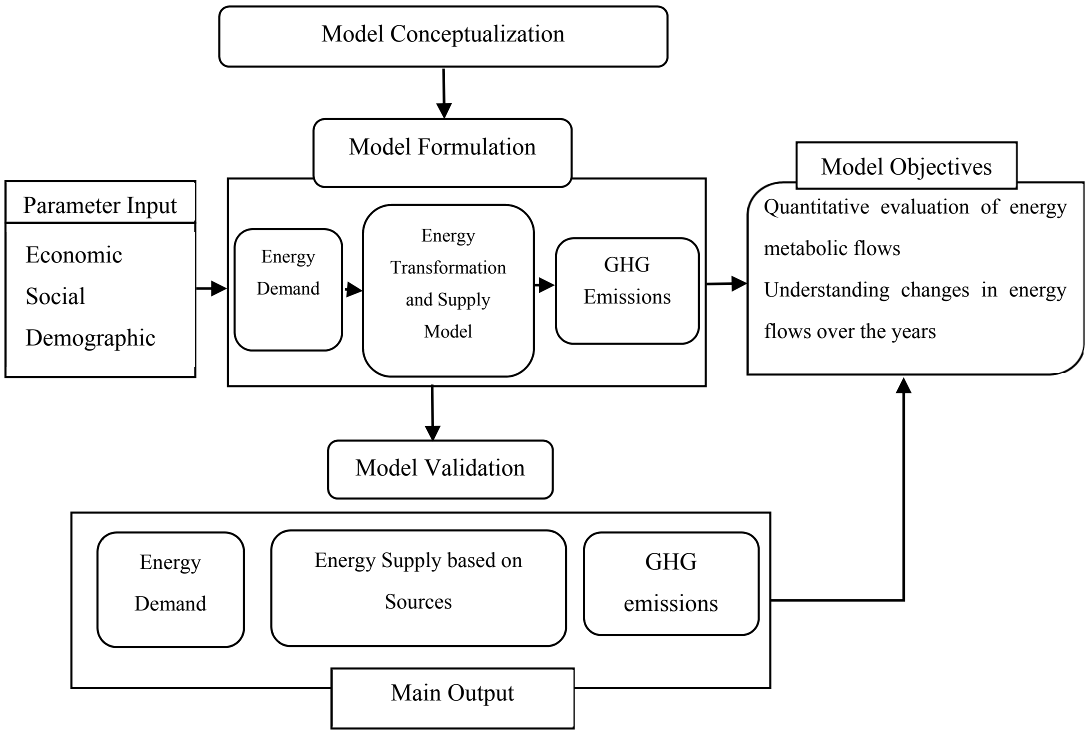

Figure 1. The development process of energy metabolic model

2.2.1 Energy Demand Sub-model of Sri Lanka

The energy metabolic model of Sri Lanka is comprised with three sub models namely energy demand sub-model, energy supply and transformation sub-model, and GHG emissions sub-model. The energy demand sub-model evaluates the energy demand of Sri Lanka from 2000-2015 and predicts the energy demand from 2015-2030.

The first part of the second model is to determine the amount of energy demand (Figure 2). The main input parameters are considered to calculate energy demand in Sri Lanka are population, GDP and energy price. Those parameters are based on Kaya identity (Kaya, 1990) which identifies significance drivers for the occurrence of carbon emissions. The Kaya's equation which decomposes energy related CO_2 emissions into four factors enables to quantify the underlying factors of change in terms of absolute or relative energy indicators (e.g. energy consumption, carbon emission, GHG emission) (Štreimikienė & Balezentis, 2016). Kaya's equation is as follows;

$$\mathrm{C} = \frac{\mathrm{C}}{\mathrm{E}} * \frac{\mathrm{E}}{\mathrm{Y}} * \frac{\mathrm{Y}}{\mathrm{P}} * P \tag{1}$$

Where is, C = Carbon emissions (or more broadly, GHG emissions)

E = Energy generated and consumed by humans

Y = Economic output (goods and services, GDP

P = Population

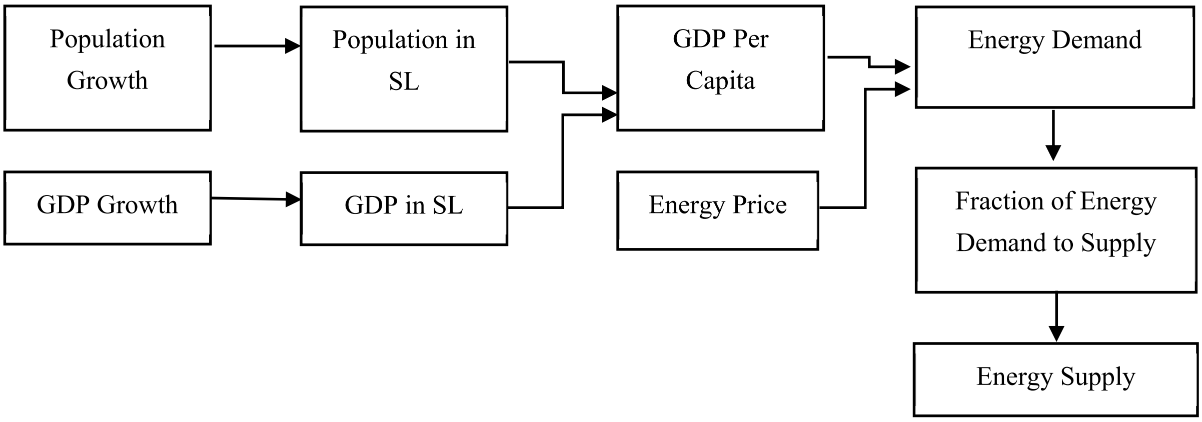

Figure 2. Energy demand sub-model of Sri Lanka

Once the energy demand is calculated energy supply has been derived by multiplying the energy demand by the fraction of energy demand to supply which is derived from the historical average discrepancy between the energy demand and supply of Sri Lanka. The assumptions of the energy demand sub-model are shown in table 1 and 2.

2.2.2 Energy Transformation and Supply Sub-model of Sri Lanka

Structure of the energy transformation sub-model is shown in Figure 3. Primary energy sources of Sri Lanka include crude oil, coal, wind, non- conventional sources, hydro, solar and biomass. Energy mix is calculated using historical patterns of data and projected percentage of energy type. Figure 3 further illustrates taking crude oil as an example, how it is transformed and consumed among different sectors. Crude oil will be used in the original form by aviation and transport sectors. While commercial and domestic sectors and industrial sectors will use the electricity transformed by crude oil while the remaining will be transmission and losses. The assumptions of energy supply and transformation sub model are shown in Table 3 and 4 in Appendix A.

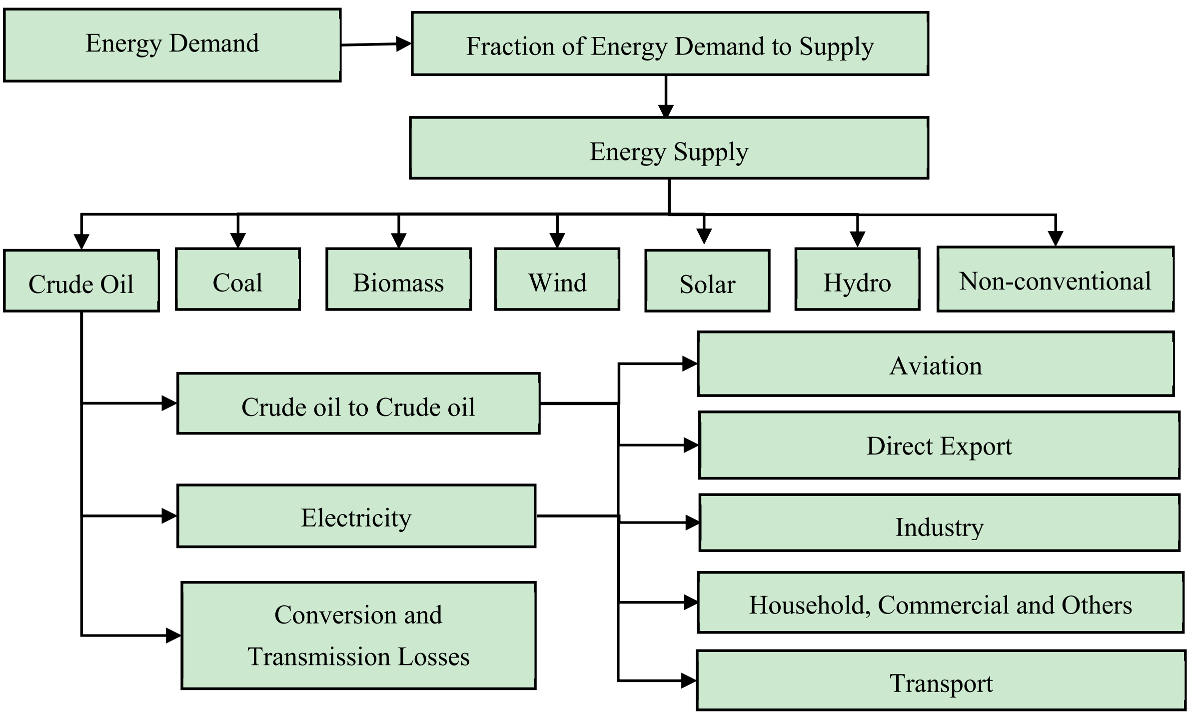

Figure 3. Energy transformation and supply sub-model of Sri Lanka

2.2.3 GHG Emissions Sub-model of Sri Lanka

Figure 4 shows the GHG emissions sub-model of Sri Lanka. GHG emissions are obtained by multiplying each GHG emitting sources i.e. crude oil, coal and biomass by its respective Emission Factor (EF).

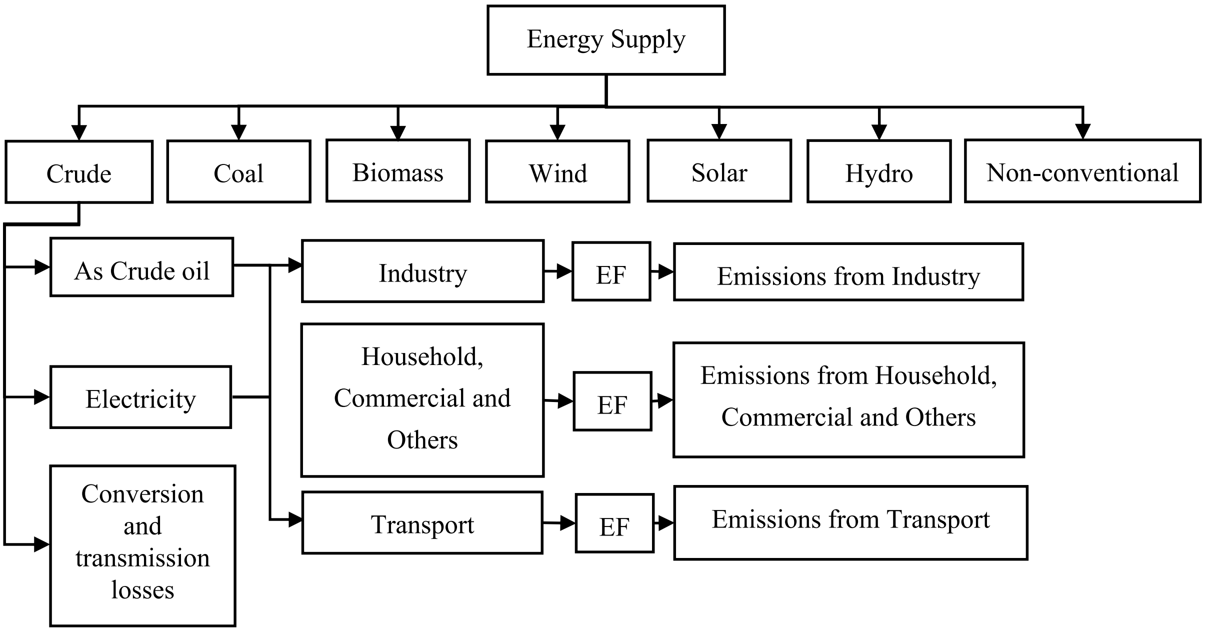

Figure 4. GHG emissions sub-model of Sri Lanka

Figure 4 shows emissions calculation process for crude oil which will be followed by coal and biomass as well. The emissions will be then divided among transport, industry, domestic and commercial sectors based on the energy consumption of each sector respectively. The assumptions of the GHG emission sub model is shown in Table 5 and 6 in Appendix A.

3. Data Analysis and Discussion

3.1 Energy Demand Sub-model of Sri Lanka

Figure 5 shows results of the energy demand sub model where main outputs are total energy demand and sectorial energy demand in Sri Lanka. Refer Table 1 and 2 in the Appendix A for the variables and input parameters of the model. Future energy demand was forecasted extrapolating the historical data. Energy demand of industrial sector, transport sector, domestic and commercial sector are also shown in the Figure 5.

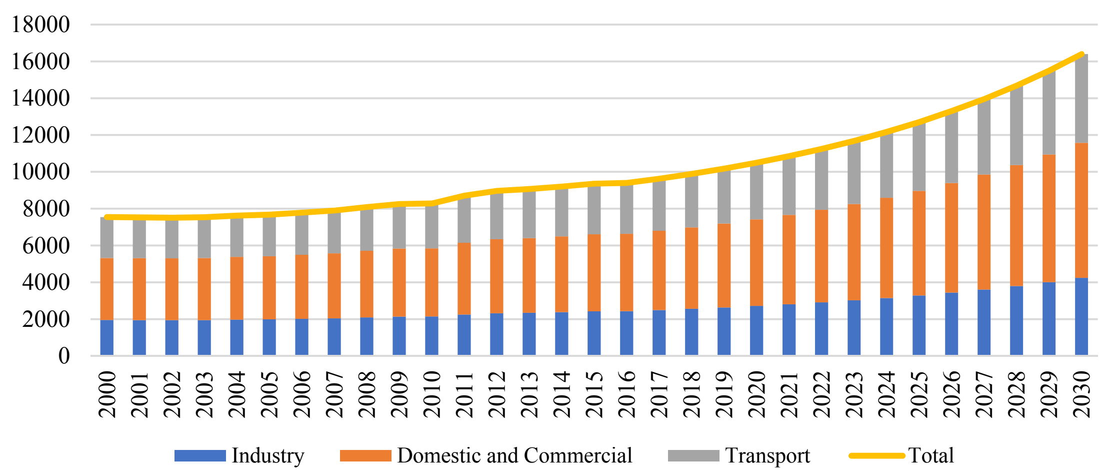

Figure 5. Energy demand of Sri Lanka (ktoe)

Annual energy demand has been less than 3% from 2000 – 2010 and in 2011 it has increased up to 5.22%. With the increasing economic development after ending the civil war of 30 years have affected the increase in annual energy demand growth rate which fluctuates 4%-6% from 2011. Domestic and commercial sector dominates energy demand of Sri Lanka with 44.73% share of total energy demand in 2015 followed by transport (29.41%) and industrial (25.86%) sectors. Increasing population and GDP have the most influence in escalating energy demand.

3.2 Energy Supply and Transformation Sub-model of Sri Lanka

Figure 6 shows the results of the energy supply and transformation sub-model. Crude oil and biomass are the most widely used energy sources followed by hydro, coal and other domestic renewable sources such as solar, wind and non-conventional energy sources. Sri Lanka always have maintained energy supply to meet energy demand. Therefore, as energy demand and consumption grow, energy supply will grow accordingly. Biomass being one of the most widely used energy sources helps reducing GHG emissions in Sri Lanka with compared to other non-renewable energy sources.

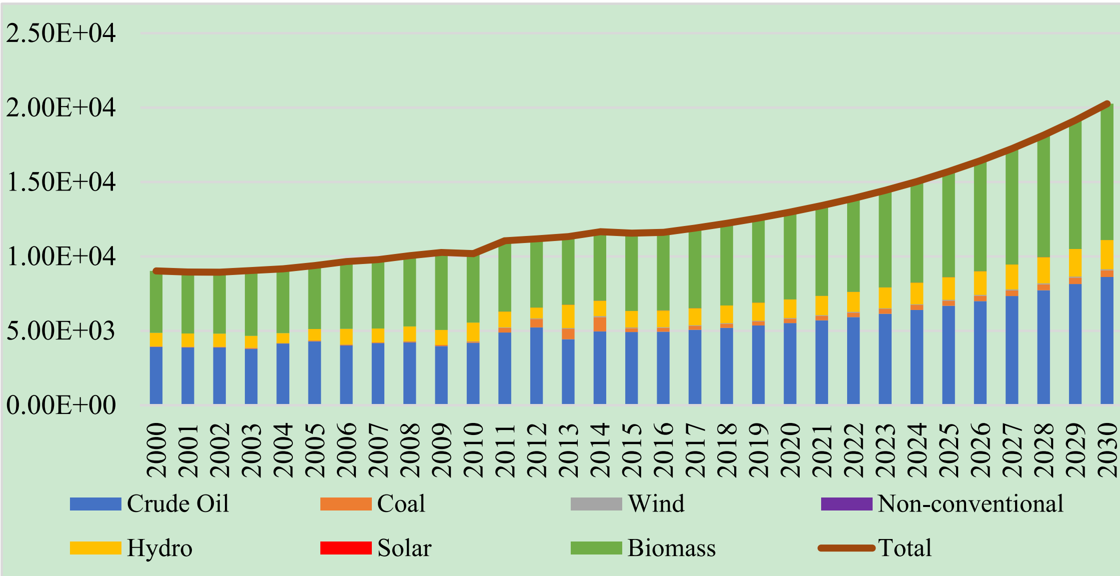

Figure 6. Energy supply based on energy sources (ktoe)

Transport sector is the highest consumer of crude oil followed by domestic and commercial sector and industrial sector. Coal is mainly used for industrial purposes and secondly domestic and commercial sector purposes. All the other energy sources i.e. biomass, hydro, solar, wind and non-conventional energy sources are heavily consumed by domestic and commercial sector and industrial sector.

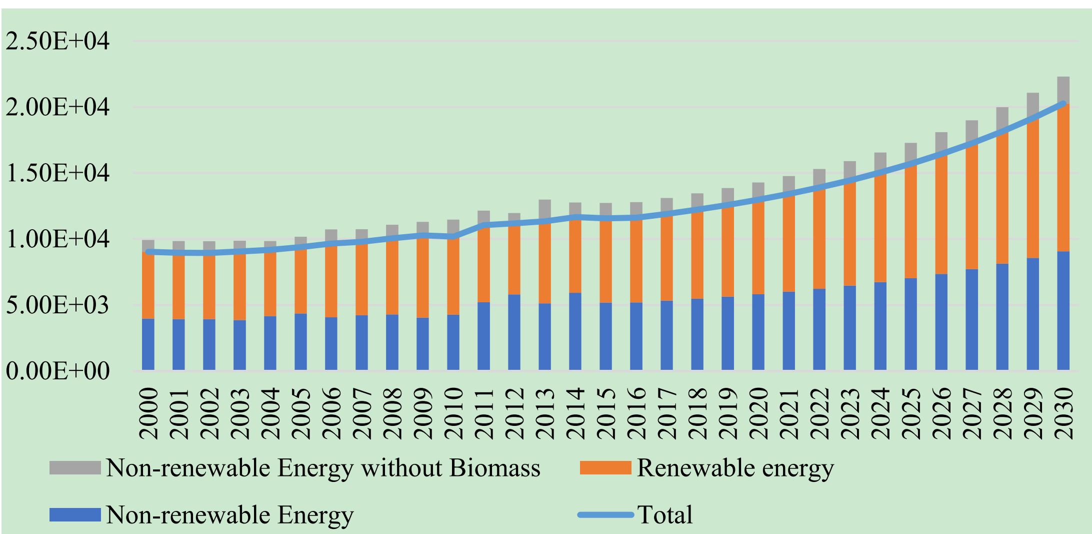

Figure 7. Renewable and non-renewable energy supply (ktoe)

According to Figure 7 percentages of non-renewable and renewable energy sources are almost equal as renewable energy consumption is only about 2-3% higher than non-renewable energy consumption. However, the majority share of renewable energy consumption is carried by biomass leaving other renewable energy consumption less than 20% in spite of Sri Lanka's high potential for wind and solar energy.

3.3 GHG emissions Sub-model of Sri Lanka

Figure 8 shows the final output of the developed energy metabolic model. GHG emissions is one of the most import indicators in evaluating environmental sustainability of a country/city. Figure 8 shows how GHG emissions in Sri Lanka has been increasing over the years with an annual growth rate of 2% - 11%, 2004 being the highest with 11.02%. GHG emissions has increased more than 25% in 2015 with compared to 2000 going from 10238 Gg to 17289 Gg in 2015 and it is expected to grow up to 25000 Gg by 2030. Crude oil has the highest percentage of emissions which is 77.44% in 2000 and 79.21% in 2014. Biomass as the second emitter is responsible for 22.26% of the total GHG emissions.

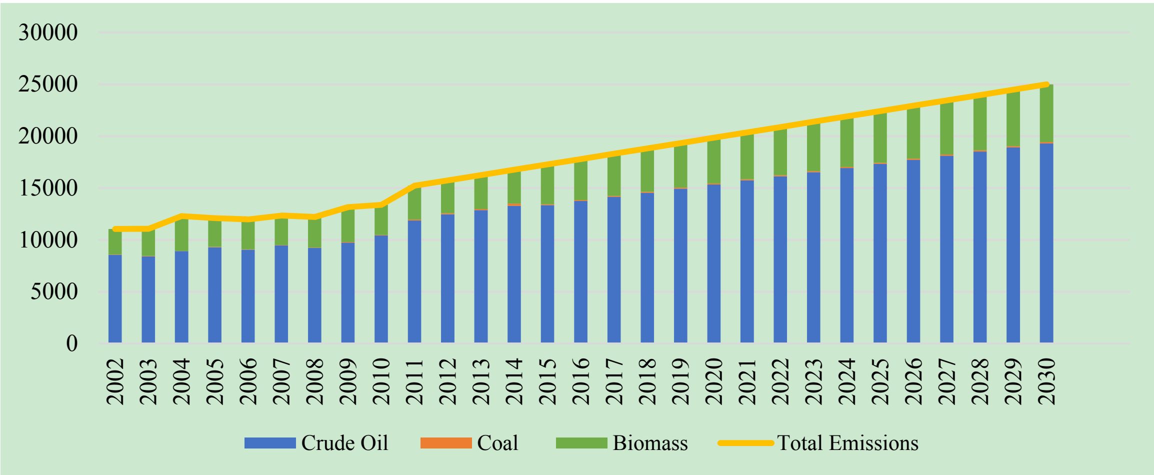

Figure 8. GHG Emissions by type of energy (Gg)

According to the sectorial GHG emissions in Sri Lanka (Figure 9) transport sector has the highest emissions fluctuating between 69%-77% during 2000-2030. Since the transport sector 100% depends on non-renewable energy, the increasing growth rate in non-renewable energy is reflected in the increasing growth rate in sectorial GHG emissions in the transport sector. Domestic and commercial sector has the second highest emissions fluctuating between 14%-23% during 2000-2030 while emissions from industrial sector has remained less than 10%.

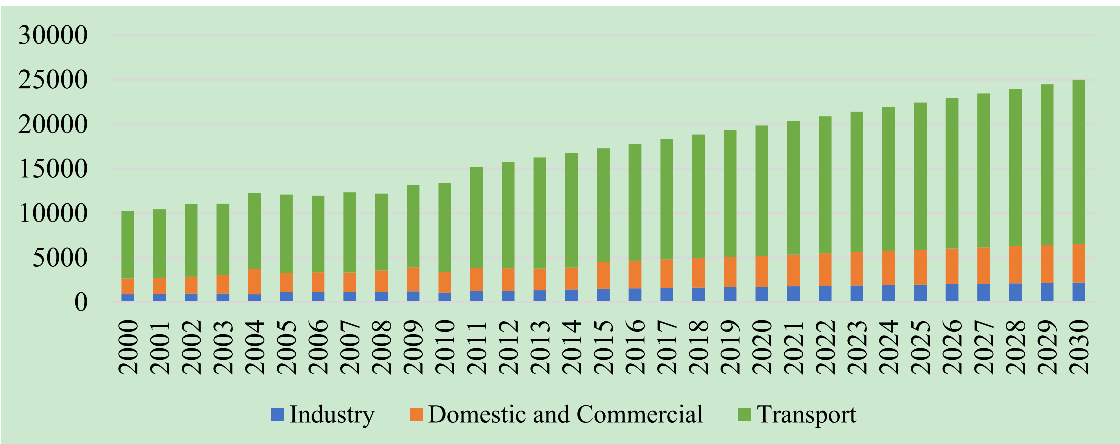

Figure 9. GHG emissions by sector (Gg)

Figure 10 shows that 100% of the emissions of the transport sector is from crude oil. Except for the minor percentage of electric vehicle usage, more than 95% of the private and public transportation use crude oil as the main energy source. Domestic and commercial sector has the second highest GHG emissions and more than 80% of the emissions are from biomass consumption. Industrial sector is the third highest GHG emitter where more than 70% of the emissions are from biomass consumption.

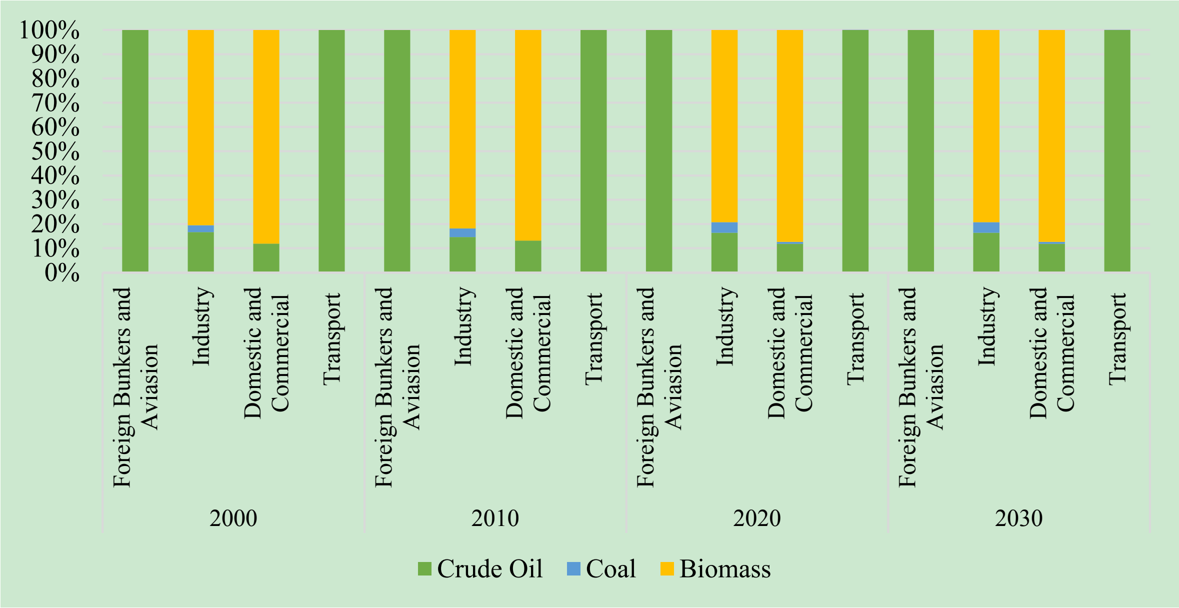

Figure 10. GHG emissions by type of energy and sector

3.4 Model Validation

Matching the output of the model with the historical data is one of the most commonly used method for model validation. The historical data series from 2000 to 2015 were used to verify the model by extrapolating the trend. The descriptive statistics of Mean Absolute Percent Error (MAPE) was used for assessing the behaviour. MAPE is one of the most popular measures to forecast the accuracy of models. It is a measure of predicting accuracy of a forecasting method in statistics and usually expresses accuracy as a percentage.

The MAPE formula is as following;

$$MAPE = \frac{1}{N}\sum_{t=1}^{N} = \left|\frac{A_t - F_t}{A_t}\right| \quad (2)$$

MAPE is the average of Absolute Percentage Errors (APE). At and Ft denote the actual and forecast values at data point t, respectively, where N is the number of data points. In order to a model to become valid MAPE should be less than 10%. Actual data of energy demand and supply from 2000 – 2014 have been compared with model output data for the same period. Mean Absolute Percentage Error (MAPE) for energy demand data was 3.54% and MAPE for energy supply data was 3.4%, which are under 10% of acceptable MAPE range. Therefore, it can be concluded that developed model can successfully replicate the actual data.

3.5 Sustainability Evaluation

Assessing social. economic and environmental factors that directly contributes to the metabolism of a city or country is imperative in order to create a more sustainable urban environment. Over the years many decision makers have used indicators as an effective tool to abstract information from available raw data. However, most of the pre-determined indicators included in most of these indices are in general far from reflecting the entire holistic nature of sustainability and data availability restricts the selection of variables (Custance & Hillier, 1998). Therefore, it is important that every sustainability evaluations rely on its own particular combination of indicators acknowledging the differences in various geographical, cultural or political aspects in each case study.

Sustainability indicators selected for this study have been based on an extensive literature survey. 13 sustainability indicators have been derived from various studies (European Foundation (1998), OECD (1998), Urban China Initiative (2011), Kostevsek et al. (2014), Afgan et al. (2000), Kılkıs (2016), González et al. (2013), Kennedy et al. (2014), Tongsopit et al. (2016), Patlitzianas et al. (2008), Sahabmanesh & Saboohi (2017), Boggia & Cortina (2010), Sozen & Nalbant (2007)) and they are classified into three main categories: economic, social and environmental.

3.5.1 Evaluation of Economic Sustainability Indicators

Economic sustainability assesses the affordability and cost effectiveness of energy. It can be assessed by observing the share of energy used for productive purposes and the efficiency with which the productivity is done (Angelis-Dimakis et al., 2012). In this research energy efficiency and effectiveness has been measured by energy intensity, per capita energy consumption, sectorial energy intensities, energy conversion and transmission losses and energy self-sufficiency.

According to results annual population growth rate of Sri Lanka is about 0.8% where the population in 2015 had increased by 10.87% with compared to 2000 and is expected to grow by 11.63% by 2030 with compared to 2015. Energy use per capita, energy demand per capita and energy supply per capita have been changing accordingly. With compared to 2000, in 2005 energy demand per capita has decreased by 2.08%, energy supply per capita decreased by 1.72% and energy use per capita decreased by 1.26% while in 2015 energy demand per capita has increased by 1.79%, energy supply per capita increased by 2.54% and energy use per capita increased by 4.49%.

Sri Lanka ended the ended civil war which was prevailing for 30 years in 2009. This has shown a remarkable improvement in living standards especially in Northern and Eastern provinces. New awakening in agriculture and fishery related industries in these provinces had a significant impact on the country's energy profile. Thus, significant increase in energy demand per capita by 9.63%, energy supply per capita by 10.63% and energy use per capita by 11.28% and GDP per capita by 56.57% with compared to 2000 was visible. Further civil war has influenced the GDP between 2003 and 2013, which shows a decline of average 3.5% per year in 2009 while a peak 8.3% in 2011. According to the predictions of the developed energy metabolic model by 2030 it can be assumed that with compared to 2015 energy demand per capita will be increased by 8.62%, energy supply per capita will be increased by 8.64% and energy use per capita will be increased by 8.64%.

The energy intensity is used as a measurement of the energy efficiency in producing a given level of output or activity. Primary energy intensity, defined as the ratio of the total primary energy supply per unit of GDP, reflects the general relationship between energy use and economic development (Streimikiene et al., 2007). As Tsai (2010) suggests trends in the energy intensity indicator provide a rough basis for projecting energy consumption and its environmental impacts (i.e. GHG emissions and air pollution emissions). Results show that energy intensity of Sri Lanka is gradually decreasing. 5.63E-07 ktoe/US$ to 1.50E-07 ktoe/US$ in 2015. On average, energy use per unit of GDP has decreased by 4% annually. Energy intensity directly corelates with the changes in the economic structure of a country. According to Asian Development Bank (2015), since 1990 Sri Lanka's economic growth has largely been driven by the service sector (which is less energy intensive) while industry's contribution to GDP has increased in a very gradual manner and share of agriculture has been declining steadily. Thus, relative incline in service sector's share of GDP could have been influencing the decline and stabilization in energy intensity from 2005 onwards.

Sectorial energy intensities indicate that energy intensities in industrial energy intensity sector, household and commercial sector and transport sector have been gradually decreasing. Household and commercial sector has the highest energy intensity with compared to other two sectors. Household and commercial sector shows a dramatic increase till 2005 and then starts decreasing. According to Asian Development Bank (2015), a combination of energy efficiency measures such as use of energy efficient appliances, regulatory instruments such as appliance labelling, phasing out of inefficient appliances and the relatively high electricity price in Sri Lanka with compared to other countries in the region may have discouraged energy intensive industries. This indicator shows how industrial sectors are taking continuous measures in achieving economic sustainability of the energy metabolic system.

Results related to energy conversion and transmission losses show that losses have remained unpredictable showing increase until 2007 and after 2011. Slight reduction in energy conversion and transmission losses is visible after 2014 causing an increase in energy conversion and transmission efficiency. Energy self-sufficiency measures the energy security in a country depending on availability of natural resources for energy consumption. Instability in the world oil prices challenges the energy security in Sri Lanka owing to its extreme dependence on the imported fossil fuels which is about 60% of the total energy supply. Thus, there is a need to improve the renewable energy sources such as biomass, wind, and solar power which currently accounts only for a significantly small fraction of the total energy supply. Until 2015 the self-sufficiency rate has been maintained around 40% which shows a high energy security with compared to developed countries like Japan which is only 10%. According to the results of the model, with the current trend of increase in renewable energy sources, its self-sufficiency is expected to grow up to 60% by 2030.

3.5.2 Evaluation of Social Sustainability Indicators

Social sustainability aspect assesses the distributional effect on the society and acceptability of energy when society sees fair and equal opportunity is given to everyone (Iddrisu & Bhattacharyya, 2015). Results shows that energy consumption per household is about 0.00182 ktoe in 2015. Energy consumption per household has increased by 2.5% in 2005 and shows a decrease of 17.94% in 2010. After 2010 it has gradually increased by 10.71% in 2015 and expected to grow about 8.31% by 2030. Average household income has been affected by the rapid growth in the economy. Thus, share of household income spent on electricity has reduced from 4% to 3.6% during the last decade. After 2010 it has shown a slight increase up to 4.2% and keep on increasing while still expected to be less than 5% by 2030.

Population without access to electricity changes along with the population density and percentage of urban population. As emphasized by Angelis-Dimakis et al. (2012) energy not being available to everyone at a fair price can lead to marginalization of poor people and social unrest. Results show that in share of population without access to electricity was 37% in 2000 which has significantly decreased to 12% by 2010. With the civil war being over and consequent efforts taken by Sri Lankan government have led utility percentage to be further reduced to 3% by 2015. Extending the grid to remote villages is expensive, and this results in disparity in access to electricity. The government is further planning to increase percentage of electrification to 100% by 2020 with a mix of grid extensions and off-grid solutions. Compared to some other countries in South Asia, Sri Lanka's electrification rate in 2015 is the second highest after Maldives (99.8%), Bhutan (90%) and Bangladesh (62%) (Asian Development Bank, 2015).

3.5.3 Evaluation of Environmental Sustainability Indicators

The total annual GHG emissions per capita and the emissions intensity, is the ratio of the GHG emissions per unit of GDP. CO_2 produces by variety of human activities such as burning fossil fuels is the key GHG contributes to global warming. As Sri Lanka is becoming more dependent on the fossil fuels the GHG emissions per capita has increased an average of 7% per year up to 2011 and in 2015 GHG emissions per capita was equivalent to 820 kilograms. According to Asian Development Bank (2015) despite Sri Lanka still being well below the average global emissions, government has initiated various GHG strategies to mitigate emissions in all sectors. As a result, there is a slight reduction in GHG per capita growth rate from 2011 which is escalating annually nonetheless. Further GHG emissions from energy production per unit of GDP has been decreasing since 2005 as Sri Lanka is moving towards a less energy intensive production. Share of renewable energy supply has been remaining steady over the last 15 years fluctuating between 40% - 45%.

4. Conclusions

Sustainable economic growth and improvement of the social welfare depend upon the sufficient supply of energy resources, while the utilization of energy resources is one of the main factors of environmental degradation. Studying the flows of materials and energy throughout a city has become useful when human activities started affecting the natural cycles of other living organisms. Evaluating energy metabolism of a city or country monitor its transformation and their contributions to sustainable development. Evaluating sustainability of energy metabolism using sustainability indicators provides variety of options to the decisionmakers.

The aim of this research is to develop a comprehensive framework to evaluate the energy metabolism in Sri Lanka. The methodology is focussed on developing an integrated top-down energy model utilising system dynamics concept. Top-down model combined with system dynamic approach will help to enhance the understanding on the inherent inter-linkages and dynamic structures impacting future urban energy metabolic system while identifying the significant contributors of sustainability of energy metabolic system. However, the model is not meant to predict the future or to produce a quantitative projection, which may not match the actual situation in the future that can be change due to many unforeseen dynamic imbalances in the energy system. Some of the major uncertainties that can influence the projections of the model in the future are technological innovations and developments, price fluctuations, government subsidies and incentives and human perceptions. Further among many economic and social demographic parameters that can affect the energy metabolism in a country, developed model mainly focused on population, GDP, income and energy price as main input variables to evaluate the energy demand and GHG emission in Sri Lanka.

Developed energy metabolic model reveals annual energy demand growth rate which fluctuates between 4%-6% is dominated by domestic and commercial sector (44.73%) followed by transport (29.41%) and industrial (25.86%) sectors. Increasing population and GDP have the most influence in escalating energy demand. Crude oil and biomass are the most widely used energy sources followed by hydro, coal and other domestic renewable sources such as solar, wind and non-conventional energy sources. According the study of Facchini et al. (2017), energy supply of most megacities is dominated by crude oil and residential and commercial sector has the highest energy consumption. Transport sector is the highest consumer of crude oil followed by domestic and commercial sector and industrial sector. According to IEA (2017), energy demand is expected to grow by about 27%, worldwide from 2017 to 2040. The share of global demand from developed countries falls from 36% to 30% while developing countries are on course to increase their combined energy demand by 45% and their share of global demand from 64% to 70%. In 2007, 60% of the energy share of Asia is from coal subsequently natural gas, hydropower, and nuclear power.

Results show that GHG emissions has increased by more than 25% in 2015 with compared to 2000 going from 10238 ktoe to 17289 ktoe in 2015 and it is expected to grow up to 25000 ktoe by 2030. Crude oil has the highest percentage of emissions which is 77.44% in 2000 and 79.21% in 2014. Biomass as the second emitter is responsible for 22.26% of total GHG emissions. According to IEA (2018), global CO_2 emissions are forecasted to reach about 41.5 billion tons by 2035 while Asian region will account for 60% of the world incremental growth of CO_2 emissions. As Asia becoming pivotal in global growth of CO_2 emissions, the need of encouraging of clean, cheap and sustainable energy sources is becoming more and more pressing. In order to mitigate CO_2 emissions, it is important to promote less carbon-intensive fossil fuels while encouraging use of nuclear and renewables in power generation.

The sustainability of energy metabolic system was evaluated using variety of sustainability indicators comprising of economic, social and environmental sustainability aspects. Results show that all the economic indicators are increasing over time showing an improvement in economic sustainability of the energy metabolism in Sri Lanka. Increase in social indicators such as energy self-sufficiency, share of population without electricity shows an improvement in social sustainability while increase in share of household income spent on electricity and energy consumption per household have affected negatively. Energy metabolic system in Sri Lanka is becoming more efficient and less energy intensive over the years with the rise of service sector's share of GDP and increasing popularity of energy efficiency measures. Energy security has been increasing, with a higher self-sufficiency rate (40%) compared to most developed countries. Energy affordability has not changed much over the years while availability of energy has rapidly increased expecting to achieve 100% by 2020. Increase in GHG emissions per capita and emission intensity have increased as escalations in GDP impact negatively. While the environmental sustainability has been positively affected by the increase in renewable energy share in total energy supply. With compared to other South Asian countries like Bangladesh, India, and the Maldives, Sri Lanka has a higher share of renewable energy supply (mainly biomass and hydropower) along with Bhutan and Nepal. According to IEA (2018), fossil fuels are expected to contribute to about 80% of the increase in primary energy consumption to 2035 in both Asia and the world, and therefore would continue to play an important role.

Along with many countries Sri Lanka is also taking imperative initiatives in order to enhance the sustainability of the energy metabolic system while improving the accessibility and self-sufficiency and achieving country's GHG reduction targets. The findings of the research give new insights to the energy metabolic system of Sri Lanka through different aspects of sustainability i.e. economic, social and environmental. Both the proposed methodology and the research outcomes from this work can be used as a decision support framework for decision makers to tackle energy demand and subsequent energy supply for the future more efficiently. This framework enables exploring alternative energy futures and assess the sustainability implications. Thus, will ultimately help the decision makers to identify the aspects in which performance is lagging and to develop strategies overcome them to create a more sustainable energy metabolic system. Developed model can be further used to achieve GHG reduction targets by analysing different policy scenarios and their long-term consequences by projecting different possible pathways into the future.

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Appendix A

Variables and Input Parameters of the Model

Table 1. Variables of energy demand sub-model

No	Variable	Equation
1	Sri Lanka population(t)	=Sri Lanka population in 2000 $+\int_{t0}^{t} \text{Sri Lanka population growth}(s)ds$
2	Sri Lanka population growth(t)	= Sri Lanka population(t) × Sri Lanka population growth rate(t)
3	Sri Lanka GDP(t)	= Sri Lanka GDP in 2000 $+\int_{t0}^{t} \text{Sri Lanka GDP growth}(s)ds$
4	Sri Lanka GDP growth(t)	= Sri Lanka GDP(t) × Sri Lanka GDP nominal growth rate (t)
5	Income per capita(t)	$=\frac{\text{Sri Lanka GDP(t)}}{\text{Sri Lanka population(t)}}$
6	Energy consumption per capita (t)	= 6960.94 + Income per capita(t) × (0.575) + Energy price(t) × ND (0.276)
7	Sri Lanka Energy Demand (t)	= Energy consumption per capita(t) × Sri Lanka population(t)

Table 2. Input parameters of energy demand sub-model

No.	Input Parameter	Value	Source
1	Sri Lanka population growth rate	0.761%, 0.755%, 0.760%, 0.755%, 0.759%, 0.759%, 0.758%, 0.758%, 0.757%, 0.756%, 0.756%, 0.760%, 0.759%,0.933%, 0.94% Normal (0.82%, 0.08%) (2016 – 2030)	World Bank, 2016
2	Sri Lanka GDP growth rate	-3.58%, 5.02%, 14.18%, 9.43%, 18.12%, 15.87%, 14.39%, 25.85%, 3.32%, 34.85%, 15.10%, 4.81%, 8.60%, 7.68%, 2.86% Normal (5.99%, 2.28%) (2016-2030)	World Bank, 2016
3	Energy Price	271.09, 308.57, 305.78, 328.21, 428.84, 425.81, 468.84, 504.34, 810.38, 607.4, 572.72, 714.2, 863.93, 937.25, 929.39 Normal (803.498, 140.444) (2016-2030)	World Bank, 2016

Table 3. Variables of energy transformation and supply sub-model

No	Variable	Equation	No	Equation
1	Crude Oil	SL Energy Supply * Crude Oil%	1	Crude Oil Supply* Crude Oil to Crude Oil%
2	Coal	SL Energy Supply * Coal %	2	Coal Supply* Coal to Coal %
3	Wind	SL Energy Supply * Wind %	3	Wind Supply* Wind to Wind %
4	Non-Conventional	SL Energy Supply * Non-Conventional %	4	Non- Conventional Supply* Non-Conventional to Non- Conventional %
5	Hydro	SL Energy Supply * Hydro %	5	Hydro Supply* Hydro to Hydro %
6	Solar	SL Energy Supply * Solar %	6	Solar Supply* Solar to Solar %
7	Biomass	SL Energy Supply * Biomass %	7	Biomass Supply* Biomass to Biomass %

Table 4. Input parameters of variables of energy transformation and supply sub-model

No.	Input Parameter	Value	Source
1	Crude Oil %	41.86%, 45.26%, 45.68%, 41.56%, 42.61%, 41.88%, 38.65%, 41.23%, 44.23%, 46.74%, 39.14%, 42.51% (2000-2015) Normal (42.61%, 2.38%) (2016-2030)	Energy Balance SL (2000 – 2016)
2	Coal%	0.74%, 0.18%, 0.64%, 0.48%, 0.48%, 0.62%, 0.69%,0.63%, 2.83%, 5.05%, 5.99%, 8.23% (2000-2015) Normal (2.21%, 2.6%) (2016-2030)	Energy Balance SL (2000 – 2016)
3	Wind%	0.03%, 0.01%, 0.01%, 0.01%, 0.01%, 0.01%,0.01%, 0.12%, 0.19%, 0.29%, 0.47%, 0.53% (2000-2015) Normal (0.32%, 0.16%) (2016-2030)	Energy Balance SL (2000 – 2016)
4	Non-Conventional %	0.03%, 0.00%, 0.04%, 0.04%, 0.04%, 0.04%, 0.04%, 0.04%, 0.03%, 0.04%, 0.04% (2000-2015) Normal (0.03%, 0.01%) (2016-2030)	Energy Balance SL (2000 – 2016)
5	Hydro%	8.88%, 7.33%, 8.19%, 11.04%, 9.55%, 10.08%, 9.88%, 12.46%, 9.67%, 6.59%, 13.96% 8.88% (2000-2015) Normal (9.71%, 1.97%) (2016-2030)	Energy Balance SL (2000 – 2016)

6	Solar%	0.0024%, 0.0040%, 0.01%, 0.04% (2010-2015) Normal (0.01%, 0.01%) (2016-2030)	Energy Balance SL (2000 – 2016)
7	Biomass%	48.48%, 47.19%, 45.48% , 46.87%, 47.32%, 47.37%, 50.73%. 45.53%, 43.04%, 41.29% , 40.39%, 39.78% (2000-2015) Normal (45.29%, 3.29%) (2016-2030)	Energy Balance SL (2000 – 2016)

Table 5. Variables of GHG emissions sub-model

No	Variable	Equation
1	Crude oil	Crude oil consumption*Crude Oil Emission Factor
2	Coal	Coal consumption*Coal Emission Factor
3	Biomass	Biomass consumption*Biomass Emission Factor

Table 6. Input parameters of GHG emissions sub-model

No	Input Parameters	Value (KG/TJ)	Source
1	Crude oil Emission Factor	69300	IPCC, 2006
2	Coal Emission Factor	94600	IPCC, 2006
3	Biomass Emission Factor	43639	IPCC, 2006