Integrated evaluation of energy system in Sri Lanka: a multidimensional sustainability perspective

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ABSTRACT

Increase in energy demand in Sri Lanka caused by rapid economic growth needs to be tackled in a sustainable way. Thus, this research intends to retrace the path of energy development during the last two decades from a multidimensional sustainability perspective which in return will help predicting its future behaviour. Integrated approach consists of a system dynamic model developed based on economic and socio-demographic factors, an indicator-based framework with stakeholder participation and a scenario analysis. Results show post-conflict economic development has taken a toll on the overall sustainability of the energy system which has become stagnant since 2010. Alternative scenarios suggest supply-side energy reforms have the highest impact on lessening the environmental burden of the energy system. Findings can provide insights and a structure guidance for the decision-makers to set the energy sector of Sri Lanka on a sustainable development path that is imperative in the long run.

1. Introduction

Rapid economic development challenges countries to provide a comfortable urban living environment while minimising resource scarcities and environmental protection. Increasing energy demand resides in the heart of the negative consequences of economic growth, population growth, rapid urbanisation and changes in lifestyle thus becoming an attractive topic among the scientific researchers. As UNDP (2000) reports commercial energy consumption of developing countries have increased more than 3.5 times when compared with OECD countries during the past 30 years. Energy security and equity-related disparities among the two groups are becoming less tolerable as developing countries are struggling to accommodate the energy their growing population needs.

South Asia as one of the fastest-growing regions is currently facing many challenges in meeting its growing energy demand combined with inclining energy inequities, increasing dependence on energy imports, fluctuating energy prices and technical or geopolitical driven supply interruptions (Shah et al. 2019). Sri Lanka which has the second highest GDP per capita (US$ 3845) in the region and an average growth rate of 3% has not been impervious to any the above challenges (World Bank 2020). Recovering from a 30-year-old civil war Sri Lanka has come a long way since 2009 in terms of its socioeconomic growth. Sri Lanka has consumed 12.8 million tons of oil equivalent energy in 2017, while energy consumption per capita has increased by 35% during the last two decades (Sri Lanka Sustainable Energy Authority (SSEA) 2017; The World Bank 2017). Energy mix that
consists of petroleum (43.9%), coal (10.8%), biomass (36.5%), hydro (5.8%) and other renewable energy including solar and wind (3.1%) has increased by 28% during the last decade. It is clear the increase in energy demand during the last decade caused by post-war economic development has been mainly tackled by fossil fuels. Fossil fuel consumption in Sri Lanka has increased by 10% last decade now accounting for more than 55% of the total energy mix (SSEA 2017). Although currently Sri Lanka is amongst the lowest Green House Gaseous (GHG) emitters in the world (ranked 194th out of a total 251 countries) as well as in South Asia (0.8 mtCO2e/capita in 2015), increase in GHG emissions during the past decade (by 89%) is worth noticing. Household and commercial sector has the highest energy demand (40%) for electricity (predominately produced using hydro power and petroleum) and biomass for cooking. Transport sector with the second highest energy demand (36%) and the highest GHG emitter depend on petroleum for 100% of its energy needs. Industrial sector with 34% energy demand relies on electricity and biomass for industrial thermal requirements (SSEA 2017; World Bank 2017).

Apart from inevitable growing demand, energy sector in Sri Lanka is facing many other issues and challenges which often leads to question the sustainability of its reforms. As many developing countries Sri Lanka is constantly suffering from either planned or unplanned power supply interruptions which have a major impact on the reliability of the energy system. Unplanned outages are often caused by technical failure due to lack of proper preventive maintenance or system instabilities where planned outages are caused by shortage of hydropower from severe drought conditions (Asian Development Bank (ADB) 2018; Wijayatunga and Jayalath 2004). Regardless of its nature the causes behind blackouts are often not disclosed to the public where the economic and social impact of them is often overlooked due to lack of information. While economic losses of supply interruptions to industrial sector are noticeable, non-monetary impact on households such as household safety/security, access to food and loss of leisure time are neglected (Meles 2020; Nduhuura, Garschagen, and Zerga 2021).

Lack of a cost-effective tariff system, high electricity price and supply cost are also among the main challenges threatening equity of the energy system in Sri Lanka. Despite relatively high electricity price among other counterparts of the region, there is a mismatch between the cost of supply and electricity price questioning the long-term viability of the sector (ADB 2018; World Bank and International Finance Corporation 2019). Current surveys show that Sri Lanka has 6000 and 5600 MW technical potential for energy generation from solar and wind power, respectively, which is yet to be harnessed (ADB 2018). With potential of hydro power stretched thinly introducing other renewable energy sources to the energy mix is becoming more urgent. High cost of energy imports, constant price fluctuations and deteriorating popularity of biomass encourage new infrastructure for wind and solar power. However, according to ADB & United Nations Development Programme (2017) many factors such as high investment cost, technical challenges, lack of R&D and lack of awareness among consumers have hindered its progress. Further lack of efficiency and transparency in procurement procedures have deterred local and foreign investors from investing in new projects (World Bank and International Finance Corporation 2019). With delay in many power plant implantation projects (last project was implemented in 2007) and an annual growth rate of 4% in energy demand, Sri Lanka is expected to enter into a generation capacity deficit crisis in the near future (ADB 2018). As Public Utilities Commission of Sri Lanka (2017) emphasises cost overruns due to expensive emergency power procurement, over dispatch of existing power plants and financial loss in delaying powerplants over the last 20 years has jeopardised the sustainable development of the energy system in Sri Lanka.

National Energy Policy and Strategies of Sri Lanka (2019) is based on the energy dilemma where the government intends to provide a secure, equitable and sustainable energy system while many of the current challenges and issues have its sustainability nature often questioned. As Mainali et al. (2014) points out sustainable energy should be reliable, affordable and accessible while meeting economic, social and environmental needs. Whilst Sri Lanka may have had some added advantages in the past with historically embedded sustainable principles and religious and cultural practices
that value sustainable consumption (Ministry of Environment 2021), current consumption patterns and changes in lifestyles show it is not the case anymore for current and future generations.

On its way to implement 2030 agenda, Sri Lanka pledges to uplift the sustainable development goals ensuring cleaner and affordable energy and be more vigilant against climate change as a country highly vulnerable to climate change-induced hazards. Therefore, it has become ever more important to retrace the steps of the economic journey of the energy system in Sri Lanka to assess its sustainability which in return can help in readjusting the future steps. However, currently little or no information available regarding the sustainability of energy system in Sri Lanka. To fill this gap, authors intend to evaluate the sustainability of the energy system in Sri Lanka using a multidimensional integrated approach. Such a study can help coordinate energy policy at national level by identifying weaknesses in the energy system not only from economic or technological aspects but also from social and environmental aspects.

Among countless studies about the sustainability of energy systems especially cross-country studies, Sri Lanka often remains unexplored partially due to data inadequacy and inaccessibility by the public. One of the noteworthy research includes measuring energy security and environmental sustainability of South Asian countries including Sri Lanka from 2006 to 2017 by Shah et al. (2019) where Sri Lanka was ranked the third place in the South Asian region. Jayasinghe, Selvanathan, and Selvanathan (2021) have studied energy poverty and associated socio-demographic and geographical factors which concludes possible adverse implications on health and education attainment of the energy-poor. Pallegedara, Mottaleb, and Rahut (2021) have explored choice and expenditure on energy for domestic works by the Sri Lankan households which implies with increased income and awareness, households are more likely to switch from dirty energy. Wijayatunga, Fernando, and Shrestha (2003) has briefly studied GHG mitigation in the Sri Lanka power sector supply side and demand side options, while Kariyakarawana, Bandara, and Leelarathne (2014) and Vidanagama and Lokupitiya (2018) evaluated potential of GHG emission savings for programmatic CDM by municipal solid waste composting and GHG emissions associated with tea and rubber manufacturing processes in Sri Lanka, respectively. Some researchers have focussed on encouraging renewable energy mainly biogas and solar (Bekchanov et al. 2019; de Alwis 2002; McEachern and Hanson 2008), while Wijayatunga and Attalage (2003) and Pathirana and Yarime (2018) have studied energy efficiency in office buildings, rural households and apparel industry, respectively.

Considering the previous body of studies, this study, to the best of our knowledge represents the first scientific study that evaluates the sustainability of the energy system in Sri Lanka using an integrated, multidimensional framework. Thus, filling an important research gap in the context of Sri Lanka expands the emerging body of empirical literature on sustainability of the energy systems in post-conflict developing countries. While authors acknowledge the existence of a variety of frameworks to evaluate the sustainability of energy systems, lack of data availability has hindered authors from using most of them wherein a customised framework seemingly became more pragmatic. As Narula and Reddy (2015) point outs different frameworks assess different aspects of an energy system which may not always give the desirable or consistent output. Further authors valued incorporating views and values of local stakeholders in developing a framework to measure sustainability. The developed integrated framework follows three stages. In the first stage, a top-down dynamic model was developed based on a variety of economic and sociodemographic variables to evaluate the performance of energy system of Sri Lanka expands the emerging body of empirical literature on sustainability of the energy systems in post-conflict developing countries. While authors acknowledge the existence of a variety of frameworks to evaluate the sustainability of energy systems, lack of data availability has hindered authors from using most of them wherein a customised framework seemingly became more pragmatic. As Narula and Reddy (2015) point outs different frameworks assess different aspects of an energy system which may not always give the desirable or consistent output. Further authors valued incorporating views and values of local stakeholders in developing a framework to measure sustainability. The developed integrated framework follows three stages. In the first stage, a top-down dynamic model was developed based on a variety of economic and sociodemographic variables to evaluate the performance of energy system of Sri Lanka.

The model simulates energy supply and transformation, energy demand and CO₂ emissions within the last two decades which was extrapolated till 2030 to predict the future behaviour of the system. The second stage develops an indicator-based framework which can analyse sustainability of the energy system from economic, social and environmental perspectives. The indicators were selected based on the literature survey which then prioritised using a questionnaire survey conducted among different stakeholders of the energy system. The weightages of indicators were then normalised to develop an integrated sustainability index which will later be used to compare different CO₂ emission reduction scenarios developed based on INDCs as the third and final stage. This study can provide insights regarding the past and future performance of the
energy system and its sustainability that can be beneficial to the decision-makers in reviewing policy reforms while increasing public awareness regarding the matter.

The structure of the paper is as follows. Section 1 provides a brief overview of the energy sector and pertaining issues. Section 2 discusses the methodology of developing the sustainability evaluating framework. Section 3 will present the results and discuss the implications followed by conclusions and policy implications in section 4.

2. Materials and methods

The developed integrated framework consists of three stages. As shown in Figure 1, first stage of developing dynamic energy system model follows four steps, namely, model conceptualisation, model formulation, model validation and model stimulation. Model was conceptualised by identifying economic and socio-demographic variables affecting energy demand, transformation, and supply and CO₂ emissions in Sri Lanka.

The second stage is to develop an indicator-based framework to evaluate the sustainability of energy system. The indicators were derived from a thorough literature review based on various indicator frameworks developed by past researchers. The selected indicators were then prioritised using Analytic hierarchy process (AHP) tool based on the results of the pairwise questionnaire survey conducted among various stakeholders, representing suppliers and consumers of the energy system in Sri Lanka. Elicited weightage of the indicators was then used to aggregate them into an integrated sustainability index for the sake of comparing various policy scenarios. The third stage consists of analysing INDC based policy scenarios that Sri Lankan government is planning to implement to reduce the GHG emissions.

2.1. Stage 1: development of dynamic energy system model

Energy models are used to simulate policy and technology choices that may influence future energy demand and supply, while providing a simplified picture of real energy system and real economy

![Figure 1. Research framework.](image-url)
While reviewing a variety of energy system models (Bhattacharyya and Timilsina 2010) emphasise the importance of top-down models for long term, national level and macro-economic energy analysis. While authors acknowledge the existence of other developed models, lack of data availability has hindered from using them. Further as Debnath and Mourshed (2018) points out since most of the developed models are based on high income economies, they often underrepresent the impact of economic variables such as GDP growth rate, GDP per capita, etc. and their relationship with energy demand. Apart from differences in socioeconomic attributes, they tend to overlook inadequacies and inaccuracies of data, inherent geographical and social vulnerabilities, supressed energy demand, impact of corruption and political instabilities in low-income economies.

The developed energy system model for this study has combined the top-down approach with system dynamics concept to analyse energy demand, energy supply and CO₂ emissions based on a variety of economic and social demographic parameters such as population, GDP, income, energy price, etc. Recorded data from 2000 to 2015 have been further extrapolated to predict the behaviour of the energy system during 2016–2030.

As findings of Japan International Cooperation Agency (2018) reveal, it has been difficulty to accurately forecast the energy demand of Sri Lanka as in many other countries. Therefore, it is best to adopt simple assumptions instead of sophisticated forecasting method. However, as Intergovernmental Panel on Climate Change (IPCC) (2007) points out all models considering economic potential of a country as a variable have limitations in considering life-style choices and other externalities.

The developed model comprised three sub models, namely, energy demand sub-model, energy supply and transformation sub-model, and CO₂ emissions sub-model. Sankey diagram in Figure 2 shows the physical boundaries of the energy system and its subsystems considering importing or extracting primary energy sources from the external environment and emissions released to the environment. Energy supply and transformation subsystem starts handling the primary energy since it is extracted from domestic sources (i.e. hydro, biomass, solar and wind) or imported (i.e. coal and crude oil). Primary energy then converted and transformed to secondary energy which will be distributed to various sectors in different forms depending on the sectorial requirements where electricity is being the most prominent energy carrier. Demand subsystem accounts for energy demand in industrial, transport, domestic, and commercial and transport sectors based on the number of input parameters (Refer Table 1 in Supplementary Material).

CO₂ emissions sub model was developed to calculate the emissions based on different energy sources and sectors. The relationship between the CO₂ emissions and its significant drivers is based on the Kaya identity (Kaya 1989), a tool that measures the changes in CO₂ emissions according to the changes of its underlying drivers, i.e. energy consumption, carbon emission, GDP and population. Kaya’s equation is as follows:

\[ C = \frac{C}{E} \times \frac{E}{Y} \times \frac{Y}{P} \]

whereas \( C = \) Carbon emissions (or more broadly, GHG emissions); \( E = \) Energy generated and consumed by humans; \( Y = \) Economic output (goods and services, GDP); \( P = \) Population.

The required data were collected from a variety of online databases, governmental reports, journal papers and proceedings. Statistical data related to sociodemographic parameters were collected from the world bank (World Bank 2017). Energy-related data in Sri Lanka were collected from energy balance reports issued by SSEA (2017) from year 2000 to 2015 (Refer supplementary material). Data were then inputted to the developed model which first simulated Business as Usual (BAU) scenario and then for the next decade until 2030. Please refer the supplementary material for further details about the data set used.

The developed model was then validated using historical behaviour reproduction test to compare the model behaviour with the historical behaviour of data. Historical data series of both energy
Figure 2. Energy balance and sub system boundaries based on SSEA (2017).
supply and energy demand between 2000 and 2015 were used to compare with the model outcome. Mean Absolute Percent Error (MAPE) was calculated to measure the predicting accuracy of the forecasting method used. MAPE for energy demand and supply were 3.54% and 3.4%, respectively, which are under 10% of acceptable MAPE range. Therefore, it was concluded that the developed model is valid and can successfully replicate the actual data.

2.2. Stage 2: development of indicator framework to evaluate sustainability of the energy system

Efforts in evaluating sustainability by researchers have led to a variety of detailed frameworks that consists of indicators which indisputably effective in simplifying and abstracting information from raw data. According to Patlitzianas et al. (2008), sustainability indicators expose the impact of economic and social activities on the sustainability of a system while clarifying relation between sustainability and human activities. Energy being in the centre of sustainability issues in most of the developing nations, energy-related sustainability indicator set will allow simplifying interdependences and interactions between energy subsystems, predicting future behaviours and compare future scenarios of achieving sustainability goals.

Idrissu and Bhattacharyya (2015) presents a composite multi-dimensional index able to evaluate sustainable energy development while Hannan et al. (2018) have used 14 indicators to provide an overview of Malaysian energy policies for optimising sustainable development. Mandelli et al. (2014) have utilised 30 indicators to measure the development and the progress towards a sustainable energy system in Africa and 8 indicators used by Sheinbaum-Pardo, Ruiz-Mendoza, and Rodríguez-Padilla (2012) calculate a general sustainability indicator for the energy sector in Mexico. While all these efforts prove the usefulness and necessity of indicators, they also highlight the limitations ranging from ambiguities to lack of stakeholder participation (Gunnarsdottir et al. 2020). Despite the convenience of applying one of the readily available sustainability indices, Custance and Hillier (1998) argue that most of the pre-determined indicator sets fail to reflect the holistic nature of sustainability while data availability restricts the selection of variables. Indicators measure the characteristics or processes of human-environmental system that can be very subjective and specific where political, philosophical and cultural differences ward off wider consensus (Hák, Moldan, and Dahl 2012). Findings of Gasser (2020) show many of these indices lack transparency. Additionally, Mori et al. (2015) highlight the importance of acknowledging the differences between developed and developing countries in developing sustainability indicators as some frameworks may over- or under-estimate a country’s sustainability based on their economic status.

Therefore, as Kaushalya Konara and Tokai (2020) states it is important to choose its own customised combination of indicators for sustainability assessment purposes considering the specific geographical and natural properties and political orientations. The objective national energy policy of Si Lanka is based on the energy trilemma namely, energy security, energy equity and energy sustainability (National Energy Policy and Strategies of Sri Lanka 2019). Within the scope of energy trilemma, Sri Lankan government focusses enhancing access to energy, optimum cost, energy efficiency and conservation, self-reliance, environment protection and renewable energy. With the objective of developing a customised indicator framework, this study has conducted an extensive literature survey to discover the indicators that fulfil the energy policy objectives of Sri Lanka which later screened and prioritised through a questionnaire survey. Selected indicators were then categorised under economic, social and environmental dimensions. Out of a variety of criteria available in categorising sustainability indicators, Liu (2014) emphasises the importance of using triple bottom lines of sustainability development as they evaluate social development, environmental protection and economic growth. Economic sustainability reduces the energy independence, social and environmental sustainability improves human health and minimises side effects and inefficiencies of energy consumption (Neves and Leal 2010).
Out of the many indicators selected from existing literature, final set of indicators were chosen based on three main reasons, namely, ability of the developed energy system model to forecast their behaviour based on the given input parameters, ability to evaluate policy objectives set by the national energy policy and finally the data availability. For a simplified yet relevant evaluation this study restricts the number of indicators under each criterion to a small number. Finalised framework consists of 13 indicators derived from and developed based upon various studies (European Foundation 1998; Kemmler and Spreng 2007; Organisation for Economic Co-operation and Development 1998; The Urban China Initiative 2010; Kostevšek et al. 2015; Chrysoulakis et al. 2013; Afgan and da Graça Carvalho 2000; Kilkiş 2016; González et al. 2013; Kennedy et al. 2014; Tongospit et al. 2016; Patlitzianas et al. 2008; Sahabmanesh and Saboohi 2017; Boggia and Cortina 2010; Sözen and Nalbant 2007; Sheinbaum-Pardo et al. 2012; Hannan et al. 2018; Angelis-Dimakis, Arampatzis, and Assimacopoulos 2012; Iddrisu and Bhattacharyya 2015; Vera and Langlois 2007) (Refer Supplementary Material).

2.2.1. Multi-criteria decision analysis (MCDA)

MCDA has dominated the research work related to decision making including decision making in sustainability (Liu 2007) over the years for its ability used to solve complex problems by assessing all the variables, both individually and collectively, assigning specific importance to each variable (Boggia and Cortina 2010). AHP is one such MCDA tool that has become popular among energy and sustainability related research that has been utilised in sustainability assessment in energy systems, evaluate energy indicators and energy-related scenario analysis (Anand et al. 2017; Luthra, Mangla, and Kharb 2015; Mirjat et al. 2018; Nakthong and Kubaha 2019; Ran 2011; Vishnupriyan and Manoharan 2018) calculating ratio-scaled importance of alternatives through pair-wise comparison of evaluation criteria and alternative (Wang et al. 2009). Kaya, Çolak, and Fulya (2018) recognise AHP as one of the most suitable MCDM methods for energy decision-making problems due to its simplicity and given focus on each criterion. However, further verification of results may be required to avoid any inaccuracies of results caused by interdependence between alternatives and objectives (Siksnelyte-Butkiene, Zavadskas, and Streimikiene 2020).

Stakeholder engagement in decision-making and the development of indicators to ensure policy relevance and stakeholder acceptance is increasingly more recognised (Gunnarsdottir et al. 2020). Therefore, authors conducted a questionnaire survey among different stakeholders of the energy system to prioritise sustainability indicators based on their experiences, knowledge and preferences. A structured questionnaire was given to 35 respondents including representatives of local authorities, private energy suppliers and technical personnel involved in power generation. All whom have more than 10 years’ experience working in both public and private organisations. Questionnaire comprised pair-wise comparisons of sustainability criteria and sustainability indicators in each criterion which was developed with the aid of the AHP decision hierarchy (Figure 3).

The respondents were asked to make pairwise comparisons of the sustainability criteria with respect to the goal, and the sustainability indicators with respect to each criterion, to articulate their relative judgment of one element versus another on Saaty’s 1–9 scale. Pair-wise comparison data were organised in the form of a matrix summarised based on Saaty’s eigenvector procedure (Saaty 1990) and absolute priority weights were used to calculate the overall score of each indicator. To overcome inconsistencies in data collection, Consistency Ratio (CR) was calculated and applied as a reference index to screen the inconsistent information

\[
CR = \frac{CI}{RI}
\]

wherein \( CI = \) Consistency Index; \( RI = \) Random Index.

According to Saaty (1990), inconsistency is considered a tolerable error in measurement only when it is of a lower order of magnitude of 0.1 than the actual measurement itself. Consistency calculations for sustainability criteria for this study were obtained from the results of pair wise
comparisons and the normalised comparisons. Consistency ratios revealed judgment matrices are reasonably consistent that the process of decision-making can be continued using AHP.

2.2.2. Developing integrated sustainability index

To evaluate the overall sustainability of the energy system, normalised sustainability indicators were aggregated into an integrated sustainability index. The procedure of developing the integrated sustainability index consists of the following three steps (Angelis-Dimakis, Arampatzis, and Assimacopoulos 2012).

(a) Scaling of the indicators’ values to a 0–1 interval, where 0 corresponds to the worst and 1 to the best value of the period examined. The following equation is used:

\[
SI_x = \text{RelMax} - \frac{(\text{RelMax} - \text{RelMin}) \times (\text{MaxSI} - SI_x)}{\text{MaxSI} - \text{MinSI}}
\]  

(3)

where \(SI_x\) is the selected indicator for the year \(x\), \(SI_x\) is the respective normalised indicator, \(\text{MaxSI}\) and \(\text{MinSI}\) are the maximum and minimum values of the indicator for the period under study (1, 2, …, \(n\) years) and \(\text{RelMax}, \text{RelMin}\) are two 0–1 values indicating whether

Figure 3. Indicators hierarchy.
the optimal value of the indicator is the lowest or the highest possible. RelMax = 1 and RelMin = 0 when the indicator has a positive influence, i.e., higher values are better, whereas RelMax = 0 and RelMin = 1 when the indicator has a negative influence.

(b) Assessment of the weights \((W_x)\) for each individual indicator. In this study weights of the individual sustainability criteria and indicators were calculated using AHP analysis. Corresponding sustainability score was used as the relevant weightage of each criterion and indicator.

(c) Integrated Sustainability Index (ISI) was calculated using the following equation:

\[
\text{ISI}_x = \frac{\sum W_x S_I_x}{\sum W_x}
\]

wherein \(ISI_x\) is the overall integrated sustainability index for the year \(x\).

2.3. Stage 3: scenario analysis

Final stage of the framework is to apply the developed model and indicators to different scenarios to evaluate and compare the performance and sustainability of the energy system. As Gunnarsdottir et al. (2020) points out the indicators are not limited to being backward-looking but rather evaluate potential implications under different policy scenarios. Sri Lanka is constantly placed among the top ten countries at risk of extreme weather conscious as a result of climate change while some of the industries with significant economic contributions (i.e., tourism, fisheries, tea) being very climate sensitive (Ministry of Environment 2021). Therefore, despite being a low carbon-emitting country, thriving to do better has direct impact on Sri Lanka in the long run. Sri Lanka as one of the countries disproportionately affected by climate change has agreed to ambitious renewable electricity generation targets by 2050. Sri Lanka is among the 43 countries of the Climate Vulnerable Forum that declared at the COP in Marrakech, Morocco to make their electricity generation 100 per cent renewable by 2050 at the latest (ADB & UNDP 2017). Further INDCs submitted by Sri Lanka in 2016 to strengthen its commitment towards United Nations Framework Convention for Climate Change (UNFCCC) and the Paris Agreement entails reducing the GHG emissions against BAU scenario by 20% in energy sector by 2030 since energy sector has the highest GHG emissions percentage (41%). To achieve the above tasks, Ministry of Mahaweli Development and Environment (2016) introduces 7 INDCs where INDC 1–4, 6, 7 focus on increasing the renewable energy share in the energy mix while INDC 5 focus on the emissions reductions through demand-side management activities. Most of the policy targets have been set during the past decade are focused on achieving 20% GHG emissions in the energy sector by demand side and supply energy management strategies. Therefore, this study intends to study feasibility of INDCs, potential CO₂ emission reductions and their impact on the sustainability of energy system in Sri Lanka. With poor performance in environmental sustainability, it is important for energy sector policy reforms to be more focused on the CO₂ reduction strategies which can have a positive impact on the performance of overall sustainability.

Supply-side energy management strategies intend to change the energy mix by increasing its renewables. Therefore scenario 1 evaluates the impact of NDC 1–4 that are focussed on increasing renewable energy by increasing the capacity of biomass power plants by 105 MW (currently 25 MW), mini hydro power plants by 176 MW (currently 328 MW), large-scale wind power plants by 514 MW (currently 128 MW) and solar power plants by 115 MW (currently1.36 MW) (Ministry of Mahaweli Development and Environment 2016). Scenario 2 based on NDC 5 which attempts to reduce annual energy demand growth by 2% through energy efficiency and conservation (Ministry of Power & Energy 2015). Identified energy conservation potential in various sectors are 25% from industrial sector, 2% from domestic and commercial sector and 5% from transport sector. Some of the policy strategies introduced to achieve the above targets include standardisation/automation of street lighting, introduction of time of use metres and tariffs, smart cities and green buildings and sustainable energy zone programmes.
3. Results and discussion

Calculated sustainability scores in Figure 4 show economic criteria have the highest importance followed by social and environmental criteria. Sustainability scores of the criteria and indicators are assumed to remain unchanged throughout the time. Energy intensity (0.291) ranks as the most important indicator in the economic criterion while efficiency of electricity conversion and distribution has ranked as the least important indicator with lowest weightage of 0.038 in the economic criterion. The calculations of the sustainability indicators of the social criterion show that the share of household income spent on electricity (0.488) is the most important indicator in the social criterion and CO2 emissions per capita (0.481) is the most important indicator in the environmental criterion.

3.1. Evaluation of economic, social and environmental sustainability criteria of BAU scenario

Economic sustainability assesses the cost effectiveness of energy ensuring energy security of a country. Assessment of economic sustainability indicators is illustrated in Figure 5 show an increase in all the economic sustainability indicators in BAU scenario except for self-sufficiency and efficiency in electricity conversion and distribution.

A country’s energy consumption and its economic activities have a strong relationship thus affecting the energy intensities. Significant reductions in energy intensity between 2000 and 2015 without much significant changes in energy consumption are caused by increase in GDP over the years (by 79%) (World Bank 2020) implying efficient use of energy resources in producing goods and services. With the end of civil war of 30 years in 2009, 2010 marks the highest GDP growth rate in 50 years thus causing the significant decrease in energy intensities. According to Kahan (2016), most developing economies in South Asian, African and Middle Eastern regions shows a decreasing trend during the last few decades and increase in energy productivity due to structural changes, efficient resource use and outsourcing of energy-intensive activities.

Industrial sector has the highest energy intensity being second-largest contribution (15.5%) to the Sri Lankan economy in which cement and lime production industries have the highest GHG
contribution (Ministry of Environment 2021). Although the relationship between energy consumption and GDP is reciprocal, the structural changes in Sri Lankan economy transitioning from agrarian economy to a more service-oriented economy has positively impacted the energy consumption. Energy intensities in Sri Lanka are still lesser than the other counterparts of the region. According to Jain and Goswami (2021), Sri Lanka, Bangladesh and Pakistan are the only countries that show improvements in energy efficiency over the last two decades contrary to Afghanistan, Maldives, Bhutan and India who show significant decline in energy efficiencies.

Sectorial intensities help in segregating energy intense and energy-efficient sectors. Data reveals industrial sector as the most energy intensive out of household, commercial and transport sectors. According to ADB (2015), high energy pricing in Sri Lanka discourages energy-intensive industries while promoting energy-efficient practices specially manufacturing. Some of the government initiatives such as appliance labelling and phasing out of inefficient appliances out of the market may have played an important role in reducing energy intensities. If current trend to be continued these indicators are expected to increase by 15% in the next decade.

Efficiency of electricity conversion and distribution implies efficient conversion of primary energy to electricity while efficiency in distribution indicates the ability to respond to demand without interruptions in a timely manner. Efficient conversion and distribution greatly influence the security of an energy system. As Grubb, Butler, and Twomey (2006) clarifies, reduction in quality, sudden supply interruptions and long-term disruptions of supply are some of the main features of a non-secure energy system. According to Wijayatunga and Jayalath (2004), Sri Lanka experiences planned and unplanned power supply interruptions almost on a regular basis due to shortage of hydropower resulting from severe drought conditions causing economic losses. Combined with its inherent nature of lower energy storage cause difficulties in reaching peak demand (about 2500 MW) at times. Latest blackout occurred in August 2020 lasted over 7 h (Daily News 2020) which was preceded by a major series of blackouts in 2019 lasted nearly a month. Increased grid instability can be disadvantageous when depending on renewable energy technologies reducing supply reliability and increasing energy insecurities. Efficiency of electricity conversion and distribution has not changed much over the last two decades despite having the lowest score among the economic indicators.

Energy self-sufficiency shows a slightly decreasing trend with increasing dependance on non-renewable energy sources which has increased by 8% over the last decade while energy imports have been doubled during the last 40 years. Biomass predominately used for cooking and industrial thermal requirements shows the most significant reduction in renewable energy sources (8%). According to Development Bank (2018), large-scale biomass power projects have been failed to attract investors due to difficulty in collecting sufficient biomass residues (rice husks, wood and

![Figure 5. Sustainability analysis of economic indicators.](image-url)
coconut shells) and developing sustainably grown biomass plantations. Findings of Hou et al. (2019) show that Sri Lanka has the second-lowest self-sufficiency rate in the region which is significantly lower than Bhutan, Bangladesh, Pakistan and India, countries with higher energy self-sufficiency. Though Sri Lanka has exhausted all the ways of increasing hydropower generation in large-scale power plants, its abundant potential for harnessing wind and solar energy is indisputable. Domestic and commercial sectors can be encouraged to use solar energy through roof-top solar photovoltaic technology while coastal areas and central highland can accommodate more wind power plants, which can boost the self-sufficiency of the energy system.

Social sustainability assesses the equity of the energy system by measuring accessibility and affordability. Overall assessment of social indicators shown in Figure 6 illustrates that only the share of population without electricity has increased over the years while a slight decrease can be visible in other two indicators diminishing the overall social sustainability. Energy availability and affordability are paramount in determining a country’s level of energy poverty. ADB (2018) calls attention to household and commercial energy prices in Sri Lanka which are comparatively higher compared with its regional counterparts such as Bangladesh, India, Bhutan, Malaysia, Korea, etc. Mainly due to lack of indigenous fossil fuels and lack of large, lower-cost baseload power plants. In Sri Lanka, only 50% of total income is distributed among 80% of middle to lower-income houses which spend more than 20% of their expenditure on energy and transport (Department of Census and Statistics 2016). Therefore, not being able to afford commercially available household energy at current prices most lower-income households tend to shift towards more traditional yet inexpensive biomass fuels which would ultimately underestimate the extent of energy poverty. It is important for the Sri Lankan government to take measures to lessen the burden of expenditure on electricity in lower-income households to uphold social sustainability. On the contrary lack of cost-effectiveness on electricity retail tariffs has been one of the crucial issues that have been threatening the long-term viability of the sector with Ceylon Electricity Board not being able to fully recover the costs of supply (World Bank and International Finance Corporation 2019). Therefore, proper cost-effective tariff system needs to be introduced to sustain the energy supply without compromising equity of the energy system.

Sri Lanka achieved 100% rural electrification in 2019 which is commendable when compared with counterparts of the South Asian region (Masud et al. 2020; Narula 2014). The electrification has increased from 75% since 2005 in a country where rural population accounts for 80% of the population. Having access to more efficient, more convenient, less polluting energy has significantly improved the living standards promoting equity among overall population. Rising per capita energy consumption and per household energy consumption is inevitable in developing economies. As Pallegedara, Mottaleb, and Rahut (2021) reveals Sri Lankan households mostly use biomass for
cooking (more than 70%), petroleum for transport and electricity for other energy-related needs. Per capita household energy consumption in Sri Lanka has increased more than 50% in the last two decades owing to many economic, social, and demographic factors. Aside from the obvious, increased access to electricity, increasing urbanisation, changes in lifestyle, increasing number of single-occupant apartments are among the noticeable causes. Though increasing consumption can impact negatively on sustainability of the country’s energy system, promoting energy-efficient apparatuses and increasing awareness specially among the rural households on energy-saving technologies and measures can lessen the setback. A study done by Yigezu and Jawo (2021) to Ethiopian households reveal improved biomass cooking stove can reduce 1.05 tonnes per year per household. According to Jayasinghe, Selvanathan, and Selvanathan (2021), not consuming modern cooking fuel due to lack of motivation, combined with financial unaffordability are the main contributing factors of energy poverty in Sri Lanka.

Environmental criteria that measure pressure placed on its surrounding environment through unsustainable energy consumption have the most negative impact on overall sustainability of the energy system in Sri Lanka. Figure 7 shows increasing CO₂ emissions per capita and decreasing renewable share in energy contribute to the decline in environmental sustainability. As an emerging economy, Sri Lanka has a constantly increasing trend in CO₂ emissions which was about 23, 310 kt in 2017. While Sri Lanka’s emissions may contribute to only 0.05% of the overall CO₂ emissions in the world, growth rate of its emissions and emissions per capita have raised concerns. CO₂ emissions per capita has increased by 72% over the last decade with an average growth rate of 2.54%. When compared to the other countries in the region Hou et al. (2019) points out Sri Lanka has the second highest energy consumption per capita yet 4th highest emissions per capita mainly due to renewable share in the energy mix.

According to Kaushalya Konara and Tokai (2020), transport sector has the highest CO₂ emissions as 95% of the public and private transportation used petroleum as the main energy source. 80% of the emissions in the domestic and commercial sector which is the second-highest emitter, are from the biomass consumption for cooking and industrial thermal requirements. Addressing issues in those two sectors can further reduce the CO₂ emissions per capita and emissions intensity in Sri Lanka. Nandasena, Wickremasinghe, and Sathiakumar (2010) reveals vehicular emissions as the main source of ambient air pollution in Sri Lanka while cooking fuel is the main source of indoor air pollution in households.

Diminishing quality of public transportation has caused a rapid increase in demand for private vehicle is rapidly changing (with 135% increase in the last decade) dominated by motorcycles and three-wheelers (Ministry of Environment and Renewable Energy 2014). Further statistics show buses which contribute to 56.9% of the share of passenger km only represent 2% of the active
fleet wherein various types of private vehicles account for the rest of 98%. Giannakis et al. (2020) point out land transport as one of the most difficult sectors to decarbonise, thus low-carbon technologies need to be more economically attractive. Some of the initiatives suggested by the Sri Lankan government to move towards cleaner energy with less emissions in transport sector includes encouraging alternative fuels such as electric vehicles, hybrid vehicles and biofuels; enhance fuel quality standards; establishing fuel quality testing laboratories and railway electrification (Ministry of Environment and Renewable Energy 2014).

The cooking in the urban households mainly dominated by the LPG while biomass is the main source of fuel in the rural households. Primary sources of biomass are firewood (from home gardens) and coconut shells (SSEA 2017). Biomass is considered a cleaned energy source presuming its harvested in a sustainable manner such as forest residues without any trees been chopped. However, a large part of the biomass-based cooking has become unsustainable due to inefficient cooking stoves, bulk use of fuelwood and indoor air pollution caused by hazardous gases released during incomplete combustion (Wijayatunga and Jayalath 2004). Authors further reveal relative cheapness and easy accessibility of biomass make switching to more convenient and safe energy sources more undesirable for the rural households. Therefore Wickramasinghe (2011) suggests rising awareness regarding the health and environmental repercussions, energy-efficient technologies (improved cook stoves or wood gasifier stoves) and making more cleaner cooking fuels such as LPG more affordable can create a positive impact. As Farabi-Asl et al. (2019) Asian region has been successful in promoting cleaner cooking fuels when compared with Sub-Saharan African region where majority of people still depend on firewood.

With increasing dependency on non-renewables and cleanliness of biomass consumption being questioned exploiting the potential of other renewable energy sources has become evident for Sri Lanka. Maxim (2014) concludes in terms of sustainability biomass is the least desirable renewable energy source (which ranked even lesser than natural gas and nuclear) due to high externalities and use of larger land surface. Okoro and Madueme (2006) reveal solar energy as the most attractive source of energy for a developing economy. Sun et al. (2020) reveal decreasing trend in renewables is alarming contrary to its counterparts in the region such as Nepal or Bhutan which is higher than 80%. Sri Lankan government is constantly planning to increase its share of renewable energy by harnessing its potential in solar, wind and geothermal energy. Various technical surveys show the technical potential for electricity generation by solar power is about 6000 MW (only 93.7 MW used currently) and 5600 MW by wind power (only 131 MW is used currently) (ADB 2018). Report further suggests reaching the potential requires advanced forecasting techniques along with proper means to overcome intermittency and seasonality to maintain the reliability of the power system.

Comparison of sustainability indicators in economic, social and environmental criteria shows that economic indicators have the most visible increase during the last two decades. The most significant increase could be visible between 2005 and 2010. Reducing energy intensities specially in the industrial sector with economic structure changing more towards a service-based economy which accounts for 57.4% of total GDP (Central Bank of Sri Lanka 2019) has the most positive impact on economic sustainability. Both social and environmental criteria do not show a positive trend due to increase in energy consumption and emissions per capita and increasing dependence on non-renewable energy imports. However, since economic criterion has the highest weightage (0.507) among sustainability criteria, weighed impact on the integrated sustainability index has been dominated by economic criterion minimising the negative impact from both social and environmental criteria. Therefore, integrated sustainability index which shows an increasing trend from 2000 to 2010 has not changed much over the years with the post-war economic development. Thus, continuing BAU activities will cause sustainability of energy system come to a standstill in the long run without much change.

Results of the analysis of scenario 1 (Figure 8) show increase in renewable share of energy supply by increasing the energy supply from new hydro, biomass, wind and solar power plants can achieve
a CO\textsubscript{2} emissions reduction up to 10\% by 2030. Significant decrease in CO\textsubscript{2} emissions per capita (reduced from 820 kg to 752 kg) and increase in renewable energy share in energy (more than 4\%) positively impact environmental sustainability which shows an increase of 34\% when compared with BAU scenario. Increase in energy self-sufficiency shows an 8\% increase in economic sustainability while social sustainability remains unaffected. Seemingly beneficial strategy is not without its own set of challenges. ADB (2017) had highlighted apart from intra-day variability and seasonal variability of renewable energy sources, significant investment needed for infrastructure development and high cost of electricity from renewable sources as some of the major challenges which are relatable to any country depends more on the renewable energy sources. Sri Lankan government has identified a variety of investors including domestic investors and foreign institutional investors that can contribute to investments. Further investment in robust peak demand management and balancing system is needed to meet the daily and seasonal variabilities. Though newly introduced feed-in tariff policy will encourage producers to invest more in the renewable energy sources, customer tariffs system is still independent from the source of energy which can deter consumers from prioritising energy from renewables (ADB and United Nations Development Programme 2017).

Results of the scenario 2 (Figure 9) show expected CO\textsubscript{2} emissions are less than 10\% by 2030. Although reducing energy demand has a significant impact on CO\textsubscript{2} emissions, scenario 2 alone cannot achieve the set CO\textsubscript{2} reduction target of 20\% by 2030, thus needs to be combined with another scenario or policy strategy. All the criteria show significant improvements between 2015 and 2030 when compared with BAU scenario (economic sustainability by 5\%, social sustainability by 6\% and environmental sustainability by 14\%). Social indicators have been positively affected by decrease in energy consumption per household with a slight decrease in share of household income spent on electricity. Reduction in annual energy demand cause decrease in CO\textsubscript{2} emissions per capita (by 15\%) and emission intensity (2.82\%) positively impacting the environmental sustainability of the energy system. Some of the demand side management policy initiatives include providing low-cost LED lamps for households, phase out inefficient refrigerators, energy-efficient and energy conservation practices for ceiling fans, motors, chillers, air conditioning and encouraging implementation of energy-efficient building code for commercial and industrial facilities and large housing complexes (Presidential Task Force on Energy Demand Side Management 2016).
4. Conclusions and recommendations

This study aims to evaluate the sustainability of the energy system in Sri Lanka using an integrated, multidimensional framework. Thus, filling an important research gap in the context of Sri Lanka, expanding the emerging body of empirical literature on sustainability of the energy systems particularly in conflict-affected developing countries. The integrated approach consists of three stages developing a dynamic energy system model, developing an indicator-based framework and integrated sustainability index followed by a scenario analysis. These objectives were achieved through various data collection (literature survey, structured questionnaire survey and secondary data survey) and data analysis methods (system dynamics, multi-criteria decision analysis).

Stakeholder participation played an important role in deciding the weightage for sustainability criteria and indicators rendering the developed framework more pragmatic. Results of the questionnaire survey concluded by giving higher weightage for economic indicators, which is the only criteria that show a cumulative increase over the years. Decrease in overall and sectorial energy intensities show an increase in efficiency in the energy system over the years. On the contrary, decreasing self-sufficiency and lower efficiency of electricity conversion and distribution have negatively impacted on the economic sustainability of the energy system. While Sri Lanka may have been able to achieve 100% accessibility to electricity increasing per household energy consumption and income share spent on electricity has diminished the social sustainability. Environmental indicators were the least performing with increasing CO₂ emissions per capita and reducing renewable energy share. A study done by Sun et al. (2020) to measure the environmental sustainability performance of South Asia shows Pakistan and Sri Lanka as the countries with lowest sustainability performance scores, making Sri Lanka one of the most vulnerable countries in terms of environmental sustainability. Hou et al. (2019) study comparing the environmental performance of South Asian countries shows a consistent decline environmental performance score of Sri Lanka since 2008. This study shows an increase in overall sustainability till 2010 which has become almost stagnant since then. Concluding that post-war economic development has taken a toll on the overall sustainability of the energy system in Sri Lanka, which is going to continue without proper reforms.

Ambitious INDCs based scenarios show the positive impact of the actions on the overall sustainability of the energy system. Supply side measures show major improvements in economic and environmental indicators while demand side energy measure shows moderate improvements in all three dimensions, i.e. economic, social and environmental. While both the scenarios show

![Figure 9. Comparison of BAU Scenario and Scenario 2.](image-url)
more than 10% reductions in CO₂ emissions to achieve the committed 20% reductions a combination of INDCs needs to be implemented. However, with the challenges currently faced by the energy sector, the economic and technological feasibility of the foresaid INDCs is debatable.

While National Energy Policy and Strategies of Sri Lanka (2019) aim for a clean, safe, sustainable, reliable and economically feasible energy supply, feasibility and urgency of some of the policy reforms need to be reconsidered. Sri Lankan government on their conquest to achieve 100% electrification as soon as possible seems often overlooked the quality and efficiency of the conversion and transmission. Monetary and non-monetary losses from planned and unplanned supply interruptions have impacted negatively on the economic and social sustainability of the energy system endangering its reliability. Consumers have often been used as scape goats of poor management and maintenance practices by the relevant authorities. Households in rural areas have been more susceptible to unreliable or sporadic electricity supply or even only supplied during the hours of darkness. Therefore, energy suppliers should explore possibilities of fostering dispersed power generation or mini power grids that require lesser time and money to cater to the rural energy demand.

In a country where more than 60% of the households depend on biomass as the main energy source, immediate shift to more cleaner sources is unrealistic. Meanwhile, publics’ unwillingness to change, more specifically rural population with lower level of education, without proper financial motivation should not be underestimated. As Jayasinghe, Selvanathan, and Selvanathan (2021) point out having access itself will not naturally motivate consumers to embrace cleaner energy sources without proper support to overcome financial and social barriers. Therefore, proper measures need to be taken to enhance public awareness on cleaner energies, energy-efficient and conservation technologies specially among the women considering the gender disparity in cooking-related activities. Investment in R&D should be encouraged in developing technological innovations such as improved cooking stoves and make them affordable to the low-income households in rural areas. Further awareness programmes should draw attention towards benefits of rooftop solar systems which have a huge potential in catering to domestic water heating requirements.

Financial burden of expensive emergency power procurement and over dispatch of existing powerplants should not be transferred to consumers, whereas a cost-reflective Feed-in-Tariff policy should be in place to minimise the financial losses of the suppliers. Decreasing share of renewable energy and increasing dependency on energy imports directly affect security and sustainability of the energy system. Without indigenous fossil fuels, the need for harnessing the power of wind and solar energy is becoming more urgent.

Government policies should be focused in exploiting these renewable sources by extending low-cost long-term credit and tax incentives. Foreign and domestic investors need to be attracted with efficient and transparent bidding procedures that boost their confidence and investing more in R&D to find solutions in overcoming technical challenges accompany renewable energy sources. The energy sector in Sri Lanka which is heavily administered by the Government needs to be open to private sectors to discover potential of other indigenous energy sources such as geothermal, wave, tidal and offshore wind power, and biogas technology which has already proven their capability in providing energy for lighting and cooking requirements (de Alwis 2002).

Developed framework gives new insights to the energy system of Sri Lanka and problematic issues to be addressed to improve its sustainability. Indicator-based framework finetuned with stakeholder perception can be used as a planning tool by projecting future performance resulting from different policy actions. Ultimately provide a more structure guidance for the decision-makers to set the energy sector in Sri Lanka on a sustainable development path that is imperative in the long run.

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References

Afgan, N. H., and M. da Graça Carvalho. 2000. “Sustainable Assessment Method for Energy Systems.” In Sustainable Assessment Method for Energy Systems, 86–88. New York: Springer.

Anand, A. D. Donfred Rufuss, V. Rajkumar, and L. Suganthi. 2017. “Evaluation of Sustainability Indicators in Smart Cities for India Using MCDM Approach.” Energy Procedia 141: 211–215.

Angelis-Dimakis, A., G. Arampatzis, and D. Assimacopoulos. 2012. “Monitoring the Sustainability of the Greek Energy System.” Energy for Sustainable Development 16 (1): 51–56.

Asian Development Bank. 2015. Assessment of Power Sector Reforms in Sri Lanka: Country Report. Asian Development Bank. 2018. Sri Lanka: Energy Sector Assessment, Strategy, and Road Map. Asian Development Bank, and United Nations Development Programme. 2017. 100% Percent Electricity Generation Through Renewable Energy by 2050: Assessment of Sri Lanka’s Power Sector.

Bekchanov, M., M. A. H. Mondal, A. de Alwis, and A. Mirzabaev. 2019. “Why Adoption Is Slow despite Promising Potential of Biogas Technology for Improving Energy Security and Mitigating Climate Change in Sri Lanka?” Renewable and Sustainable Energy Reviews 105: 378–390.

Bhattacharyya, S. C., and G. R. Timilsina. 2010. “A Review of Energy System Models.” International Journal of Energy Sector Management 4 (4): 494–518.

Boggia, A., and C. Cortina. 2010. “Measuring Sustainable Development Using a Multi-Criteria Model: A Case Study.” Journal of Environmental Management 91 (11): 2301–2306.

Central Bank of Sri Lanka. 2019. Annual Report 2019.

Chryssoulakis, N., M. Lopes, R. San José, C. S. B. Grimmond, M. B. Jones, V. Magliulo, J. E. M. Klostermann, et al. 2013. “Sustainable Urban Metabolism as a Link Between Bio-Physical Sciences and Urban Planning: The BRIDGE Project.” Landscape and Urban Planning 112 (1): 100–117.

Custance, J., and H. Hillier. 1998. “Statistical Issues in Developing Indicators of Sustainable Development.” Journal of the Royal Statistical Society. Series A: Statistics in Society 161 (3): 281–290.

Daily News. 2020, August 17. “Electricity Supply Island-Wide was Disrupted.” Daily News. http://www.dailynews.lk/2020/08/17/local/226107/electricity-supply-island-wide-was-disrupted.

de Alwis, A. 2002. “Biogas – A Review of Sri Lanka’s Performance with a Renewable Energy Technology.” Energy for Sustainable Development 6 (1): 30–37.

Debnath, K. B., and M. Mourshed. 2018. “Challenges and Gaps for Energy Planning Models in the Developing-World Context.” Nature Energy 3 (March): 172.

Department of Census and Statistics. 2016. “Household Income and Expenditure Survey – 2016 Ministry of National Policies and Economic Affairs October 2017 Household Income and Expenditure Survey – 2016.” http://www.statistics.gov.lk/.

European Foundation. 1998. Urban Sustainability Indicators. www.eurofound.ie/

Farabi-Asl, H., F. Taghizadeh-Hesary, A. Chapman, and S. Mohammadzadeh Bina. 2019. ADBI Working Paper Series Energy Challenges for Clean Cooking in Asia, The Background, and Possible Policy Solutions Asian Development Bank Institute. https://www.adb.org/publications/energy-challenges-clean-cooking-asia.

Gasser, P. 2020. “A Review on Energy Security Indices to Compare Country Performances.” Energy Policy 139 (August 2019): 111339.

Giannakis, E., D. Serghides, S. Dimitriou, and G. Zittis. 2020. “Land Transport CO2 Emissions and Climate Change: Evidence from Cyprus.” International Journal of Sustainable Energy 39 (7): 634–647.

González, A., A. Donnelly, M. Jones, N. Chryssoulakis, and M. Lopes. 2013. “A Decision-Support System for Sustainable Urban Metabolism in Europe.” Environmental Impact Assessment Review 38: 109–119.

Grubb, M., L. Butler, and P. Twomey. 2006. “Diversity and Security in UK Electricity Generation: The Influence of Low-Carbon Objectives.” Energy Policy 34 (18): 4050–4062.

Gunnarsdottir, I., B. Davidsdottir, E. Worrell, and S. Sigurgeirsdottir. 2020. “Review of Indicators for Sustainable Energy Development.” Renewable and Sustainable Energy Reviews 133 (July): 110294.

Hák, T., B. Moldan, and A. L. Dahl. 2012. Scientific Committee on Problems of the Environment (SCOPE) Series: Sustainability Indicators: A Scientific Assessment. Island Press. http://site.ebrary.com/lib/wpi/detail.action?docID=10222014.

Hannan, M. A., R. A. Begum, M. G. Abdolrasol, M. S. Hossain Lipu, A. Mohamed, and M. M. Rashid. 2018. “Review of Baseline Studies on Energy Policies and Indicators in Malaysia for Future Sustainable Energy Development.” Renewable and Sustainable Energy Reviews 94 (May): 551–564.
Herbst, A., F. Toro, F. Reitze, and E. Jochem. 2012. “Introduction to Energy Systems Modelling.” *Swiss Journal of Economics and Statistics* 148 (2): 111–135.

Hou, Y., W. Iqbal, G. Muhammad Shaikh, Y. A. Solangi, A. Fatima, and N. Iqbal. 2019. “Measuring Energy Efficiency and Environmental Performance: A Case of South Asia.” *Processes* 7: 325.

Iddrisu, I., and S. C. Bhattacharyya. 2015. “Sustainable Energy Development Index: A Multi-Dimensional Indicator for Measuring Sustainable Energy Development.” *Renewable and Sustainable Energy Reviews* 50: 513–530.

Jain, P., and B. Goswami. 2021. “Energy Efficiency in South Asia: Trends and Determinants.” *Energy* 221: 119762.

International Project on Electricity Sector Master Plan Study in Democratic Socialist Republic of Sri Lanka Final Report Ministry of Power and Renewable Energy (MPRE) Ceylon Electricity Board (CEB) Project on Electricity Sector Master Plan Study in Democratic Socialist Republic of Sri Lanka Final Report.

Jayasinghe, M., E. A. Selvananthan, and S. Selvananthan. 2021. “Energy Poverty in Sri Lanka.” *Energy Economics* 101: 105450.

Kahan, Ari. 2016. *Global Energy Intensity Continues to Decline.* https://www.eia.gov/todayinenergy/detail.php?id=27032.

Kaushalya Konara, K. M. G., and A. Tokai. 2020. “Evaluating the Energy Metabolic System in Sri Lanka.” *Journal of Sustainable Development* 13 (4): 235.

Kaya, Y. 1989. *Impact of Carbon Dioxide Emission on GNP Growth: Interpretation of Proposed Scenarios*.

Kaya, İ., Çolak M., and Terzi Fulya. 2018. “Use of MCDM Techniques for Energy Policy and Decision-Making Problems: A Review.” *International Journal of Energy Research* 42: 2344.

Kemmler, A., and D. Spreng. 2007. “Energy Indicators for Tracking Sustainability in Developing Countries.” *Energy Policy* 35 (4): 2466–2480.

Kennedy, C., I. D. Stewart, N. Ibrahim, A. Facchini, and R. Mele. 2014. “Developing a Multi-Layered Indicator Set for Urban Metabolism Studies in Megacities.” *Ecological Indicators* 47: 7–15.

Kilki, Ş. 2016. “Sustainable Development of Energy, Water and Environment Systems Index for Southeast European Cities.” *Journal of Cleaner Production* 130: 222–234.

Kosteviček, A., J. J. Klemš, P. S. Varbanov, L. Čuček, and J. Petek. 2015. “Sustainability Assessment of the Locally Integrated Energy Sectors for a Slovenian Municipality.” *Journal of Cleaner Production* 88: 83–89.

Liu, K. F. R. 2007. “Evaluating Environmental Sustainability: An Integration of Multiple-Criteria Decision-Making and Fuzzy Logic.” *Environmental Management* 39 (5): 721–736.

Liu, G. 2014. “Development of a General Sustainability Indicator for Renewable Energy Systems: A Review.” *Renewable and Sustainable Energy Reviews* 31: 611–621.

Luthra, S., S. K. Mangla, and R. K. Kharb. 2015. “Sustainable Assessment in Energy Planning and Management in Indian Perspective.” *Renewable and Sustainable Energy Reviews* 47: 58–73.

Mainali, B., S. Pachauri, N. D. Rao, and S. Silveira. 2014. “Assessing Rural Energy Sustainability in Developing Countries.” *Energy for Sustainable Development* 19 (1): 15–28.

Mandelli, S., J. Barbieri, L. Mattarolo, and E. Colombo. 2014. “Sustainable Energy in Africa: A Comprehensive Data and Policies Review.” *Renewable and Sustainable Energy Reviews* 37: 656–686.

Masud, M. H., M. Nuruzzaman, R. Ahamed, A. A. Ananno, and A. N. M. A. Tomal. 2020. “Renewable Energy in Bangladesh: Current Situation and Future Prospect.” *International Journal of Sustainable Energy* 39 (2): 132–175.

Maxim, A. 2014. “Sustainability Assessment of Electricity Generation Technologies Using Weighted Multi-Criteria Decision Analysis.” *Energy Policy* 65: 284–297.

McCachern, M., and S. Hanson. 2008. “Socio-Geographic Perception in the Diffusion of Innovation: Solar Energy Technology in Sri Lanka.” *Energy Policy* 36 (7): 2578–2590.

Meles, T. H. 2020. “Impact of Power Outages on Households in Developing Countries: Evidence from Ethiopia.” *Energy Economics* 91: 104882.

Meles, T. H. 2020. “Impact of Power Outages on Households in Developing Countries: Evidence from Ethiopia.” *Energy Economics* 91: 104882.

Ministry of Environment and Renewable Energy. 2014. *A Road Map for Cleaner Fuels and Vehicles in Sri Lanka: Ministry of Environment and Renewable Energy*. Ministry of Mahaweli Development and Environment. 2016. *Sri Lanka’s Nationally Determined Contributions*. September, 1–26. http://www4.unfccc.int/ndcregistry/PublishedDocuments/Nepal First/Nepal First NDC.pdf.

Ministry of Power & Energy. 2015. *Sri Lanka Energy Sector Development Plan for a Knowledge-Based Economy*.

Mirjat, N. H., M. A. Uqaili, K. Harjjan, M. W. Mustafa, M. M. Rahman, and M. W. A. Khan. 2018. “Multi-Criteria Analysis of Electricity Generation Scenarios for Sustainable Energy Planning in Pakistan.” *Energies* 11 (4): 1–33.

Mori, K., T. Fujii, T. Yamashita, Y. Mimura, Y. Uchiyama, and K. Hayashi. 2015. “Visualization of a City Sustainability Index (CSI): Towards Transdisciplinary Approaches Involving Multiple Stakeholders.” *Sustainability* 7 (9): 12402–12424.
Nakthong, V., and K. Kubaha. 2019. “Development of a Sustainability Index for an Energy Management System in Thailand.” *Sustainability* 11: 17.

Nandasena, Y. L. S., A. R. Wickremasinghe, and N. Sathiakumar. 2010. “Air Pollution and Health in Sri Lanka: A Review of Epidemiologic Studies.” *BMC Public Health* 10 (1): 1–14.

Narula, K. 2014. “Is Sustainable Energy Security of India Increasing or Decreasing?” *International Journal of Sustainable Energy* 33 (6): 1054–1075.

Narula, K., and B. S. Reddy. 2015. “Three Blind Men and an Elephant: The Case of Energy Indices to Measure Energy Security and Energy Sustainability.” *Energy* 80: 148–158.

National Energy Policy and Strategies of Sri Lanka. 2019. [http://data.worldbank.org/Country/Sri](http://data.worldbank.org/Country/Sri).

Nduhuura, P., M. Garschagen, and A. Zerga. 2021. “Impacts of Electricity Outages in Urban Households in Developing Countries: A Case of Accra, Ghana.” *Energies* 14: 12.

Neves, A. R., and V. Leal. 2010. “Energy Sustainability Indicators for Local Energy Planning: Review of Current Practices and Derivation of a New Framework.” *Renewable and Sustainable Energy Reviews* 14 (9): 2723–2735.

Okoro, O. I., and T. C. Madueme. 2006. “Solar Energy: A Necessary Investment in a Developing Economy.” *International Journal of Sustainable Energy* 25 (1): 23–31.

Organisation for Economic Co-operation and Development. 1998. *Towards Sustainable Development*. Paris: OECD Publishing.

Pallegedara, A., K. A. Mottaleb, and D. B. Rahut. 2021. “Exploring Choice and Expenditure on Energy for Domestic Works by the Sri Lankan Households: Implications for Policy.” *Energy* 222: 119899.

Pathirana, S., and M. Yarime. 2018. “Introducing Energy Efficient Technologies in Small- and Medium-Sized Enterprises in the Apparel Industry: A Case Study of Sri Lanka.” *Journal of Cleaner Production* 178: 247–57.

Palitzianas, K. D., H. Doukas, A. G. Kagiannas, and J. Psarras. 2008. “Sustainable Energy Policy Indicators: Review and Recommendations.” *Renewable Energy* 33 (5): 966–973.

Presidential Task Force on Energy Demand Side Management. 2016. *Operation DSM National Energy Management Action Plan 2016–2020 Presidential Task Force on Energy Demand Side Management*. [www.save.energy.gov.lk](http://www.save.energy.gov.lk).

Public Utilities Commission of Sri Lanka. 2017. *Financial Impact of Delay in Implementation of Power Plants*.

Ran, W. 2011. “AHP Study on Energy Indicators System for Sustainable Development of Henan Province.” 2011 *IEEE 3rd International Conference on Communication Software and Networks, ICCSN 2011*, 175–179.

Saaty, T. L. 1990. “How to Make a Decision: The Analytic Hierarchy Process.” *European Journal of Operational Research* 48 (1): 9–26.

Sahabamnesh, A., and Y. Sabooshi. 2017. “Model of Sustainable Development of Energy System, Case of Hamedan.” *Energy Policy* 104: 66–79.

Shah, S. A. A., P. Zhou, G. D. Walasai, and M. Mohsin. 2019. “Energy Security and Environmental Sustainability Index of South Asian Countries: A Composite Index Approach.” *Ecological Indicators*, 106, 105507.

Sheinbaum-Pardo, C., B. J. Ruiz-Mendoza, and V. Rodriguez-Padilla. 2012. “Mexican Energy Policy and Sustainability Indicators.” *Energy Policy* 46: 278–283.

Siksneleyte-Butkiene, I., E. K. Zavadskas, and D. Streimikiene. 2020. “Multi-Criteria Decision-Making (MCDM) for the Assessment of Renewable Energy Technologies in a Household: A Review.” *Energies* 13: 5.

Sözen, A., and M. Nalbant. 2007. “Situation of Turkey’s Energy Indicators Among the EU Member States.” *Energy Policy* 35 (10): 4993–5002.

Sri Lanka Sustainable Energy Authority. 2017. *Sri Lanka Energy Balance 2017*.

Sun, H., M. Mohsin, M. Alharthi, and Q. Abbas. 2020. “Measuring Environmental Sustainability Performance of South Asia.” *Journal of Cleaner Production* 251: 119519.

Tongsopit, S., N. Kittner, Y. Chang, A. Aksornkij, and W. Wangjiraniran. 2016. “Energy Security in ASEAN: A Quantitative Approach for Sustainable Energy Policy.” *Energy Policy* 90: 60–72.

United Nations Development Programme (UNDP). 2000. *World Energy Assessment: Energy and the Challenge of Sustainability*. Development Programme.

The Urban China Initiative. 2010. *The Urban China Initiative The Urban Sustainability Index: A New Tool for Measuring China’s Cities*.

Vidanagama, J., and E. Lokupitiya. 2018. “Energy Usage and Greenhouse Gas Emissions Associated with Tea and Rubber Manufacturing Processes in Sri Lanka.” *Environmental Development* 26: 43–54.

Vera, I., and L. Langlois. 2007. “Energy Indicators for Sustainable Development.” *Energy* 32 (6): 875–882.

Vishnupriyan, J., and P. S. Manoharan. 2018. “Multi-Criteria Decision Analysis for Renewable Energy Integration: A Southern India Focus.” *Renewable Energy* 121: 474–488.

Wang, J. J., Y. Y. Jing, C. F. Zhang, and J. H. Zhao. 2009. “Review on Multi-Criteria Decision Analysis Aid in Sustainable Energy Decision-Making.” *Renewable and Sustainable Energy Reviews* 13 (9): 2263–2278.

Wickramasinghe, A. 2011. “Energy Access and Transition to Cleaner Cooking Fuels and Technologies in Sri Lanka: Issues and Policy Limitations.” *Energy Policy* 39 (12): 7567–7574.

Wijayatunga, P. D.C., and R. A. Attalage. 2003. “Analysis of Rural Household Energy Supplies in Sri Lanka: Energy Efficiency, Fuel Switching and Barriers to Expansion.” *Energy Conversion and Management* 44 (7): 1123–1130.
Wijayatunga, P. D. C., and M. S. Jayalath. 2004. “Assessment of Economic Impact of Electricity Supply Interruptions in the Sri Lanka Industrial Sector.” *Energy Conversion and Management* 45 (2): 235–247.

Wijayatunga, P. D. C., W. J. L. S. Fernando, and R. M. Shrestha. 2003. “Greenhouse Gas Emission Mitigation in the Sri Lanka Power Sector Supply Side and Demand Side Options.” *Energy Conversion and Management* 44 (20): 3247–3265.

The World Bank. 2017. *Sri Lanka | Data*. https://data.worldbank.org/country/LK.

World Bank. 2020. *GDP Growth (Annual %) – Sri Lanka | Data*. https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=LK.

World Bank and International Finance Corporation. 2019. *Sri Lanka Energy Infrastructure Sector Assessment Program – Final Report 2019*. www.worldbank.org.

Yigezu, Z. D., and T. O. Jawo. 2021. “Empirical Analysis of Fuelwood Consumptions and its Environmental Implications in Rural Sub-City, Southern Ethiopia.” *International Journal of Sustainable Energy* 40 (5): 448–459.