Doctoral Dissertation

Exploring socioeconomic metabolism of Sri Lanka: Moving towards sustainable production and consumption

Konara Mudiyanselage Gayani Kaushalya Konara

January 2023

Division of Sustainable Energy and Environmental Engineering
Graduate School of Engineering
Osaka University

ACKNOWELEDGEMENT

This doctoral thesis was made possible through the assistance, help, guidance and support of numerous personnel and institutions. I would like to take this opportunity to sincerely express my gratitude towards them.

First and foremost, I would like to express my sincere gratitude towards my supervisor and mentor, Professor Akihiro Tokai, for his priceless support, endless encouragement, and motivation. His precious advice has been the guiding star for me throughout my postgraduate studies. His patience, compassion and kindness towards my academic and personal matters have been unparallel to no other.

Secondly, I am greatly thankful to the vice examiners of this thesis: and Professor Masanori Sawaki and Professor Akira Kondo for their valuable time and effort in giving insightful comments and suggestions. Their contributions have helped me in improving this thesis immensely.

My sincere gratitude must also be expressed to all the members of the Environmental Management Lab at Osaka University, particularly my fellow doctoral students and the staff, who patiently listened to my monthly progress reports and rehearsal presentations. Their comments helped me to improve my research and their moral support has consistently revigorated me into completing my postgraduate studies.

I would like to thank my parents and my sister for always recognising my potential and encouraging me to reach the greatest of heights. I am yet to understand the depth of your selflessness, love, and support.

I am grateful for my husband Madhawa, for the sacrifices you have made to embark this journey with me, and for the constant support and companionship given throughout. My daughter and I are the luckiest to be at the receiving end of your love and kindness. Thank you for believing in me always and inspiring me every day.

Last but not least, I dedicate this thesis to my daughter, Aimi for giving me the tremendous joy of becoming your mother during this journey. For accepting me for who I am without any judgement or expectations and for showing me the true meaning of unconditional love. Everything I do, I do it for you.

ABSTRACT

With rapidly declining energy, water, and food securities, increasing carbon emissions and underwhelming performance in global sustainable development indices, Sri Lankan government has introduced a national policy on sustainable consumption and production in 2019 to increase awareness among people regarding sustainable lifestyles and to develop tools to monitor sustainable development impacts by 2030. With little to no information currently being available, timely need to unravel and comprehend the performance of socio-economic metabolic flows surging through Sri Lankan urban systems is undeniable. Thus, this research intends to explore the past and present patterns for energy, water, food flows and related emissions to reveal sustainability and environmental consequences of energy production and household consumption in Sri Lanka.

In the second chapter the dynamic energy metabolic model which consists of energy demand, energy supply and transformation and CO2 emissions was developed based on population, population growth, GDP, GDP growth and income from 2000 to 2015. Forecasted energy flows show an average annual growth rate of 4.06% in energy demand and 3.36% in CO2 emissions compared to 2000. The strongest flow is between biomass and domestic and commercial sectors. Evaluated metabolic indicators reveal decreasing energy intensity and decreasing energy security with increasing dependence of energy imports.

The third chapter further simulates the developed dynamic energy metabolic model to evaluate the sustainability of energy metabolic flows using an integrated sustainability index followed by 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. Intended nationally determined contributions-based scenarios show more than 10% CO2 reductions in each scenario. Supply side measures show major improvements in economic and environmental indictors while demand side energy measure shows moderate improvements but in all three dimensions i.e., economic, social, and environmental.

Chapter Four focus on evaluating household resource flows i.e., energy, water, food, CO2 emissions and food waste in Sri Lanka using a bottom-up approach by converting household expenditure survey data into physical quantities. Mapped out resource flow diagrams demonstrate the inputs, outputs, and the distribution of resources among metabolic processes. Metabolic indicators evaluated against environmental sustainability indicate declining intensities of energy and food consumption and inclining intensities of water consumption and emissions can be observed during the past decade. Tracing consumption patterns across metabolic flows reveal extensively linear metabolic flows with comparatively pro-environmental patterns in resources extraction. Lack of proper disposal/recycle measures for food waste and wastewater has jeopardized the circularity of metabolic flows causing irreversible environmental deterioration.

Chapter five analyse direct and indirect carbon flows in Japanese one-person households using embodied emission intensity data based on input-output tables coupled with household consumer expenditure survey data of more than 50000 households spread over 500 distinct categories of goods and services. Results show that declining members per household can increase carbon emissions 1.5 times. Further improving environmentally conscious behaviour of householders and reducing embodied carbon emissions can reduce energy consumption and related emissions.

This study highlights the environmental impact of increasing dependence in non-renewable energy sources and environmentally harmful water consumption, food waste and wastewater disposal practices. The past and present energy production and household patterns can provide insights and structural guidance for the decision makers to set the production and consumption patterns on a sustainable development path that is imperative in the long run.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 – INTRODUCTION

1.1 Background

1.1.1 Sustainable consumption and production

Rapid structural economic and sociodemographic changes, land-use patterns, technological changes and changes in lifestyles (OECD, 1999) result in unsustainable extraction of resources from environment leading to higher resource footprints (Cai et al., 2019; Caird & Roy, 2009; Goldstein et al., 2020; Kala, 2015; Salo et al., 2021; S. Yang et al., 2018). According to Akenji et al. (2012), Asia-Pacific has overtaken the rest of the world to become the single largest user of materials. The use of materials had grown to 32 billion tonnes by 2005 which accounts for over half of global resource use and expected to grow by further 80 billion tonnes by 2050 (UNEP 2011). The nature of resource use has also shifted from mainly biomass (over 50% in 1970) to mainly mineral materials (over 70% in 2005) with doubled extraction rates in Asia. Further, Asia region consumes about one third of global primary energy use. While primary energy base has shifted to coal and the share of renewable energy in the energy mix has decreased. This level of resource use was largely based on the assumption of limitless resources and overlooked the connections between resource use and environmental impacts (Akenji et al., 2012). Thus, environmental impacts of consumption and production, such as loss of natural resources, climate change and other environmental damage caused by emissions and waste, need to be addressed to promote sustainable consumption and production patterns (Shittu, 2020). With the intention of enforcing policies influencing HC and affect their decisions in 2015 sustainable consumption and production was identified as a stand-alone goal (SDG 12) and as a central component of many of goals and targets proposed (UNEP, 2016). In Oslo Symposium (1994) Sustainable Consumption (SC) was defined as ‘use of goods and services that respond to basic needs and bring better quality of life while minimizing use of natural resources, toxic materials and emissions of waste and pollutants over life cycle, so as not to jeopardise needs of future generations’. Currently progress of governmental actions to promote SC is monitored through numerous statistics and models such as consumption based material flows (UNEP, 2016).

1.1.2 Socio-economic Metabolism in national and household level

Resource consumption has been attracting attention as an important driver for societal metabolism during recent years influencing to change the focus to final demand associated requirements (Donato et al., 2015). As shown in Figure 1-1 ecosystems at different scales provide societies with raw materials, energy carriers, and water. Some of the resources are directly consumed by households in terms of or materials generating emissions and wastes (direct outputs) to nature. Others are employed to provide economic goods and services (indirect inputs) consumed by cities/households, also generating emissions and wastes (indirect outputs) partially treated or recycled to provide new goods and services (Donato et al., 2015). As countries/cities/households attract resources from outside its boundaries, it is imperative for these resource flows to be transformed and returned to environment in the most sustainable way possible to lessen the burden on the environment (Villarroel Walker et al., 2014). Metabolism assessments provide a detailed examination of this transformation by tracing metabolic flows, which helps in identifying opportunities for shaping these flows towards more sustainable forms of consumption and urbanism (Giampietro et al., 2009; Haberl et al., 2009; Rodríguez-Huerta et al., 2019; Strydom et al., 2020). As Harder (2013) explains with our needs, desires, preferred activities, routines and practices we have choice over characteristics and magnitude of Socioeconomic Metabolism (SEM) of households/cities. Thus, identifying metabolic patterns from a quantitative perspective along with associated socioeconomic drivers will allow us to influence these choices to reduce their environmental impact (Donato et al., 2015; Harder, 2013; Lucertini & Musco, 2020). Further as Bancheva (2014) shows in Figure 1-2, transitioning from a "linear" metabolism (i.e., based on the assumption of a limitless supply of resources from the hinterland and high amounts of expelled waste) towards a more "circular" metabolism has been identified as a condition to achieve a more sustainable development of urban systems. More recently, has been further explored and developed throughout a wide range of case studies across the globe, based on evidence that cities lie at the beginning and at the end of many production-consumption chains and material waste paths.

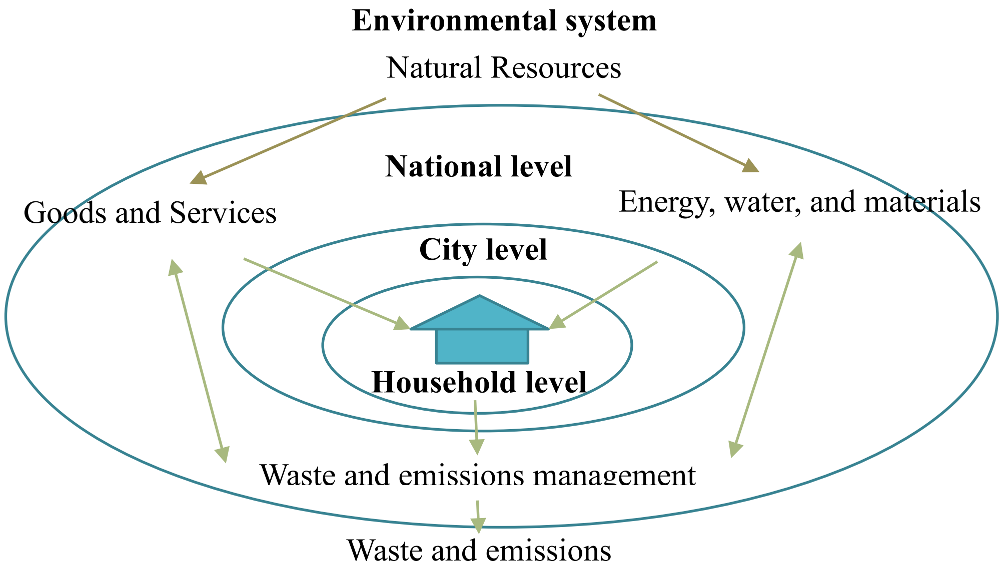

Figure 1-1: Conceptual SEM framework

Figure 1: Conceptual SEM framework

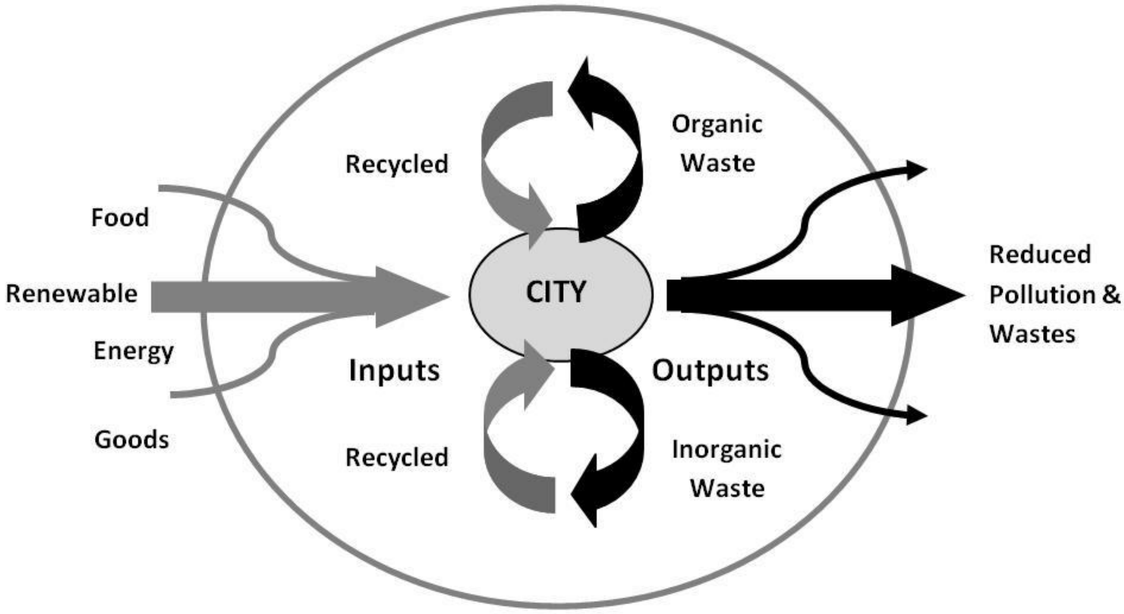

Figure 1-2: Circular metabolism model of cities

Source : (Bancheva, 2014)

1.1.3 Case study and past research

As 90% of increase world's urban population is expected to take place in urban areas of Asia and Africa by 2050, it has become imperative to more than ever for researches to focus on Global South to aid with growth related pressures as they are accompanied by additional challenges such as resource scarcity and climate change (Khalifa et al., 2019; United Nations, 2015). South Asia as one of the fastest growing regions is currently facing many challenges in meeting its growing resource consumption needs due increasing population, GDP growth, urbanisation and changes in life styles (Shah et al., 2019). As a region, South Asia has the highest per capita household expenditure growth rate in Global South which is more than 6% in 2018 (World Bank, 2018). 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 of 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 its socioeconomic growth. Sri Lanka has consumed 12.8 million tonnes of oil equivalent energy in 2017 while energy consumption per capita has increased by 35% during last two decades (Sri Lanka Sustainable Energy Authority (SSEA), 2017; The World Bank, 2017). Energy mix 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 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 $mtCO_2e$/capita in 2015), increase in GHG emissions during 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 second highest energy demand (36%) and 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). Further Sri Lanka still struggle with achieving adequate food security while ranked low in global food security indices (WFP, 2017). To address the increasing consumption of natural resources and their negative impact Sri Lankan government introduced a national policy on SC and production for Sri Lanka in 2019. Policy targets to achieve sustainable and efficient use of resources, reduce food waste by half at consumer levels, increase awareness among people regarding sustainable lifestyles and to develop tools to monitor sustainable development impacts by 2030 (MMDE, 2019).

Household consumption in Sri Lanka has gained attention during last few years being the highest energy consumer and 2nd highest GHG emitter (SSEA, 2017). Further water consumption and waste generation in household sector has increased exponentially during last few decades. Sri Lanka currently have more than 5.4 million households in which only 17.3% are considered as urban households as countries UN (2015) rank as the 7th in worlds' least urbanised countries. Food expenditure accounts for 34.8% of total expenditure and housing, energy, transportation and other non-consumer expenditures claims higher proportions (DCSSL, 2018). There is a substantial income disparity among households while richest 20% of the households share 50% of income per household.

Among countless studies about sustainability of energy systems especially cross-country studies, Sri Lanka often remains unexplored partially due 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 at the third place in the South Asian region. Jayasinghe et al. (2021) has studies energy poverty and associated socio-demographic and geographical factors which concludes possible adverse implications on health and education attainment of the energy-poor. Pallegedara et al. (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 et al. (2003) has briefly studied GHG mitigation in the Sri Lanka power sector supply side and demand side options while Kariyakarawana et al. (2014) and Vidanagama & 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 & Hanson, 2008; Wijayatunga, 2014) while Wijayatunga, Fernando, & Ranasinghe (2003); Wijayatunga & Attalage (2003) and Pathirana & Yarime (2018) have studied energy efficiency in office buildings, rural households, and apparel industry respectively.

In recent decades, an increasing number of studies have been conducted to study both direct and indirect energy consumption and related carbon emissions to understand socioeconomic determinants, behavioural patterns and occupancy (S. Chen & Chen, 2016; Damari & Kissinger, 2018; Hu et al., 2020; Kim, 2018; Jinyu Liu et al., 2021; Poortinga & Darnton, 2016; Rosales Carreón & Worrell, 2018; Shah et al., 2019; Strydom et al., 2019; Sugiura et al., 2013; Weiss de Abreu et al., 2021; Q. Yang et al., 2015; Zhou & Gu, 2020; Zou & Luo, 2019). Household water consumption has been assessed against socioeconomic and demographic characteristics that can be used to forecast demand (Cai et al., 2019; Chang et al., 2010; Chenoweth et al., 2016; Fontdecaba et al., 2013; Hussain et al., 2015; Jorge et al., 2015; Liao et al., 2019; Sarker & Gato-Trinidad, 2015; Shan et al., 2015; Willis et al., 2013). Some of the food consumption related studies include Geislar, (2018); Harder et al. (2014) and Leray et al. (2016); Hoek et al. (2021); Issock et al. (2021); Woolley et al. (2021); Y. Liu et al. (2021) where researchers attempts to understand environmental pressure of food consumption caused by different food consumption patterns and food wastage.

A limited number of studies have addressed household consumption through a metabolic perspective. Jingru Liu et al. (2020) developed an accounting frame for household metabolism evaluating durable goods and bulk materials in Chinese households which emphasises growth of transportation tools. While Strydom et al. (2020) assessed household energy metabolic flows in Cape Town to visualise energy inflows and throughflows in different income groups, L. Chen et al. (2021) employed MultiScale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach to identify factors affecting Chinese residential energy metabolic patterns. Leray et al. (2016) and Di Donato & Carpintero (2021) attempted to understand the household food metabolism in Bangalore, India and Spain respectively giving insights to food consumption practices and food wastage. Studies which evaluate household metabolism more holistically have considered land use, energy, water, and material consumption along with emissions to evaluate the environmental impact of each flow (Harder et al., 2017; Kissinger & Damari, 2021). As Strydom et al. (2020) explains some of the recent approaches have attempted to understand the metabolic flows as a nexus rather than individually to explore their interdependencies and potential co-benefits and some studies have explored these nexus activities at a household scale (Berman et al., 2019; Casazza et al., 2021; Hussien et al., 2017, 2018; Kenway et al., 2013; Yagita & Iwafune, 2021).

While many researchers have utilised SEM metabolism concept successfully to improve the sustainability in regional or national scale (Baccini, 1997; Caputo et al., 2016; Chrysoulakis et al., 2013a; Conke & Ferreira, 2015; Davoudi & Sturzaker, 2017; González et al., 2013; W. Huang et al., 2015; Pincetl et al., 2014), its contribution to improve sustainability at household level consumption patterns is yet to be explored in detail. Household metabolism being centred in investigating behaviour of households can easily help to change old and unsustainable practices (Padovan et al., 2015). Jingru Liu et al. (2005) who study water and energy metabolism of Chinese households to identify biological, economic, and demographic driving factors calls for further research considering wider range of household activities to formulate effective policies in promoting SC. Donato et al. (2015) focusing on biophysical assessment of households through material and energy consumption, emphasise importance of further advancements in metabolic narrative to extract information related to SC policies. Moll et al. (2005) studied European household metabolism to encourage SC patterns but have been only limited to evaluating energy requirements in HC. Thus, there is a research gap in utilising the metabolic perspective on national and household scale to identify the sustainable tendencies of extracting resources, transformation and releasing back to the environment.

1.2 Objectives of the Study

This study intends to identify and quantify socio-economic metabolic flows in national and household scale to provide insights to their behaviour to promote sustainable production and consumption production patterns.

- Evaluate the changes in energy metabolism and CO_2 emissions in Sri Lanka from 2000-2030.

- Assess the sustainability of energy metabolic system in Sri Lanka using economic, social, and environmental sustainability indicators.
- Explore behavioural patterns of household metabolic flows and the impact of different socio-economic and demographic factors
- Identify environmentally sustainable and unsustainable consumption patterns
- Quantify the carbon emissions from one-person Japanese households

1.3 Research Scope and Limitations

This study evaluates the socio-economics metabolic flows of Sri Lanka at national and household level using a combination of top-down and bottom-up approaches. Due to lack of data availability, in evaluating the SEM flows at national level only energy flows and related emissions have been considered. While the existence of variety of frameworks to evaluate the sustainability of energy systems are acknowledged, lack of data availability has hindered from using most of them wherein a customized framework seemingly became more pragmatic. Further incorporating views and values of local stakeholders in developing a framework to measure sustainability is valued. In using the bottom-up approach at the household level, expenditure data taken Household Income and Expenditure Survey (HIES) which is nationwide household survey that cover stratified sample of 20,000 household selected from all 25 administrative districts in Sri Lanka, were generalized for all the households. Depending on the availability of data in evaluating the SEM flows at household level, only energy, food, water flows, and related emissions were considered.

1.4 Research Framework and Research Questions

This study intends to identify and quantify socio-economic metabolic flows in national and household scale to provide insights to their behaviour to promote sustainable production and consumption production patterns. Following the objectives, the following research questions were answered. Topic 1 answers changes and performance of energy metabolic system in Sri Lanka from 2000-2030. A conceptual energy metabolic model was developed identifying economic, social and demographic variables affecting energy demand, transformation and supply and CO_2 emissions in Sri Lanka. The 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 a number of metabolic indicators. Topic 2 seeks to assess the sustainability of energy metabolic system in Sri Lanka using economic, social and environmental sustainability indicators and to identify the best possible scenario with reduced CO2 emissions and improved sustainability. An indicator-based framework which can analyse sustainability of the energy system from economic, social, and environmental perspectives was developed. 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 CO_2 emission reduction scenarios developed based on INDCs as the final stage. Topic 3 explores behavioural patterns of household metabolic flows to identify environmentally sustainable and unsustainable consumption patterns. This topic focus on evaluating household resource flows i.e., energy, water, food, CO_2 emissions and solid waste in Sri Lanka using a bottom-up approach by converting household expenditure survey data into physical quantities to explore the sustainability of resource consumption patterns. And resource flow was mapped out diagrams demonstrate the inputs, outputs, and the distribution of resources among metabolic processes. Topic 4 presents a case study of Japanese one-person households that was analysed to understand the direct and indirect energy and carbon flows of household consumption. Lessons learned will be applied in improving the energy and carbon flows of Sri Lankan households.

1.5 Outline of the Thesis

Figure 1-3 presents the outline of this thesis. Chapter One presents an introduction to the thesis while describing concepts and sustainable consumption and production, socio-economic metabolism and introducing Sri Lanka as the case study by describing current sustainability related issues in energy, water, food consumption and handling related emissions, in the background of the research followed by objectives and construction of the research framework. Chapter two discuss the development of conceptual energy metabolic model and quantification of CO_2 emissions. In Chapter three, sustainability of energy metabolic flows was evaluated using an integrated approach consists of three stages i.e. stimulating developed dynamic energy metabolic model, developing an indicator-based framework and integrated sustainability index followed by a scenario analysis. Chapter four focus on evaluating household resource flows i.e., energy, water, food, CO_2 emissions and solid waste in Sri Lanka using a bottom-up approach by converting household expenditure survey data into physical quantities to explore the sustainability of resource consumption patterns. Chapter five presents the quantification of carbon footprint of Japanese one-person households. Lastly, in Chapter six, the summary of the main findings, the contribution of the thesis, and proposal for future studies, are presented.

Chapter 1 Introduction

Chapter 2 Evaluating the energy metabolic system in Sri Lanka

Chapter 3 Sustainability evaluation and future scenarios for energy metabolic system

Top-down approach National level Energy production

Chapter 4 Exploring behaviour of socio-economic metabolic flows at household scale

Chapter 5 Quantifying carbon emissions from one-person Japanese households

Bottom-up approach Household level Household consumption

Chapter 6 Conclusions and recommendations

Figure 1-3: Outline of the thesis

CHAPTER 2 – EVALAUATING ENERGY METABOLIC SYSTEM

2.1 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). According to Hoornweg et al. (2012), urban metabolism represents a comprehensive framework that helps monitor the transformation occurring in cities, as well as their contributions to sustainable development. Energy metabolism mainly considers energy flows within a system. According to Hu & Mu (2019) excessive consumption and emissions related to urban energy have resulted resource exhaustion environmental deterioration and climate change.

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). In Figure 2-1 Hu & Mu (2019) conceptual urban energy metabolic framework supply and demand functions along with other sub-sectors with different functions. Arrows demonstrate flows of energy between sectors and with external environment when countries/cities fail to self-sustain within their own administrative boundaries.

To evaluate the energy throughput and overall condition of urban energy metabolic system researchers have utilised Material Flow Analysis (MFA) to study urban energy metabolism by quantifying the energy inputs and outputs. 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). 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 (Herbst et al., 2012). While reviewing variety of energy system models (Bhattacharyya & Timilsina, 2010) emphasise importance of top-down models for long term, national level and macroeconomic energy analysis. While the existence of other developed models are acknowledged, lack of data availability has hindered from using them. Further as Debnath & 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. As findings Japan International Cooperation Agency (2018) reveals, 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 methods. However, as the 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.

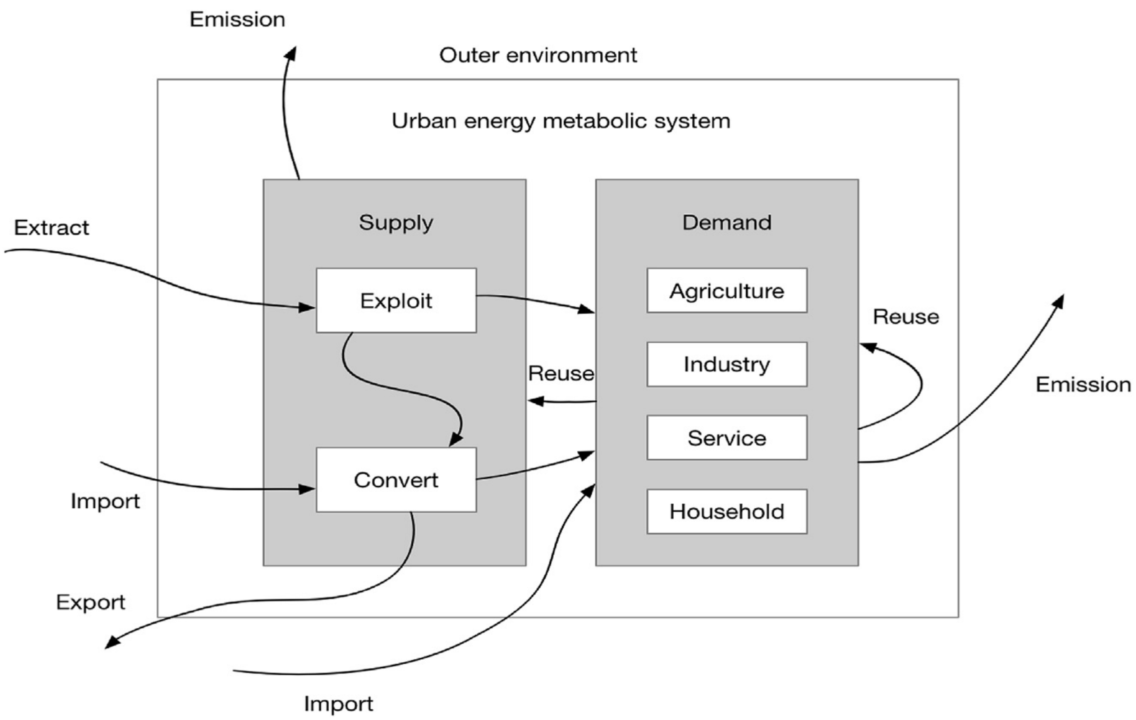

Figure 2-1: Conceptual framework of urban energy metabolic system

(G. Hu & Mu, 2019)

This chapter intends to develop a customized dynamic energy metabolic model by combining top-down approach with system dynamics concept to analyse energy demand, energy supply and CO_2 emissions based on variety of economic and social demographic parameters such as population, GDP, income, energy price, etc. Then recorded data from 2000-2015 have been further extrapolated to predict the behavior of the energy system during 2016-2030. Lastly the energy flows and their relationship with inputs and outputs of energy metabolic system and overall performance of the energy metabolic system have been evaluated. Next section of the chapter will further explain the materials and methods that have been used to achieve objectives and section 2.3 will discuss the results of the analysis while concluding remarks are presented in section 2.4.

2.2 Materials and Methods

2.2.1 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 (Keirstead 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 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 et al., 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.

The developed model in this Chapter is comprised with three sub models namely energy demand sub-model, energy supply and transformation sub-model, and CO_2 emissions sub-model. The Sankey diagram in Figure 2-2 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 subsystems start handling the primary energy since its extracted from domestic sources (i.e., hydro, biomass, solar and wind) or imported (i.e., coal and crude oil). Primary energy is then converted and transformed to secondary energy which will be distributed to various sectors in different forms depending on the sectorial requirements where electricity being the most prominent energy carrier. Demand subsystem accounts for energy demand in industrial, transport, domestic, and commercial and transport sectors based on number of input parameters. CO_2 emissions sub model was developed to calculate the emissions based on different energy sources and sectors. The relationship between the CO_2 emissions and its significant drivers are based on the Kaya identity (Kaya, 1989). Next section elaborates the development process of energy metabolic model of this study.

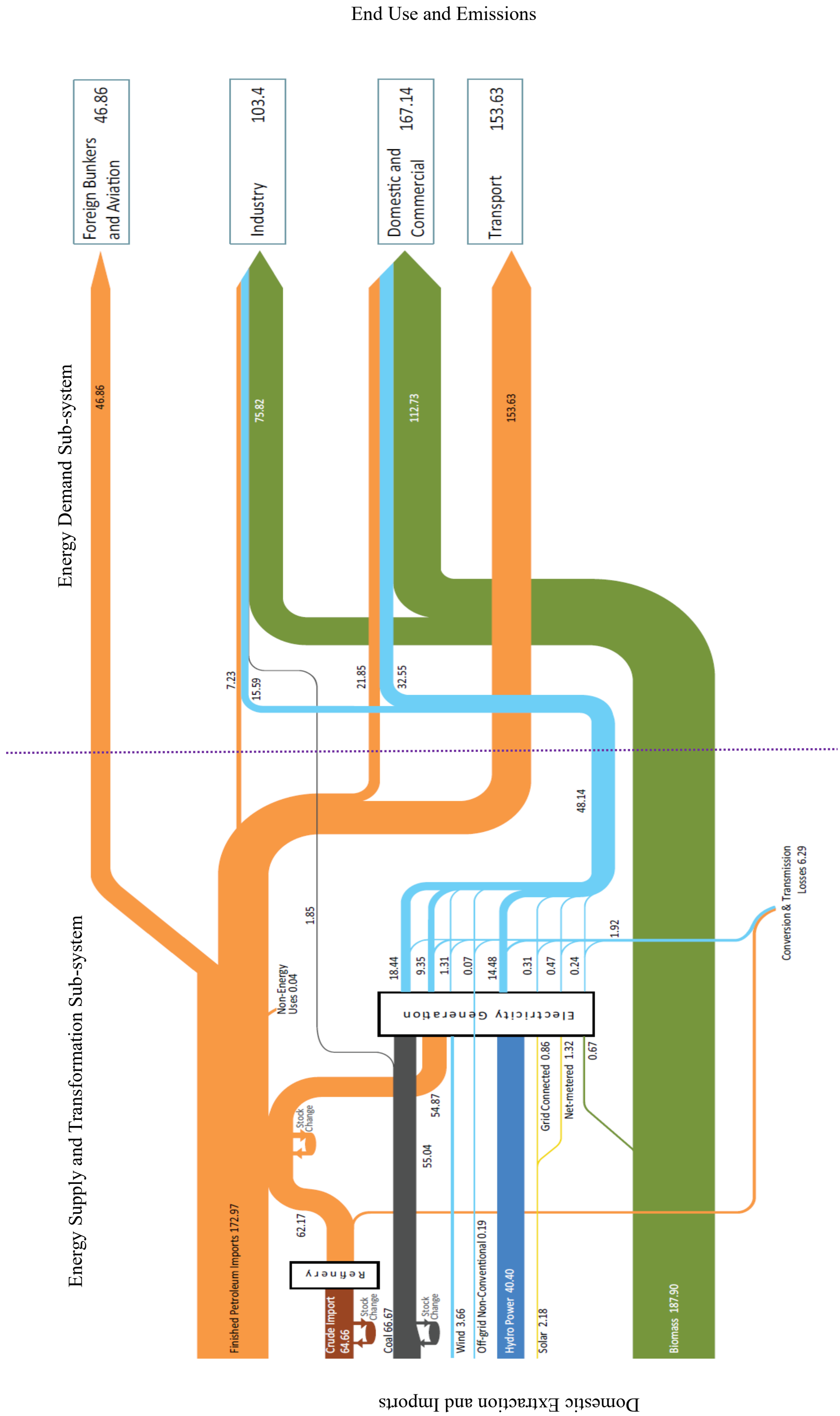

Figure 2-2: Energy Balance and sub system boundaries based on SSEA (2017)

2.2.2 Model development

The model is constructed to evaluate the energy metabolism in Sri Lanka by analysing energy demand, energy supply and CO2 emissions. Figure 2-3 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 CO2 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 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.

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 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 Data were then inputted to the developed model which first simulated Business as Usual (BAU) scenario and then for the next decade until 2030.

2.2.2.1 Energy Demand Sub-model of Sri Lanka

The first model is to determine the amount of energy demand (Figure 2-4). The main input parameters are considered to calculate energy demand in Sri Lanka are population, GDP and energy price. The relationship between the CO_2 emissions and its significant drivers are based on the Kaya identity (Kaya, 1989), a tool that measures the changes in CO_2 emissions according to the changes of its underlying drivers i.e. energy consumption, carbon emission, GDP and population. Kaya's equation is as follows.

$$C = \frac{C}{E}.\frac{E}{Y}.\frac{Y}{P} \qquad \text{(Equation 1-1)}$$

Whereas C = Carbon emissions (or more broadly, CO2 emissions)
E = Energy generated and consumed by humans
Y = Economic output (goods and services, GDP)
P = Population

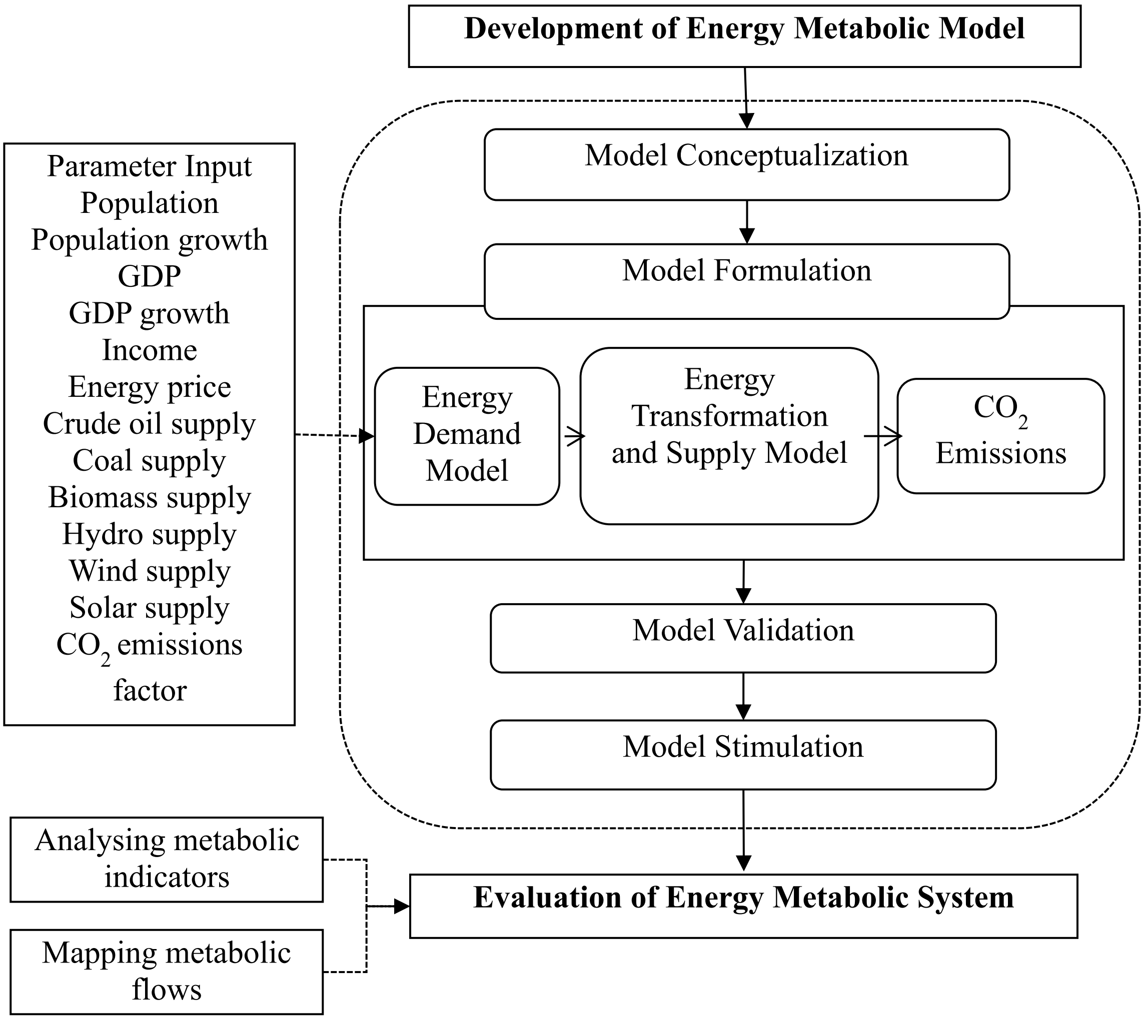

Figure 2-3: The development process of energy metabolic model

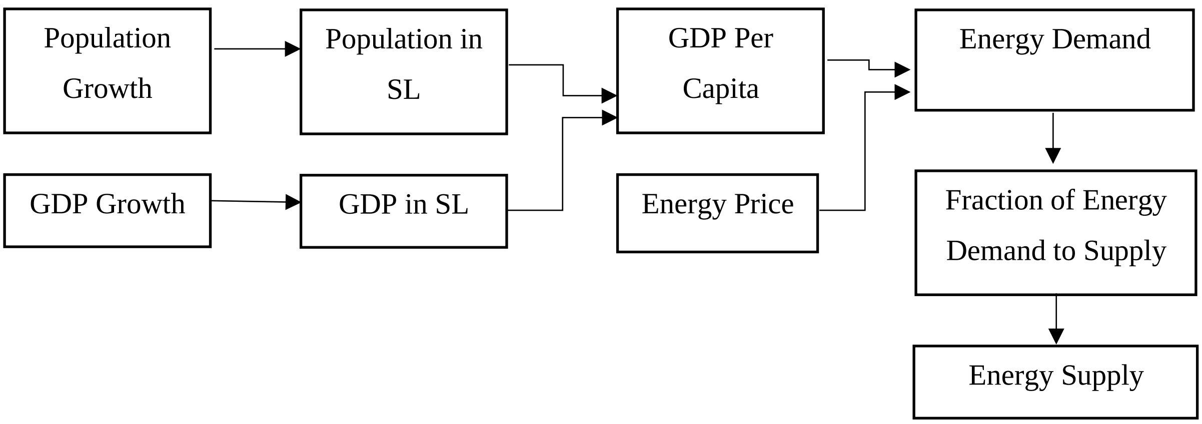

Figure 2-4: Energy demand sub-model of Sri Lanka

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 variables and equations used in developing the model is shown in Table 2-1.

Table 2-1: Variables and equations of the energy system model

Variable	Equation	No.
Sri Lanka population(t)	*=Sri Lanka population in 2000* $+\int_{t0}^{t} Sri\ Lanka\ population\ growth(s)ds$	Equation (1-2)
Sri Lanka population growth(t)	*= Sri Lanka population(t) × Sri Lanka population growth rate(t)*	Equation (1-3)
Sri Lanka GDP(t)	*= Sri Lanka GDP in 2000* $+\int_{t0}^{t} Sri\ Lanka\ GDP\ growth(s)ds$	Equation (1-4)
Sri Lanka GDP growth(t)	*= Sri Lanka GDP(t) × Sri Lanka GDP nominal growth rate (t)*	Equation (1-5)
Income per capita(t)	$= \frac{Sri\ Lanka\ GDP(t)}{Sri\ Lanka\ population(t)}$	Equation (1-6)
Energy consumption per capita (t)	*= 6960.94 + Income per capita(t) × (0.575) + Energy price(t) × ND (0.276)*	Equation (1-7)
Sri Lanka Energy Demand (t)	*= Energy consumption per capita(t) × Sri Lanka population(t)*	Equation (1-8)

2.2.2.2 Energy Transformation and Supply Sub-model of Sri Lanka

Structure of the energy transformation sub-model is shown in Figure 2-5. 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 2-5 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 A1 in Appendix A.

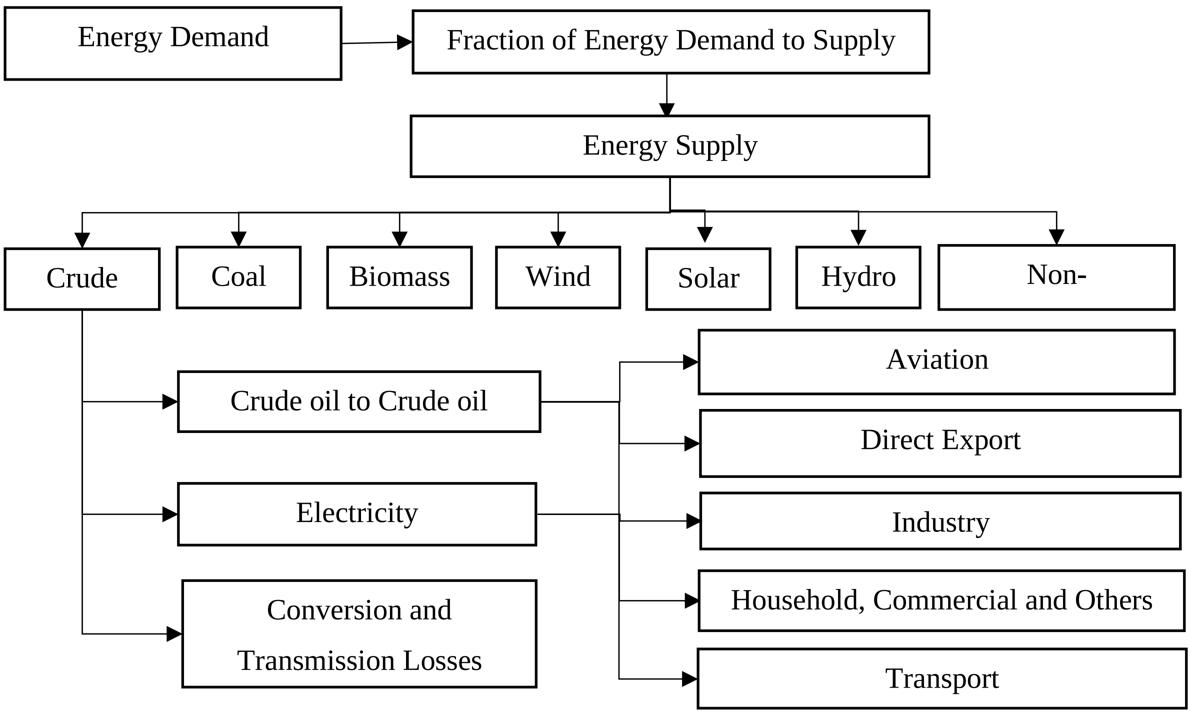

Figure 2-5: Energy transformation and supply sub-model of Sri Lanka

2.2.2.3 CO_2 emissions Sub-model of Sri Lanka

Figure 2-6 shows the CO_2 emissions sub-model of Sri Lanka. CO_2 emissions are obtained by multiplying each CO_2 emitting sources i.e. crude oil, coal and biomass by its respective Emission Factor (EF).

Figure 2-6 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 CO_2 emission sub model are shown in Table A3 in Appendix A.

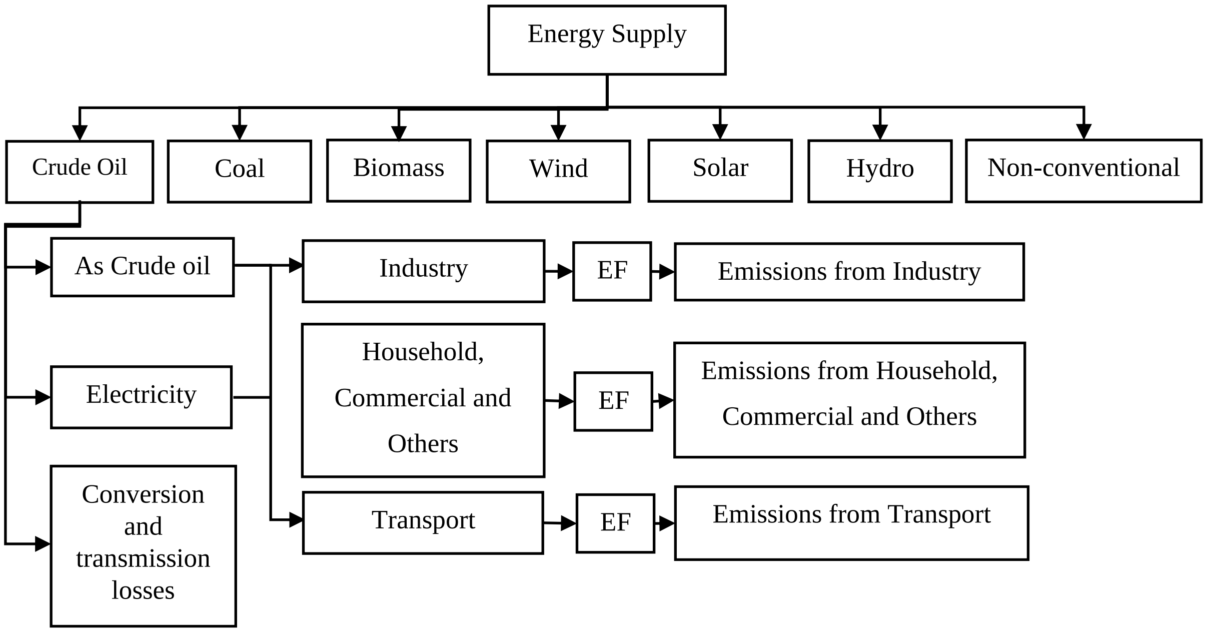

Figure 2-6: GHG emissions sub-model of Sri Lanka

2.2.3 Model Simulation and Validation

Once the model is conceptualised and formed, the model should pass the model validation procedures before the model is used for experimentations/ simulation. Matching the output of the model with the historical data (data actual) is one of the most 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 behavior. MAPE is one of the most popular measures to forecast the accuracy of models. It is a measure of prediction accuracy of a forecasting method in statistics and usually expresses accuracy as a percentage.

The MAPE formula is as following.

$$MAPE = \frac{1}{N}\sum_{t=1}^{N}\left|\frac{A_t - F_t}{A_t}\right| \qquad \text{Equation (1-9)}$$

MAPE is the average of Absolute Percentage Errors (APE). A_t and F_t denote the actual and forecast values at data point t, respectively, where N is the number of data points. To a model to become valid MAPE should be less than 10%.

Figure 2-7 and 2-8 show comparison of data in a scatter diagram between the model output and the actual data for energy demand and energy supply respectively. Actual data of energy demand and supply from 2000 – 2014 have been compared with model output data for the same period.

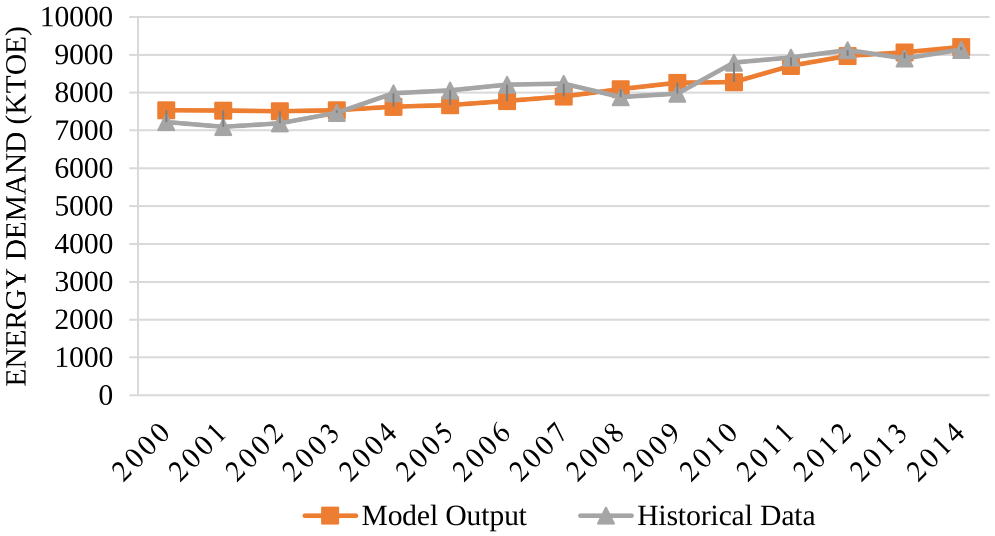

Figure 2-7: Comparison of estimated and reported energy demand in Sri Lanka

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.

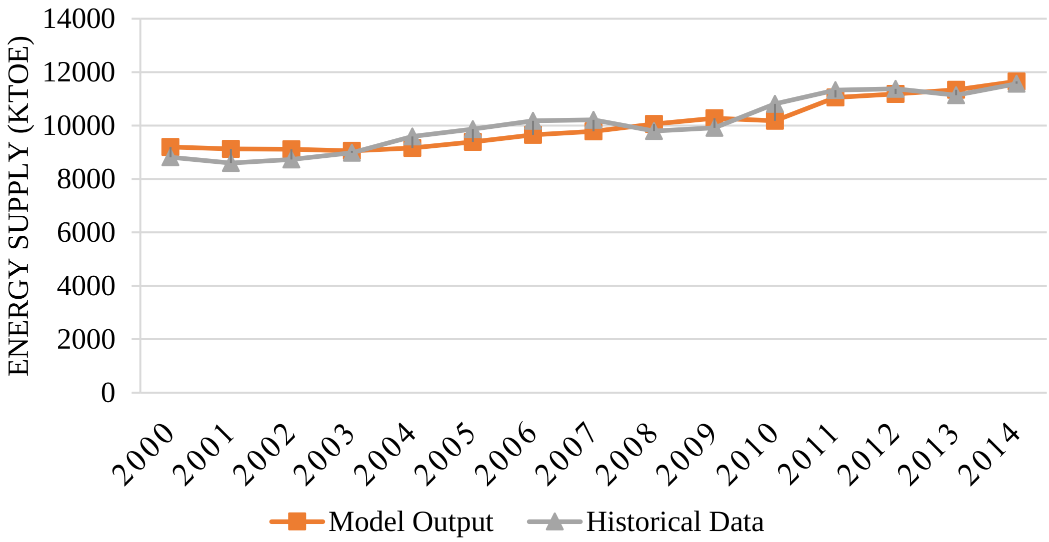

Figure 2-8: Comparison of estimated and reported on energy supply in Sri Lanka

2.2.4 Mapping energy metabolic flows and indicators

Energy flows between energy sources and consumers were mapped to understand the relationship and intensity of the energy flows between sources and sectors. Based on literature survey energy metabolic indicators were selected to evaluate the efficiency, security, availability and affordability of energy metabolic system in Sri Lanka (Kemmler & Spreng (2007); Organisation for Economic Co-operation and Development (1998); Kostevšek et al. (2015); Chrysoulakis et al.(2013); Afgan & da Graça Carvalho (2000); Kilkiş (2016); González et al. (2013); Kennedy et al.(2014); Patlitzianas et al. (2008); Sahabmanesh & Saboohi (2017); Boggia & Cortina (2010); Sözen & Nalbant (2007); Sheinbaum-Pardo et al.(2012); Hannan et al. (2018); Angelis-Dimakis et al. (2012); Iddrisu & Bhattacharyya (2015)). Table 2-2 defines the selected energy metabolic indicators.

Table 2-2: Description of selected energy metabolic indicators

Energy metabolic indicator	Description
Efficiency	
Energy intensity	Ratio between total primary energy supply and GDP
Energy use per capita	Ratio between total energy consumption and population
Efficiency of electricity conversion and distribution	Ratio between total energy conversion and transmission losses and total primary energy supply
Security	
Energy self-sufficiency	Ratio between total domestically extracted energy supply and total primary energy supply
Availability	
Share of population without electricity (%)	Ration between number of households without electricity supply and total number of households
Energy consumption per household	Ratio between total energy consumption and total number of households
Affordability	
Share of household income spent on electricity	Ration between amount of income spent on electricity and average household income per year

2.3 Data Analysis and Discussion

2.3.1 Energy supply and consumption patterns

Figure 2-9 shows results of the energy demand sub model where main outputs are total energy demand and sectorial energy demand in Sri Lanka. 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 2-9.

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.

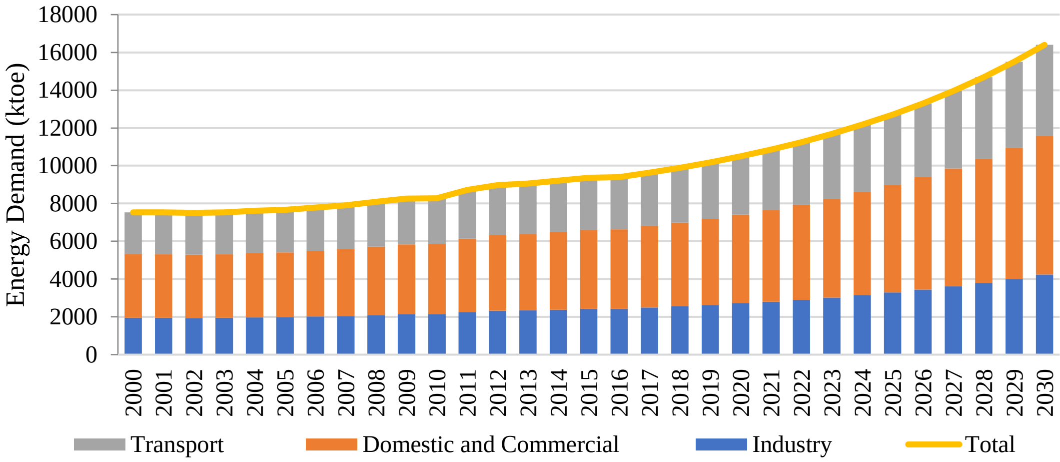

Figure 2-9: Energy demand of Sri Lanka

According to 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 CO_2 emissions in Sri Lanka with compared to other non-renewable energy sources. 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. Majority share of renewable energy supply is carried by biomass leaving other renewable energy supply less than 20% despite Sri Lanka's high potential for wind and solar energy.

Figure 2-10 shows the final output of the developed energy metabolic model. CO_2 emissions is one of the most import indicators in evaluating environmental sustainability of a country/city. Figure 2-10 shows how CO_2 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%. CO_2 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 CO_2 emissions.

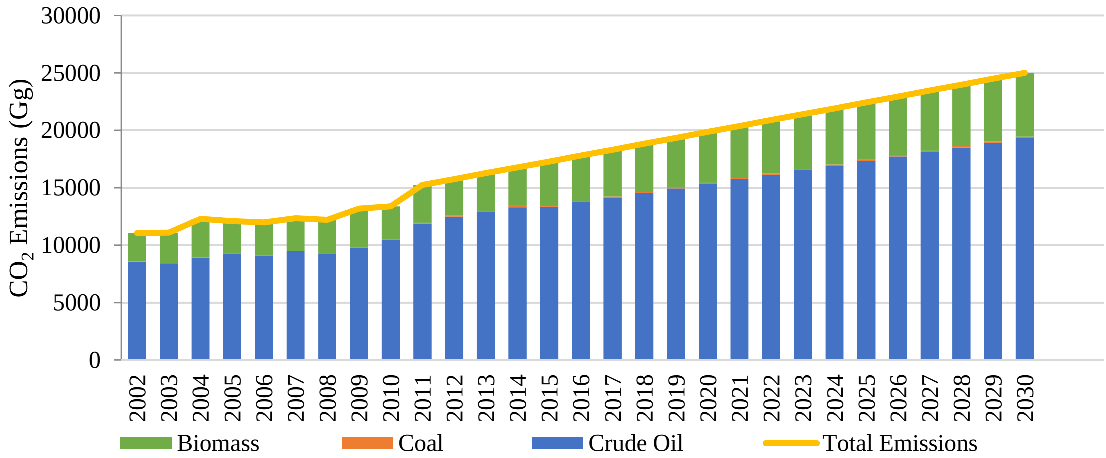

Figure 2-10: CO_2 emissions by type of energy

According to the sectorial CO_2 emissions in Sri Lanka (Figure 2-11) 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 CO_2 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 2-12 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 CO_2 emissions and more than 80% of the emissions are from biomass consumption. Industrial sector is the third highest CO_2 emitter where more than 70% of the emissions are from biomass consumption

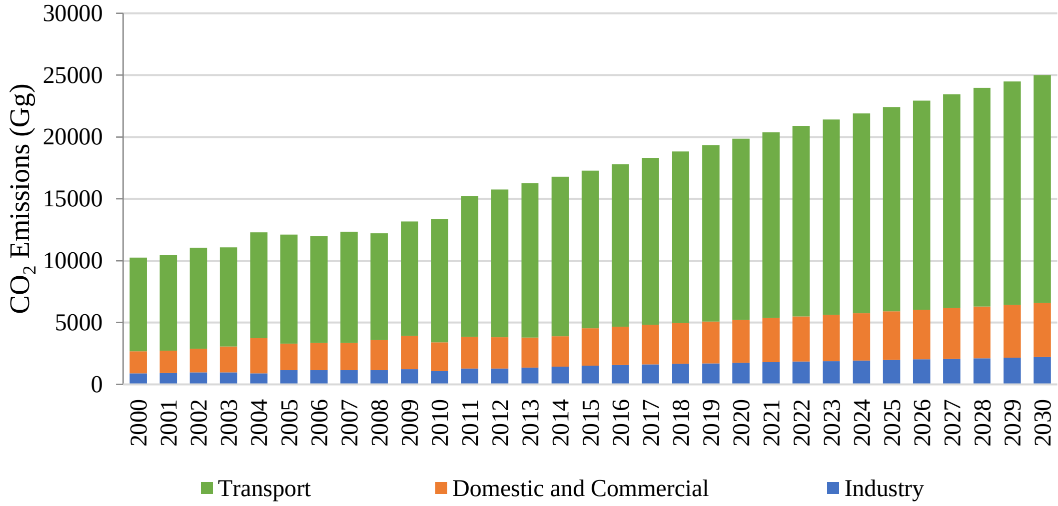

Figure 2-11: CO_2 emissions by sector

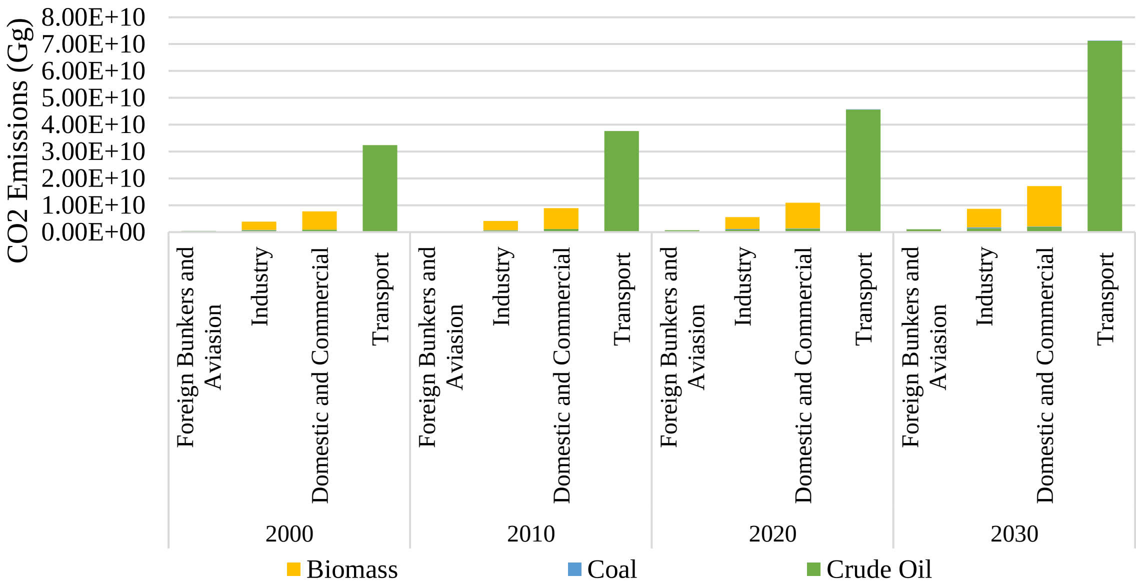

Figure 2-12: CO_2 emissions by type of energy and sector

2.3.1 Energy metabolic flows

Figure 2-13 demonstrates direct energy flow maps of 2000, 2005, 2010, and 2015. Arrows indicate energy consumption pathways and their direction. Bolder the arow higher the energy consumption. Biomass/domestic and commercial sector remains the strongest arrow indicating the largest flow of energy. The second strongest arrow, crude oil/transport is the seems to have grown over the years and expected to grow further along with crude oil/aviation. Crude oil/electricity and hydro/electricity flows have slightly increased over the years.

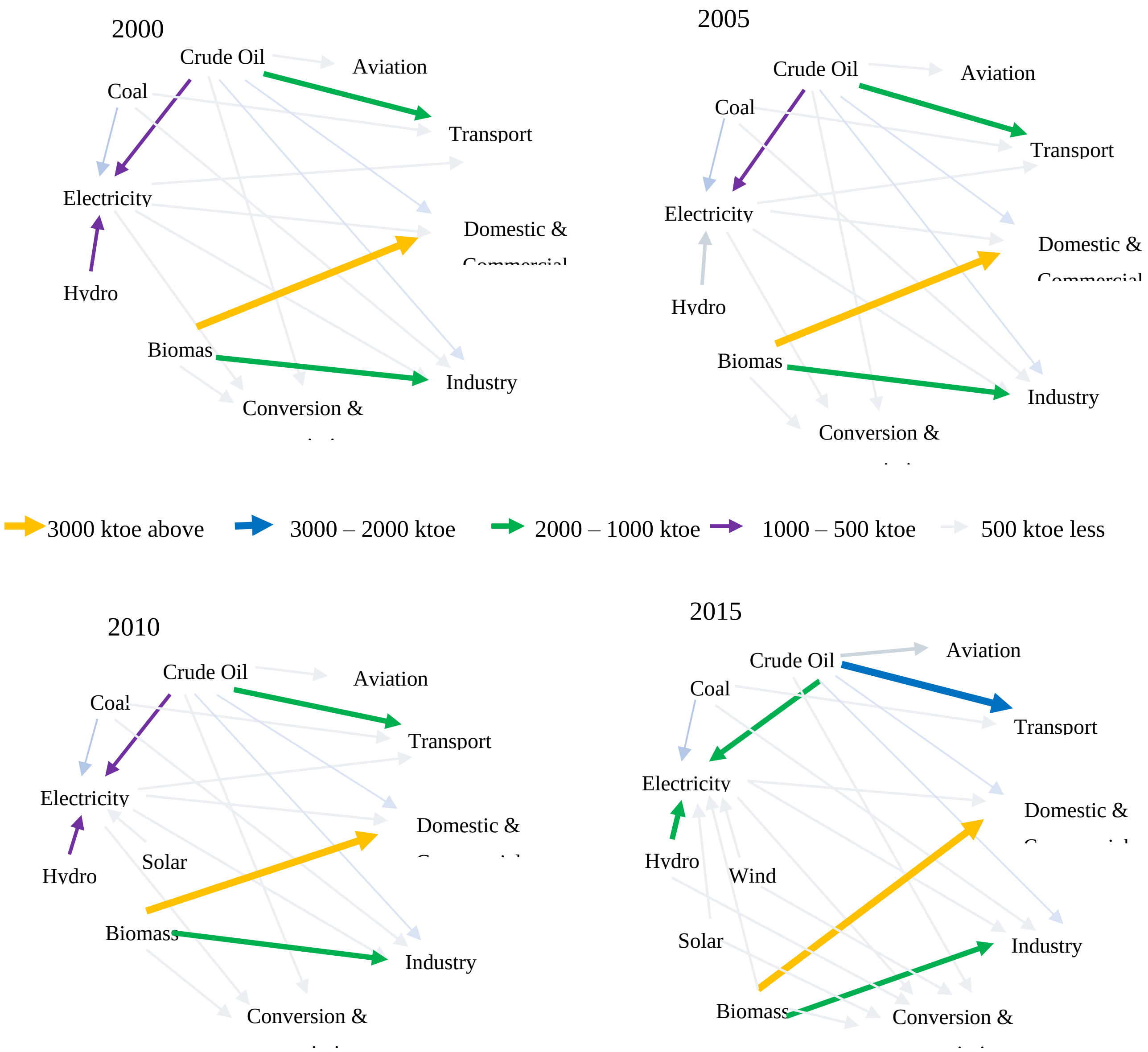

Figure 2-13: Sri Lanka's direct energy flow map in 2000, 2005, 2010 and 2015

2.3.2 Evaluation of energy metabolic indicators

Table 2-2 indicators evaluating the energy metabolic system based on efficiency, security, availability, and affordability. Increase in energy efficiency can be observed with energy intensity gradually decreasing from 5.63x10-7 ktoe/US$ in 200 to 1.5x10-7ktoe/US$ in 2015. Energy use per unit of GDP has decreased by 4% annually on average. Energy conversion and transmission losses have remained unpredictable. Security of energy system has been threatened by dependant on imported fossil fuels for more than 60% of total energy supply. Until 2015 self-sufficiency rate has been maintained around 40%. Current trend of increase in non-renewable energy sources, has threatened self-sufficiency is expected to decline by 2030. Affordability of energy system has been positively impacted by share of household income spent on electricity reducing from 4% to 3.6% during 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. In 2015, population has increased by 10.87%, energy demand per capita by 1.79%, energy supply per capita by 2.54% with compared to 2000. With increase in GDP, similar increments can be predicted in the future. Share of population without access to electricity has decreased from 37% in 2000 to 12% by 2010 and further 3% by 2015.

Table 2-3: Indicators for evaluation the energy metabolic system in Sri Lanka

Energy Metabolic Indicators	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Efficiency							
Energy intensity	5.63E-07	4.71E-07	2.51E-07	1.50E-07	1.22E-07	9.79E-08	7.98E-08
Energy use per capita	4.64E-07	3.90E-07	2.11E-07	1.24E-07	1.01E-07	8.12E-08	6.62E-08
Efficiency of electricity conversion and distribution	14.67%	16.83%	14.67%	16.24%	16.24%	16.24%	16.24%
Security							
Energy self-sufficiency	43.09%	46.32%	41.86%	44.82%	43.66%	42.58%	40.40%
Availability							
Share of population without electricity (%)	37%	23%	12%	3%	1%	0%	0%
Energy consumption per household	0.00186	0.00191	0.00162	0.00182	0.00192	0.00206	0.00225
Affordability							
Share of household income spent on electricity	4%	3.53%	3.60%	4.20%	4.39%	4.60%	4.82%

2.4 Conclusions

The aim of this chapter 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 CO_2 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 to 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 further show that CO_2 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. Due to lack of data availability case studies and research work based on developing Asian countries are minimal. Further lack of data availability prevents most of the developing countries using available complex energy models in analysing energy systems. Thus this chapter gives insights to energy metabolism of a data poor, developing country like Sri Lanka while providing the first and only dynamic model to evaluate the current and future performance of the energy metabolic system in Sri Lanka.

CHAPTER 3 SUSTAINABILITY EVALUATION AND FUTURE CO_2 EMISSION REDUCTION SCENARIOS FOR THE ENERGY METABOLIC SYSTEM IN SRI LANKA

3.1 Introduction

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 has 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 & 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, loss of leisure time are neglected (Meles, 2020; Nduhuura et al., 2021).

Lack of a cost reflective tariff system, high electricity price and supply cost is also among 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 MW 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). 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 jeopardized the sustainable development of the energy system in Sri Lanka.

National Energy Policy and Strategies of Sri Lanka (2019) is based on 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's 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 this chapter intend to evaluate the sustainability of the energy system in Sri Lanka using a multidimensional integrated approach. Such a study can help coordinated 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. 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. Further author valued incorporating views and values of local stakeholders in developing a framework to measure sustainability.

This chapter elaborated three stages of developing the integrated framework. In the first stage is developing a top-down dynamic model based on variety of economic and sociodemographic variables that was discussed in Chapter 2. The model simulates energy supply and transformation, energy demand and CO_2 emissions within last two decades which was extrapolated till 2030 to predict the future behaviour of the system. The second stage develops a sustainability indictor-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 CO_2 emission reduction scenarios developed based on INDCs as the third and final stage. Next section of the chapter further explains the materials and method that were used to develop the multidimensional indicator-based framework while section 3.3 elaborates the results of the multicriteria analysis along with scenario analysis. Lastly section 3.5 concludes the chapter.

3.2 Materials and Methods

As shown in the research framework in Figure 3-1, the developed integrated framework consists of three stages. First stage has been explained in Chapter 2. 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 the stakeholders, representing suppliers and consumers of the energy system in Sri Lanka. Elicited weightage of the indicators were then used aggregate them into an integrated sustainability index for the sake of comparing various policy scenarios. The third stage consist of analysing INDC based policy scenarios that Sri Lankan government is planning to implement to reduce the GHG emissions.

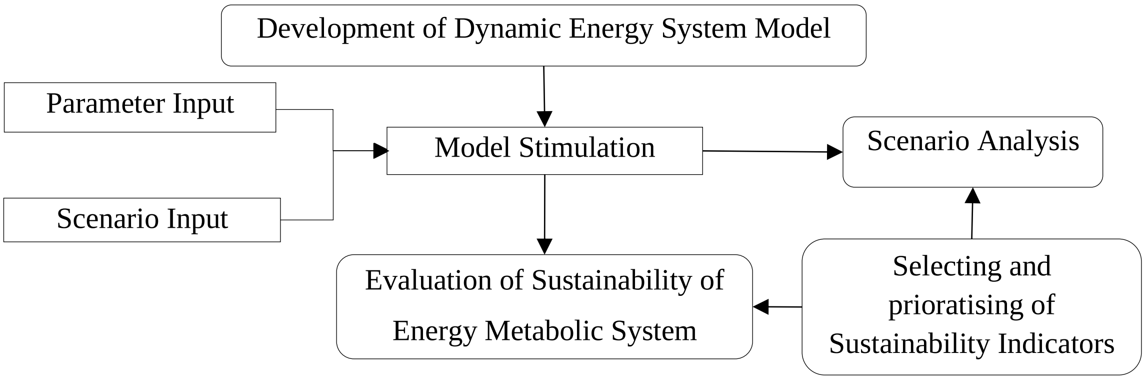

Figure 3-1: Research framework

3.2.1 Development of Indicator Framework to Evaluate Sustainability of the Energy System

Efforts in evaluating sustainability by researchers has led to variety of detailed frameworks 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.

Iddrisu & 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 optimizing 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 et al. (2012) calculate a general sustainability indicator for the energy sector in Mexico. While all these efforts proves 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 & Hillier (1998) argues that most of the pre-determined indicator sets fails to reflect the holistic nature of sustainability while data availability restricts the selection of variables. Indictors 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 et al., 2012). Findings of Gasser (2020) shows many of these indices lacks transparency. Additionally Mori et al. (2015) highlights 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 Konara & Tokai (2020) states it is important to choose its own customized combination of indicators for sustainability assessment purposes considering the specific geographical and natural properties and political orientations. The objectives national energy policy of Sri 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 customized 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 variety of criteria available in categorising sustainability indicators, Liu (2014) emphasizes the importance of using triple bottom lines of sustainability development as they evaluates 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 & 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 consist of 13 indicators derived from and developed based upon various studies (European Foundation (1998); Kemmler & Spreng (2007); Organisation for Economic Co-operation and Development (1998); The Urban China Initiative (2010); Kostevšek et al. (2015); Chrysoulakis et al.(2013); Afgan & da Graça Carvalho (2000); Kilkiş (2016); González et al. (2013); Kennedy et al.(2014); Tongsopit et al. (2016); Patlitzianas et al. (2008); Sahabmanesh & Saboohi (2017); Boggia & Cortina (2010); Sözen & Nalbant (2007); Sheinbaum-Pardo et al.(2012)' Hannan et al. (2018); Angelis-Dimakis et al. (2012); Iddrisu & Bhattacharyya (2015); Vera & Langlois (2007)) (Refer Table B-1 of Appendix B). Table 3-1 defines the selected sustainability indicators.

Table 3-1: Description of selected sustainability indicators

Sustainability Indicators	Description
Economic Indicators	
Energy intensity	Ratio between total primary energy supply and GDP
Energy use per capita	Ratio between total energy consumption and population
Energy intensity of industrial sector	Ratio between total primary energy supply to industrial sector and GDP
Energy intensity of domestic and commercial sector	Ratio between total primary energy supply to domestic and commercial sector and GDP
Energy intensity of transport sector	Ratio between total primary energy supply to transport sector and GDP
Efficiency of electricity conversion and distribution	Ratio between total energy conversion and transmission losses and total primary energy supply
Energy self-sufficiency	Ratio between total domestically extracted energy supply and total primary energy supply
Social Indicators	
Share of population without electricity	Ration between number of households without electricity supply and total number of households
Share of household income spent on electricity	Ration between amount of income spent on electricity and average household income per year
Energy consumption per household	Ratio between total energy consumption and total number of households
Environmental Indicators	
CO_2 emissions per capita	Ration between total CO_2 emissions and population
Emission intensity	Ration between total CO_2 emissions and GDP
Renewable energy share in energy	Ratio between total renewable energy supply and total primary energy supply

3.2.2 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 & Cortina, 2010). AHP is one such MCDA tool 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 et al., 2015; Mirjat et al., 2018; Nakthong & Kubaha, 2019; Ran, 2011; Vishnupriyan & Manoharan, 2018) calculating ratio-scaled importance of alternatives through pair-wise comparison of evaluation criteria and alternative (J. J. Wang et al., 2009). Kaya et al. (2018) recognises 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 et al., 2020).

3.2.2.1 Questionnaire Survey

Stakeholder engagement in decision-making and the development of indicators to ensure policy relevance and stakeholder acceptance is increasingly more recognized (Gunnarsdottir et al., 2020). Therefore, a questionnaire survey was conducted among different stakeholders of the energy system to prioratise 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 and public (Refer the questionnaire in Table B-2 in Appendix B). Questionnaire survey was conducted 2019 January to October. The first questionnaire was emailed on 23rd of January 2019 while the last questionnaire was received on 19th of October via email. All experts who have extensive experience working in both public and private organisations. Questionnaire was comprised with pair-wise comparisons of sustainability criteria and sustainability indicators in each criterion which was developed with the aid of the AHP decision hierarchy (Figure 3-2). The demographic characteristics of the participants are provided in Table 3-2.

Table 3-2: Demographic characteristics of the participants

Characteristics	Number
Gender	
Male	28
Female	7
Age	
31-40 years	11
41-50 years	16
50+ years	8
Education level	
High school	6
Bachelor’s degree	18
Master’s degree	11
Experience in energy production industry	
< 5 years	7
5-10 years	12
10+ years	6

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. To make comparisons it is necessary a scale of numbers that indicates how many times more important one element is over another with respect to the criterion and to which they are compared (Saaty, 2008). Table 3-3 present the ratio scale of numbers demonstrated by Saaty (2008).

Table 3-3: The fundamental scale of absolute numbers based on Saaty (2008)

Intensity of importance	Definition	Explanation
1 2	Equal importance Weak or slight	Two criteria contribute equally to the objective
3 4	Moderate importance Moderate plus	Experience and judgement slightly favour one criterion over the other
5 6	Strong importance Strong plus	Experience and judgement strongly favour one criterion over the other
7 8	Very strong Very, very strong	One criterion is very strongly favour over the other
9	Extreme importance	The evidence favouring one criterion over the other is of the highest possible order of affirmation

3.2.2.2 AHP Analysis

AHP consists of mathematical calculations worked out in three steps. Pair-wise comparisons, normalise the comparison and consistency calculations.

The pair-wise comparison data which are organized in the form of a matrix summarized based on Saaty's eigenvector procedure and in the absolute priority weights used to calculate the overall score of each factor as indicated in Table 3-4. Geometric means of pairwise comparison responses given for each criterion is indicated as W1, W2, W3, etc and their reciprocal values are indicated as 1/W1, 1/ W2, 1/ W3, etc. The sums in bottom row (S1, S2, S3, S4, S5, S6 and S7) represent the sum of each column.

Table 3-4: Square matrix of pair-wise comparison of criteria

Indicators	I1	I2	I3	I4	I5	I6	I7
I1	1.000	W_1	W_2	W_3	W_4	W_5	W_6
I2	1/ W_1	1.000	W_7	W_8	W_9	W_{10}	W_{11}
I3	1/ W_2	1/ W_7	1.000	W_{12}	W_{13}	W_{14}	W_{15}
I4	1/ W_3	1/ W_8	1/ W_{12}	1.000	W_{16}	W_{17}	W_{18}
I5	1/ W_4	1/ W_9	1/ W_{13}	1/ W_{16}	1.000	W_{19}	W_{20}
I6	1/ W_5	1/ W_{10}	1/ W_{14}	1/ W_{17}	1/ W_{19}	1.000	W_{21}
I7	1/ W_6	1/ W_{11}	1/ W_{15}	1/ W_{18}	1/ W_{20}	1/ W_{21}	1.000
SUM	S_1	S_2	S_3	S_4	S_5	S_6	S_7

Normalised comparison matrix is presented in Table 3-5. The comparison matrix is normalised by dividing each entry by the sum of the entries in its column (Ehrhardt and Tullar, 2008). After the normalising the entries in the pairwise comparison matrix, the sums of each row (x1, x2, x3, etc) will be calculated. X indicates the total row sum. The averages of each row will be calculated to obtain the "relative importance/weightage" or the "sustainability score" which will allow the researcher to compare and prioritise indicator.

Table 3-5: Normalized comparison matrix

Indicators	I1	I2	I3	I4	I5	I6	I7	SUM	Weightage
I1	1.000 / S_1	$\frac{W_1}{S_2}$	$\frac{W_2}{S_3}$	$\frac{W_3}{S_4}$	$\frac{W_4}{S_5}$	$\frac{W_5}{S_6}$	$\frac{W_6}{S_7}$	x_1	$x_1/X=Y_1$
I2	$\frac{1/W_1}{S_1}$	$\frac{1.000}{S_2}$	$\frac{W_7}{S_3}$	$\frac{W_8}{S_4}$	$\frac{W_9}{S_5}$	$\frac{W_{10}}{S_6}$	$\frac{W_{11}}{S_7}$	x_2	$x_2/X=Y_2$
I3	$\frac{1/W_2}{S_1}$	$\frac{1/W_7}{S_2}$	$\frac{1.000}{S_3}$	$\frac{W_{12}}{S_4}$	$\frac{W_{13}}{S_5}$	$\frac{W_{14}}{S_6}$	$\frac{W_{15}}{S_7}$	x_3	$x_3/X=Y_3$
I4	$\frac{1/W_3}{S_1}$	$\frac{1/W_8}{S_2}$	$\frac{1/W_{12}}{S_3}$	$\frac{1.000}{S_4}$	$\frac{W_{16}}{S_5}$	$\frac{W_{17}}{S_6}$	$\frac{W_{18}}{S_7}$	x_4	$x_4/X=Y_4$
I5	$\frac{1/W_4}{S_1}$	$\frac{1/W_9}{S_2}$	$\frac{1/W_{13}}{S_3}$	$\frac{1/W_{16}}{S_4}$	$\frac{1.00}{S_5}$	$\frac{W_{19}}{S_6}$	$\frac{W_{20}}{S_7}$	x_5	$x_5/X=Y_5$
I6	$\frac{1/W_5}{S_1}$	$\frac{1/W_{10}}{S_2}$	$\frac{1/W_{14}}{S_3}$	$\frac{1/W_{17}}{S_4}$	$\frac{1/W_{19}}{S_5}$	$\frac{1.000}{S_6}$	$\frac{W_{21}}{S_7}$	x_6	$x_6/X=Y_6$
I7	$\frac{1/W_6}{S_1}$	$\frac{1/W_{11}}{S_2}$	$\frac{1/W_{15}}{S_3}$	$\frac{1/W_{18}}{S_4}$	$\frac{1/W_{20}}{S_5}$	$\frac{1/W_{21}}{S_6}$	$\frac{1.00}{S_7}$	x_7	$x_7/X=Y_7$
								X	

Judgments in a matrix may not be always consistent. In eliciting judgments, one makes redundant comparisons to improve the validity of the answer, given that respondents may be uncertain or may make poor judgments in comparing some of the elements (Saaty, 1994). Saaty (1994) further states that redundancy gives rise to multiple comparisons of an element with other elements and hence to numerical inconsistencies. To overcome inconsistencies in data collection it is used as a reference index to screen information by calculating the Consistency Ratio (CR) (Saaty, 2000 cited in Wu et al., 2007). The CR is calculated as per the following steps:

Step 1 - Entries in square matrix of pair-wise comparison are multiplied by the relative sustainability scores to obtain the eigenvector as indicated in Table 3-6. The sum of each row is calculated to obtain the new vector Z and the sum is divided from the relative sustainability score (a_1, a_2, a_3, a_4, a_5, a_6, and a_7).

Table 3-6: Consistency calculations

Indicators	I1	I2	I3	I4	I5	I6	I7	SUM	SUM/ Weightage
I1	$1.0*Y_1$	W_1*Y_2	W_2*Y_3	W_3*Y_4	W_4*Y_5	W_5*Y_6	W_6*Y_7	Z_1	$Z_1/Y_1 = a_1$
I2	$1/W_1*Y_1$	$1.0*Y_2$	W_7*Y_3	W_8*Y_4	W_9*Y_5	$W_{10}*Y_6$	$W_{11}*Y_7$	Z_2	$Z_2/Y_2 = a_2$
I3	$1/W_2*Y_1$	$1/W_7*Y_2$	$1.0*Y_3$	$W_{12}*Y_4$	$W_{13}*Y_5$	$W_{14}*Y_6$	$W_{15}*Y_7$	Z_3	$Z_3/Y_3 = a_3$
I4	$1/W_3*Y_1$	$1/W_8*Y_2$	$1/W_{12}*Y_3$	$1.0*Y_4$	$W_{16}*Y_5$	$W_{17}*Y_6$	$W_{18}*Y_7$	Z_4	$Z_4/Y_4 = a_4$
I5	$1/W_4*Y_1$	$1/W_9*Y_2$	$1/W_{13}*Y_3$	$1/W_{16}*Y_4$	$1.0*Y_5$	$W_{19}*Y_6$	$W_{20}*Y_7$	Z_5	$Z_5/Y_5 = a_5$
I6	$1/W_5*Y_1$	$1/W_{10}*Y_2$	$1/W_{14}*Y_3$	$1/W_{17}*Y_4$	$1/W_{19}*Y_5$	$1.0*Y_6$	$W_{21}*Y_7$	Z_6	$Z_6/Y_6 = a_6$
I7	$1/W_6*Y_1$	$1/W_{11}*Y_2$	$1/W_{15}*Y_3$	$1/W_{18}*Y_4$	$1/W_{20}*Y_5$	$1/W_{21}*Y_6$	$1.0*Y_7$	Z_7	$Z_7/Y_7 = a_7$

Step 2 - The λ_{max} value is the average of the of the column sum.

$$\lambda_{max} = \frac{a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7}{7} \quad \text{Equation (3-1)}$$

Step 3 - The Consistency Index (CI) for each matrix is calculated as per following.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad \text{Equation (3-2)}$$

n represents the number of criteria.

Step 4 - The ratio of CI to the average Random Index (RI) for the same order matrix is called the Consistency Ratio (CR) (Saaty, 1994). The CR is then calculated using following equation;

$$CR = \frac{CI}{RI} \quad \text{Equation (3-3)}$$

Table 3-7 shows the value of the random consistency index (RI) for matrices of order 1 to 10 obtained by approximating random indices using a sample size of 500 (Saaty, 2000 cited in Wu et al., 2007).

Table 3-7: Average RI based on matrix size (Source - Saaty, 1990)

Size of matrix (*n*)	1	2	3	4	5	6	7	8	9	10
Random consistency index (RI)	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

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.

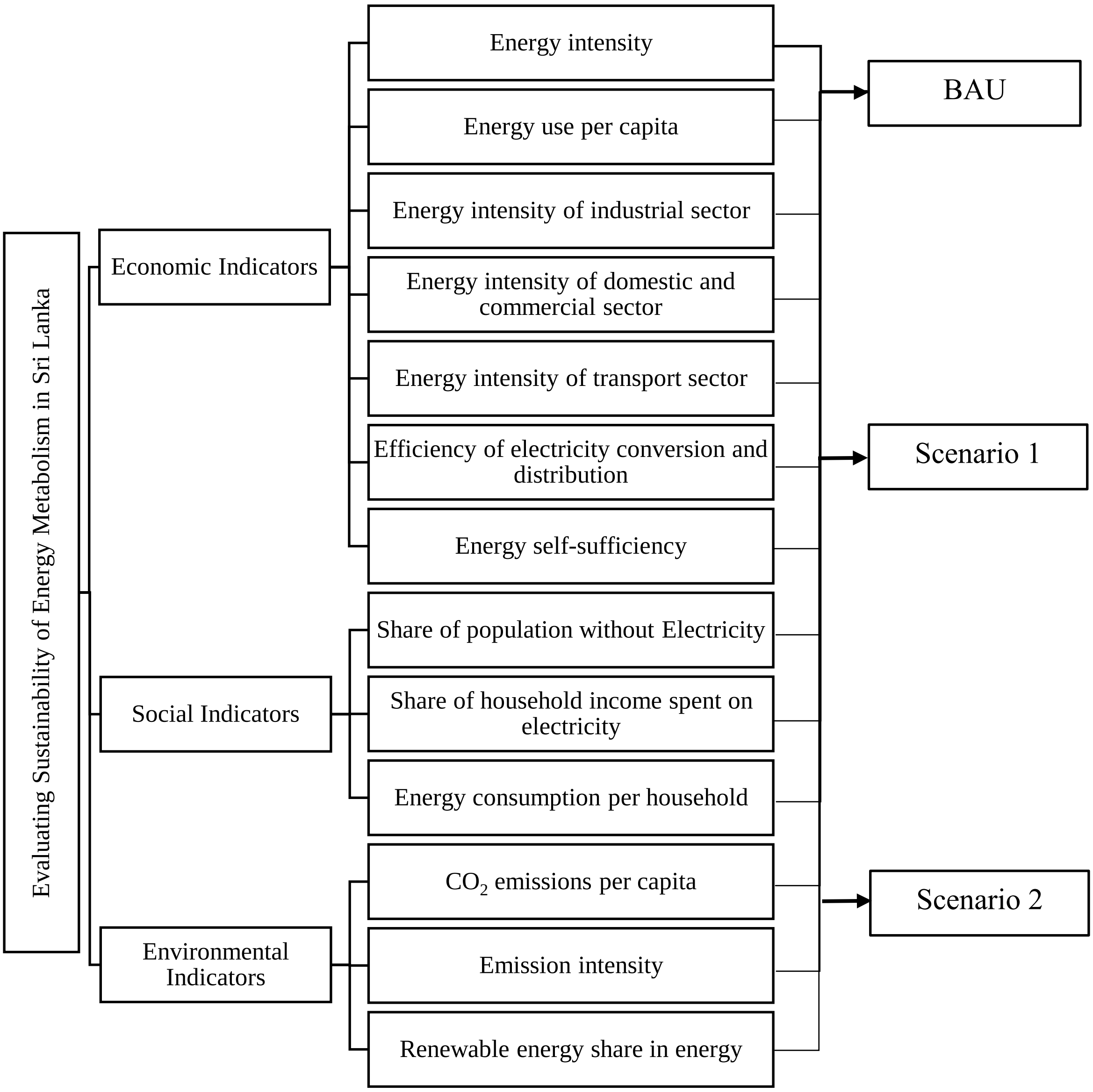

Figure 3-2: Indicators hierarchy

3.2.3 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 et al., 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:

$$S\acute{I}_x = RelMax - \frac{(RelMax - RelMin) * (MaxSI - SI_x)}{MaxSI - MinSI} \quad \text{Equation (3-4)}$$

where SI_x is the selected indicator for the year x, $S\acute{I}_x$ is the respective normalized indicator, MaxSI and MinSI are the maximum and minimum values of the indicator for the period under study (1, 2,…, n years) and *RelMax, RelMin* are two 0–1 values indicating whether 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 scores were used as the relevant weightage of each criterion and indicator.

c. Integrated Sustainability Index (ISI) was calculated using the following equation: $$ISIx = \frac{\Sigma W x S\acute{I}_x}{\Sigma W x} \quad \text{Equation (3-5)}$$

d. Wherein ISI_x is the overall integrated sustainability index for the year x.

3.2.4 Scenario Description

The 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. Summary of the scenarios are demonstrated in Table 3-8.As Gunnarsdottir et al. (2020) pints out the indicators are not limited to being backward-looking but rather evaluate potential implications under different policy scenarios. Sri Lanka is constantly place among 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. 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 CO_2 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 CO_2 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 25MW), mini hydro power plants by 176 MW (currently 328MW), large scale wind power plants by 514 MW (currently 128MW) and solar power plants by 115 MW (currently1.36MW) (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 standardization/automation of street lighting, introduction of time of use meters and tariffs, smart cities and green buildings and sustainable energy zone programs.

Table 3-8: Summary of the Scenarios

Scenario	BAU Scenario	Scenario 1	Scenario 2
Input variables	Population, GDP, Energy Price, Energy Consumption		
Policy Basis	Continuation of past trend	Change energy mix to increasing renewables	Reduce annual energy demand growth by 2%
Changing variables	-	Energy composition	Energy demand growth rate
Variable Changes	-	Crude oil -36% Coal -3% Renewables +37% Hydro +1% Biomass +1%	No change in energy composition Energy demand growth rate -2%
Simulation Time	2000-2030	2015-2030	2015-2030

3.3 Results and Discussion

3.3.1 Results of questionnaire survey and AHP analysis

The gathered data from the questionnaire survey were entered to the pair-wise comparison matrix as follows. The sustainability criteria and sustainability indicators in each criterion represent separate pair-wise comparison matrices. The geometric averages of all the responses for each criterion comparison and their reciprocal values are shown in Table 3-9. The sum of each column was calculated thereafter.

Table 3-9: Pair-wise comparison of sustainability criteria

Criterion	Economic	Social	Environmental
Economic	1.000	2.200	2.120
Social	0.455	1.000	2.133
Environmental	0.472	0.469	1.000
SUM	1.926	3.669	5.253

Each matrix was normalised by dividing each element of the matrix by its column sum. After the normalisation of the entries, the sums of each row were calculated with averages of each row as shown in Table 3-10. The averages give the relative weight or the sustainability score for each criterion, which can be used to compare each criterion with each other.

The priority weights of elements at each level were computed using eigenvector and the process is repeated for each level of the hierarchy until a decision is finally reached by overall composite weights. Ehrhardt and Tullar (2008) stated a criterion with a higher sustainability score is preferred over one with a lower sustainability score.

Table 3-10: Normalise comparison of sustainability criteria

Criterion	Economic	Social	Environmental	SUM	Sustainability Score
Economic	0.519	0.600	0.404	1.522	0.507
Social	0.236	0.273	0.406	0.915	0.305
Environmental	0.245	0.128	0.190	0.563	0.188

The consistency calculations for sustainability criteria were obtained from the results of pair wise comparisons and the normalised comparisons are shown in Table 3-11.

Table 3-11: Consistency comparison of sustainability criteria

Criterion	Economic	Social	Environmental	SUM	SUM/Sustainability Score
Economic	0.507	0.671	0.398	1.576	3.106
Social	0.231	0.305	0.400	0.936	3.070
Environmental	0.239	0.143	0.188	0.570	3.037

As CR of the sustainability criteria is 0.061, it can be decided that the collected data has the significant level of the consistency and the outcome obtained from the comparisons had the superior level of validity. Each sustainability indicator under each sustainability criterion was compared in pairs for further analysis. The Calculations of the sustainability indicators of the economic criterion are presented in Tables 3-12, 3-13 and 3-14.

Table 3-12: Pair-wise comparison of economic criterion

Economic Indicators	Energy intensity	Energy use per capita	Energy intensity of industrial sector	Energy intensity of domestic and commercial sector	Energy intensity of transport sector	Efficiency of electricity conversion and distribution	Energy self-sufficiency
Energy intensity	1.000	1.720	3.200	3.600	3.600	4.000	3.400
Energy use per capita	0.581	1.000	4.200	4.200	3.800	4.600	3.600
Energy intensity of industrial sector	0.313	0.238	1.000	3.200	1.467	3.400	1.821
Energy intensity of domestic and commercial sector	0.278	0.238	0.313	1.000	3.000	3.600	1.634
Energy intensity of transport sector	0.278	0.263	0.682	0.333	1.000	3.800	1.368
Efficiency of electricity conversion and distribution	0.250	0.217	0.294	0.278	0.263	1.000	0.236
Energy self-sufficiency	0.294	0.278	0.549	0.612	0.731	4.234	1.000
SUM	2.994	3.955	10.238	13.223	13.861	24.634	13.059

Table 3-13: Normalise comparison of economic criterion

Economic Indicators	Energy intensity	Energy use per capita	Energy intensity of industrial sector	Energy intensity of domestic and commercial sector	Energy intensity of transport sector	Efficiency of electricity conversion and distribution	Energy self-sufficiency	SUM	Sustainability Score
Energy intensity	0.334	0.435	0.313	0.272	0.260	0.162	0.260	2.036	0.291
Energy use per capita	0.194	0.253	0.410	0.318	0.274	0.187	0.276	1.912	0.273
Energy intensity of industrial sector	0.104	0.060	0.098	0.242	0.106	0.138	0.139	0.888	0.127
Energy intensity of domestic and commercial sector	0.093	0.060	0.031	0.076	0.216	0.146	0.125	0.747	0.107
Energy intensity of transport sector	0.093	0.067	0.067	0.025	0.072	0.154	0.105	0.582	0.083
Efficiency of electricity conversion and distribution	0.084	0.055	0.029	0.021	0.019	0.041	0.018	0.266	0.038
Energy self-sufficiency	0.098	0.070	0.054	0.046	0.053	0.172	0.077	0.570	0.081

Ranked the economic indicators based on the sustainability scores of normalised comparisons of economic criteria show that energy intensity (0.291) is 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.

Table 3-14: Consistency comparison of economic criterion

Economic Indicators	Energy intensity	Energy use per capita	Energy intensity of industrial sector	Energy intensity of domestic and commercial	Energy intensity of transport sector	Efficiency of electricity conversion and distribution	Energy self-sufficiency	SUM	SUM / Sustainability Score
Energy intensity	0.291	0.470	0.406	0.384	0.299	0.152	0.277	2.278	7.833
Energy use per capita	0.169	0.273	0.533	0.448	0.316	0.175	0.293	2.207	8.081
Energy intensity of industrial sector	0.091	0.065	0.127	0.341	0.122	0.129	0.148	1.023	8.072
Energy intensity of domestic and commercial sector	0.081	0.016	0.040	0.107	0.250	0.137	0.133	0.763	7.150
Energy intensity of transport sector	0.081	0.072	0.086	0.036	0.083	0.144	0.111	0.613	7.375
Efficiency of electricity conversion and distribution	0.073	0.059	0.037	0.030	0.022	0.038	0.019	0.278	7.322
Energy self-sufficiency	0.086	0.076	0.070	0.065	0.061	0.161	0.081	0.599	7.365

As CR of the economic criterion is 0.074, it can be concluded that the collected data has the required level of the consistency and the outcome obtained from the comparisons has the superior level of validity. Same steps were followed in calculating sustainability score of social and environmental indicators (Refer Tables B3 to B8 in Appendix B).

Calculated sustainability scores in Figure 3-3 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 share of household income spent on electricity (0.488) is the most important indicator in the social criterion and CO_2 emissions per capita (0.481) is the most important indicator in the environmental criterion.

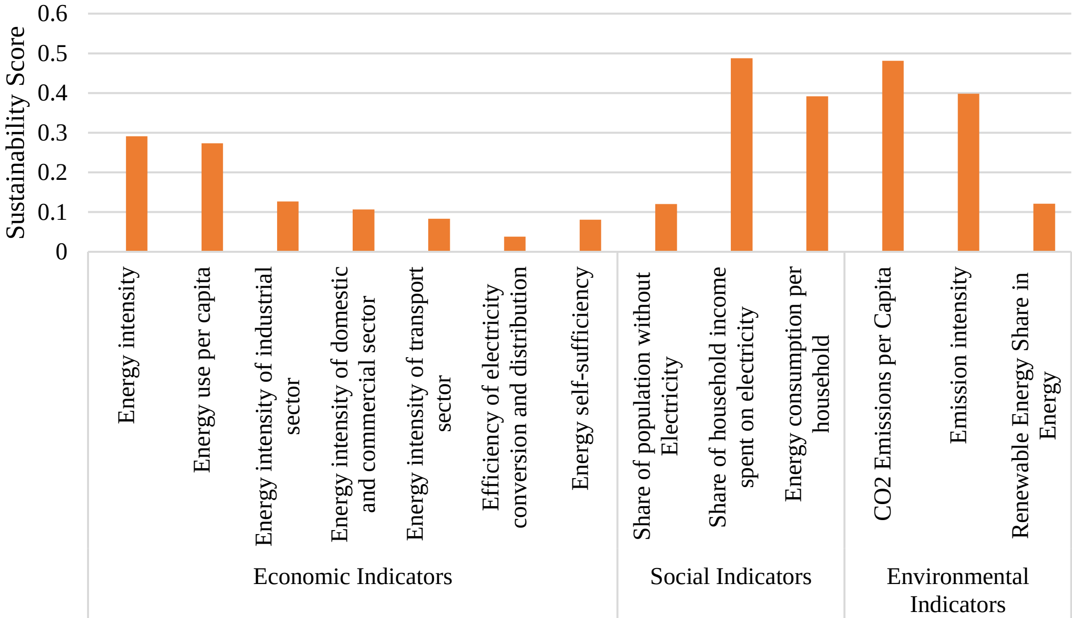

Figure 3-3: Ranking of Economic, Social and Environmental Indicators

3.3.2 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 3-4. 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 bear 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 on 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 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 CO_2 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 is still lesser than the other counterparts of the region. According to Jain & Goswami (2021), Sri Lanka, Bangladesh and Pakistan are the only countries show improvements in energy efficiency over the 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 the 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.

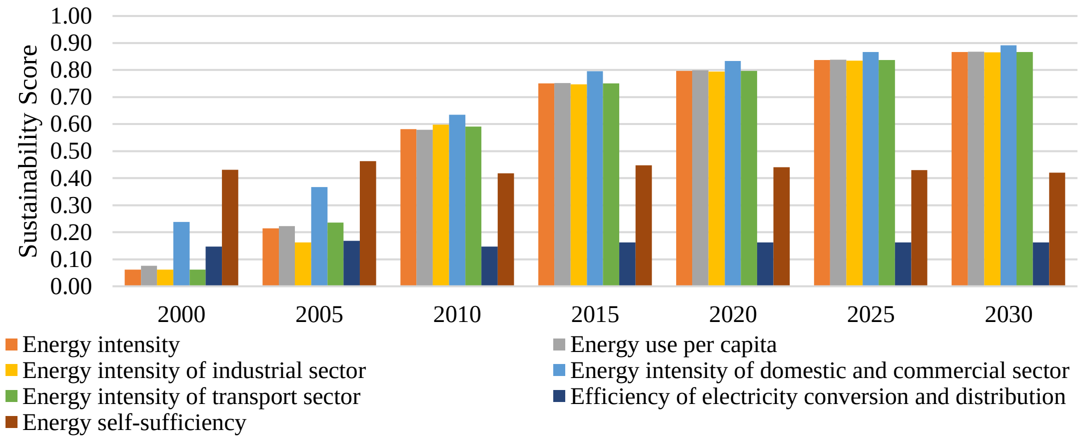

Figure 3-4: Sustainability analysis of economic indicators

Efficiency of electricity conversion and distribution implies efficient conversion of primary energy to electricity while efficiency in distribution indicates ability respond to demand without interruptions in a timely manner. Efficient conversion and distribution greatly influence the security of an energy system. As Grubb et al. (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 & Jayalath (2004) Sri Lanka experiences planned and unplanned power supply interruptions almost on a regular basis due shortage of hydropower resulting from severe drought conditions causing economic losses. Combined with its inherent nature of lower energy storage causes difficulties in reaching peak demand (about 2500 MW) at times. Latest blackout occurred in August 2020 lasted over 7 hours (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 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 sale biomass power projects have been failed to attract investors due to difficulty in collecting sufficient biomass residues (rice husks, wood, and coconut shells) and developing sustainably grown biomass plantations. Findings of Hou et al. (2019) shows 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.

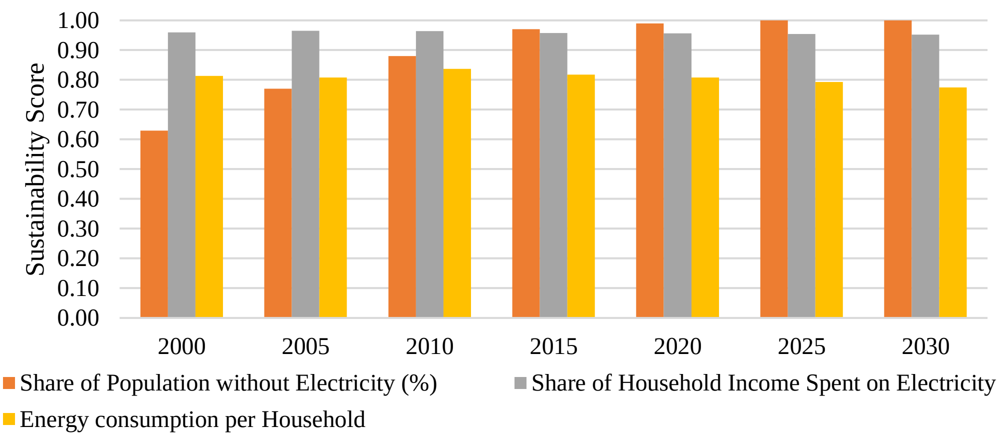

Figure 3-5: Sustainability analysis of social indicators

Social sustainability assesses the equity of the energy system by measuring accessibility and affordability. Overall assessment of social indicators shown in Figure 3-5 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 is paramount in determining a countries level of energy poverty. ADB (2018) call attention to household and commercial energy prices in Sri Lanka which are comparatively higher compared to 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 Statictics, 2016). Therefore, not being unable 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-reflectiveness on electricity retail tariffs has been one of the crucial issues that has 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, a proper cost reflective tariff system needs to be introduced to sustain the energy supply without compromising the equity of the energy system.

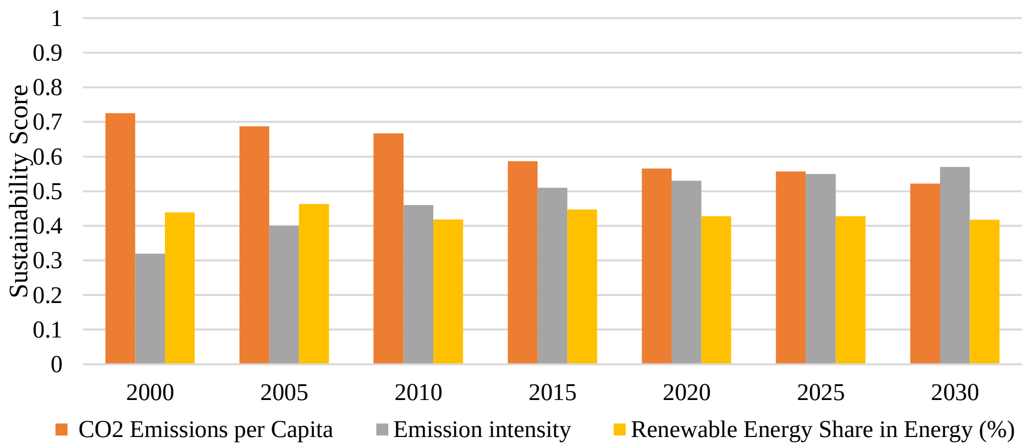

Figure 3-6: Sustainability analysis of environmental indicators

Sri Lanka achieved 100% rural electrification in 2019 which is commendable with compared to 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 et al. (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 urbanization, changes in lifestyle, and 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 & Jawo (2021) to Ethiopian households reveal improved biomass cooking stove can reduce 1.05tonnes on per year per household. According to Jayasinghe et al., (2021), not consuming modern cooking fuel due to lack of motivation, combined with financial unaffordability are the main contributing factor of energy poverty in Sri Lanka.

Environmental criteria that measure pressure placed on its surrounding environment through unsustainable energy consumption, has the most negative impact on overall sustainability of the energy system in Sri Lanka. Figure 3-6 shows increasing emissions intensity 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 CO_2 emissions which was about 23, 310 kt in 2017. While Sri Lanka's emissions may contribute to only 0.05% of the overall CO_2 emissions in the world, growth rate of its emissions and emissions per capita have raised concerns. CO_2 emissions per capita have 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 4^{th} highest emissions per capita mainly due to renewable share in the energy mix.

According to Konara & Tokai (2020) transport sector has the highest CO_2 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 CO_2 emissions per capita and emissions intensity in Sri Lanka. Nandasena et al. (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 rapid increase in demand for private vehicle is rapidly changing (with 135% increase in 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 accounts for the rest of 98%. Giannakis et al. (2020) points 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).

Cooking in urban households is mainly dominated by 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 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 & Jayalath, 2004). It was further revealed 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 with compared to Sub-Saharan African region where majority of people still depends 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 & Madueme (2006) reveal solar energy as the most attractive source of energy for a developing economy. Sun et al. (2020) reveals 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 93.7MW used currently) and 5600MW by wind power (only 131MW is used currently) (ADB, 2018). Report further suggests reaching the potential require 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 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 minimizing the negative impact from both social and environmental criteria. Therefore, the Integrated sustainability index which shows an increasing trend from 2000 – 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.

3.3.3 Scenario Analysis

Results of the analysis of scenario 1 (Figure 3-7) show an 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_2 emissions reduction of up to 10% by 2030. A significant decrease in CO_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% compared to BAU scenario. As shown in Figure 3-8 increase in energy self-sufficiency shows and 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 have identified 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 produces to invest more in the renewable energy sources, customer tariffs system is still independent from source of energy which can deter consumers from prioritizing energy from renewables (ADB & United Nations Development Programme, 2017).

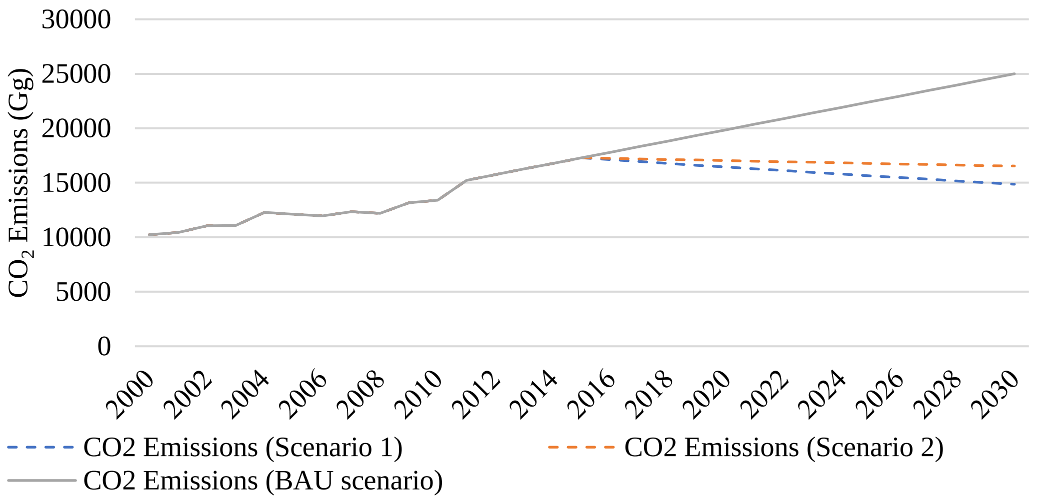

Figure 3-7: Comparison of CO_2 reductions scenario 1 and 2 against BAU scenario

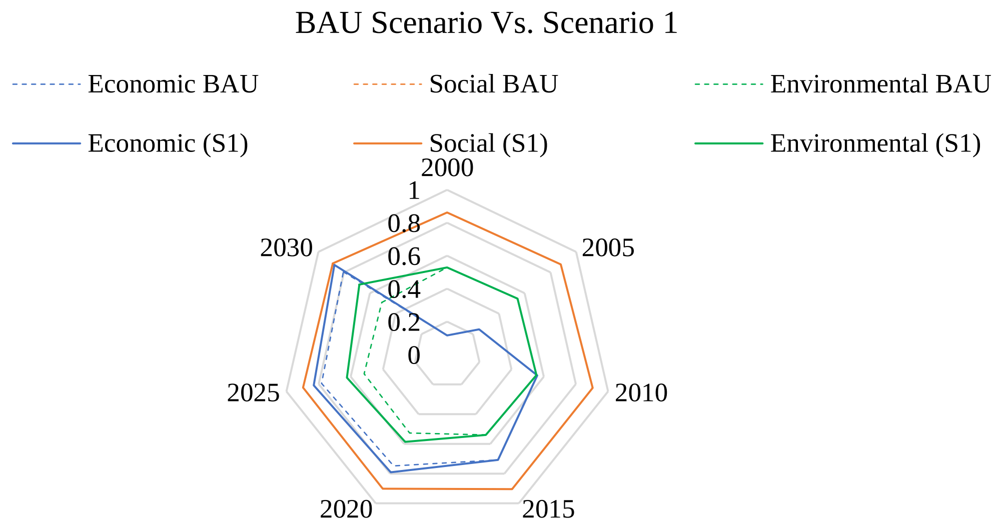

Figure 3-8: Comparison of BAU scenario and scenario 1

Results of the scenario 2 (Figure 3-7) shows expected CO_2 emissions are less than 10% by 2030. Although reducing energy demand has a significant impact on CO_2 emissions, scenario 2 alone cannot achieve the set CO_2 reduction target of 20% by 2030, thus need to be combined with another scenario or policy strategy. According to Figure 3-9, all the criteria show significant improvements between 2015 – 2030 compared to BAU scenario (economic sustainability by 5%, social sustainability by 6% and environmental sustainability by 14%). Social indicators have been positively affected by a decrease in energy consumption per household with a slight decrease in the share of household income spent on electricity. Reduction in annual energy demand causes decrease in CO_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).

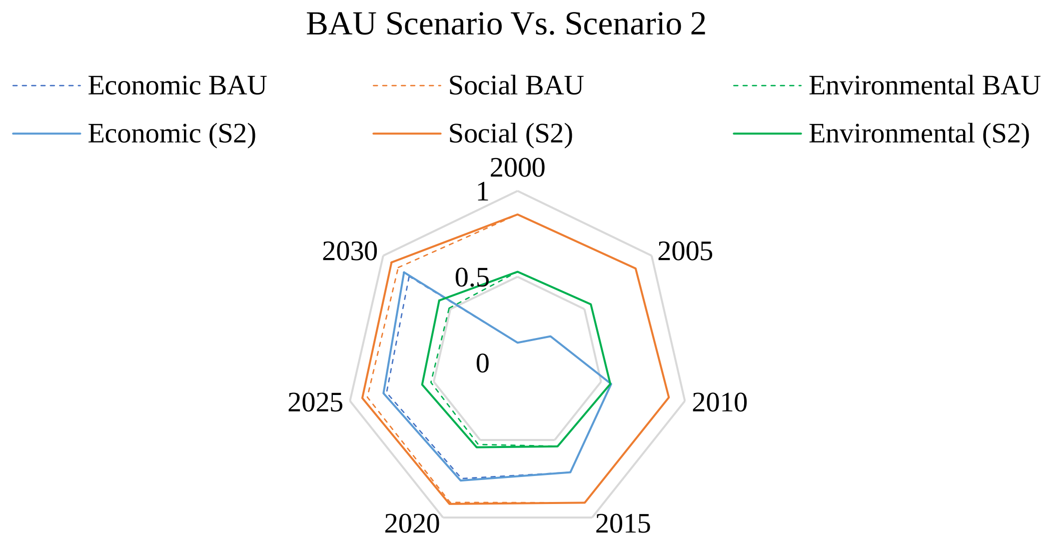

Figure 3-9:Comparison of BAU scenario and scenario 2

3.4 Conclusions

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, 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 shows a cumulative increase over the years. Decrease in overall and sectorial energy intensities show and 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 CO_2 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 indictors while demand side energy measure shows moderate improvements but in all three dimensions i.e., economic, social, and environmental. While both the scenarios show more than 10% reductions in CO_2 emissions to achieve the committed 20% reductions a combination of INDCs need 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 the policy reforms need to be reconsidered. Sri Lankan government on their conquest to achieve 100% electrification 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 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.

CHAPTER 4 EXPLORING BEHAVIOUR OF SOCIO-ECONOMIC METABOLIC FLOWS TO PROMOTE ENVIRONMENTALLY SUSTAINABLE CONSUMPTION PATTERNS IN HOUSEHOLDS

4.1 Introduction

Household consumption has been attracting attention as an important driver for societal metabolism during the recent years influencing to change the focus to final demand associated requirements (Donato et al., 2015). As households attract resources from outside its boundaries, it is imperative for these resource flows to be transformed and returned to the environment in the most sustainable way possible to lessen the burden on the environment (Villarroel Walker et al., 2014). Metabolism assessments provide a detailed examination of this transformation by tracing metabolic flows, which helps in identifying opportunities for shaping these flows towards more sustainable forms of consumption and urbanism (Giampietro et al., 2009; Haberl et al., 2009; Rodríguez-Huerta et al., 2019; Strydom et al., 2020). As Harder (2013) explains with our needs, desires, preferred activities, routines and practices we have choice over the characteristics and magnitude of socioeconomic metabolism of households/cities. Thus, identifying metabolic patterns from a quantitative perspective along with associated socioeconomic drivers will allow us to influence these choices to reduce their environmental impact (Donato et al., 2015; Harder, 2013; Lucertini & Musco, 2020).

Figure 4-1 describes the conceptual household metabolic mode adapted in this study. Physical flows of energy, water and food are entering and leaving a household as air emissions, solid waste and wastewater allowing its inhabitants to sustain activities and practices. In terms of the scope of the metabolic studies Harder (2013) explains they can be exploratory, explanatory, indicative or persuasive in nature. Intention of an exploratory study which this chapter based on is to reveal past and present patterns of household metabolic flows to understand the factors influencing and magnitude. Further disaggregation is needed to understand the share of flows contributing to each activity, rather than considering the socio-economic entity as a black box by only calculating inputs and outputs flowing in and out of the system boundary (Zhen Guo et al., 2014; Harder, 2013; Q. Huang et al., 2018; Ravalde & Keirstead, 2017). As Harder (2013) explains traditionally linear flow of resources are often considered unsustainable as they resources from wide hinterlands, digests them and releases wastes into the environment. Thus, importance of circularity in achieving sustainable flows have been emphasised by researches promoting reuse and recycling practices of waste and emissions (Lucertini & Musco, 2020). It can be further argued that studying metabolic flows can contribute in strengthening the circular economy model as both concepts attempt to rethink socioeconomic activities in encouraging reduction, reuse, and recovery of resources.

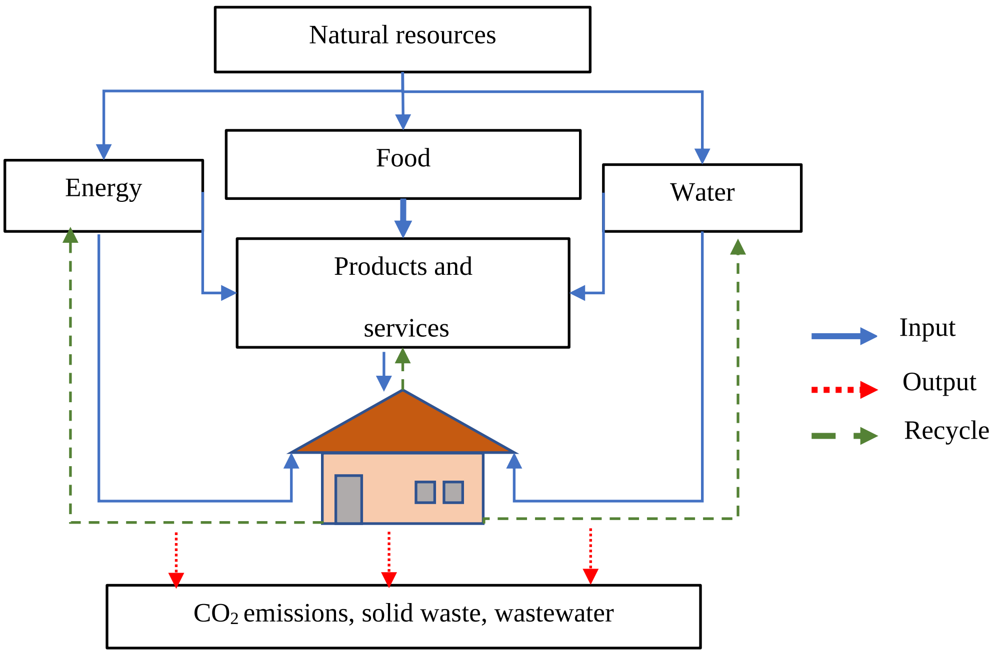

Figure 4-1: Conceptual household metabolism model with socioeconomic Metabolic flows (Adapted from Liu et al. (2005)

While studying household metabolic flows have been clearly recognised imperative to assessment of final consumption for sustainability policies, limited number of studies shows that maturity of this research field is yet to be reached (Harder, 2013). Most of these studies have used a top-down approach relying high-level disaggregation and estimation. Strydom et al. (2019) argues the importance bottom-up data collection and analysis from household level as differential household energy behaviours depend on a variety of household attributes and geographic locations. Kissinger & Damari (2021) points out most studies analyse metabolic flows at household scale often focus on limited number of households without attempting to capture overall metabolism of a society or country. Further, most of these studies are based on data-rich environments of the Global North, and minimal studies have been undertaken in the Global South, due to limited research capacity and funding (Currie & Musango, 2017).

As shown in Figure 4-2 Sri Lanka has the highest per capita household expenditure in the South Asian region which has grown exponentially during the last few years. According to Ivanova et al. (2016), there is a robust and significant relationship between households' expenditure and their environmental impacts. With growing pressure on environment with increasing household consumption, it is deemed imperative to investigate household consumption and related socio-economic metabolic flows in Sri Lanka. Among countless cross-country studies, Sri Lanka often remains unexplored partially due data inadequacy or inaccessibility by the public. Evidence from these studies based on developed countries shows the possibility of shifting to less environmentally damaging consumption patterns without compromising quality of life (OECD, 1999).

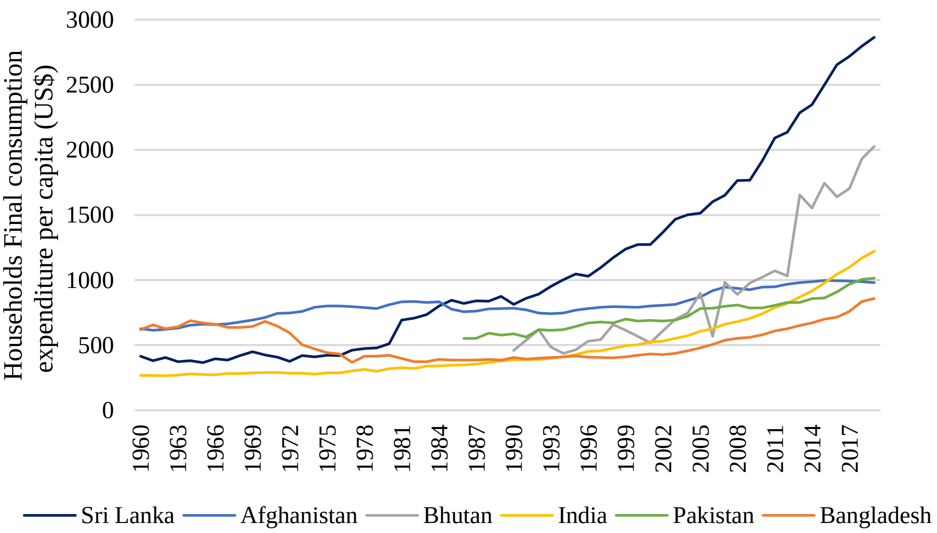

Figure 4-2: Households Final consumption expenditure per capita in South Asian region (The World Bank (2020)

Therefore, this chapter aims explore the metabolic flows of Sri Lankan households during the past decade based on the household expenditure survey data by converting them to physical quantities. Objectives of this chapter are three-fold; identifying behavioural patterns of household metabolic flows i.e., energy, water, food, and related emissions i.e., CO_2 emissions, food waste and wastewater over the past decade; identifying the impact of different socio-economic and demographic factors such as urbanisation and impact of other social characteristics such as level of education, gender of the head of the household on the household consumption; and finally to identify environmentally sustainable and unsustainable consumption patterns. Considering the previous body of studies, this study, to the best of our knowledge this represents the first scientific study that evaluates household metabolic flows in Sri Lanka and the sustainability of their consumption patterns. Thus, filling an important research gap in the context of Sri Lanka, expanding the emerging body of empirical literature on socioeconomic metabolism of households in the Global South. Section 4.2 of the chapter will further explain the materials and methods used in quantifying and evaluating households SEM flows while section 4.3 discusses the results of the analysis in details before presenting concluding remarks in section 4.4.

4.2 Materials and Methods

This study aims to evaluated input and outflows of an average Sri Lankan household and the impact on the household activities. As a bottom-up approach gives a more realistic view of the consumption, this study relies on four sets of Household Income and Expenditure Survey (HIES) data compiled by the Department of Census and Statistics (DCS) of the Government of Sri Lanka in 2002, 2006/2007, 2009/2010, 2012/2013 and 2016 (Department of census and Statistics, 2010; Department of Census and Statistics, 2002; Department of Census and Statistics of Sri Lanka, 2018; Department of Census and Statistics of Sri Lanka, 2014). As Kissinger & Damari (2021), HIES is a good source of data often available in many countries to calculate environmental pressure created by specific activities and products. The HIES is a nationwide household survey that cover stratified sample of 20,000 household selected from all 25 administrative districts in Sri Lanka (Figure 4-3). The HIES generally collects data for twelve consecutive monthly rounds to capture seasonal variations in income, expenditure, and consumption. The district is the main domain used for the stratification and the urban, rural, and estate sectors in each district are the second selection domains. Department of Census and Statistics of Sri Lanka (2018) categorise areas governed by the municipal or urban council as urban sector while tea and rubber plantation areas are considered as estate sector leaving rest of the households to the rural sector.

Figure 4-4 elaborates the inflows, processes, and outflows considered in the study. Energy input from kerosene oil, firewood and LPG were derived from converting the physical outputs into relevant calorific value given by UNFCC (2000). The amount of electricity consumed was derived from expenditure records and the history of kilowatt/hour (KWh) prices and price structure obtained from the Ceylon Electricity Board (2020). The fixed monthly payment, paid by all customers without regard to their actual use of electricity, was subtracted from the amount paid for a month. Then the amount paid was divided by the price of a KWh in the relevant month. To calculate the fuel consumption of private transportation the expenditure for fuel was divided by the fuel price for the corresponding month (Ceylon Petroleum Corporation, 2020), yielding the total litres used. Electricity consumption for lighting, refrigeration, cooling, communication and entertainment and washing was based on electricity units consumed by an average household, calculated by Sri Lanka Sustainable Energy Authority (2016). Percentage of kerosene consumption for lighting and cooking is based on (Department of Census and Statistics of Sri Lanka (2018). CO_2 emissions related to electricity, petroleum products and firewood were calculated based on the emission factors given by UNFCC (2000). CO_2 emissions related to water consumption was calculated based on the emission factors given by Ministry of Mahaweli Development & Environment (2016) for the respective year. Refer the supplementary materials for further details.

The amount of water consumed was derived from expenditure records and the history of water prices and price structure obtained from the National Water Supply and Drainage Board (2020) for the respective year. Water tariff has been renewed only once during the past decade in 2012. Therefore, the same tariff structure was assumed for the period of 2012 to 2002. The fixed monthly payment, paid by all customers without regard to their actual use of water, was subtracted from the amount paid for a month. Then the amount paid was divided by the price of a m^3 in the relevant month. Water consumption for cooking, cooling, bathing, washing, cleaning and gardening was based on Kaushalya et al. (2020) as their case studies were based on water consumption semi-urban and rural households. Therefore, it was deemed it was appropriate to generalise the results for an average Sri Lankan household. Since data on activity-based consumption of groundwater were not available, it was assumed the percentages to be the same as pipe-borne water. Composition of pipe-borne water was based on IGES Freshwater Management Project (2007) which reveals 31% of the total pipe-borne water supply depends on purely on groundwater. Refer the supplementary materials for further details. Indirect CO_2 emissions from water supply was based Ministry of Mahaweli Development & Environment (2016) on where annual electricity consumption only for pumping source to feeding point has been estimated as 0.35kwh/m^3.

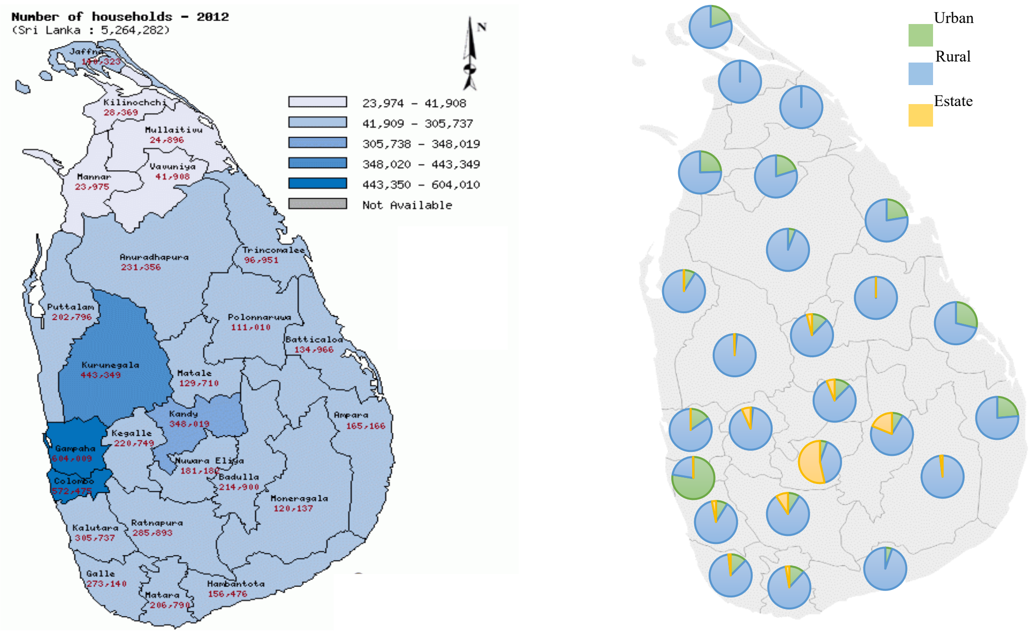

Figure 4-3: Household Distribution and Level of Urbanisation among the Districts of Sri Lanka (Department of Census and Statistics Sri Lanka (2012)

The amount of food purchased by each household included more than 200 food items, which capture most of the food items purchased in a typical household. Most of the records were processed using the reported quantity, with expenditure data used only in rare cases. In such cases, the median price for each product was calculated, and used to convert the expenditure into a quantity. For the purpose of calculating related food wastage, the food items were then categorised into seven groups according to the guideline given by (Food and Agriculture & Organization of the United Nations (FAO), 2011). Then the food wastage was calculated based on the coefficients of South Asian region including Sri Lanka given by FAO. The food items where the coefficient values were not given were assumed to be zero wastage. Due to lack of data only the food wastage in the consumption stage of the supply chain was considered. Refer the supplementary materials for further details. Food waste disposal percentages based on disposal modes were calculated based on HIES data.

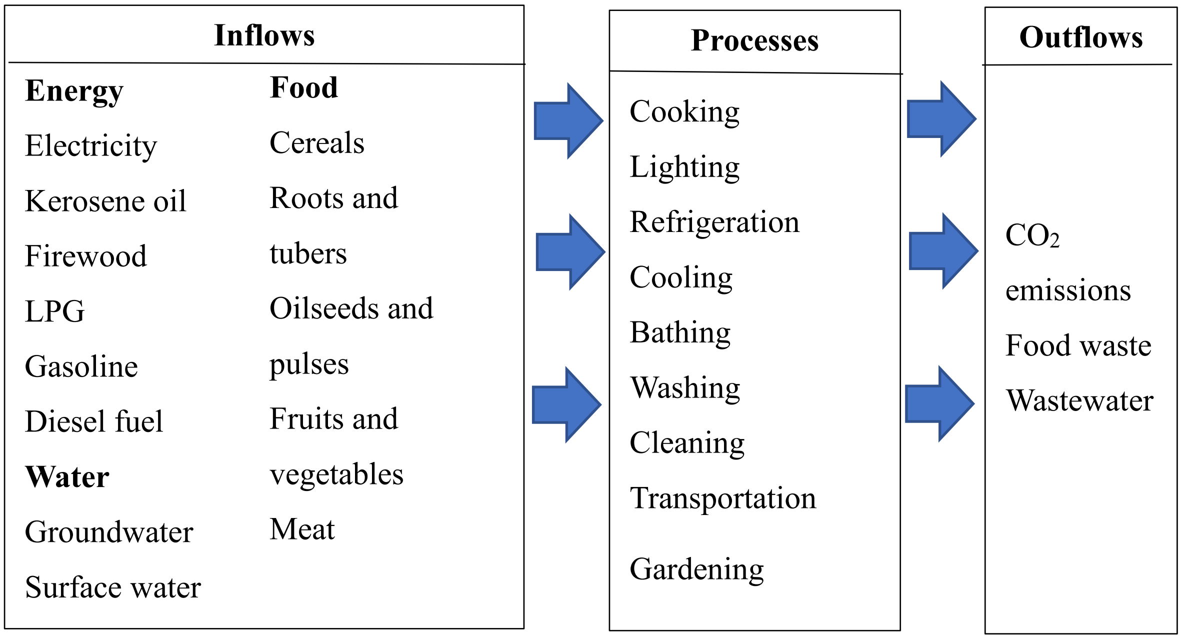

Figure 4-4: Inflows, Processes and Outflows of Household Metabolic System in Sri Lanka

Environmental sustainability indicators were then selected based on literature survey to evaluate the environmental sustainability of household SEM flows. Table 4-1 defines the selected environmental sustainability indicators.

Table 4-1: Description of selected environmental sustainability indicators

Environmental Sustainability Indicator	Description
Energy consumption intensity per capita	Ratio between total household energy consumption and population
Energy consumption intensity per GDP	Ratio between total household energy consumption and GDP
Share of consumption of renewable energy resources	Ratio between total renewable energy consumption per household and total household energy consumption
Consumption of road fuels per capita	Ratio between road fuels consumption per household and population
Water consumption intensity per capita	Ratio between total household water consumption and population
Water consumption intensity per GDP	Ratio between total household water consumption and GDP
Share of households connected to waste treatment plants	Ratio between number of households connected to waste treatment plants and total number of households
Food consumption intensity per capita	Ratio between total household food consumption and population
Food consumption intensity per GDP	Ratio between total household food consumption and GDP
Share of processed food	Ratio between total processed food consumption per household and total household food consumption
Reuse/recycle rate of food waste	Ratio between total reuse/recycle food waste per household and total household food waste

Sustainability indicators were normalised using the following equation for the comparison purpose of energy, water and food related indicators (Angelis-Dimakis et al., 2012).

$$S\acute{I}_x = RelMax - \frac{(RelMax - RelMin) * (MaxSI - SI_x)}{MaxSI - MinSI} \quad \text{Equation (4-1)}$$

where SI_x is the selected indicator for the year x, $S\acute{I}_x$ is the respective normalized indicator, MaxSI and MinSI are the maximum and minimum values of the indicator for the period under study (1, 2,…, n years) and *RelMax, RelMin* are two 0–1 values indicating whether 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.

Assessment of the weights (W_x) for each individual indicator. In this study weights of the individual indicators were considered as equal.

4.3 Results and discussion

4.3.1 Behaviour of metabolic flows and affecting economic and socio-demographic characteristics

4.3.1.1 Energy Consumption and emissions

Natural resources extracted from the environment are converted to energy carriers i.e., electricity, firewood, kerosene, LPG, gasoline, and diesel oil to be used for cooking, lighting, operate other electric appliances (refrigeration, cooling, washing, entertainment) and transportation. As shown on Figure 4-5 and 4-6, a typical Sri Lankan household consumes an average of 15700 MJ per year in which firewood accounts for 63%, electricity 25% and petroleum products (LPG, kerosene, and gasoline) accounts for the rest of the 11%. 75% of the electricity generation depends on crude oil (Sri Lanka Sustainable Energy Authority, 2017) whilst rest of the 25% bared by renewables (hydro, wind and solar). Firewood and LPG are used for cooking purposes only while 30% of kerosine oil is used for cooking and rest of the 70% is used for lighting. LPG has an exponential growth in consumption during the last decade followed by gasoline, diesel fuel and electricity which have doubled their consumption. Consumption of kerosine oil and firewood have dropped by 88% and 46% respectively. As shown in Figure 4-7 an average household in Sri Lanka emits 1943 kg of CO_2 per year which is predominately from firewood accounts for 43% of the emissions from energy consumption of an average household followed by electricity by 33%. Emission from kerosine has the highest growth proportional to its growth in consumption. However, while electricity consumption only doubled during past decade, related CO_2 has almost tripled.

Energy consumption and related choices in Sri Lankan households heavily depend on income, urbanisation, household size and education level of the household head. Survey results show more than 77% rural households use firewood as the main energy source for cooking while more than 69% urban households use LPG as the main energy source for cooking. Which is an improvement from 50% and 86% in 2006 in urban and rural households respectively. Further kerosene consumption for lighting has reduced to 3% and 7% in rural and estate households from 19% and 37% in 2006. As Rajmohan & Weerahewa (2010) emphasises as Sri Lanka move up the energy ladder longitudinally household with higher energy and more access to cleaner energy will embrace cleaner energy sources over traditional firewood or kerosene. Urban household have more than 50% higher household income with compared to rural sector and 150% more higher than the estate sector. Electricity consumption in higher income households are more than 3 times higher than of lower income households. As more than 40% urban high-income households own a refrigerator and a washing machine and in rural households it is less than 17%. Urban households tend to consume more gasoline as more than 47% use private vehicles as their mode of travel to work where 43% and 72% households in rural and estate households respectively walk or use bicycle to work. Higher percentage of rural

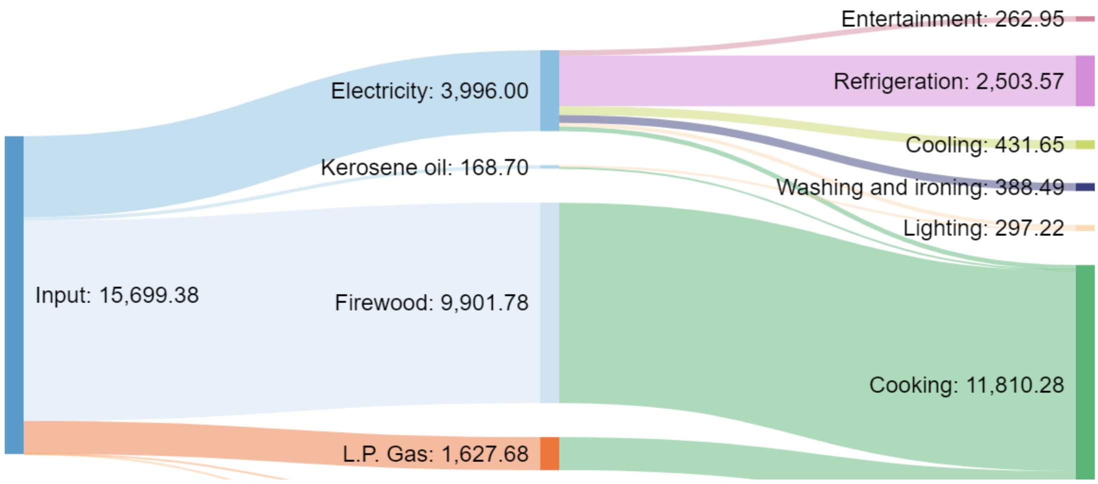

Figure 4-5: Annual Energy Flows of an Average Household (MJ)

household use public transportation with compared to urban households. Pallegedara et al. (2021) reveals when the size of the household increases household tend to move towards electricity due to accessibility and convenience. Jayasinghe et al. (2021) and Pallegedara et al.(2021) highlight the positive impact of education level of the head of household and female-headed households moving towards more cleaner energy sources in Sri Lanka.

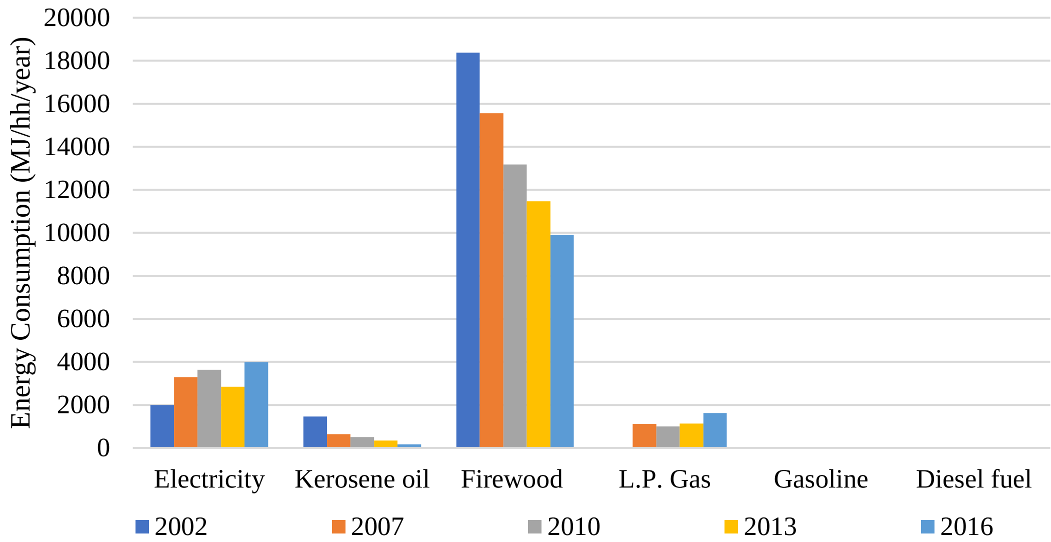

Figure 4-6: Annual Household Energy Consumption by Source per Household

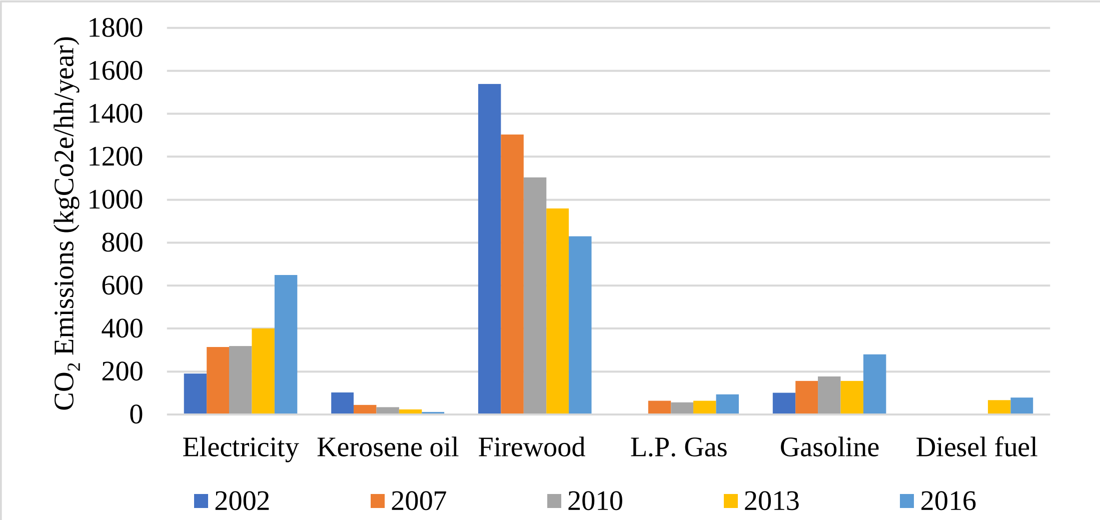

Figure 4-7: Annual Household CO_2 emissions by Source

4.3.1.2 Water Consumption and wastewater

On a national basis Sri Lanka has 127192mm^3 of net water inflow from precipitation where homesteads only use 23% and an uncommitted water outflow of 43386mm^3 (Bastiaanssen & Chandrapala, 2003). However only 87.8% of the households have access to safe water sources out of which 49.2% have access to pipe-borne water system, 36.4% depends on protected dug wells, 3.2% depends on tube wells/hand pumps and 12% obtain water from unprotected sources (Figure 4-8). Findings show while the usage of freshwater for the country's agriculture has decreased, the usage of water in both domestic and industry has increased over the last decade. Currently, 87.37% of freshwater is used for agriculture, 6.22% and 6.42% for domestic and industry usage, respectively. As shown in Figure 4-9 the total pipe-borne water consumption per household has increased by eight times during the last decade. In which bathing accounts for 34% of total water consumption followed by washing, toilet (24% each) and cooking 10%. According to Rajeevan & Mishra (2020) households use more than one water source prefer to use pipe borne water or bottled water for drinking and cooking purposes while majority of other water needs such as washing, bathing, sanitation, gardening fulfilled by water from dug wells. Wastewaters consist of a combination of domestic effluents consisting of black water (excreta, urine, and faecal sludge) and grey water (kitchen and bathing wastewater).

Piped sewerage systems (off-site) currently cover only 2.5% of the population in major urban areas and condominiums, where other forms of sanitation are unrealistic due to housing density (Fan, 2015). 86% of the households use water sealed septic tank/pit, 4.8% and 5.5% of the households dispose wastewater to direct pits and shared direct pits respectively. 1.4% of the households do not have toilet facilities (Jayathilake et al., 2020).

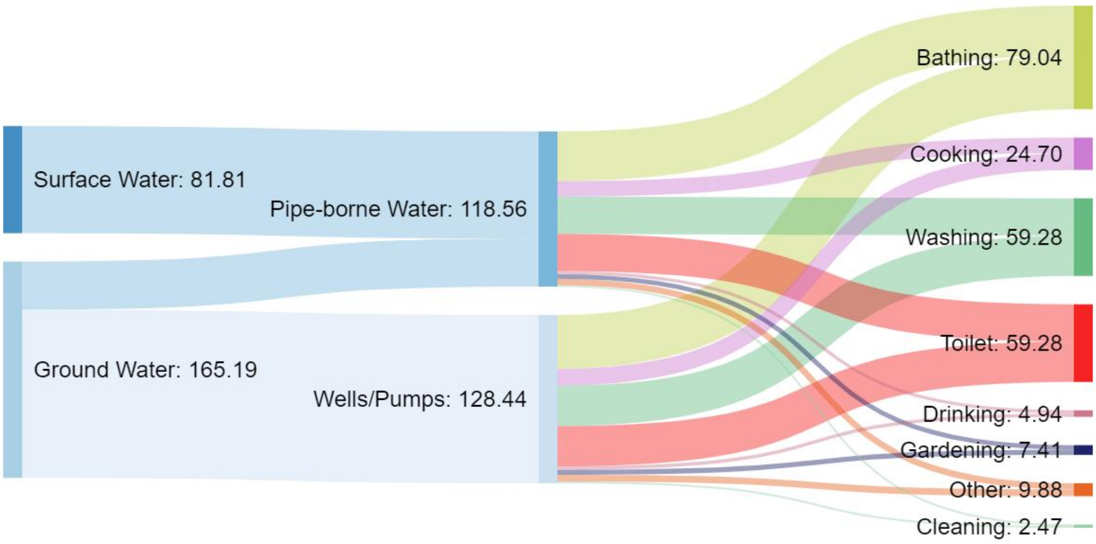

Figure 4-8: Annual Water Flows of an Average Household (m^3)

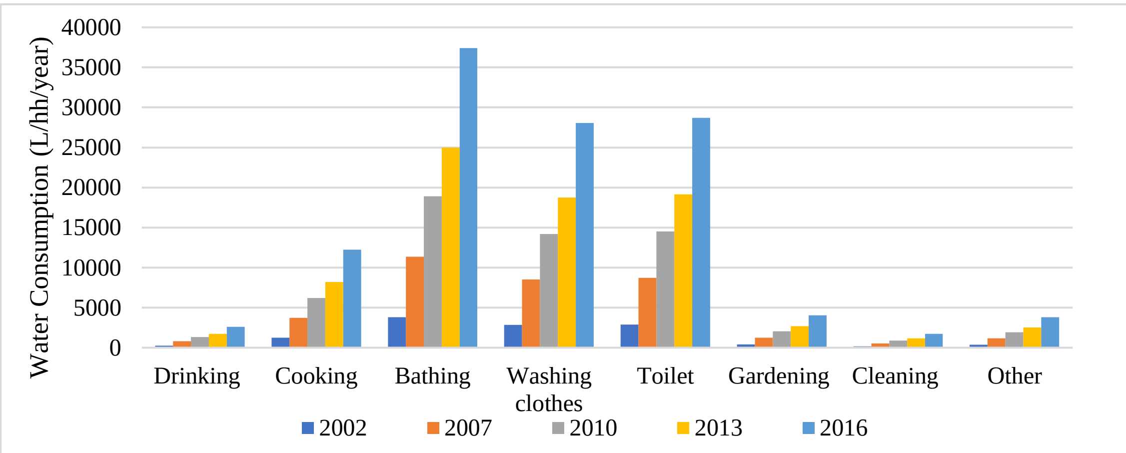

Figure 4-9: Annual Pipe-Borne Water Consumption of an Average Household

There is a significant difference in availability of piped water in urban and rural areas where 66.9% of the western province have access to piped water, Northern province is limited to 11.8% (NWSDB, 2017). Therefore the proportion of urban households that use pipe-borne water has increased by 47% during last two decades wherein for rural households its only 23% (Pallegedara, 2019a). Further reliability and quality of water supply differs in rural and estate areas as most estate areas do not have a 24 hour water supply (JICA, 2016b). Off-site sewerage system does not cover the any of the rural locations. According to Rajeevan & Mishra (2020) having access to own water source devoid of economic burden leads to excessive consumption of water particularly in rural households. Additionally Kaushalya et al. (2020) , Pallegedara (2019a) and Gamini (2015) explain that monthly household income, the level of education of the head of household and the number of family members have a strong positive impact on an average water consumption of a Sri Lankan household. Rural households with higher level of education that are typically more affluent tend to consume more piped water due to accessibility and cleanliness of water. It was also observed by Kaushalya et al. (2020) that time spent at home and the age of the household head have a negative correlation with daily domestic water consumption.

4.3.1.3 Food consumption and food waste

A typical Sri Lankan diet accounts for average of 2100kcal which has not changed much over the years. Household expenditure on food has reduced from 44% in 2002 to 35%. Out of which 89% is spent on raw food items and condiments as prepared/processed food is economically and culturally somewhat undesirable. Once the food is purchased it will be consuming energy and water during storage, preparation, cooking and disposal stages. As shown Figure 4-10 household food consumption predominantly consist of cereals and wheat related products (90% consists of rice) followed by vegetables and fruits (16%) and oilseeds and pulses (16%). Meat (2%) and Milk (3%) account for the least consumed food category. During the past decade a significant decreasing trend can be observed in cereals (19%) while increasing trend can be observed in meat (36%) and fish and seafood (21%). Waste from households accounts for more than 50% of the total waste generated in a municipality in which more than 45% accounts for food waste (JICA, 2016; Negombo Municipal Council, 2020). As shown in Figure 4-12 waste generated from cereals, vegetables, and fruits accounts for more than 85% of the total food waste generated by an average household. With the declining consumption of those food categorises the overall food waste has reduced by 10% during the last decade. Figure 4-13 reveals that most of the waste (73%) generated by households is handled by the householder either by burning or dumping within the premises. Only 22% of the household waste is collected by the local authorities which has only improved by 9% during the last decade. Only 4% of the waste is reused as fertiliser.

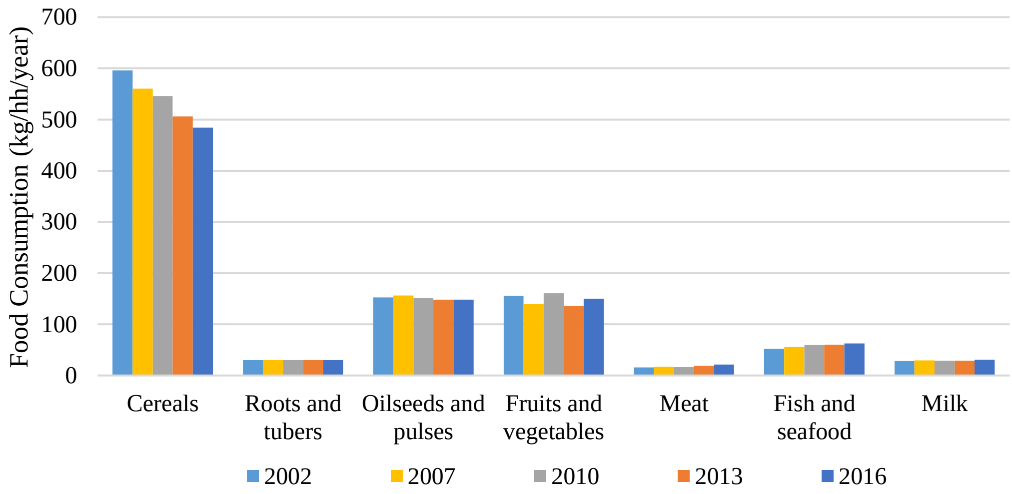

Figure 4-10: Annual Food Consumption of an Average Household

As Geislar (2018) proposes there are many determinants affecting household food metabolism. And properly managing food waste can reduced the negative environmental and socioeconomic footprints and environmental externalities to a certain extent. In Sri Lanka a higher income household consumes 47% more calories per person per day. Further results show urban households with higher income consume more fish and seafood as opposed to rural lower income households which mainly depend on rice, vegetables, and fruits. A study by Pallegedara (2019) reveals household food consumption is highly sensitive to food prices and the household size. While the education level of the household head has a positive impact on consuming a nutritious balanced diet, the role of a woman in a typical Sri Lankan household when making food consumption related decisions is substantial. Kalansooriya & Chandrakumara (2014) point out in more than 80% of the households, women prepare the food thus households with more educated women tend to consume more fruits, fish, and milk. FAO (2018) reveals, higher income urban households have a higher percentage of waste generation particularly due to overpreparation of certain foods such a rice wherein lower income households tend to share extra food among neighbours. Findings of Kumara & Pallegedara (2020) points out urban households and households with higher income levels prefer their waste to be handled by local authorities where rural households prefer to burn within premises. However more than 85% collected wasted is dumped on open dumpsites without any treatment causing contamination problems and methene emissions (Danthurebandara et al., 2015). With higher consumption urban and high-income households generate more waste than the rural and low-income households. There is a substantial difference in waste disposal methods in rural and urban households. While 80% of the household food waste collected by the local authorities in urban households, rural households only accounts for 10%. Due to poor waste collection services provided by municipalities of rural areas, rural households often turn to burning or dumping waste within the premises. Findings of

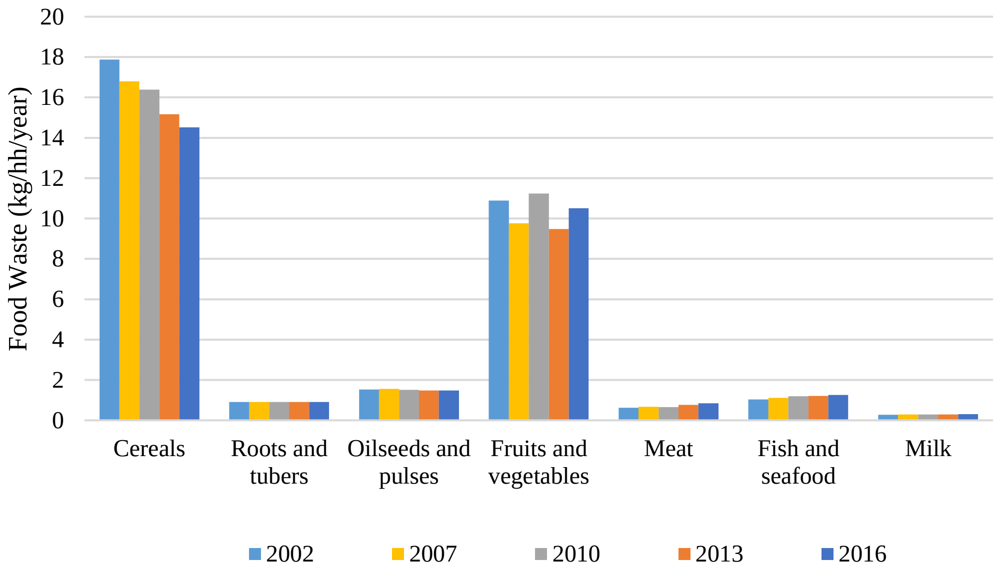

Figure 4-11: Annual Food Waste Generation of an Average Household

Kumara & Pallegedara (2020) reveals income level, education level of the household head, age and household size have a positive impact on relying on local authorities over self-handling of waste.

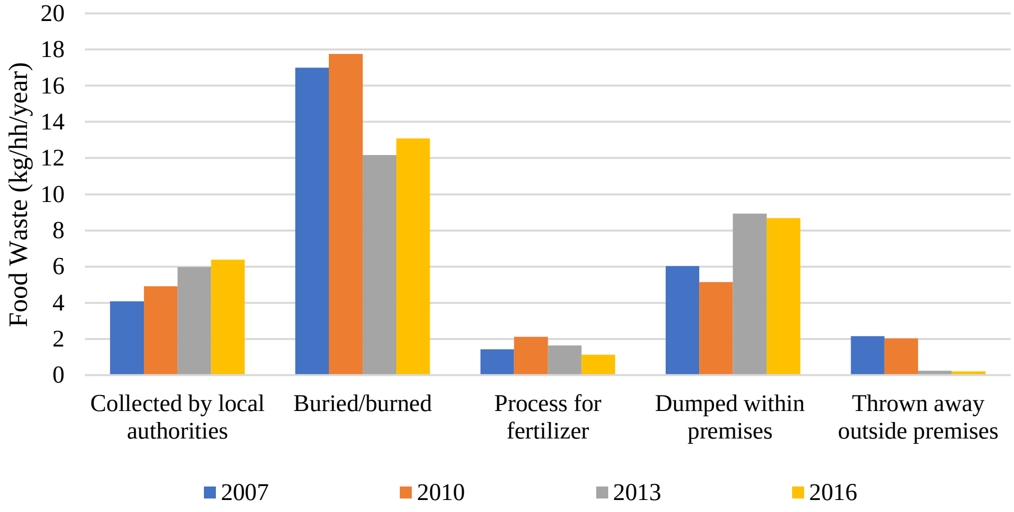

Figure 4-12: Household Food Waste Disposal Methods

4.3.2 Environmental sustainability of household consumption patterns

Behaviour and sustainability of household consumption patterns are demonstrated in Table 4-2, Figure 4-13 and Figure 4-14. Over the last decade overall energy consumption of a household has reduced by 28% indicating increase in efficiency in metabolic process while CO_2 per household has increased by 1% questioning their environmental sustainability. Renewable share in household energy mix is 69% which has declined by 16% during the last decade compromising its self-sufficiency. Reducing biomass consumption doubling demand for electricity, gasoline, and exponential increase in LPG consumption over the last decade have made households more dependent on energy imports. Which can be threatening to the overall sustainability of the household metabolic system yet inevitable as households adhere to energy ladder hypothesis.

Cooking is the most energy and emission intensive process in a household mostly due to inefficient burning of firewood. Apart from higher CO_2 emissions it has caused serious health repercussions due to higher particulate matter concentrations in kitchen and other microenvironments of the households (Nandasena et al., 2010). However, over the years with shifting to cleaner fuels cooking has become more efficient causing cooking related energy consumption to be reduced by 41% during past decade. Yet, shifting to more cleaner fuels has not helped in reducing the overall CO_2 emissions which shows a slight increasing trend. Therefore, considering the sources of generation the "cleanliness" of electricity or LPG is debatable. It is proven during the last few years as CO_2 emissions from electricity in Sri Lanka which predominately depends on crude oil (75%) are gradually becoming the largest emitter of households. Electricity which only accounts for 25%of the household energy consumption contributes to 33% of the CO_2 emissions where in firewood contributes only 43% being more than 63% in the energy profile. Survey results declare more than 75% of the firewood used for energy is collected in a sustainable way for free such as twigs and branches collected from forests or waste reside such as paddy and coconut husks with no forests being harmed. Which positively affect the sustainability of metabolic flows and need to be encouraged (Perera & Sugathapala, 2002). As Bhattacharya & Abdul Salam (2002) suggest enhancing efficiency in biomass use and proper control of other health impacts from air pollutants of biomass consumption, can not only lessen the environmental burden but also avoid further aggravation the fossil fuel crisis (Jin et al., 2019).

Some of the demand-side energy management policies such as providing low-cost LED lamps for households, phase out inefficient refrigerators, energy efficient and energy conservation practices for ceiling fans, motors, air conditioning and encouraging implementation of energy efficient building code for large housing complexes has contributed to reducing household energy consumption (Presidential Task Force on Energy Demand Side Management, 2016). While consumption from private transportation is neglectable, related emissions accounts for almost one fifth of the emissions profile. As people move away from public transportation, number of motorcycles and three-wheelers have doubled in numbers during last decade adding more than 3million vehicles to the active vehicle fleet in the country (Sri Lanka Sustainable Energy Authority, 2017). As vehicles predominantly depends on imported petroleum, demand for gasoline and diesel is expected to drastically rise with the foreseeable future.

With 127192mm^3 of net water inflow from precipitation where homesteads only use 29,254mm^3 leaving uncommitted outflow of 43386mm^3 makes a self-sufficient net water flow in Sri Lanka (Bastiaanssen & Chandrapala, 2003). Household water consumption depends on ground water (67%) and surface water (33%) with only 48% of the household receiving pipe-borne water. Further findings show that 11.2% of the households currently do not have access to safe drinking water sources wherein 6.7% of the population don't have sufficient water for drinking and 9.5% of the population don't have sufficient water for bathing/washing. 18.4% of the households don't have safe drinking water sources within the premises in which more than 12% of the households must travel more than 500m to obtain drinking water (Department of Census and Statistics of Sri Lanka, 2018).

As IGES (2007) points out increasing trend in groundwater can be observed in recent times as households prefer to maintain a supplementary groundwater supply due to restricted hours of piper water supply. However, there are many sustainability issues attached to groundwater consumption in terms of quantity and quality. Water scarcity during dry season, over abstraction and declining quality of water with increasing salinity have been recognised through literature (Arulnesan et al., 2015; Kaushalya et al., 2020; Rajeevan & Mishra, 2020). Without proper monitoring actual safety of drinking water extracted from groundwater sources are debatable (IGES, 2007). Lack of wastewater and sewerage management, poor on-site sanitation combined with poor solid waste disposal has threatened the quality of ground water and water sedimentation levels in stormwater drains and other surface water sources. Particularly during the rainy season fecal sludge often combine with solid waste clogging and contaminating water bodies near households causing irreversible environmental damage (JICA, 2016b). Therefore, there is a compelling need for increasing coverage of pipe-borne water to tackle the increasing water demand while protecting quality of drinking water. With minimum of 1250mm rain fall and rainfall runoff of $50km^2$ per annum, rainwater harvesting has been considered as a potential sustainable water source for drinking and cooking purposes for many years. Despite many development efforts such as constructing water tanks, rainwater harvesting is yet to gain popularity among households due lack of awareness and confidence in quality of rainwater (Ariyananda, 1999; Aheeyar & Ariyananda, 2014).

According to Edirisinghe & Pathirana (2021), along with the demand the wastage of drinkable water has increased over the past decade with an average water-saving potential of 30%, which accounted for a significant saving of resources used for supplying potable water to the urban households, from transboundary water resources. As Ministry of Mahaweli Development & Environment (2016) calculates, NWSDB spends approximately 23% of the total cost on electricity in producing a litre of quality drinkable water. Pumping from source to feeding point consume 0.35 kwh of electricity for a cubic meter of drinkable water. Which accounts for 311.22 MJ and 50.53 $kgCO_2e$ emissions in total per household per year. Thus, high consumption water causes higher energy and emission footprints. According to Rajeevan & Mishra (2020), having access to own water source devoid of economic burden often discourages water saving measures and less likely to use water efficient appliances. Without proper metering and monitoring of groundwater consumption, households aren't held accountable for their excessive use of water. Water tariffs in Sri Lanka are relatively low with compared to other countries, making financial burden of water consumption merely negligible (0.1% of monthly household expenditure) (JICA, 2016b). Gamini (2015) argues that heavily subsidised consumers bare only 1/3rd of the cost of piped water undermining sustainability of service delivery encouraging overconsumption.

Without proper wastewater management practices in place, excessively used water is released to the environment without treatment. According to Jayathilake et al. (2020), disposing of wastewater and sewerage has become a very prominent environmental concern in Sri Lanka with 96% of the households using onsite disposal facilities such as septic tanks or shared pits. Poorly managed septic tanks often lead to septic overflow to spilled into nearest waterbodies or infiltrate groundwater. Findings by JICA (2016b) households tend to release overflow from septic tanks and pit latrines into rainwater drains and rivers in secret either at night or during rains, when it cannot be detected. Potential of domestic wastewater reuse for irrigation, landscape requirements, fire protection and toilet flushing has been deliberated over the years with plans for construction of new wastewater treatment plants in urban areas (Fan, 2015). However, with low social acceptability of use of wastewater, currently functioning wastewater treatment facilities discharge their output to nearby water bodies (Jayalal et al., n.d.).

At present only 20% of the food requirements are imported while Sri Lanka produce the rest domestically including rice and vegetables which are the staple in the diet (World Food Programme, 2017). Table 4-2 shows the total annual food consumption per household has reduced by 10% due to decline in rice consumption reducing the overall burden from waste and related emissions. Schneider & Smith (2009) highlight that a diet based on locally produced seasonal foods that require less energy to grow, and cook can enhance the sustainability of the food system in a country. The carbon footprint can be reduced by consuming more plant based whole foods or minimally processed foods.

Current dietary habits in a typical Sri Lankan household currently adheres most of these principles by consuming more whole food that are available in local markets and less animal products. Religious and cultural biases and prejudices preclude the consumption of meat among Sri Lankans (Mihiranie et al., 2020). Though milk, meat, fish, and seafood consumption have increased by 20% over the years, the red meat which is known for their high CO_2 intensities have decreased from 4.6kg to 3kg per household in 2016. On the other hand like most other Asian countries food consumption in Sri Lanka is high in blue water footprint with higher consumption of cereals and fruits, and can go up to 527 - 986 L/d/capita (Harris et al., 2020).

An average processed food consumption per household is 44kg which accounts for 4% of total consumption which has reduced by 61% during the last decade. However, with changing lifestyles demand for processed or convenient foods have increased in urban markets. On the contrary Weerasekara et al (2018) points out dietary changes associated with urbanization have made rural households more self-reliant in obtaining food. Home gardening has become popular among rural households that add fruits and vegetable to their everyday increasing diversity in food consumption and food security (Thamilini et al., 2019). Urban households started adopting home gardening specially during the COVID19 pandemic motivated by uncertainty in food supply where most countries transitioned to alternative and local food systems (Nemes et al., 2021). Some of the programmes promoted by the local authorities such as “Divi Neguma”, “Deyata Sevana”, and “Deyata Kirula” have positively contributed in promoting home gardening among households (Ginigaddara, n.d.). When considering the environmental sustainability benefits of consuming organic food products are undeniable (Azzurra et al., 2019). However in Sri Lanka share of organic food in the supermarkets is very minimal and household consumers are reluctant to but due to high cost, lack of awareness and availability (Abeyrathna, 2021; Malkanthi, 2020; Bandara et al., 2020)

Cooking consumes more than 65% of the energy of an average household in Sri Lanka. Leray et al. (2016) point out developing countries like Sri Lanka has a cultural perception of freshness of food which leads to buy food more regularly and cook from scratch. Thus, using food storing appliances like refrigerator and freezer less frequently but using more energy in cooking process. Daily consumption of rice or beans which longer cooking periods (De et al., 2014) also contribute to increase in energy use. As FAO (2011) highlights lower income countries have higher energy consumption during preparation and cooking stage of the food chain with compared to higher income countries yet higher emissions during cropping production stage. Globally cooking consumes 5-7 MJ per kg of food. Results show a Sri Lankan household consume average of 13MJ in cooking 1 kg of food which has reduced by 35% during last decade with shifting to more cleaner fuels and efficient cooking stoves.

The environmental pressures associated with household food consumption includes emissions and waste generation from consumption. According to FAO (2011) countries in South Asian region has food waste generation rate during consumption phase with compared to other stages of the supply chain. Despite solid waste collection and disposal remains as one of the critical environmental problems that Sri Lanka yet to solve in which food waste accounts for more than 50% municipal waste generation (Fernando, 2019; Gunarathne et al., 2019; Kumara & Pallegedara, 2020). 73% of the total waste which is self-handled either open burned, buried within the premises, or thrown to waterways or roadside generate unnecessary CO_2 emissions. The amount of waste collected by the local authorities have changed only by 8% over the last decade. 85% of the waste collected by local authorities are disposed to open dumpsites as heterogeneous waste piles. without any pre-treatment increasing global warming potential and polluting surface water (Danthurebandara et al., 2015). Source segregation practices have demanded by law since early 2017 lack compliance from households, discouraging recycling opportunities (Reitemeier et al., 2021). Reuse of food waste as fertilizer through composting has been practiced among rural households for many years. However currently only 4% of the total organic wasted generated used as fertiliser and that proportion has not changed over the years. In spite of many government initiatives such as “Pilisaru” programmes where compost bins were distributed to households, composting either on-site or off-site is yet to gain traction in Sri Lanka (Caucci, 2020). Potential of biogas production using municipal biodegradable waste as practiced in many other neighbouring countries such as India, Bangladesh and Nepal, has been recognised for many years (Bekchanov et al., 2019; de Alwis, 2002b; Suphachalasai et al., 2013). However many waste to energy projects have launched or announced have not being completed yet (JICA, 2016).

Table 4-2: Environmental sustainability indicators of household consumption

Environmental Sustainability Indicator	2002	2007	2010	2013	2016	Change
Energy consumption intensity per capita (MJ/per capita)	5198	5026	4577	4044	4131	-21%
Energy consumption intensity per GDP (MJ/Rs.)	1.67	1.23	0.50	0.34	0.25	-85%
Share of consumption of renewable energy resources	88%	82%	80%	83%	75%	-14%
Consumption of road fuels per capita (L/per capita)	0.35	0.56	0.65	0.82	1.37	287%
Water consumption intensity per capita (L/per capita)	2857	8780	15000	20308	31200	992%
Water consumption intensity per GDP (L/Rs.)	0.92	2.15	1.65	1.73	1.90	107%
Share of households connected to waste treatment plants	N/A	2.4%	2.5%	1.9%	2.6%	8.3%
Food consumption intensity per capita (Kg/per capita)	245	241	248	238	244	-0.5%
Food consumption intensity per GDP (Kg/Rs.)	0.019	0.014	0.007	0.005	0.004	-79%
Share of processed food	4%	4%	6%	7%	10%	130%
Reuse/recycle rate of food waste	N/A	4.6%	6.6%	5.6%	3.8%	-17%

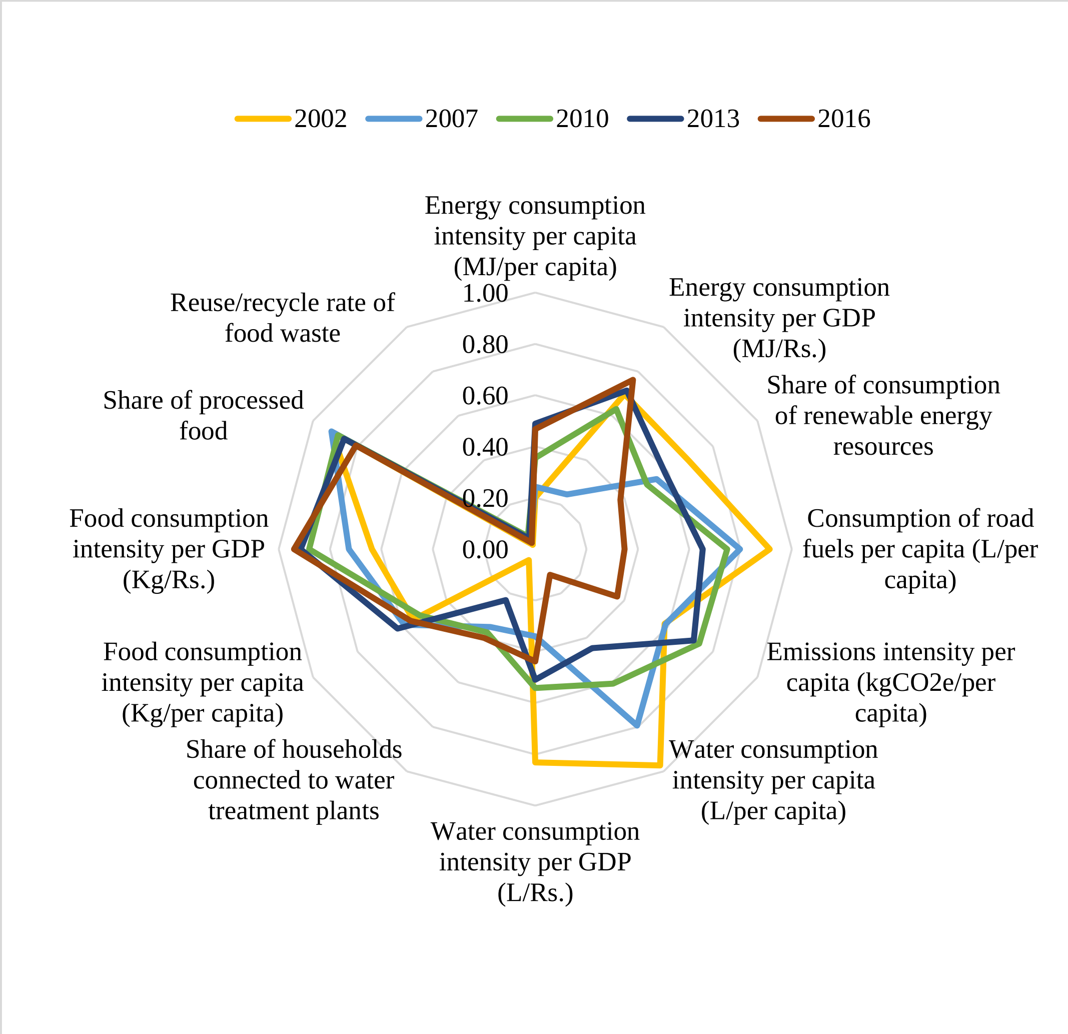

Figure 4-13: Sustainability score of environmental sustainability indicators

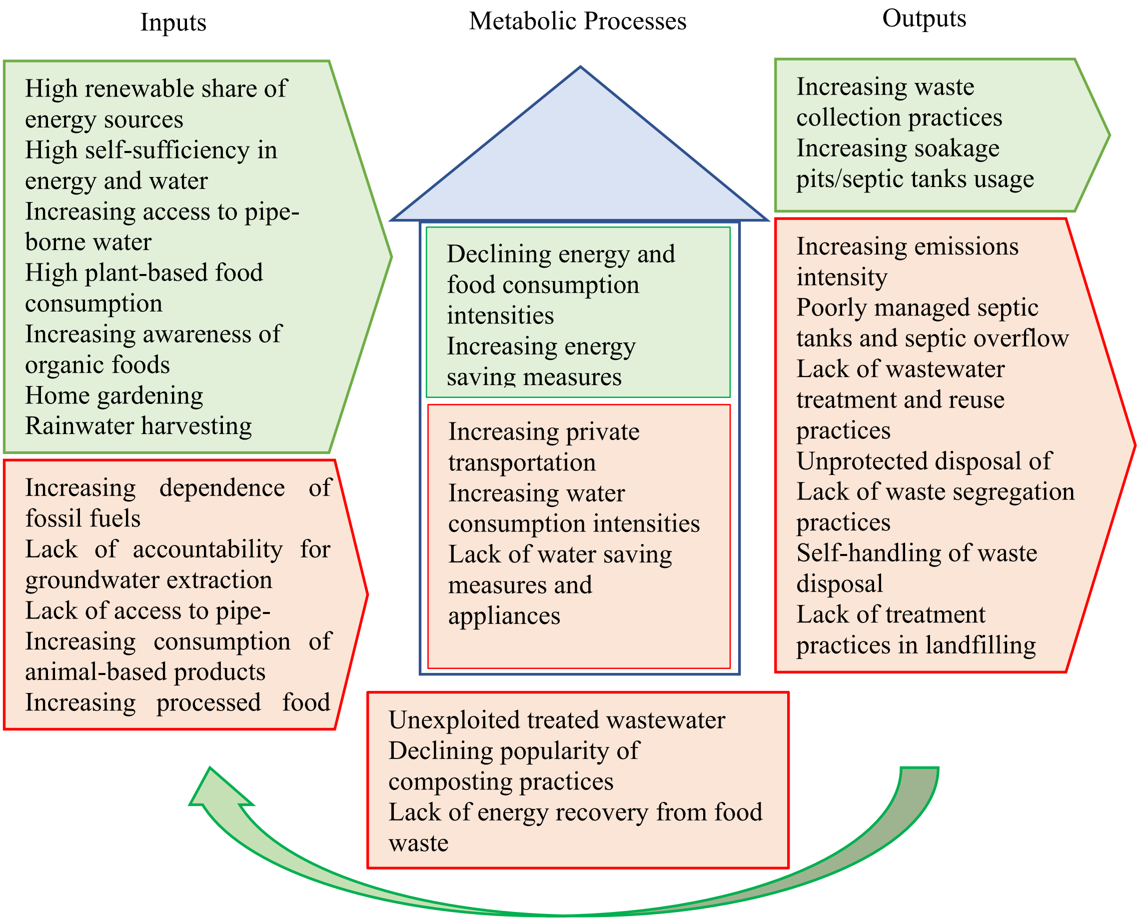

Figure 4-14: Household consumption patterns that promote and hinder environmental sustainability

4.4 Conclusions

While households depend on various material and energy inflows from outside their boundaries, their behaviour have changed over the years with rabid economic development and urbanisation. Therefore, monitoring these resource inflows and outflows and understanding how they relate to household consumption patterns crucial to uplift environmentally sustainable policies and practices. With that intention this chapter aimed to evaluate the inflows, processes and outflows of a typical Sri Lankan household metabolic system and the impact of household activities on the metabolic flows which ultimately help in reducing the consumer metabolism and related environmental burden. The evaluation was based on the household expenditure surveys during the last decade which provided access to energy, waste, and food consumption related data of households.

Further data related to household consumption patterns by different socio-economic and demographic factors such as urbanisation and impact of other social characteristics such as level of education, gender of the head of the household were derived from related research based on Sri Lankan households.

This chapter intends to identify and quantify resource flows in households to provide insights to their behaviour in terms of their environmental sustainability. As Céspedes Restrepo & Morales-Pinzón (2018) points out a metabolic system depends on imported resources which in return export high amount of waste to the ecosystem are considered unsustainable. Some of the practices in Sri Lankan households that encourages sustainable inflows include high self -sufficiency rate in energy and water consumption, increasing home gardening practices and awareness of organic food. While declining energy intensities, increasing use of energy saving appliances and measured and decreasing energy use for cooking improve the sustainability of household process while improvements in wastewater treatment and waste segregation and collection practices lessen the environmental impact of outflows. Some of the household practices that discourages sustainability of inflows are increasing dependence of fossil fuels, decreasing self-sufficiency, over extraction and lack of accountability for groundwater consumption and increasing consumption of animal-based products. Still prevalent inefficient cooking practices, increasing private transportation and increasing water intensities in absence of water saving measures negatively impact the environmental sustainability of metabolic process of a typical household. Further increasing CO_2 emissions, increasing wastewater with poor reuse/recycle practices, poor waste management practices absence of reuse/energy recovery measures amplifies the negative environmental impact of the outflows.

Results concludes more pro-environmental consumption patterns can be observed during the extraction stage of energy, water, and food by households from its hinterlands. Wherein handling of waste and wastewater emissions in which responsibility is shared by householders and local authorities yet to implement environmental-friendly disposal/reuse/recycle practices. Reducing intensities of water and food shows consumption patterns reinforced by efficient metabolic processes and vice versa. According to Strydom et al. (2020) studying metabolic flows ultimately leads to reshaping them either by improving efficiency, changing carriers or behaviours that leads to a more sustainable metabolic system. While a sustainable metabolic system desire more circular metabolic flows that reuse waste outputs as new inputs of the same system (Lucertini & Musco, 2020), findings show the household metabolic flows in Sri Lanka have remained linear over the years without much improvements. Shaping circular metabolic flows intervene in creating a more circular economy with improved resource sustainability (Barro, 2021).

This chapter highlights the importance of identifying and evaluating resource flows across the metabolic processes from extraction to emissions to effectively identify the environmental impact of the consumption patterns. Further, successfully demonstrates the applicability of SEM concept on a household scale to identify the environmental sustainability of household consumption patterns. Lack of recent data availability regarding sociodemographic factors, groundwater consumption, waste and wastewater emissions has been one of the major limitations of this study. Which is particularly prevalent in conflict-affected areas during the civil war period (1983-2009). Overcoming the above limitations future studies should explore quantitative analysing sustainability of integrated metabolic flows that allows to compare sustainability in consumption between households across cities and countries. Further current study should expand across the boundaries of the metabolic system considering the lifecycle of resources to better understand the interdependencies and trade-offs among resources.

CHAPTER 5 CARBON EMISSIONS IN JAPANESE ONE-PERSON HOUSEHOLDS

5.1 Introduction

The one-person household has being the fastest growing type of household in many areas around the world, while more than 120 million new one-person households are expected to be added over the period 2016–2030 (Yeung and Cheung, 2015). This growth could be attributed to many factors including declining marriage rates and inclining divorce rates, rising personal income, changing preferences for privacy, decreasing incidence of multigenerational households, and labor migration (Bradbury et al., 2014; Keilman, 1988; Jianguo Liu et al., 2003; Wulff, 2001; Yeung and Cheung, 2015; Yu and Liu, 2007; Yeung and Cheung, 2015; Piekut, 2020). Figure 5-1 illustrates the acceleration in one-person households after 1960s across all regions of the world. During the recent decades, in high-income European countries it has accounted for more than 40% and less than 5% in low-income Asian countries (Snell, 2017). Prevalence of one-person households in Asia is less significant than in Europe and North America. Japan, South Korea and Taiwan have the highest proportion of one-person households in Asia, at 32.4%, 23.9%, and 22% respectively (Yeung and Cheung, 2015). Further Rude (2020) attributed half of the 31% growth in one-person households during last decade, to Asia Pacific.

Despite the declining population over the past decades, number of Japanese households has increased by 2.73 million in last five years. According to the 2020 census, one-person households account for 38% of all households in Japan, which was once 19.8% in 1980. According to the estimates of (MIAC, 2020) the rate of single-person households is expected to reach nearly 40% in 2040. With household size reducing from 3.22 to 2.49 during last four decades, “Married couple and children” households, which was standard type of households for many decades now only account for 25% of the total households in 2020 (MIAC, 2020). Tokyo has the highest number of one-person households (3.63 million) which is more than 50% of Tokyo’s population followed by Osaka, Kyoto, Fukuoka, and Kanagawa.

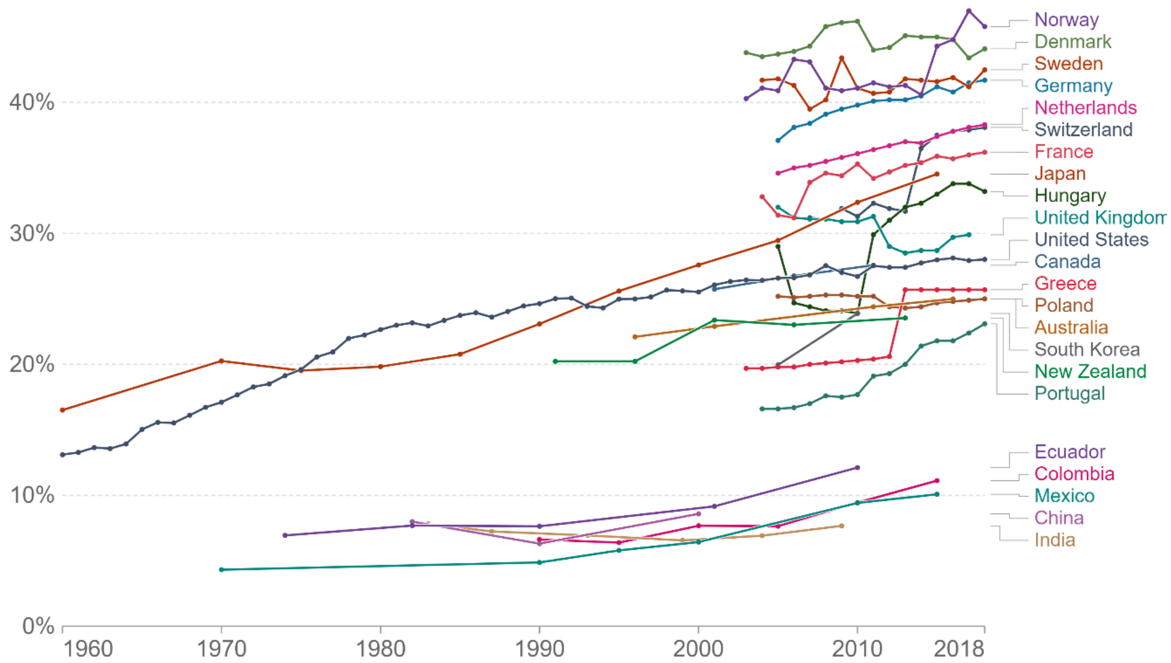

Figure 5-1: Percentage of one-person households, 1960 to 2018 (OWID, 2020)

According to the household surveys conducted by (MIAC, 2020) average age of one-person householders has reached 59.3 years in which 26% and 16% accounts for females and males that are 60 years or older respectively. Householders that are in 35 - 39 years accounts for 32% followed by less than 34-year householders. With compared to elderly one-person households, younger one-person households show a declining trend. Majority of elderly one-person householders that are either retired depending on pension and government benefits belongs to lower income deciles. MIAC (2020) further reveals with the increase of elderly one-person householders, employment rate of one-person householders is declining which was 51% in 2018. On the contrary the home ownership of one-person householders and increased up to 57.8% while the percentage of one-person householders that rents a house has decreased up to 36.6%. Per capita household expenditure of a one-person household is 160% higher than that of multiple-person households in 2020 (MIAC, 2020) which has shown a slight decreasing trend over the years.

As Ivanova et al. (2016) highlight households consume 50–80% of total land, material, and water use while emitting 65% of GHG. Therefore many researches have emphasized the importance of focusing on household resource consumption is crucial in reducing environmental impact (Bradbury et al., 2014). The environmental implications of declining household size and increasing one-person households have been a concern of researches since last decade (Liu et al., 2003; Williams, 2005; Yu and Liu, 2007). Liu et al. (2003) emphasize serious challenges to biodiversity caused by increasing per capita resource consumption in smaller households. Bradbury et al. (2014) highlight importance of strengthening the policies and incentives considering the negative impact of increasing detached single-unit suburban houses on environmental sustainability. Ellsworth-Krebs, (2020), foresee the possibility of future GHG reduction targets been hindered by increasing direct energy in smaller households. Williams (2005) recognizes one-person households as resource time-bombs due to their comparatively higher per capita land, energy, goods, and materials consumption, thus calling for more research in determining consumption patterns and their environmental impact. Further Yeung and Cheung (2015) calls for further theoretical development and empirical work in understanding changes in lifestyle and consumption particularly Asian one-person households. However, consumption behaviors and related environmental impact of one-person households are yet to be explored.

Understanding environmental impact is imperative to minimize the damage caused by increasing resource consumption of one-person households. Carbon footprint is one such analytical technique that systematically evaluates the carbon emissions associated with human activity (Long, Dong, et al., 2018). Many researches have utilized this method to assess the environmental burden of household consumption for the last few decades (Caponio et al., 2014; Hardadi et al., 2021; Salo et al., 2021; Shigetomi et al., 2014; Sun et al., 2021; Wang and Chen, 2020; Zen et al., 2021; Feng & Hubacek, 2016; Hubacek et al., 2017). Carbon footprint calculate all GHG emissions of global supply chain from production to consumption of final goods and services within the territory of a human settlement within a given year (Minx et al., 2013). It mainly consists of direct i.e., gas, kerosene, gasoline; and indirect i.e. other non-energy related goods and services; GHG emissions of household consumption. For a long time, the studies on carbon footprint of households' consumption have only being considering direct emissions which accounts for only a small portion of total emissions (Guo and Liu, 2013). Including indirect emissions will ensure embedded emissions of imported goods are considered as well thus embracing all stages of supply chain from the extraction of resource to the final consumption (Long et al., 2017; Long, Jiang, et al., 2021b; Ma et al., 2016a; Wu et al., 2019). Many input-output (IO) models have been successfully utilized in quantifying consumption based indirect emissions in households (Long, Dong, et al., 2018). IO table represent the flow of goods and services throughout the global economy along with related emissions and resources required (Ivanova et al., 2016). Environmentally Extended Input-Output (EEIO) method, derived from the Leontief's top-down economic IO model (Leontief, 1936), link consumption of goods and services with associated environmental ecological elements such as energy and carbon emissions (Xu et al., 2021). Therefore it has been widely used for calculating carbon footprint to assess economy-wide environmental burdens stemming from household consumption (Hertwich, 2011; Huysman et al., 2016; Ivanova et al., 2016; Kanemoto et al., 2020a; Long, Yoshida, et al., 2018; Shigetomi et al., 2014).

Japan is constantly striving in promoting low-carbon policies in its efforts to realize a carbon neutral society in 2050 (Gokhale, 2021; Kuriyama et al., 2019; Shigetomi et al., 2014; Yagita and Iwafune, 2021). Household sector accounts for a significant portion of overall GHG emissions (191million $MtCO_2$ in 2014) (Ministry of Environment, 2015) and Japan's average carbon footprint is estimated to be 2.7 times higher than the global average (Koide et al., 2019). Number of researchers have utilized carbon footprint in evaluating household consumption related emissions in Japanese households. Some researchers have considered only energy related or fuel specific carbon footprint of Japanese households (Long, Dong, et al., 2018; Long, Yoshida, et al., 2021; Taniguchi-Matsuoka et al., 2020). Shigetomi et al. (2021) and Koide et al. (2021) have explored carbon footprint potential in lifestyle choices in Japan yet differences based on household composition has not being considered. Kanemoto et al. (2020a) and Shigetomi et al. (2014) have studied household carbon footprint based on spatial and age variations. Studies analyzed household attributes contributing to variations in carbon footprint have concluded household size is contributing to high-carbon lifestyle (Koide, Kojima, et al., 2021). However, most studies have not separated carbon footprint of one-person households from multiple-person households hindering comprehensive understanding of emissions related to one-person household consumption patterns (Koide, Kojima, et al., 2021; Long et al., 2017, 2019). Long, Jiang, et al. (2021a) justified exclusion of one-person households in calculated average household carbon footprint due to their prevalence, distinctive patterns of consumption, which overestimate per capita emissions in Japan.

Difficulties in changing the energy mix by incorporating alternative energy sources and slowly progressing energy conservation measures (Arimura and Matsumoto, 2020) have emphasized importance of energy conservation measures and pro-environmental consumption patterns more than ever. Thus, there is a need to understand environmental impact of high-carbon life choices such as living alone. This chapter intends to fill the knowledge gap caused by lack of research regarding in-depth understanding of GHG missions related to one-person household consumption by assessing carbon footprint on Japanese one-person households. Methodical analysis of GHG emissions and mitigation focused on one-person households can aid in lessening the critical negative impacts of climate change by designing countermeasures to alternate consumption patterns. With a better understanding of the carbon intensive lifestyle choices, policymakers can thus influence householders in adapting an economically and environmentally friendly lifestyle (Long, Dong, et al., 2018). Aim of this chapter will be achieved quantify the direct and indirect consumption based GHG emission of one-person households in 2001 and 2015, quantifying carbon footprint of one-person households and comparing that of multiple person household carbon footprint of respective years.

Starting with a comprehensive literature background, this section is comprised with three more sections. Methods and materials will explain the utilization of EEIO with household expenditure data. Results and discussion section will elaborate the findings of the GHG emissions and carbon footprint while last section will conclude the paper with policymaking implications.

5.2 Materials and Methods

Carbon footprint consists of direct and indirect GHG emissions of household consumption. Carbon emissions coefficients have been used to quantify the direct emissions and embodied carbon emissions based on EEIO method has been used to quantify the indirect emissions (Figure 5-2). The indirect and direct GHG emissions were estimated using two sets of microdata namely household expenditures of goods and services and related GHG intensities. Household consumption expenditure which was obtained from Family Income and Expenditure Survey (FIES) (Statistics Bureau of Japan, 2011, 2015) which is a monthly survey regarding the household expenditure conducted by Statistics Bureau of Japan's Ministry of Internal Affairs and Communication. The survey covers one-person and multiple-person households in cities with a population of over 50,000 ranging from major cities to smaller cities and towns. Expenditure data spread over more than 500 distinctive types of goods and services which have been aggregated into 12 consumption domains in Table 5-1. This study calculates direct and indirect GHG emissions for year 2011 and 2015 as to couple with Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (3EID), which is only calculated every 5 years (Nansai et al., 2002).

5.2.1 Direct emissions

In this study four types of fuel namely kerosene, gasoline, Liquefied Petroleum Gas (LPG) and city gas were considered in quantifying direct emission. Electricity was considered as an indirect emitting GHG emitting source as it will not have direct emissions upon consumption. Firstly, household fuel expenditure data was converted from monetary values to physical quantities following several steps. Retail prices were used to convert subsequent fuel mass or volume by dividing the expenditure amounts obtained from FIES by retail prices. Then CO_2 emissions coefficients were used to convert the fuel volume or mass into Mt CO_2e (Equation 5-1). Average unit price for gasoline, kerosene and LPG is given in annual FIES report (Statistics Bureau of Japan, 2011, 2015) and prices for city gas taken from Statistics of Japan, (2011, 2015) which were used to calculate the volume and then subsequently multiplied with respective emission coefficients provided by Ministry of the Environment (2020). Conversion coefficient suggested by Ministry of the Environment (2020) were used in converting liquid LPG (ton) weight into gaseous LPG (m3) volume. Direct emissions are then calculated as follows.

$$E_i^{di} = \quad e_j^i \, Exp_i \qquad \text{Equation (5-1)}$$

where E_i^{di} is the direct emission of each fuel expenditure item; e_j^i is the CO_2 emissions coefficient of consumption item i based on fuel type j and Exp_i refers to the monetary expenditure on consumption *i.*

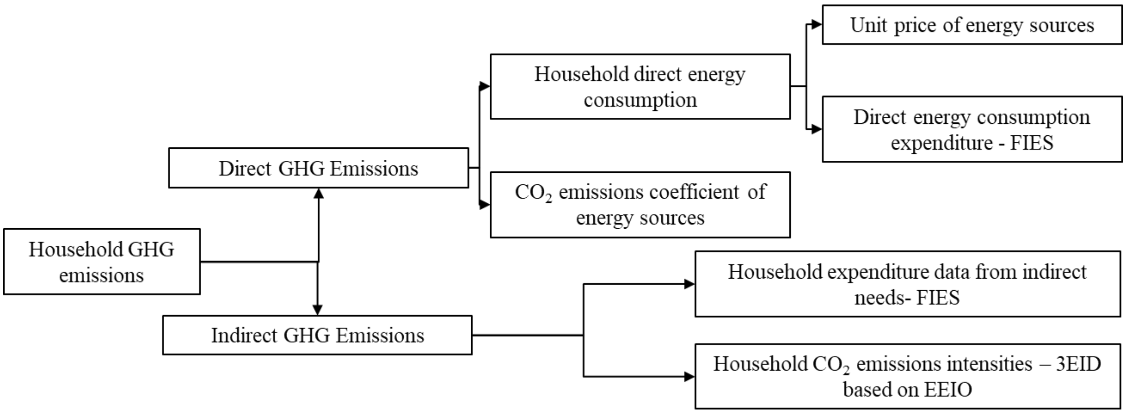

Figure 5-2: Research flowchart

5.2.2 Indirect emissions

This study utilizes EEIO method to trace the indirect emissions related to consumption of all products and services. Leontief (1936) founded the IO model correlating production and consumption with the total demand coefficient to reveal the quantitative interdependencies between IO in all sectors of an economic system (Ma et al., 2016b). IO model has then transformed into EEIO table to trace flows of indirect energy and transfer of related emissions. The correlation between final consumption and related impact to the environment is shown by Equation 5-2.

$$Y = (I - A)^{-1}F \qquad \text{Equation (5-2)}$$

where Y is the total domestic production output of each sector, I is the identity matrix, A is the direct input coefficient matrix, and F is the final consumption of each sector. $(I - A^d)^{-1}$ represents the Leontief inverse matrix when sectorial emission intensities are calculated considering imported goods. When the input ratios of imports differ among sectors inverse matrix coefficients of "non-competitive import type" is utilized (Statistics Bureau of Japan, 2011, 2015). Equation 5-3 displays the modified version of total domestic production considering imports.

$$Y = (I - A^d)^{-1} F^d \qquad \text{Equation (5-3)}$$

Matrix of domestic input coefficients and the domestic final consumption are indicated by A^d and F^d respectively. Finally embodied emissions in daily consumption of goods and services in households are calculated using Equation 5-4 by combining with household consumption inventory.

$$E_i^{in} = Exp^i \sum_{j=i} e_j^i * (I - A^d)^{-1} \qquad \text{Equation (5-4)}$$

Embodied emission of consumption item *i* is indicated by E_i^{in}; financial expenses of consumption item *I* is referred by Exp^i; intensity of direct emission of consumption item *i* related to fuel type j is indicated by e_j^i. Direct emission intensity is then transformed into indirect emission intensity multiplying by Leontief Inverse Matrix.

$$\text{Household carbon footprint (HCFP)} = E_i^{di} + E_i^{in} \qquad \text{Equation (5-5)}$$

Household carbon footprint was then calculated by combining direct E_i^{di} and indirect E_i^{in} GHG emissions. The same process was applied to both one-person and multiple-persons households. Multiple-persons households consist of all the households that are not one-person households. The household carbon footprint of multiple-persons households was then divided by average household size to obtain the per capita carbon footprint. The average household size for multiple-persons households was 3.08 in 2011 and 3.02 in 2015.

Nansai et al., (2002) has developed from 3EID database of Japan's sectoral intensity of lifecycle environmental burden composed using IO tables for Japan using a globally linked EEIO model. 2011 and 2015 3EID data tables which were respectively based on 2011 and 2015 IO Tables for Japan were used to calculate the indirect emissions of this study. However, emission classifications from 3EID and consumption classification from FIES don does not overlap in goods or services concerned. Therefore, FIES consumption expenditure data that have been categorised into 12 consumption domains (Table 4-2) have been matched and cross-mapped with 3EID emissions intensity categories based on best possible outcome.

Table 5-1: Household consumption inventory based on family income expenditure survey

Household consumption domain	**Items in household consumption inventory**
Food	Rice, bread, Noodles, other cereals, fish and shellfish, meat, dairy products and eggs, vegetables, soybean products, fruits, oils, fats and seasonings, cakes and candies, cooked food, tea, coffee and cocoa, alcoholic beverages, meals outside the home
Housing	Rents for dwelling, private, repairs and maintenance
Fuel, light and water charges	Electricity, gas, other fuel and light, Kerosene, water and sewerage charges
Household durable goods	Electric appliances, gas cooking appliances, other heating and cooling appliances, general furniture, Interior furnishings and decorations, Lighting appliances, Interior decorations, domestic utensils
Household non-durable goods	Facial tissue and rolled toilet paper, detergent, polyethylene bag and food wrap, Insecticide and moth repellent, domestic services
Clothing and footwear	Japanese clothing, men's clothing , women's clothing, children's clothing, shirts and sweaters, underwear, cloth and thread, footwear, other services
Medical care	Medicines, health fortification, medical supplies and appliances, medical treatment, massage fee, Etc., fees for complete medical checkup etc., other medical services
Transportation	Public and private transportation, gasoline, automotive parts, automotive maintenance, and repairs, yearly and monthly rent for park, insurance premium
Communication	Postage, telephone charges, other communication equipment

Education	Class fees, textbooks and learning reference materials, supplementary education
Culture and recreation	Recreational durable goods, repair charges of recreational durable goods, accommodation services, Package tours, lesson fees, admission fees for movies, plays, etc., membership dues, photography, and photographic processing charges
Other consumption expenditures	Personal care goods and services, personal effects, services related to personal effects, tobacco

5.2.3 Results and discussion

Results reveal that the average household carbon footprint of one-person households and multiple-person households are 6.5MtCO_2 and 12.9MtCO_2, respectively. However, per capita carbon footprint is 56% higher in one-person households (7.13MtCO_2) than multiple-person households (4.56 MtCO_2) in 2011 and its 51% higher in 2015 which is 6.53 MtCO_2 in one-person households and 4.3 MtCO_2 in multiple-person households. There is an overall reduction in carbon footprint in both types of households between the years. As expected, Figure 5-3 shows indirect emissions account for more than 80% of carbon footprint of both one-person and multiple-person households where direct emissions only account for less than 20%. Both types of households show a 9% reduction in direct emissions between years. The pie chart in Figure 5-3 represents the proportion of expenditure of each household domain in the inner ring and corresponding carbon emissions from the outer ring. Results show fuel, light and water only account for 8% of a typical household expenditure while contributes to half of the carbon emissions from a household.

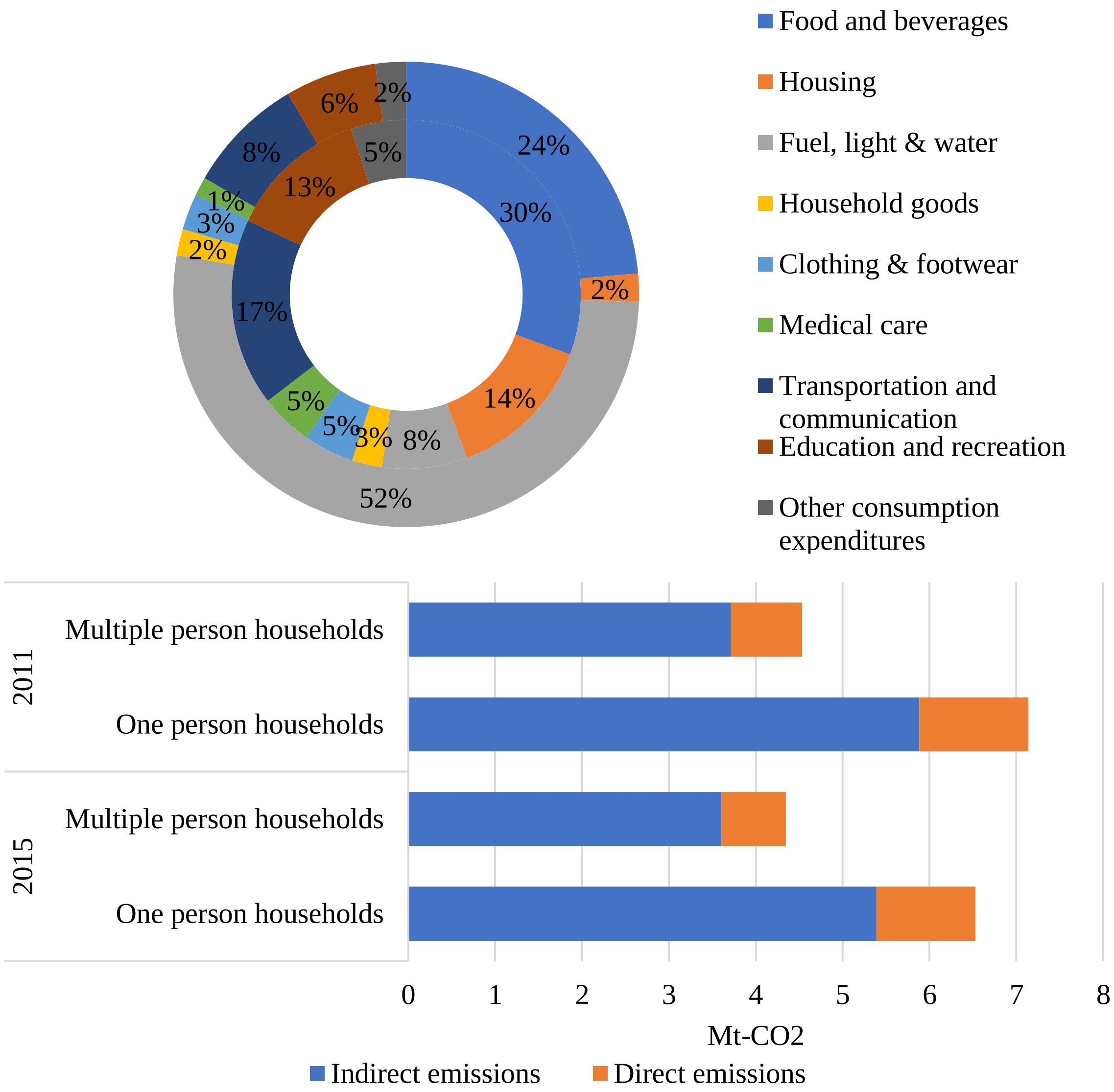

Figure 5-3: Carbon footprint of one-person and multiple-person households compared with household expenditure

Further according to Figure 5-4, when fuel, light and water only accounts for 6% of one-person household expenditure, it contributes to 50% of the carbon footprint of one-person household. Whereas food accounts for 46% of one-person household expenditure, when it contributes to 30% of the carbon footprint of one-person households. Results show regardless of the low emission intensities of food and beverages, higher consumption has led to significant contributions to total CO_2 emissions. Results show private transportation accounts for more than 50% of the emissions from transportation and communication followed by public transportation.

The average per capita direct carbon footprint from one-person household is 1.25 $MtCO_2$ in 2011 and 1.14 $MtCO_2$ in 2015. Direct carbon footprint of one-person households are 1.5 times higher than multiple-person households. Results in Figure 5-4 recognize gasoline as the major source of direct emissions both one-person and multiple-person households which is more than 40%. Li et al. (2021) reveals that 87% of transportation related emissions in Japan originate from private transportation. Expenditure data shows multiple-person households are more prone to use private transportation while one-person households prefer public transportation. However due to sharing of vehicle by multiple persons, per capita transportation carbon footprint of multiple persons recedes that of one-person households.

Results further show total carbon emissions from gas account for more than 30% combing city gas and LPG which has the least contribution. Kerosene which is more widely used in small and rural cities for heating purposes (Long, Dong, et al., 2018) contributes to

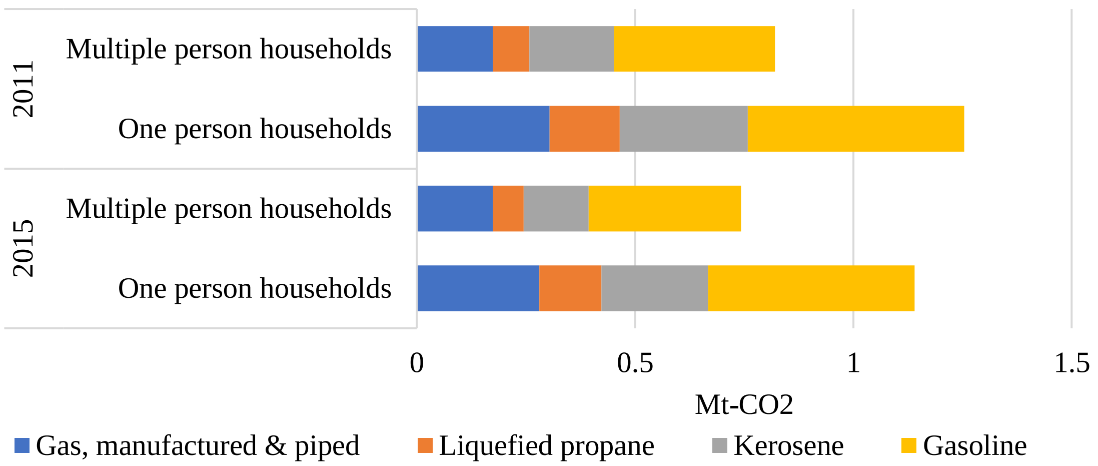

Figure 5-4: Per capita direct GHG emissions of one-person and multiple-person households

about 20% of direct emissions which has slightly reduced in 2015. However, emissions from LPG which are often used for cooking are more than two times higher in one-person households. Based on consumer expenditure, one-person householders prefer to go out to eat and buy cooked food. In spite emissions from LPG than in one-person households more than two times higher one-person householders have higher consumption of gas and subsequent emissions with compared to multiple person householders who prefer homecooked meals with their families. This implies energy savings derived from economies scale of cooking by multiple person householders outweighs the energy reduction by cooking less frequently by one-person householders. A slight decline (9%) in direct carbon footprint is visible from 2011 to 2015, in which emissions from kerosene (17%) and LPG (11%) show visible decreasing trends due to decrease in consumption.

The indirect carbon footprint from one-person household is 5.88MtCO_2 in 2011 and 5.39MtCO_2 in 2015, 3.71MtCO_2 in 2011 and 3.6MtCO_2 in 2015 which are 1.5 times higher in one-person households. Except for indirect emissions related to educational services, indirect emissions in one-person households are higher in all the consumption domains. Emissions from housing, culture and recreation, and other consumption expenditures are twice as much higher in one-person households. As Williams (2002) explains, emissions from housing which consists of rents, repairs and maintenance and service charges for repairs and maintenance could pose a major challenge for one-person households in absence of shared living benefits. Escalating emissions from culture and recreation, and other consumption expenditures can be attributed to urban singles who prefer socializing and splurge on entertainment related activities.

As shown in Figure 5-5 fuel, light and water accounts for more than 40% of the per capita indirect emissions from both household types which has slightly averaged moving from 2011 to 2015. Significant proportion of indirect emissions from fuel, light and water consumption is attributable to electricity followed by water and sewerage related emissions. According to Long et al. (2018) suspension of Fukushima Nuclear Power Plant prompted by the Great Earthquake of 2011, have increased dependence on fossil fuel-based power plants that have higher carbon emissions. Thus, Japan is struggling to shift towards alternative energy sources and changing the energy mix which would benefit in reducing indirect emissions from electricity (Arimura and Matsumoto, 2020). Survey conducted by MIAC (2020) reveals majority of electricity in one-person households is consumed by lighting and home appliances (36.8%) and heating (25%) which often benefits from economies of scale in reducing consumption. Survey further shows usage hours of lighting, heating and air conditioning appliances do not significantly differ between one-person and multiple-person households. Ellsworth-Krebs (2020) has highlighted decreasing household size had led to increase in floor area thus leading to higher energy consumption induced by other housing related activities. According to the household survey (MIAC, 2020) in 2013, average floor area of 58% of the self-owned one-person households and 64% of self-owned multiple-person households rages from 70 to 149 sq.m., implying higher per capita floor area in one-person households. in addition Yagita and Iwafune (2021) show that elderly people which accounts for more than 50% of the one-person households and predominantly growing type of one-person household, often remain in their houses for longer periods, owns older or larger houses and older home appliances causing higher energy consumption and carbon footprints.

Food related carbon footprint accounts for 28% of the overall carbon footprint in both household types. Except for emissions from meat consumption, one-person households have higher emissions from all types of food items in which emissions from cooked food consumption and beverages are twice as high. Carbon footprints of all consumption domains show a declining trend from 2011 to 2015, education (82%) and housing (26%) related emissions showing the highest decline. However, being the highest emitting consumption domains, food (4%) and fuel, light and water (3%) show the lowest decline over the five years. Within food related carbon footprint meat, dairy products and eggs, sugar and confectionery and cooked food shown an inclining footprint in one-person households.

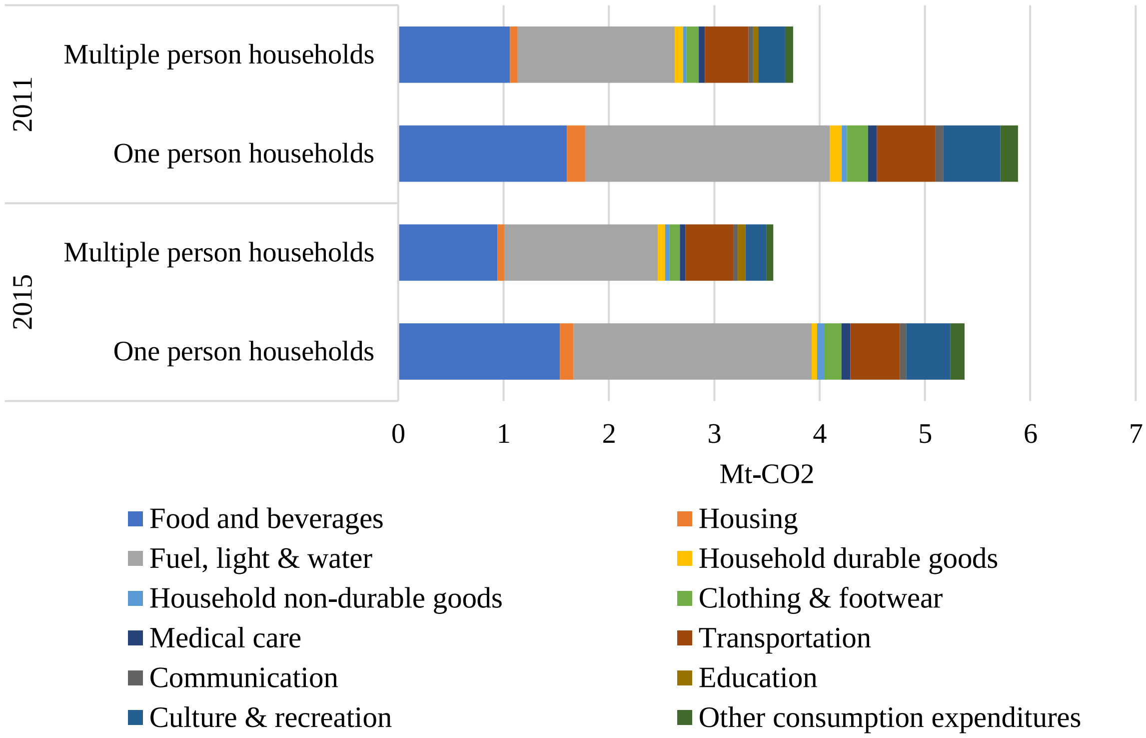

Figure 5-5: Per capita indirect GHG emissions of one-person and multiple-person households

5.3 Lessons learned from Japanese household consumption

Declining members per household is becoming one of the main concerns threatening resource consumption in both developed and developing countries. According to World Bank (2020), average household size in Sri Lanka has reduces from 5.1 to 3.7 during the last two decades. Household consumption and emissions results based on Japanese one-person households shows that reducing household size can increase the consumption and related emissions significantly. Indirect emissions contribute to more than 80% of the total carbon emissions showing the importance of considering both direct and indirect energy flows in understanding household consumption. However, the total carbon emissions in Japanese households show a declining trend over the years along with declining resource consumption. Decline in direct energy consumption and related emissions without much change in energy mix can be attributed to increase in efficiency in equipment and appliances used by householders. Further increased use of public transportation and availability of durable and non-durable goods and services with low embodied carbon has contributed to the decline in indirect carbon footprint.

5.4 Conclusions

This topic utilized EEIO to quantify the indirect emissions using consumer expenditure data combining with 3EID data table. Then direct emissions were calculated by converting the expenditure data of each fuel obtained from the FIES and converting into subsequent mass. Results reveal total per capita GHG emissions of one-person households are 7.13MtCO_2 in 2011 and 6.53 MtCO_2 in 2015 which is 150% higher with compared to corresponding multiple-person households. While direct emissions only accounts for 20% of carbon footprint in which gasoline accounts for 41% in 2015 followed by city gas. One-person household has emitted 5.8MtCO_2 and 5.3MtCO_2 indirect emissions in 2011 and 2015 respectively where GHG emissions from electricity been the highest carbon emitter followed by food and beverages consumption. One-person household emits twice as much indirect emissions in three out of twelve consumption domains and more than 50% in nine consumption domains. However, carbon footprint shows a decline from 2011 to 2015 in both types of households.

When considering the household carbon emissions within the Japanese context gasoline being the highest carbon intensive direct energy source, one-person householders should be further encouraged to use more public transportation in absence of sharing benefits when using private transportation. Since cooking for a one-person can lead to higher gas induced carbon footprints, householders should be encouraged to use more efficient cooking appliances or cooking in bulk. Efficient and less frequent use of household electrical equipment and appliances can reduce the electricity related carbon footprint. Energy saving technologies and energy efficient equipment need to be promoted among elderly one-person householders who spend most of their time at home. As electricity being the highest one-person household emitter, policies should be more strengthened in changing the energy mix by transferring to alternative energy sources to reduce electricity related carbon intensities. Younger one-person householders should be persuaded of more efficient spending in recreational activities, in which indirect emissions are two times higher than the multiple-person households. Means of promoting home cooked meals need to be introduced in reding high carbon emissions related to consumption of cooked food and eating out. Local policies endorsing communal and collaborative housing (Williams, 2007) specially among young urban singles could substantially reduce carbon footprint reaping the benefits of economies of scale. Though carbon footprint shows a declining trend been 2011 and 2015, critical carbon emitters such as gasoline, food and beverages and fuel, light and water have the lowest emission decline. Thus, implicating carbon mitigating policies should focus more on the highest emitting consumption domains.

Due to inadequacy of knowledge available regarding direct and indirect GHG emissions of one-person household consumption, this study can provide insights in promoting sustainable consumption and production. Prevalence and distinct consumption patterns between one-person and multiple-person households emphasize the need to be separated in resource consumption related evaluations of households, which can otherwise lead to higher national averages of per capita household consumption and emissions. Policy makers should be persuaded to further explore household dynamics and socio-demographic differences in one-person households in promoting environmentally friendly life choices and lest carbon intensive consumption patterns. Improving local policies considering consumer responsibility in reducing consumption-based emissions can further the effectiveness GHG mitigation policies. One-person householders should be made aware the environmental consequences of household purchasing decisions. One-person household consumption needs which resulted in majority of GHG emissions such as consumption of electricity, cooked food and transportation should be the focal point in designing tailored and targeted policies for household GHG emissions reductions.

Lastly, this study sets a foundation for future studies with regards one-person household consumption patterns and related emissions in transitioning towards a low-carbon future. Further research could focus on variations in socio-demographic and economic characteristics of one-person households and their impact on household consumption and emissions patterns.

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Chapter 1 introduces the research background while defining sustainable production and consumption and socio-economic metabolic flows and national and household level. Chapter elaborates the aim and objectives of the study along with research questions while solidifying the timely need of the topics with comprehensive literature review.

Chapter 2 addresses the first stage of the thesis, which is to develop an energy metabolic model. 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. Results show that CO_2 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. Mapped direct energy metabolic flows demonstrates biomass/domestic and commercial sector as the strongest arrow indicating the largest flow of energy. Indicators evaluating the energy metabolic system show increase in energy efficiency with energy intensity gradually decreasing. Decreasing security of energy system with declining self-sufficiency rate and increasing accessibility and affordability of energy can be observed.

Chapter 3 demonstrated the sustainability evaluation of the of energy metabolic system with regards to social, economic and environmental indicators that were selected and analysed using stakeholder participation and multi-criteria decision analysis respectively. Results show increasing economic sustainability with decreasing overall and sectorial energy intensities over the years. 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 CO_2 emissions per capita and reducing renewable energy share. 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 indictors while demand side energy measure shows moderate improvements but in all three dimensions i.e., economic, social, and environmental. While both the scenarios show more than 10% reductions in CO_2 emissions, to achieve the committed 20% reductions a combination of INDCs needs to be implemented.

Chapter 4 focus on exploring metabolic flows of Sri Lankan households during the past decade based on the household expenditure survey data by converting them to physical quantities. Overall findings show the household metabolic system in Sri Lanka consumes 60 million of electricity units, 846 million litres of petroleum products and 31.5 million tons of firewood and LPG per year emitting 10 million tons of carbon dioxide. Household consumes 640 billion litres of pipe-borne water and 600 million tons of food while generating more than 19 million tons of food waste. Firewood predominately used for cooking dominates 63% of the energy profile as the main energy carrier and 43% of the CO_2 emissions from energy consumption. Overall energy consumption of a household has reduced by 28% during the last decade indicating increase in efficiency in metabolic process while CO_2 per household has increased by 1%. More than 60% of the water needs of a household is fulfilled by groundwater with pipe-borne water consumption per household increasing eight-fold last decade. Bathing, washing, and toilet flushing are responsible for 80% of the water use while more than 95% of the households disposes wastewater on-site. Without much change in calorie intake the composition of a typical household diet has changed from lesser rice consumption to more animal-based products consumption. Majority of food waste generated are handled by the householder either by burning or dumping. Findings show strong discrepancies in energy, water and food consumption based on the location of the households. Household consumption in Sri Lanka increases with level of urbanisation, income and education which significantly affect in deciding sources of cleaner energy, consumption of pipe-borne water, and dietary related decisions such as meat consumption. However, incline in metabolic consumption is higher in rural low-income households with compared to urban households over the years. While rural households are comparatively self-sufficient and sustainable in extracting resources, they lag in handling emissions due to inefficiency in resources consumption and disparities in wastewater and solid waste disposal mechanisms provided by local authorities. Figure 6-1 summarises the SEM flows of energy production and household consumption of Sri Lanka in 2016.

Chapter five utilized EEIO to quantify the indirect carbon emissions using consumer expenditure data combining with 3EID data table. Results reveal total per capita GHG emissions of one-person households are 7.13MtCO_2 in 2011 and 6.53 MtCO_2 in 2015 which is 150% higher compared to corresponding multiple-person households. While direct emissions only account for 20% of carbon footprint in which gasoline accounts for 41% in 2015 followed by city gas. One-person household has emitted 5.8MtCO_2 and 5.3MtCO_2 indirect emissions in 2011 and 2015 respectively where GHG emissions from electricity been the highest carbon emitter followed by food and beverages consumption. One-person household emits twice as much indirect emissions in three out of twelve consumption domains and more than 50% in nine consumption domains. However, carbon footprint shows a decline from 2011 to 2015 in both types of households. Decreasing energy consumption and carbon emissions shows positive impact of current energy and environmental policies.

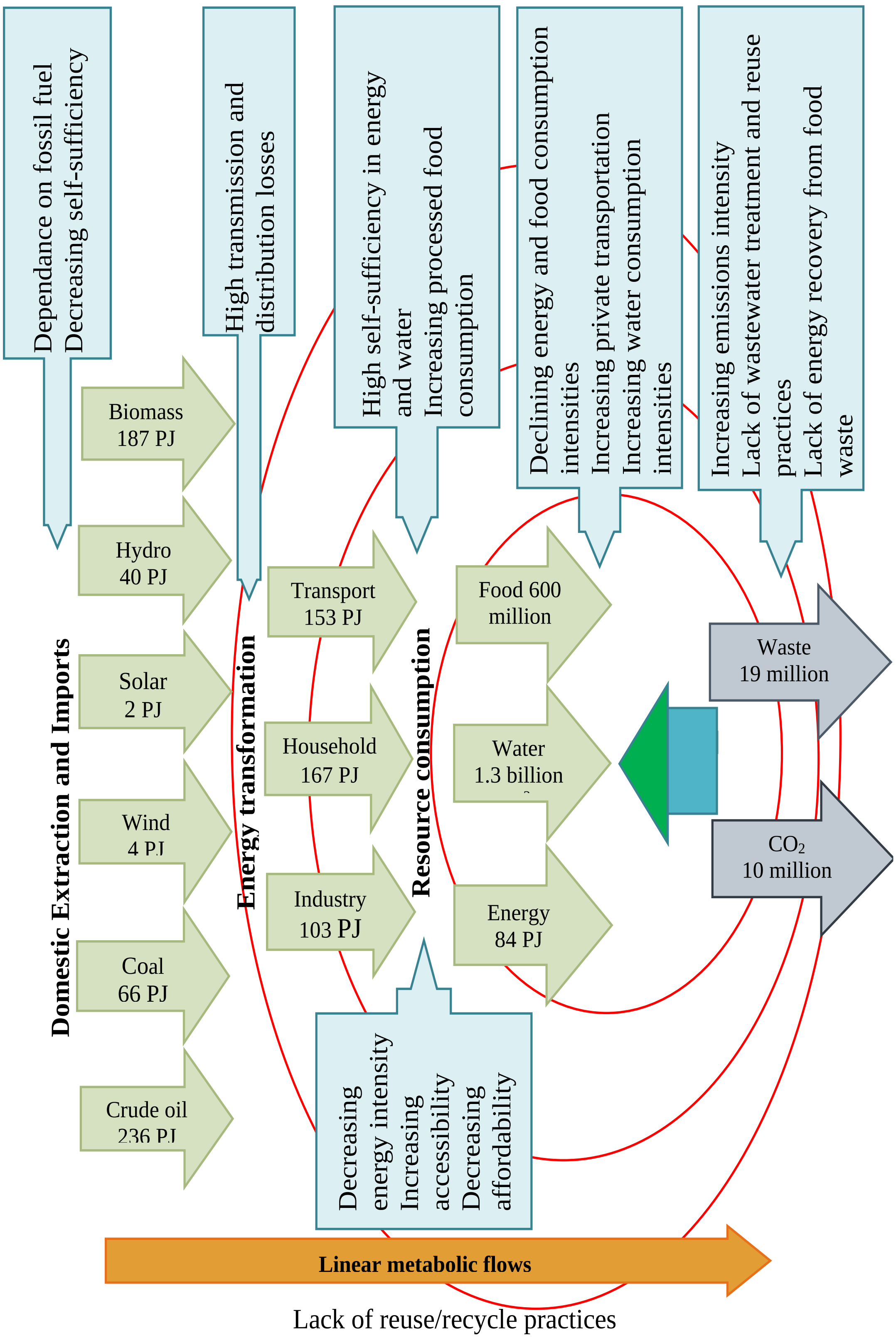

Figure 6-1: SEM flows of Sri Lanka in 2016

6.2 Implications and recommendations of the study

As Sri Lanka becomes more dependent on the imported fossil fuels more its security and affordability are threatened. Energy conservation measures need to be strengthened in domestic sector and transport sector to reduce energy consumption and CO_2 emissions, respectively. 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 et al (2021) points 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 has 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 need 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, 2002a). Developed framework give new insights to the energy system of Sri Lanka and problematic issues to be addressed to improves 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.

The findings of household metabolic flows call for expanding the focus of policies from structures to consumption practices of households and the interdependencies of resources to encourage consumer engagement in minimising environmentally unsustainable consumption patterns. Results show environmentally unsustainable consumption practices are more prominent in energy inflows. As electricity is becoming more popular among households it is imperative to improve the cleanliness of electricity as an energy source by changing the energy mix which currently heavily depend on fossil fuels. While 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 (ADB, 2018). Interventions for increasing sustainability of water inflows should include increasing accountability for groundwater consumption, tackling the disparities in availability of pipe-borne water to rural areas and promoting rainwater harvesting. As the most energy intensive metabolic process cooking needs to be improved by promoting energy efficient cooking appliances and use of clean energy sources. With highest incline in emissions during the past decade, reducing environmental impact of private transportation need to be prioritised by uplifting public transportation and encouraging alternative fuel vehicles. Water saving measures need to be promoted to reduce water consumption of bathing, washing clothes and toilet flushing. Unstainable consumption practices are most visible in food and water outflows as households fail harness the power of secondary resources (waste, wastewater) by feeding them back into the metabolic system creating a circular metabolic system. Therefore, streamlining of waste management system has become impetrative with the participation of all the stakeholders across the borders with efficient source separation, timely and adequate means of collection, and treatment practices. Wastewater disposal and treatment facilities need to be improved with equal access to urban and rural households. Further, private sector engagement needs to be encouraged in resource recovery and reuse in waste management. Lastly as Delis & Iosifidi (2020) reveals the role of households' environmental awareness should not be underestimated in improving environmental-friendly consumption patterns. Therefore, awareness regarding environmental impact of consumption needs to be raised through proper environmental education at school level and public education campaigns by local authorities.

Study of Japanese one-person households show prevalence and distinct consumption patterns between one-person and multiple-person households emphasize the need to be separated in resource consumption related evaluations of households, which can otherwise lead to higher national averages of per capita household consumption and emissions. Policy makers should be persuaded to further explore household dynamics and socio-demographic differences in one-person households in promoting environmentally friendly life choices and lest carbon intensive consumption patterns. Improving local policies considering consumer responsibility in reducing consumption-based emissions can further the effectiveness GHG mitigation policies.

Developed novel multidimensional sustainability indicator-based framework can be utilised to comprehensively evaluate sustainability of socio-economic metabolic flows of energy production and household consumption in data poor, least developed countries. This study provides insights into energy, food water and emissions flows driven by socioeconomic activities of least urbanized, developing, post-conflict country like Sri Lanka.

6.3 Limitations of the study and future studies

Within the broader field of socioeconomic metabolism, this study attempts to identify and evaluate metabolic flows at the household scale using bottom-up approach to understand consumption profiles and provide insights to the energy, water, and food flows in households. Lack of recent data availability regarding sociodemographic factors, groundwater consumption, waste and wastewater emissions has been one of the major limitations of this study. Which is particularly prevalent in conflict-affected areas during the civil war period (1983-2009). Further as Beegle et al. (2012) points out, accuracy of the data could be debatable at times particularly in illiterate rural households when filling out comprehensive questionnaires. Overcoming the above limitations future studies should explore quantitative analysing sustainability of integrated metabolic flows that allows to compare sustainability in consumption between households across cities and countries.

This study can further expand across the boundaries of metabolic system using lifecycle analysis to better understand the interdependencies and trade-offs among resources across the life span of resources. Depending on availability of data quantitative integration of metabolic flows that allows to compare sustainability across cities and countries.

REFERENCES

Abeyrathna, K. G. N. W. (2021). Factors affecting to organic food buying intention. *International Journal of Research -GRANTHAALAYAH*, *9*(4), 583–589. https://doi.org/10.29121/granthaalayah.v9.i4.2021.3900 (Accessed 31 July 2022)

Afgan, N. H., & da Graça Carvalho, M. (2000). Sustainable Assessment Method for Energy Systems. In *Sustainable Assessment Method for Energy Systems*. Springer US. https://doi.org/10.1007/978-1-4615-4479-1(Accessed 31 July 2022)

Akenji, L., Bengtsson, M., Chiu, A., Briggs, E., Daconto, G., Fadeeva, Z., Fotiou, S., Gandhi, R., Mohanty, B., Salem, J., Sang-Arun, J., Schandl, H., & Tabucanon, M. (2012). *Sustainable consumption and production: A handbook for policy makers, with cases from Asia and the Pacific*. 200.

Anand, A., Winfred Rufuss, D. D., Rajkumar, V., & Suganthi, L. (2017). Evaluation of Sustainability Indicators in Smart Cities for India Using MCDM Approach. *Energy Procedia*, *141*, 211–215. https://doi.org/10.1016/j.egypro.2017.11.094 (Accessed 31 July 2022)

Angelis-Dimakis, A., Arampatzis, G., & Assimacopoulos, D. (2012). Monitoring the sustainability of the Greek energy system. *Energy for Sustainable Development*, *16*(1), 51–56. https://doi.org/10.1016/j.esd.2011.10.003 (Accessed 31 July 2022)

Ankrah Twumasi, M., Jiang, Y., Addai, B., Asante, D., Liu, D., & Ding, Z. (2021). Determinants of household choice of cooking energy and the effect of clean cooking energy consumption on household members' health status: The case of rural Ghana. *Sustainable Production and Consumption*, *28*, 484–495. https://doi.org/10.1016/J.SPC.2021.06.005 (Accessed 31 July 2022)

Ari Kahan. (2016). *Global energy intensity continues to decline* . https://www.eia.gov/todayinenergy/detail.php?id=27032

Arimura, T. H., & Matsumoto, S. (2020). *Carbon Pricing in Japan*. https://link.springer.com/book/10.1007/978-981-15-6964-7 (Accessed 10 August 2022)

Ariyananda, T. (1999). Rain water harvesting for domestic use in Sri Lanka. *Integrated Development for Water Supply and Sanitation: Proceedings of the 25th WEDC*

Conference, 369–372.

Arulnesan, C. A., Kamsan, S., Rajeshkannan, N., Sivapalan, K., & Murugananthan, K. (2015). Microbial contamination of public drinking water sources and associated factors in Kopay Medical Officer of Health area Jaffna, Sri Lanka. *Sri Lankan Journal of Infectious Diseases*, *5*(2), 64–72.

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*.

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*. https://doi.org/10.22617/TCS190557-2 (Accessed 10 August 2022)

Azzurra, A., Massimiliano, A., & Angela, M. (2019). Measuring sustainable food consumption: A case study on organic food. *Sustainable Production and Consumption*, *17*, 95–107. https://doi.org/10.1016/j.spc.2018.09.007 (Accessed 10 August 2022)

Baccini, P. (1997). A city's metabolism: Towards the sustainable development of urban systems. *Journal of Urban Technology*, *4*(2), 27–39. https://doi.org/10.1080/10630739708724555 (Accessed 10 August 2022)

Bancheva, S. (2014). *Integrating the concept of urban metabolism into planning of sustainable cities : Analysis of the Eco Cities Initiative*. *168*, 36. https://www.bartlett.ucl.ac.uk/dpu/latest/publications/dpu-working-papers/WP168.pdf (Accessed 10 August 2022)

Barro, J. H. (2021). Sustainable Cities and Communities. In *For God So Loved the World*. https://doi.org/10.2307/j.ctv1v08zhx.14 (Accessed 10 August 2022)

Bastiaanssen, W. G. M., & Chandrapala, L. (2003). Water balance variability across Sri Lanka for assessing agricultural and environmental water use. *Agricultural Water Management*, *58*(2), 171–192. https://doi.org/10.1016/S0378-3774(02)00128-2

Bekchanov, M., Mondal, M. A. H., de Alwis, A., & Mirzabaev, A. (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. https://doi.org/10.1016/j.rser.2019.02.010 (Accessed 10 August 2022)

Berman, H., Shwom, R., & Cuite, C. (2019). Becoming FEW conscious: A conceptual typology of household behavior change interventions targeting the food-energy-water (FEW) nexus. *Sustainability (Switzerland)*, *11*(18). https://doi.org/10.3390/su11185034 (Accessed 10 August 2022)

Bhattacharya, S. C., & Abdul Salam, P. (2002). Low greenhouse gas biomass options for cooking in the developing countries. *Biomass and Bioenergy*, *22*(4), 305–317. https://doi.org/10.1016/S0961-9534(02)00008-9 (Accessed 10 August 2022)

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. *International Journal of Energy Sector Management*. https://doi.org/10.1108/17506221011092742 (Accessed 10 August 2022)

Boggia, A., & Cortina, C. (2010). Measuring sustainable development using a multi-criteria model: A case study. *Journal of Environmental Management*, *91*(11), 2301–2306. https://doi.org/10.1016/j.jenvman.2010.06.009 (Accessed 10 August 2022)

Bradbury, M., Peterson, M. N., & Liu, J. (2014). Long-term dynamics of household size and their environmental implications. *Population and Environment*, *36*(1), 73–84. https://doi.org/10.1007/s11111-014-0203-6 (Accessed 10 August 2022)

Cai, B., Liu, B., & Zhang, B. (2019). Evolution of Chinese urban household's water footprint. *Journal of Cleaner Production*, *208*, 1–10. https://doi.org/10.1016/j.jclepro.2018.10.074 (Accessed 10 August 2022)

Caird, S., & Roy, R. (2009). Household ecological footprints - Demographics and sustainability. *Tools, Techniques and Approaches for Sustainability: Collected Writings in Environmental Assessment Policy and Management*, *8*(4), 145–167. https://doi.org/10.1142/9789814289696_0008 (Accessed 10 August 2022)

Caponio, G., Digiesi, S., Massaro, V., Mossa, G., & Mummolo, G. (2014). Urban energy planning a system dynamics approach for carbon footprint reduction. *Proceedings of the Summer School Francesco Turco*, *09-12-Sept*, 333–338.

Caputo, P., Pasetti, G., & Bonomi, M. (2016). Urban Metabolism Analysis as a Support to Drive Metropolitan Development. *Procedia Engineering*, *161*, 1588–1595.

https://doi.org/10.1016/j.proeng.2016.08.631 (Accessed 7 September 2022)

Casazza, M., Xue, J., Du, S., Liu, G., & Ulgiati, S. (2021). Simulations of scenarios for urban household water and energy consumption. In *PLoS ONE* (Vol. 16, Issue 4 April). https://doi.org/10.1371/journal.pone.0249781 (Accessed 10 August 2022)

Caucci, S. (2020). Organic Waste Composting through Nexus Thinking. In *Organic Waste Composting through Nexus Thinking*. https://doi.org/10.1007/978-3-030-36283-6 (Accessed 7 September 2022)

Central Bank of Sri Lanka. (2019). *Annual Report 2019*.

Céspedes Restrepo, J. D., & Morales-Pinzón, T. (2018). Urban metabolism and sustainability: Precedents, genesis and research perspectives. *Resources, Conservation and Recycling*, *131*(16), 216–224. https://doi.org/10.1016/j.resconrec.2017.12.023 (Accessed 7 September 2022)

Ceylon Electricity Board. (2020). *CEB | Business With CEB*. https://ceb.lk/tariff_catergory/en (Accessed 7 September 2022)

Ceylon Petroleum Corporation. (2020). *Historical Prices – CEYPETCO*. http://ceypetco.gov.lk/historical-prices/ (Accessed 10 August 2022)

Chang, H., Parandvash, G., & Shandas, V. (2010). Spatial variations of single-family residential water consumption in Portland, Oregon. *Urban Geography*, *31*(7), 953–972. https://doi.org/10.2747/0272-3638.31.7.953 (Accessed 10 August 2022)

Chen, L., Xu, L., Velasco-Fernández, R., Giampietro, M., & Yang, Z. (2021). Residential energy metabolic patterns in China: A study of the urbanization process. *Energy*, *215*. https://doi.org/10.1016/j.energy.2020.119021 (Accessed 7 September 2022)

Chen, S., & Chen, B. (2016). Modelling carbon-energy metabolism of cities: A systems approach. *Energy Procedia*, *88*, 31–37. https://doi.org/10.1016/j.egypro.2016.06.009

Chenoweth, J., López-Avilés, A., Morse, S., & Druckman, A. (2016). Water consumption and subjective wellbeing: An analysis of British households. *Ecological Economics*, *130*, 186–194. https://doi.org/10.1016/j.ecolecon.2016.07.006 (Accessed 7 September 2022)

Chrysoulakis, N., Lopes, M., San José, R., Grimmond, C. S. B., Jones, M. B., Magliulo, V., Klostermann, J. E. M., Synnefa, A., Mitraka, Z., Castro, E. A., González, A., Vogt, R., Vesala, T., Spano, D., Pigeon, G., Freer-Smith, P., Staszewski, T., Hodges, N., Mills, G., & Cartalis, C. (2013a). Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project. *Landscape and Urban Planning*, *112*(1), 100–117. https://doi.org/10.1016/j.landurbplan.2012.12.005 (Accessed 7 September 2022)

Chrysoulakis, N., Lopes, M., San José, R., Grimmond, C. S. B., Jones, M. B., Magliulo, V., Klostermann, J. E. M., Synnefa, A., Mitraka, Z., Castro, E. A., González, A., Vogt, R., Vesala, T., Spano, D., Pigeon, G., Freer-Smith, P., Staszewski, T., Hodges, N., Mills, G., & Cartalis, C. (2013b). Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project. *Landscape and Urban Planning*, *112*(1), 100–117. https://doi.org/10.1016/j.landurbplan.2012.12.005 (Accessed 7 September 2022)

Conke, L. S., & Ferreira, T. L. (2015). Urban metabolism: Measuring the city's contribution to sustainable development. *Environmental Pollution*, *202*(November 2016), 146–152. https://doi.org/10.1016/j.envpol.2015.03.027 (Accessed 7 September 2022)

Currie, P. K., & Musango, J. K. (2017). African Urbanization: Assimilating Urban Metabolism into Sustainability Discourse and Practice. *Journal of Industrial Ecology*, *21*(5), 1262–1276. https://doi.org/10.1111/jiec.12517 (Accessed 7 September 2022)

Custance, J., & Hillier, H. (1998). Statistical issues in developing indicators of sustainable development. *Journal of the Royal Statistical Society. Series A: Statistics in Society*, *161*(3), 281–290. https://doi.org/10.1111/1467-985X.00108 (Accessed 7 September 2022)

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 (Accessed 7 September 2022)

Damari, Y., & Kissinger, M. (2018). An integrated analysis of households' electricity consumption in Israel. *Energy Policy*, *119*(June 2017), 51–58. https://doi.org/10.1016/j.enpol.2018.04.010 (Accessed 7 September 2022)

Danthurebandara, M., Steven, V. P., & Karel, V. A. (2015). Environmental and economic assessment of "open waste dump" mining in Sri Lanka. *Resources, Conservation and Recycling*, *102*, 67–79. https://doi.org/10.1016/j.resconrec.2015.07.004 (Accessed 2 Novemebr 2022)

Davoudi, S., & Sturzaker, J. (2017). Urban form, policy packaging and sustainable urban metabolism. *Resources, Conservation and Recycling*, *120*, 55–64. https://doi.org/10.1016/j.resconrec.2017.01.011 (Accessed 2 Novemebr 2022

de Alwis, A. (2002a). Biogas - a review of Sri Lanka's performance with a renewable energy technology. *Energy for Sustainable Development*, *6*(1), 30–37. https://doi.org/10.1016/S0973-0826(08)60296-3 (Accessed 2 Novemebr 2022

de Alwis, A. (2002b). Biogas – a review of Sri Lanka's performance with a renewable energy technology. *Energy for Sustainable Development*, *6*(1), 30–37. https://doi.org/10.1016/S0973-0826(08)60296-3 (Accessed 2 Novemebr 2022

De, D. K., De, N. N., Nathaniel, M., & Olawole, O. (2014). Minimizing Energy Usage in Cooking To Protect Environments. *International Journal of Energy and Environmental Research*, *2*(3), 20–44. www.eajournals.org (Accessed 2 Novemebr 2022

Debnath, K. B., & Mourshed, M. (2018). Challenges and gaps for energy planning models in the developing-world context. *Nature Energy*, *3*(March). https://doi.org/10.1038/s41560-018-0095-2 (Accessed 2 Novemebr 2022

Department of Census and Statictics. (2016). *Household Income and Expenditure Survey – 2016 Ministry of National Policies and Economic Affairs October 2017 Household Income and Expenditure Survey – 2016. October*, 8. http://www.statistics.gov.lk/ (Accessed 2 Novemebr 2022

Department of census and Statistics. (2010). Household Income and Expenditure Survey - 2009/2010. In *Department of census and Statistics*.

Department of Census and Statistics. (2002). *Household Income andand Expenditure Survey – 2002*.

Department of Census and Statistics of Sri Lanka. (2018). *Household Income and Expenditure Survey - 2016*. http://www.statistics.gov.lk/HIES/HIES2016/HIES2016_FinalReport.pdf (Accessed 2 Novemebr 2022

Department of Census and Statistics Sri Lanka. (2012). *Census of Population and Housing - 2012*. http://www.statistics.gov.lk/pophousat/cph2012visualization/htdocs/index.php?usecase=indicator&action=Map&indId=600 (Accessed 2 Novemebr 2022

Development Bank, A. (2018). *Sri Lanka: Energy Sector Assessment, Strategy, and Road Map*. https://doi.org/10.22617/TCS190557-2 (Accessed 2 Novemebr 2022

Di Donato, M., & Carpintero, Ó. (2021). Household food metabolism: Losses, waste and environmental pressures of food consumption at the regional level in spain. *Foods*, *10*(6), 1–22. https://doi.org/10.3390/foods10061166 (Accessed 2 Novemebr 2022

Dombi, M., Karcagi-Kováts, A., Tóth-Szita, K., & Kuti, I. (2018). The structure of socio-economic metabolism and its drivers on household level in Hungary. *Journal of Cleaner Production*, *172*, 758–767. https://doi.org/10.1016/j.jclepro.2017.10.220 (Accessed 2 Novemebr 2022

Donato, M. Di, Lomas, P. L., & Carpintero, Ó. (2015). Metabolism and environmental impacts of household consumption: A review on the assessment, methodology, and drivers. *Journal of Industrial Ecology*, *19*(5), 904–916. https://doi.org/10.1111/jiec.12356 (Accessed 2 Novemebr 2022

Druckman, A., Sinclair, P., & Jackson, T. (2008). A geographically and socio-economically disaggregated local household consumption model for the UK. *Journal of Cleaner Production*, *16*(7), 870–880. https://doi.org/10.1016/j.jclepro.2007.05.004 (Accessed 2 Novemebr 2022

Edirisinghe, R. D., & Pathirana, S. (2021). Reduction potential of potable water consumption at urban households: a case study in Sri Lanka. *Environment, Development and Sustainability*, *0123456789*. https://doi.org/10.1007/s10668-021-01234-1 (Accessed 2 Novemebr 2022

Ellsworth-Krebs, K. (2020). Implications of declining household sizes and expectations of home comfort for domestic energy demand. *Nature Energy*, *5*(1), 20–25. https://doi.org/10.1038/s41560-019-0512-1 (Accessed 2 Novemebr 2022

European Foundation. (1998). *Urban Sustainability Indicators* . www.eurofound.ie/

Fan, M. (2015). Sri Lanka's water supply and sanitation sector: Achievements and a way forward. *ADB South Asia Working Paper Series*, *35*, 1–51. www.adb.org

FAO. (2011). Energy-smart food for people and climate. Issue Paper. *Food and Agriculture Organization of the United Nations.*, 66. (Accessed 2 Novemebr 2022

Farabi-Asl, H., Taghizadeh-Hesary, F., Chapman, A., & Mohammadzadeh Bina, S. (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 (Accessed 2 Novemebr 2022

Feng, K., & Hubacek, K. (2016). Carbon implications of China's urbanization. *Energy, Ecology and Environment*, *1*(1), 39–44. https://doi.org/10.1007/S40974-016-0015-X/FIGURES/3 (Accessed 2 Novemebr 2022

Fernando, R. L. S. (2019). Solid waste management of local governments in the Western Province of Sri Lanka: An implementation analysis. *Waste Management*, *84*, 194–203. https://doi.org/10.1016/j.wasman.2018.11.030 (Accessed 2 Novemebr 2022

Fontdecaba, S., Sánchez-Espigares, J. A., Marco-Almagro, L., Tort-Martorell, X., Cabrespina, F., & Zubelzu, J. (2013). An Approach to Disaggregating Total Household Water Consumption into Major End-Uses. *Water Resources Management*, *27*(7), 2155–2177. https://doi.org/10.1007/s11269-013-0281-8 (Accessed 2 Novemebr 2022

Food And Agriculture Organization Of The United Nations. (2018). *Assessing and Planning City Region Food System Colomb*.

Food and Agriculture, & Organization of the United Nations (FAO). (2011). *Global food losses and food waste – Extent, causes and prevention*. http://www.fao.org/3/i2697e/i2697e.pdf (Accessed 11 October 2022)

Fu, W., Zhou, Y., Li, L., & Yang, R. (2021). Understanding household electricity-saving behavior: Exploring the effects of perception and cognition factors. *Sustainable Production and Consumption*, *28*, 116–128. https://doi.org/10.1016/J.SPC.2021.03.035 (Accessed 11 October 2022)

Gasser, P. (2020). A review on energy security indices to compare country performances. *Energy Policy*, *139*(August 2019), 111339. https://doi.org/10.1016/j.enpol.2020.111339 (Accessed 11 October 2022)

Geislar, S. (2018). The determinants of household food waste reduction, recovery, and reuse: Toward a household metabolism. In *Encyclopedia of Food Security and Sustainability*. Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.22448-7 (Accessed 11 October 2022)

Giampietro, M., Mayumi, K., & Ramos-Martin, J. (2009). Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. *Energy*, *34*(3), 313–322. https://doi.org/10.1016/j.energy.2008.07.020 (Accessed 11 October 2022)

Giannakis, E., Serghides, D., Dimitriou, S., & Zittis, G. (2020). Land transport CO2 emissions and climate change: evidence from Cyprus. *International Journal of Sustainable Energy*, *39*(7), 634–647. https://doi.org/10.1080/14786451.2020.1743704 (Accessed 11 October 2022)

Ginigaddara, G. A. S. (n.d.). *Sri Lankan Home Gardens and Household Food Security*.

Gokhale, H. (2021). Japan's carbon tax policy: Limitations and policy suggestions. *Current Research in Environmental Sustainability*, *3*, 100082. https://doi.org/10.1016/j.crsust.2021.100082 (Accessed 11 October 2022)

Goldstein, B., Gounaridis, D., & Newell, J. P. (2020). The carbon footprint of household energy use in the United States. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 117, Issue 32, pp. 19122–19130). https://doi.org/10.1073/pnas.1922205117 (Accessed 11 October 2022)

González, A., Donnelly, A., Jones, M., Chrysoulakis, N., & Lopes, M. (2013). A decision-support system for sustainable urban metabolism in Europe. *Environmental Impact Assessment Review*, *38*, 109–119. https://doi.org/10.1016/J.EIAR.2012.06.007 (Accessed 11 October 2022)

Grubb, M., Butler, L., & Twomey, P. (2006). Diversity and security in UK electricity generation: The influence of low-carbon objectives. *Energy Policy*, *34*(18), 4050–4062. https://doi.org/10.1016/J.ENPOL.2005.09.004 (Accessed 11 October 2022

Gunarathne, A. D. N., Tennakoon, T. P. Y. C., & Weragoda, J. R. (2019). Challenges and opportunities for the recycling industry in developing countries: the case of Sri Lanka. *Journal of Material Cycles and Waste Management*, *21*(1), 181–190. https://doi.org/10.1007/s10163-018-0782-x (Accessed 11 October 2022)

Gunnarsdottir, I., Davidsdottir, B., Worrell, E., & Sigurgeirsdottir, S. (2020). Review of indicators for sustainable energy development. *Renewable and Sustainable Energy Reviews*, *133*(July), 110294. https://doi.org/10.1016/j.rser.2020.110294 (Accessed 11 October 2022)

Guo, Zhen, Hu, D., Zhang, F., Huang, G., & Xiao, Q. (2014). An integrated material metabolism model for stocks of Urban road system in Beijing, China. *Science of the Total Environment*, *470–471*, 883–894. https://doi.org/10.1016/j.scitotenv.2013.10.041 (Accessed 11 October 2022)

Guo, Zhengquan, & Liu, H. (2013). Carbon footprint of the households' consumption in China. *International Journal of Global Energy Issues*, *36*(2–4), 181–196. https://doi.org/10.1504/IJGEI.2013.061787 (Accessed 11 October 2022)

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Martinez-Alier, J., & Winiwarter, V. (2009). A Socio-metabolic Transition towards Sustainability ? Challenges for. *Sustainable Development*, *19*(September 2008), 1–14. http://www3.interscience.wiley.com/resolve/doi/pdf?DOI=10.1002/sd.410 (Accessed 11 October 2022)

Hák, T., Moldan, B., & Dahl, A. L. (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 (Accessed 11 October 2022)

Hannan, M. A., Begum, R. A., Abdolrasol, M. G., Hossain Lipu, M. S., Mohamed, A., & Rashid, M. M. (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. https://doi.org/10.1016/j.rser.2018.06.041 (Accessed 21 May 2021)

Hardadi, G., Buchholz, A., & Pauliuk, S. (2021). Implications of the distribution of German household environmental footprints across income groups for integrating environmental and social policy design. *Journal of Industrial Ecology*, *25*(1), 95–113. https://doi.org/10.1111/jiec.13045 (Accessed 21 May 2021

Harder, R. (2013). *Quantifying the Metabolism of Individual Households*. 1–88. http://publications.lib.chalmers.se/records/fulltext/174853/174853.pdf (Accessed 11 October 2022)

Harder, R., Dombi, M., & Peters, G. M. (2017). Perspectives on quantifying and influencing household metabolism. *Journal of Environmental Planning and Management*, *60*(2), 178–203. https://doi.org/10.1080/09640568.2016.1142864 (Accessed 21 May 2021)

Harder, R., Kalmykova, Y., Morrison, G. M., Feng, F., Mangold, M., & Dahlén, L. (2014). Quantification of goods purchases and waste generation at the level of individual households. *Journal of Industrial Ecology*, *18*(2), 227–241. https://doi.org/10.1111/jiec.12111 (Accessed 21 May 2021)

Harris, F., Moss, C., Joy, E. J. M., Quinn, R., Scheelbeek, P. F. D., Dangour, A. D., & Green, R. (2020). The Water Footprint of Diets: A Global Systematic Review and Meta-analysis. *Advances in Nutrition*, *11*(2), 375–386. https://doi.org/10.1093/ADVANCES/NMZ091 (Accessed 11 October 2022)

Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). *Introduction to Energy Systems Modelling*. *148*(2), 111–135. (Accessed 21 May 2021)

Hertwich, E. G. (2011). The Life Cycle Environmental Impacts Of Consumption. *Economic Systems Research*, *23*(1), 27–47. https://doi.org/10.1080/09535314.2010.536905 (Accessed 21 May 2021)

Hoek, A. C., Malekpour, S., Raven, R., Court, E., & Byrne, E. (2021). Towards environmentally sustainable food systems: decision-making factors in sustainable food production and consumption. *Sustainable Production and Consumption*, *26*, 610–626. https://doi.org/10.1016/J.SPC.2020.12.009 (Accessed 21 May 2021)

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

Hu, G., & Mu, X. (2019). Analysis of urban energy metabolic system: An ecological network framework and a case study for Beijing. *Journal of Cleaner Production*, *210*, 958–969. https://doi.org/10.1016/j.jclepro.2018.11.088 (Accessed 11 October 2022)

Hu, Z., Wang, M., Cheng, Z., & Yang, Z. (2020). Impact of marginal and intergenerational effects on carbon emissions from household energy consumption in China. *Journal of Cleaner Production*, *273*, 123022.

https://doi.org/10.1016/j.jclepro.2020.123022 (Accessed 21 May 2021)

Huang, Q., Zheng, X., Liu, F., Hu, Y., & Zuo, Y. (2018). Dynamic analysis method to open the "black box" of urban metabolism. *Resources, Conservation and Recycling*, *139*(September), 377–386. https://doi.org/10.1016/j.resconrec.2018.09.010 (Accessed 11 October 2022)

Huang, W., Cui, S., Yarime, M., Hashimoto, S., & Managi, S. (2015). Improving urban metabolism study for sustainable urban transformation. *Environmental Technology and Innovation*, *4*, 62–72. https://doi.org/10.1016/j.eti.2015.04.004 (Accessed 21 May 2021)

Hubacek, K., Baiocchi, G., Feng, K., Muñoz Castillo, R., Sun, L., & Xue, J. (2017). Global carbon inequality. *Energy, Ecology and Environment*, *2*(6), 361–369. https://doi.org/10.1007/S40974-017-0072-9/FIGURES/7 (Accessed 11 October 2022)

Hussain, M., Ajmal, M. M., Khan, M., & Saber, H. (2015). Competitive priorities and knowledge management: An empirical investigation of manufacturing companies in UAE. *Journal of Manufacturing Technology Management*, *26*(6), 791–806. https://doi.org/10.1108/JMTM-03-2014-0020 (Accessed 11 October 2022)

Hussien, W. A., Memon, F. A., & Savic, D. A. (2017). An integrated model to evaluate water-energy-food nexus at a household scale. *Environmental Modelling and Software*, *93*, 366–380. https://doi.org/10.1016/j.envsoft.2017.03.034 (Accessed 21 May 2021)

Hussien, W. A., Memon, F. A., & Savic, D. A. (2018). A risk-based assessment of the household water-energy-food nexus under the impact of seasonal variability. *Journal of Cleaner Production*, *171*, 1275–1289. https://doi.org/10.1016/j.jclepro.2017.10.094 (Accessed 21 May 2021)

Huysman, S., Schaubroeck, T., Goralczyk, M., Schmidt, J., & Dewulf, J. (2016). Quantifying the environmental impacts of a European citizen through a macro-economic approach, a focus on climate change and resource consumption. *Journal of Cleaner Production*, *124*, 217–225. https://doi.org/10.1016/J.JCLEPRO.2016.02.098 (Accessed 21 May 2021)

Iddrisu, I., & Bhattacharyya, S. C. (2015). Sustainable Energy Development Index: A multi-dimensional indicator for measuring sustainable energy development. *Renewable and Sustainable Energy Reviews*, *50*, 513–530. https://doi.org/10.1016/j.rser.2015.05.032 (Accessed 21 May 2021)

IGES Freshwater Management Project. (2007). Sustainable Groundwater Management in Asian Cities: A final report of Research on Sustainable Water Management Policy. In *Sustainable Groundwater Management in Asian Cities2*. Institute for Global Environmental Strategies. https://www.iges.or.jp/en/pub/sustainable-groundwater-management-asian-0/en (Accessed 21 May 2021)

Intergovernmental Panel on Climate Change (IPCC). (1996). *IPCC Second Assessment Climate Change 1995*.

Issock, P. B. I., Mpinganjira, M., & Roberts-Lombard, M. (2021). Trying to recycle domestic waste and feelings of guilt: a moderated mediation model applied to South African households. *Sustainable Production and Consumption*, *27*, 1286–1296. https://doi.org/10.1016/J.SPC.2021.03.003 (Accessed 21 May 2021)

Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., & Hertwich, E. G. (2016). Environmental Impact Assessment of Household Consumption. *Journal of Industrial Ecology*, *20*(3), 526–536. https://doi.org/10.1111/jiec.12371 (Accessed 21 May 2021)

Jain, P., & Goswami, B. (2021). Energy efficiency in South Asia: Trends and determinants. *Energy*, *221*, 119762. https://doi.org/10.1016/j.energy.2021.119762(Accessed 21 May 2021)

Japan International Cooperation Agency. (2016). *Data Collection Survey on Solid Waste Management in Democratic Socialist Republic of Sri Lanka Final Report Democratic Socialist Republic of Sri Lanka Japan International Cooperation Agency (JICA) Ten (10) Priority Local Authorities* (Issue February). http://open_jicareport.jica.go.jp/pdf/12250213.pdf (Accessed 21 May 2021)

Japan International Cooperation Agency. (2018). *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*.

Japan International Cooperation Agency (JICA). (2016a). *Data Collection Survey on Solid Waste Management in Democratic Socialist Republic of Sri Lanka Final Report Democratic Socialist Republic of Sri Lanka Ten (10) Priority Local Authorities*.

Japan International Cooperation Agency (JICA). (2016b). *Toward Sustainable Water and Sanitation Services in Sri Lanka Beyond Sustainable Development Goals to Supporting the National Economic Vision*.

Jayalal, Tba., Niroshani, Sln., & Lanka, S. (n.d.). *Wastewater Production, Treatment, and Use in Sri Lanka*.

Jayasinghe, M., Selvanathan, E. A., & Selvanathan, S. (2021). Energy poverty in Sri Lanka. *Energy Economics*, *101*, 105450. https://doi.org/10.1016/J.ENECO.2021.105450 (Accessed 21 May 2021)

Jayathilake, N., Kumara, I. U., & Fernando, S. (2020). *Inventory of Solid and Liquid Waste Management and Resource Recovery in Sri Lanka : A 20 city analysis*.

Jin, J., He, R., Kuang, F., Wan, X., & Ning, J. (2019). Different sources of rural household energy consumption and influencing factors in Dazu, China. *Environmental Science and Pollution Research*, *26*(21), 21312–21320. https://doi.org/10.1007/s11356-019-05439-w (Accessed 21 May 2021)

Jorge, C., Vieira, P., Rebelo, M., & Covas, D. (2015). Assessment of water use efficiency in the household using cluster analysis. *Procedia Engineering*, *119*(1), 820–827. https://doi.org/10.1016/j.proeng.2015.08.945 (Accessed 21 May 2021)

Kala, L. (2015). The environmental impact of singles' consumer behaviour: Is the lifestyle of singles inevitably environmentally more damaging? *Socialni Studia/Social Studies*, *12*(3), 53–69. https://doi.org/10.5817/soc2015-3-53 (Accessed 13 February 2022)

Kalansooriya, C. W., & Chandrakumara, D. P. S. (2014). Women's role in household food security in rural Sri Lanka. *International Journal of Multidisciplinary Studies*, *1*(1), 41. https://doi.org/10.4038/IJMS.V1I1.31 (Accessed 13 February 2022)

Kanemoto, K., Shigetomi, Y., Hoang, N. T., Okuoka, K., & Moran, D. (2020a). Spatial variation in household consumption-based carbon emission inventories for 1200 Japanese cities. In *Environmental Research Letters* (Vol. 15, Issue 11).

https://doi.org/10.1088/1748-9326/abc045(Accessed 13 February 2022)

Kanemoto, K., Shigetomi, Y., Hoang, N. T., Okuoka, K., & Moran, D. (2020b). Spatial variation in household consumption-based carbon emission inventories for 1200 Japanese cities. *Environmental Research Letters*, *15*(11). https://doi.org/10.1088/1748-9326/abc045 (Accessed 13 February 2022)

Kaushalya, G. ., Wijeratne, V. P. I. ., & Manawadu, L. (2020). Spatiotemporal Characteristics of the Domestic Water Consumption Patterns and Related Issues in Sri Lanka. *International Journal of Scientific and Research Publications (IJSRP)*, *10*(8), 718–721. https://doi.org/10.29322/ijsrp.10.08.2020.p10492 (Accessed 13 February 2022)

Konara, K. M. G. K., & Tokai, A. (2020). Evaluating the Energy Metabolic System in Sri Lanka. *Journal of Sustainable Development*, *13*(4), 235. https://doi.org/10.5539/jsd.v13n4p235 (Accessed 13 February 2022)

Kaya, İ., Murat Çolak, |, & Fulya Terzi, |. (2018). *Use of MCDM techniques for energy policy and decision-making problems: A review*. https://doi.org/10.1002/er.4016 (Accessed 13 February 2022)

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

Keilman, N. (1988). Recent trends in family and household composition in europe. *European Journal of Population*, *3*(3–4), 297–325. https://doi.org/10.1007/BF01796903 (Accessed 13 February 2022)

Keirstead, J., Jennings, M., & Sivakumar, A. (2012). A review of urban energy system models: Approaches, challenges and opportunities. *Renewable and Sustainable Energy Reviews*, *16*(6), 3847–3866. https://doi.org/10.1016/j.rser.2012.02.047 (Accessed 13 February 2022)

Kemmler, A., & Spreng, D. (2007). Energy indicators for tracking sustainability in developing countries. *Energy Policy*, *35*(4), 2466–2480. https://doi.org/10.1016/j.enpol.2006.09.006 (Accessed 13 February 2022)

Kennedy, C., Stewart, I. D., Ibrahim, N., Facchini, A., & Mele, R. (2014). Developing a multi-layered indicator set for urban metabolism studies in megacities. *Ecological Indicators*, *47*, 7–15. https://doi.org/10.1016/J.ECOLIND.2014.07.039 (Accessed

13 February 2022)

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings*, *58*, 378–389. https://doi.org/10.1016/j.enbuild.2012.08.035 (Accessed 13 February 2022)

Khalifa, Y., George, S., & Catney, P. (2019). *Resources Management for Urban Sustainability in the Global South*. *December*.

Kilkiş, Ş. (2016). Sustainable development of energy, water and environment systems index for Southeast European cities. *Journal of Cleaner Production*, *130*, 222–234. https://doi.org/10.1016/J.JCLEPRO.2015.07.121 (Accessed 13 February 2022)

Kim, M. J. (2018). Characteristics and determinants by electricity consumption level of households in Korea. *Energy Reports*, *4*, 70–76. https://doi.org/10.1016/j.egyr.2017.12.001 (Accessed 13 February 2022)

Kissinger, M., & Damari, Y. (2021). Household metabolism: Integrating socio-economic characteristics and lifestyles on individual and national scales as a mean for advancing environmental management. *Journal of Environmental Management*, *279*(November 2020), 111526. https://doi.org/10.1016/j.jenvman.2020.111526 (Accessed 13 February 2022)

Koide, R., Kojima, S., Nansai, K., Lettenmeier, M., Asakawa, K., Liu, C., & Murakami, S. (2021). Exploring carbon footprint reduction pathways through urban lifestyle changes: a practical approach applied to Japanese cities. *Environmental Research Letters*, *16*(8), 084001. https://doi.org/10.1088/1748-9326/ac0e64 (Accessed 13 February 2022)

Koide, R., Lettenmeier, M., Akenji, L., Toivio, V., Amellina, A., Khodke, A., Watabe, A., & Kojima, S. (2021). Lifestyle carbon footprints and changes in lifestyles to limit global warming to 1.5 °C, and ways forward for related research. *Sustainability Science*, *16*(6), 2087–2099. https://doi.org/10.1007/s11625-021-01018-6(Accessed 13 February 2022)

Koide, R., Lettenmeier, M., Kojima, S., Toivio, V., Amellina, A., & Akenji, L. (2019). Carbon footprints and consumer lifestyles: An analysis of lifestyle factors and gap analysis by consumer segment in Japan. *Sustainability (Switzerland)*, *11*(21). https://doi.org/10.3390/SU11215983 (Accessed 13 February 2022)

Kostevšek, A., Klemeš, J. J., Varbanov, P. S., Čuček, L., & Petek, J. (2015). Sustainability assessment of the Locally Integrated Energy Sectors for a Slovenian municipality. *Journal of Cleaner Production*, *88*, 83–89. https://doi.org/10.1016/J.JCLEPRO.2014.04.008(Accessed 13 February 2022)

Kumara, A. S., & Pallegedara, A. (2020). Household waste disposal mechanisms in Sri Lanka: Nation-wide survey evidence for their trends and determinants. *Waste Management*, *114*, 62–71. https://doi.org/10.1016/j.wasman.2020.06.028 (Accessed 13 February 2022)

Kuriyama, A., Tamura, K., & Kuramochi, T. (2019). Can Japan enhance its 2030 greenhouse gas emission reduction targets? Assessment of economic and energy-related assumptions in Japan's NDC. *Energy Policy*, *130*(October 2018), 328–340. https://doi.org/10.1016/j.enpol.2019.03.055 (Accessed 13 February 2022)

Leontief, W. W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, *18*(3). https://www.jstor.org/stable/pdf/1927837.pdf?casa_token=ecWW4DpIfBIAAAAA:QvCjt_kSs0OjS3lenVU7ASapxO7QALXp0QlTMdWuARWtnEwLD95eO2obk2UMU--pWgxwN4STN84ztPUohtAFXjY9iTm0xd4sfVG7SLe1YLdN0Kzgn84(Accessed 13 February 2022)

Leray, L., Sahakian, M., & Erkman, S. (2016). Understanding household food metabolism: Relating micro-level material flow analysis to consumption practices. *Journal of Cleaner Production*, *125*, 44–55. https://doi.org/10.1016/j.jclepro.2016.03.055 (Accessed 13 February 2022)

Li, X., Zhang, R., Chen, J., Jiang, Y., Zhang, Q., & Long, Y. (2021). Urban-scale carbon footprint evaluation based on citizen travel demand in Japan. *Applied Energy*, *286*(September 2020). https://doi.org/10.1016/j.apenergy.2021.116462 (Accessed 13 February 2022)

Liao, X., Chai, L., Ji, J., Mi, Z., Guan, D., & Zhao, X. (2019). Life-cycle water uses for energy consumption of Chinese households from 2002 to 2015. *Journal of Environmental Management*, *231*(September 2018), 989–995. https://doi.org/10.1016/j.jenvman.2018.10.109(Accessed 13 February 2022)

Liu, G. (2014). Development of a general sustainability indicator for renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, *31*, 611–621. https://doi.org/10.1016/j.rser.2013.12.038 (Accessed 13 February 2022)

Liu, Jianguo, Daily, G. C., Ehrlicht, P. R., & Luck, G. W. (2003). Effects of household dynamics on resource consumption and biodiversity. *Nature*, *421*(6922), 530–533. https://doi.org/10.1038/nature01359 (Accessed 13 February 2022)

Liu, Jingru, Wang, M., Zhang, C., Yang, M., & Li, Y. (2020). Material flows and in-use stocks of durable goods in Chinese urban household sector. *Resources, Conservation and Recycling*, *158*(October 2019), 104758. https://doi.org/10.1016/j.resconrec.2020.104758 (Accessed 13 February 2022)

Liu, Jingru, Wang, R., & Yang, J. (2005). Metabolism and driving forces of Chinese urban household consumption. *Population and Environment*, *26*(4), 325–341. https://doi.org/10.1007/s11111-005-3345-8 (Accessed 13 February 2022)

Liu, Jinyu, Murshed, M., Chen, F., Shahbaz, M., Kirikkaleli, D., & Khan, Z. (2021). An empirical analysis of the household consumption-induced carbon emissions in China. *Sustainable Production and Consumption*, *26*, 943–957. https://doi.org/10.1016/j.spc.2021.01.006 (Accessed 13 February 2022)

Liu, K. F. R. (2007). Evaluating environmental sustainability: An integration of multiple-criteria decision-making and fuzzy logic. *Environmental Management*, *39*(5), 721–736. https://doi.org/10.1007/s00267-005-0395-8 (Accessed 13 February 2022)

Liu, Y., Wood, L. C., Venkatesh, V. G., Zhang, A., & Farooque, M. (2021). Barriers to sustainable food consumption and production in China: A fuzzy DEMATEL analysis from a circular economy perspective. *Sustainable Production and Consumption*, *28*, 1114–1129. https://doi.org/10.1016/J.SPC.2021.07.028 (Accessed 13 February 2022)

Long, Y., Dong, L., Yoshida, Y., & Li, Z. (2018). Evaluation of energy-related household carbon footprints in metropolitan areas of Japan. *Ecological Modelling*, *377*(August 2017), 16–25. https://doi.org/10.1016/j.ecolmodel.2018.03.008 (Accessed 13 February 2022)

Long, Y., Jiang, Y., Chen, P., Yoshida, Y., Sharifi, ayyoob, Gasparatos, alexandros, Wu, Y., Kanemoto, K., Shigetomi, Y., & Guan, D. (2021a). Monthly direct and indirect greenhouse gases emissions from household consumption in the major Japanese cities. *Scientific Data*, *8*(301). https://doi.org/10.1038/s41597-021-01086-4 (Accessed 13 February 2022)

Long, Y., Jiang, Y., Chen, P., Yoshida, Y., Sharifi, A., Gasparatos, A., Wu, Y., Kanemoto, K., Shigetomi, Y., & Guan, D. (2021b). Monthly direct and indirect greenhouse gases emissions from household consumption in the major Japanese cities. In *Scientific Data* (Vol. 8, Issue 1). https://doi.org/10.1038/s41597-021-01086-4 (Accessed 13 February 2022)

Long, Y., Yoshida, Y., & Dong, L. (2017). Exploring the indirect household carbon emissions by source: Analysis on 49 Japanese cities. *Journal of Cleaner Production*, *167*, 571–581. https://doi.org/10.1016/j.jclepro.2017.08.159(Accessed 13 February 2022)

Long, Y., Yoshida, Y., Fang, K., Zhang, H., & Dhondt, M. (2019). City-level household carbon footprint from purchaser point of view by a modified input-output model. *Applied Energy*, *236*(December 2018), 379–387. https://doi.org/10.1016/j.apenergy.2018.12.002 (Accessed 13 February 2022)

Long, Y., Yoshida, Y., Zeng, I. Y., Xue, J., & Li, Y. (2021). Fuel-Specific Carbon Footprint Embodied in Japanese Household Lifestyles. In *Earth's Future* (Vol. 9, Issue 9). https://doi.org/10.1029/2021EF002213 (Accessed 13 February 2022)

Long, Y., Yoshida, Y., Zhang, R., Sun, L., & Dou, Y. (2018). Policy implications from (revealing consumption-based carbon footprint) of major economic sectors in Japan. *Energy Policy*, *119*, 339–348. https://doi.org/10.1016/j.enpol.2018.04.052 (Accessed 13 February 2022)

Lucertini, G., & Musco, F. (2020). Circular Urban Metabolism Framework. *One Earth*, *2*(2), 138–142. https://doi.org/10.1016/j.oneear.2020.02.004 (Accessed 13 February 2022)

Luthra, S., Mangla, S. K., & Kharb, R. K. (2015). Sustainable assessment in energy planning and management in Indian perspective. *Renewable and Sustainable Energy Reviews*, *47*, 58–73. https://doi.org/10.1016/j.rser.2015.03.007 (Accessed 13 February 2022)

M.M.M. Aheeyar;, & Ariyananda, T. (2014). Domestic Rainwater Harvesting Interventions in Sri Lanka: Some Lessons Learned. *Mainstreaming Rainwater Harvesting as a Water Supply Option*. https://www.researchgate.net/publication/266207951_Domestic_Rainwater_Harvesting_Interventions_in_Sri_Lanka_Some_Lessons_Learned (Accessed 13 February 2022)

Ma, X. W., Du, J., Zhang, M. Y., & Ye, Y. (2016a). Indirect carbon emissions from household consumption between China and the USA: based on an input–output model. *Natural Hazards*, *84*, 399–410. https://doi.org/10.1007/s11069-016-2508-5 (Accessed 25 Novemebr 2020)

Ma, X. W., Du, J., Zhang, M. Y., & Ye, Y. (2016b). Indirect carbon emissions from household consumption between China and the USA: based on an input–output model. *Natural Hazards*, *84*, 399–410. https://doi.org/10.1007/S11069-016-2508-5 (Accessed 25 Novemebr 2020)

Mainali, B., Pachauri, S., Rao, N. D., & Silveira, S. (2014). Assessing rural energy sustainability in developing countries. *Energy for Sustainable Development*, *19*(1), 15–28. https://doi.org/10.1016/j.esd.2014.01.008 (Accessed 25 Novemebr 2020)

Malkanthi, S. H. . (2020). Willingness to pay for locally produced organic foods by urban consumers in Sri Lanka. *Applied Studies in Agribusiness and Commerce*, *14*(1–2). https://doi.org/10.19041/APSTRACT/2020/1-2/2 (Accessed 25 Novemebr 2020)

Mandelli, S., Barbieri, J., Mattarolo, L., & Colombo, E. (2014). Sustainable energy in Africa: A comprehensive data and policies review. *Renewable and Sustainable Energy Reviews*, *37*, 656–686. https://doi.org/10.1016/j.rser.2014.05.069 (Accessed 25 Novemebr 2020)

Masud, M. H., Nuruzzaman, M., Ahamed, R., Ananno, A. A., & Tomal, A. N. M. A. (2020). Renewable energy in Bangladesh: current situation and future prospect. *International Journal of Sustainable Energy*, *39*(2), 132–175. https://doi.org/10.1080/14786451.2019.1659270 (Accessed 25 Novemebr 2020)

Maxim, A. (2014). Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. *Energy Policy*, *65*, 284–297. https://doi.org/10.1016/j.enpol.2013.09.059 (Accessed 25 Novemebr 2020)

Meles, T. H. (2020). Impact of power outages on households in developing countries: Evidence from Ethiopia. *Energy Economics*, *91*, 104882. https://doi.org/10.1016/j.eneco.2020.104882 (Accessed 25 Novemebr 2020)

Mihiranie, S., Jayasinghe, J. K., Jayasinghe, C. V. L., & Wanasundara, J. P. D. (2020). Indigenous and traditional foods of Sri Lanka. *Journal of Ethnic Foods*, *7*(1). https://doi.org/10.1186/s42779-020-00075-z (Accessed 25 Novemebr 2020)

Ministry of Environment. (2015). *Japan 's National Greenhouse Gas Emissions in Fiscal Year 2015* (Vol. 2015, Issue April 2017).

Ministry of Environment. (2021). *Sri Lanka: Updated Nationally Determined Contributions* (Issue July). https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Sri Lanka First/NDCs of Sri Lanka-2021.pdf (Accessed 25 Novemebr 2020)

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 Internal Affairs and Communications. (2020). *Ministry of Internal Affairs and Communications*. https://www.soumu.go.jp/english/ (Accessed 25 Novemebr 2020)

Ministry of Mahaweli Development & Environment. (2016). *A Guide for Carbon Footprint Assessment*. 30. http://www.climatechange.lk/Documents/A_Guide_for_Carbon_Footprint_Assessment.pdf (Accessed 25 Novemebr 2020)

Ministry of Mahaweli Development & Environment. (2019). *National Policy on Sustainable Consumption & Production for Sri Lanka*. *March*. http://scp.mmde.gov.lk/news_events_view.php?n_id=79 (Accessed 25 Novemebr 2020)

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 (Accessed 25 Novemebr 2020)

Ministry of Power & Energy. (2015). *SRI LANKA ENERGY SECTOR DEVELOPMENT PLAN FOR A KNOWLEDGE-BASED ECONOMY*.

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

Ministry of the Environment. (2020). *List of emission coefficients (In Japanese)*. https://ghg-santeikohyo.env.go.jp/calc (Accessed 25 Novemebr 2020)

Minx, J., Baiocchi, G., Wiedmann, T., Barrett, J., Creutzig, F., Feng, K., Förster, M., Pichler, P. P., Weisz, H., & Hubacek, K. (2013). Carbon footprints of cities and other human settlements in the UK. *Environmental Research Letters*, *8*(3). https://doi.org/10.1088/1748-9326/8/3/035039 (Accessed 25 Novemebr 2020)

Mirjat, N. H., Uqaili, M. A., Harijan, K., Mustafa, M. W., Rahman, M. M., & Khan, M. W. A. (2018). Multi-criteria analysis of electricity generation scenarios for sustainable energy planning in Pakistan. *Energies*, *11*(4), 1–33. https://doi.org/10.3390/en11040757 (Accessed 25 Novemebr 2020)

Moll, H. C., Noorman, K. J., Kok, R., Engström, R., Throne-Holst, H., & Clark, C. (2005). Pursuing more sustainable consumption by analyzing household metabolism in European countries and cities. *Journal of Industrial Ecology*, *9*(1–2), 259–275. https://doi.org/10.1162/1088198054084662 (Accessed 25 Novemebr 2020)

Mori, K., Fujii, T., Yamashita, T., Mimura, Y., Uchiyama, Y., & Hayashi, K. (2015). Visualization of a City Sustainability Index (CSI): Towards transdisciplinary approaches involving multiple stakeholders. *Sustainability (Switzerland)*, *7*(9), 12402–12424. https://doi.org/10.3390/su70912402 (Accessed 25 Novemebr 2020)

Nakthong, V., & Kubaha, K. (2019). Development of a sustainability index for an energy management system in Thailand. *Sustainability (Switzerland)*, *11*(17). https://doi.org/10.3390/su11174587(Accessed 25 Novemebr 2020)

Nandasena, Y. L. S., Wickremasinghe, A. R., & Sathiakumar, N. (2010). Air pollution and health in Sri Lanka: a review of epidemiologic studies. *BMC Public Health 2010 10:1*, *10*(1), 1–14. https://doi.org/10.1186/1471-2458-10-300 (Accessed 25 Novemebr 2020)

Nansai, K., Moriguchi, Y., & Tohno, S. (2002). *Embodied energy and emission intensity* *data for Japan using input-output tables (3EID).* https://www.cger.nies.go.jp/publications/report/d031/D031.pdf (Accessed 25 Novemebr 2020)

Narula, K. (2014). Is sustainable energy security of India increasing or decreasing? *International Journal of Sustainable Energy*, *33*(6), 1054–1075. https://doi.org/10.1080/14786451.2013.811411

National Water Supply and Drainage Board. (2017). *National Water Supply and Drainage Board*. http://www.waterboard.lk/web/index.php?option=com_content&view=category&id=56&Itemid=101&lang=en (Accessed 25 Novemebr 2020)

National Water Supply and Drainage Board. (2020). *Current Tariff*. http://www.waterboard.lk/web/index .php?option=com_content&view=article&id=34&Itemid=192&lang=en (Accessed 25 Novemebr 2020)

Nduhuura, P., Garschagen, M., & Zerga, A. (2021). Impacts of electricity outages in urban households in developing countries: A case of accra, ghana. *Energies*, *14*(12). https://doi.org/10.3390/en14123676 (Accessed 25 Novemebr 2020)

Negombo Municipal Council. (2020). *Waste Management Strategy and Action Plan for Negombo City , Sri Lanka , 2020 – 2030*.

Nemes, G., Chiffoleau, Y., Zollet, S., Collison, M., Benedek, Z., Colantuono, F., Dulsrud, A., Fiore, M., Holtkamp, C., Kim, T. Y., Korzun, M., Mesa-Manzano, R., Reckinger, R., Ruiz-Martínez, I., Smith, K., Tamura, N., Viteri, M. L., & Orbán, É. (2021). The impact of COVID-19 on alternative and local food systems and the potential for the sustainability transition: Insights from 13 countries. *Sustainable Production and Consumption*, *28*, 591–599. https://doi.org/10.1016/j.spc.2021.06.022 (Accessed 25 Novemebr 2020)

OECD. (1999). Towards More SUSTAINABLE HOUSEHOLD CONSUMPTION PATTERNS INDICATORS TO MEASURE PROGRESS. *Environment Policy Committee*, *98*.

Okoro, O. I., & Madueme, T. C. (2006). Solar energy: a necessary investment in a developing economy. *International Journal of Sustainable Energy*, *25*(1), 23–31. https://doi.org/10.1080/14786450600593147 (Accessed 25 Novemebr 2020)

Organisation for Economic Co-operation and Development. (1998). *Towards Sustainable Development : Environmental Indicators.* OECD Publishing.

Padovan, D., Martini, F., & K. Cerutti, A. (2015). Social Practices of Ordinary Consumption: An Introduction to Household Metabolism. *Journal of Socialomics*, *04*(02). https://doi.org/10.4172/2167-0358.1000119 (Accessed 25 Novemebr 2020)

Pallegedara, A. (2019a). An exploration into the household pipe-borne water consumption: Empirical evidence from Sri Lankan household surveys. *International Journal of Economics and Business Research*, *17*(4), 473–490. https://doi.org/10.1504/IJEBR.2019.099976 (Accessed 25 Novemebr 2020)

Pallegedara, A. (2019b). Food consumption choice and demand by the Sri Lankan households: Trends, drivers and policy implications. *Journal of Agribusiness in Developing and Emerging Economies*, *9*(5), 520–535. https://doi.org/10.1108/JADEE-01-2019-0014 (Accessed 25 Novemebr 2020)

Pallegedara, A., Mottaleb, K. A., & Rahut, D. B. (2021). Exploring choice and expenditure on energy for domestic works by the Sri Lankan households: Implications for policy. *Energy*, *222*, 119899. https://doi.org/10.1016/j.energy.2021.119899 (Accessed 25 Novemebr 2020)

Patlitzianas, K. D., Doukas, H., Kagiannas, A. G., & Psarras, J. (2008). Sustainable energy policy indicators: Review and recommendations. *Renewable Energy*, *33*(5), 966–973. https://doi.org/10.1016/J.RENENE.2007.05.003 (Accessed 25 Novemebr 2020)

Perera, K. K. C. K., & Sugathapala, A. G. T. (2002). Fuelwood-fired cookstoves in Sri Lanka and related issues. *Energy for Sustainable Development*, *6*(1), 85–94. https://doi.org/10.1016/S0973-0826(08)60302-6 (Accessed 25 Novemebr 2020)

Piekut, M. (2020). Living standards in one-person households of the elderly population. *Sustainability (Switzerland)*, *12*(3), 1–26. https://doi.org/10.3390/su12030992

Pincetl, S., Chester, M., Circella, G., Fraser, A., Mini, C., Murphy, S., Reyna, J., & Sivaraman, D. (2014). Enabling Future Sustainability Transitions: An Urban Metabolism Approach to Los Angeles Pincetl et al. Enabling Future Sustainability Transitions. *Journal of Industrial Ecology*, *18*(6), 871–882.

https://doi.org/10.1111/jiec.12144 (Accessed 25 Novemebr 2020)

Poortinga, W., & Darnton, A. (2016). Segmenting for sustainability: The development of a sustainability segmentation model from a Welsh sample. *Journal of Environmental Psychology*, *45*, 221–232. https://doi.org/10.1016/J.JENVP.2016.01.009 (Accessed 25 Novemebr 2020)

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 (Accessed 25 Novemebr 2020)

Public Utilities Commission of Sri Lanka. (2017). *Financial impact of delay in implementation of power plants*.

Rajeevan, U., & Mishra, B. K. (2020). Sustainable management of the groundwater resource of Jaffna, Sri Lanka with the participation of households: Insights from a study on household water consumption and management. *Groundwater for Sustainable Development*, *10*, 100280. https://doi.org/10.1016/j.gsd.2019.100280 (Accessed 25 Novemebr 2020)

Rajmohan, K., & Weerahewa, J. (2010). Household Energy Consumption Patterns in Sri Lanka. *Sri Lankan Journal of Agricultural Economics*, *9*(0), 55. https://doi.org/10.4038/sjae.v9i0.1833 (Accessed 25 Novemebr 2020)

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. https://doi.org/10.1109/ICCSN.2011.6014245 (Accessed 25 Novemebr 2020)

Ravalde, T., & Keirstead, J. (2017). Comparing performance metrics for multi-resource systems: the case of urban metabolism. *Journal of Cleaner Production*, *163*, S241–S253. https://doi.org/10.1016/j.jclepro.2015.10.118 (Accessed 25 Novemebr 2020)

Reitemeier, M., Aheeyar, M., & Drechsel, P. (2021). Perceptions of food waste reduction in sri lanka's commercial capital, Colombo. In *Sustainability (Switzerland)* (Vol. 13, Issue 2, pp. 1–16). https://doi.org/10.3390/su13020838 (Accessed 25 Novemebr 2020)

Report, F. (2014). *Household Income and Expenditure Survey - 2012/2013*. http://www.statistics.gov.lk/IncomeAndExpenditure/StaticalInformation (Accessed 25 Novemebr 2020)

Rodríguez-Huerta, E., Rosas-Casals, M., & Hernández-Terrones, L. M. (2019). Water societal metabolism in the Yucatan Peninsula. The impact of climate change on the recharge of groundwater by 2030. *Journal of Cleaner Production*, *235*, 272–287. https://doi.org/10.1016/J.JCLEPRO.2019.06.310 (Accessed 23 January 2021)

Rosales Carreón, J., & Worrell, E. (2018). Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism. *Resources, Conservation and Recycling*, *132*(August), 258–266. https://doi.org/10.1016/j.resconrec.2017.08.004 (Accessed 23 January 2021)

Rude, J. (2020). Half the World's New Single Person Households to Emerge in Asia Pacific. *Euromonitor International*, 1–6. https://www.euromonitor.com/article/half-the-worlds-new-single-person-households-to-emerge-in-asia-pacific%0Ahttps://blog.euromonitor.com/half-the-worlds-new-single-person-households-to-emerge-in-asia-pacific/ (Accessed 23 January 2021)

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, *48*(1), 9–26. https://doi.org/10.1016/0377-2217(90)90057-I (Accessed 23 January 2021)

Sahabmanesh, A., & Saboohi, Y. (2017). Model of sustainable development of energy system, case of Hamedan. *Energy Policy*, *104*, 66–79. https://doi.org/10.1016/J.ENPOL.2017.01.039 (Accessed 23 January 2021)

Salo, M., Savolainen, H., Karhinen, S., & Nissinen, A. (2021). Drivers of household consumption expenditure and carbon footprints in Finland. *Journal of Cleaner Production*, *289*, 125607. https://doi.org/10.1016/j.jclepro.2020.125607 (Accessed 23 January 2021)

Sarath Gamini, P. H. (2015). *Challenges in the Water Sector and Wastewater Sector*.

Sarker, R. C., & Gato-Trinidad, S. (2015). Developing a demand model integrating end uses of water (DMEUW): Structure and process of integration. *Water Science and Technology*, *71*(4), 529–537. https://doi.org/10.2166/wst.2015.002 (Accessed 23

January 2021)

Schneider, U. A., & Smith, P. (2009). Energy intensities and greenhouse gas emission mitigation in global agriculture. *Energy Efficiency*, *2*(2), 195–206. https://doi.org/10.1007/s12053-008-9035-5

Shah, S. A. A., Zhou, P., Walasai, G. D., & Mohsin, M. (2019). *Energy security and environmental sustainability index of South Asian countries: A composite index approach*. https://doi.org/10.1016/j.ecolind.2019.105507

Shan, Y., Yang, L., Perren, K., & Zhang, Y. (2015). Household water consumption: Insight from a survey in Greece and Poland. *Procedia Engineering*, *119*(1), 1409–1418. https://doi.org/10.1016/j.proeng.2015.08.1001

Sheinbaum-Pardo, C., Ruiz-Mendoza, B. J., & Rodríguez-Padilla, V. (2012). Mexican energy policy and sustainability indicators. *Energy Policy*, *46*, 278–283. https://doi.org/10.1016/j.enpol.2012.03.060

Shigetomi, Y., Kanemoto, K., Yamamoto, Y., & Kondo, Y. (2021). Quantifying the carbon footprint reduction potential of lifestyle choices in Japan. *Environmental Research Letters*, *16*(6). https://doi.org/10.1088/1748-9326/abfc07 (Accessed 23 January 2021)

Shigetomi, Y., Nansai, K., Kagawa, S., & Tohno, S. (2014). Changes in the carbon footprint of Japanese households in an aging society. *Environmental Science and Technology*, *48*(11), 6069–6080. https://doi.org/10.1021/ES404939D/SUPPL_FILE/ES404939D_SI_001.PDF

Shittu, O. (2020). Emerging sustainability concerns and policy implications of urban household consumption: A systematic literature review. *Journal of Cleaner Production*, *246*(xxxx), 119034. https://doi.org/10.1016/j.jclepro.2019.119034 (Accessed 23 January 2021)

Siksnelyte-Butkiene, I., Zavadskas, E. K., & Streimikiene, D. (2020). Multi-criteria decision-making (MCDM) for the assessment of renewable energy technologies in a household: A review. *Energies*, *13*(5). https://doi.org/10.3390/en13051164

Snell, K. D. M. (2017). The rise of living alone and loneliness in history. *Social History*, *42*(1), 2–28. https://doi.org/10.1080/03071022.2017.1256093 (Accessed 23 January 2021)

Sözen, A., & Nalbant, M. (2007). Situation of Turkey's energy indicators among the EU member states. *Energy Policy*, *35*(10), 4993–5002. https://doi.org/10.1016/J.ENPOL.2007.04.019 (Accessed 23 January 2021)

Sri Lanka Sustainable Energy Authority. (2016). *Ways to Reduce Electricity Bill*.

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

Statistics Bureau of Japan. (2011). *Statistics Bureau Home Page/Family Income and Expenditure Survey*. https://www.stat.go.jp/english/data/kakei/index.html

Statistics Bureau of Japan. (2015). *Statistics Bureau Home Page/Family Income and Expenditure Survey/Results of One-person Households*. https://www.stat.go.jp/english/data/tanshin/1.html (Accessed 23 January 2021)

Statistics of Japan. (2011). *Retail price survey Retail Price Survey (Trend Survey) Yearly 2011 | File | Browse Statistics | Portal Site of Official Statistics of Japan*. https://www.e-stat.go.jp/en/stat-search/files?page=1&layout=datalist&toukei=00200571&tstat=000000680001&cycle=7&year=20110&month=0&result_back=1&tclass1val=0 (Accessed 23 January 2021)

Statistics of Japan. (2015). *Retail price survey Retail Price Survey (Trend Survey) Yearly 2015 | File | Browse Statistics | Portal Site of Official Statistics of Japan*. https://www.e-stat.go.jp/en/stat-search/files?page=1&layout=datalist&toukei=00200571&tstat=000000680001&cycle=7&year=20150&month=0&result_back=1&tclass1val=0 (Accessed 23 January 2021) (Accessed 23 January 2021)

Strydom, A., Musango, J. K., & Currie, P. K. (2019). Conceptualizing household energy metabolism: A methodological contribution. *Energies*, *12*(21). https://doi.org/10.3390/en12214125 (Accessed 23 January 2021)

Strydom, A., Musango, J. K., & Currie, P. K. (2020). Connecting energy services, carriers and flows: Rethinking household energy metabolism in Cape Town, South Africa. *Energy Research and Social Science*, *60*(N ovember 2018), 101313. https://doi.org/10.1016/j.erss.2019.101313 (Accessed 23 January 2021)

Sugiura, S., Miwa, A., & Uno, T. (2013). Analysis of Household Energy Consumption of Lighting and Electric Appliances and Predictions for 2020. *Intercultural*

Understanding, *3*, 17–21. http://www.mukogawa-u.ac.jp/%7B~%7Ditcs/publications/IU_vol3/pdf/IU_vol.3_1-2_article.pdf (Accessed 23 January 2021)

Sun, H., Mohsin, M., Alharthi, M., & Abbas, Q. (2020). Measuring environmental sustainability performance of South Asia. *Journal of Cleaner Production*, *251*, 119519. https://doi.org/10.1016/j.jclepro.2019.119519 (Accessed 23 January 2021)

Sun, M., Chen, G., Xu, X., Zhang, L., Hubacek, K., & Wang, Y. (2021). Reducing Carbon Footprint Inequality of Household Consumption in Rural Areas: Analysis from Five Representative Provinces in China. *Environmental Science & Technology*, *55*(17), 11511–11520. https://doi.org/10.1021/acs.est.1c01374 (Accessed 23 January 2021)

Suphachalasai, S., Ahmed, M., Lasco, R. D., Shrestha, R. M., & Asian Development Bank. (2013). *Economics of reducing greenhouse gas emissions in South Asia : options and costs*.

Taniguchi-Matsuoka, A., Shimoda, Y., Sugiyama, M., Kurokawa, Y., Matoba, H., Yamasaki, T., Morikuni, T., & Yamaguchi, Y. (2020). Evaluating Japan's national greenhouse gas reduction policy using a bottom-up residential end-use energy simulation model. In *Applied Energy* (Vol. 279). https://doi.org/10.1016/j.apenergy.2020.115792 (Accessed 12 March 2022)

Thamilini, J., Wekumbura, C., Mohotti, A. J., Kumara, A. P., Kudagammana, S. T., Silva, K. D. R. R., & Frossard, E. (2019). Organized Homegardens Contribute to Micronutrient Intakes and Dietary Diversity of Rural Households in Sri Lanka. *Frontiers in Sustainable Food Systems*, *0*, 94. https://doi.org/10.3389/FSUFS.2019.00094 (Accessed 12 March 2022)

The Oslo Symposium. (1994). *[Oslo Roundtable] 1.2 Defining sustainable consumption*. 1994. https://enb.iisd.org/consume/oslo004.html (Accessed 23 January 2021)

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

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

The World Bank. (2020). *Households and NPISHs Final consumption expenditure* *(current US$) | Data*. https://data.worldbank.org/indicator/NE.CON.PRVT.CD?end=2018&start=1960

Tongsopit, S., Kittner, N., Chang, Y., Aksornkij, A., & Wangjiraniran, W. (2016). Energy security in ASEAN: A quantitative approach for sustainable energy policy. *Energy Policy*, *90*, 60–72. https://doi.org/10.1016/J.ENPOL.2015.11.019 (Accessed 5 October 2022)

UNEP. (2016). Monitoring the shift to sustainable consumption and roduction patterns in the context of the SDGs. *Environmental Accounts*, *4*, 85. http://www.scpclearinghouse.org/upload/file_management/file/170.pdf%5Cnhttp://www.scpclearinghouse.org/news/188-advance-copy-of-paper-monitoring-the-shift-to-sustainable-consumption-and-production-patterns-in-the-context-of-the-sdgs-.html (Accessed 12 March 2022)

UNFCC. (2000). *Initial National Communication under the United Nations Framework Convention on Climate Change Sri Lanka Foreword Acknowledgements*.

UNFCCC. (2005). *UNFCCC (2005) climate change, small island developing States*.

Unger, T., Springfeldt, P. E., Tennbakk, B., Ravn, H., Havskjold, M., Niemi, J., Koljonen, T., Fritz, P., Koreneff, G., Ryden, B., Lehtilae, A., Skoeldberg, H., Jakobsson, T., & Honkatukia, J. (2010). *Coordinated use of energy system models in energy and climate policy analysis - lessons learned from the Nordic Energy Perspectives project*. [Profu]. (Accessed 5 October 2022)

United Nations. (2015). *World Urbanization Prospects*.

Vera, I., & Langlois, L. (2007). Energy indicators for sustainable development. *Energy*, *32*(6), 875–882. https://doi.org/10.1016/j.energy.2006.08.006 (Accessed 12 March 2022)

Villarroel Walker, R., Beck, M. B., Hall, J. W., Dawson, R. J., & Heidrich, O. (2014). The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*, *141*, 104–115. https://doi.org/10.1016/j.jenvman.2014.01.054 (Accessed 5 October 2022)

Vishnupriyan, J., & Manoharan, P. S. (2018). Multi-criteria decision analysis for renewable energy integration: A southern India focus. *Renewable Energy*, *121*, 474–488. https://doi.org/10.1016/j.renene.2018.01.008 (Accessed 5 October

2022)

W. M. A. A. M. Bandara, P. V. S. Harshana, & G. C. Samaraweera. (2020). CONSUMER ATTITUDE AND AWARENESS ON ORGANIC FOODS. A STUDY ON URBAN AREAS IN SRI LANKA. *1st National Symposium on Agro-Technology and Rural Sciences – 2020*. https://www.researchgate.net/publication/347711593_CONSUMER_ATTITUDE_AND_AWARENESS_ON_ORGANIC_FOODS_A_STUDY_ON_URBAN_AREAS_IN_SRI_LANKA (Accessed 12 March 2022)

Wang, J. J., Jing, Y. Y., Zhang, C. F., & Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021 (Accessed 12 March 2022)

Wang, X., & Chen, S. (2020). Urban-rural carbon footprint disparity across China from essential household expenditure: Survey-based analysis, 2010–2014. *Journal of Environmental Management*, *267*(April), 110570. https://doi.org/10.1016/j.jenvman.2020.110570 (Accessed 12 March 2022)

Weerasekara, P. C., Withanachchi, C. R., Ginigaddara, G. A. S., & Ploeger, A. (2018). Nutrition transition and traditional food cultural changes in Sri Lanka during colonization and post-colonization. *Foods*, *7*(7), 1–18. https://doi.org/10.3390/foods7070111 (Accessed 5 October 2022)

Weiss de Abreu, M., Ferreira, D. V., Pereira, A. O., Cabral, J., & Cohen, C. (2021). Household energy consumption behaviors in developing countries: A structural decomposition analysis for Brazil. *Energy for Sustainable Development*, *62*, 1–15. https://doi.org/10.1016/j.esd.2021.03.001 (Accessed 5 October 2022)

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. https://doi.org/10.1016/J.ENPOL.2011.07.032 (Accessed 12 March 2022)

Wijayatunga, P. D. C., & Jayalath, M. S. (2004). Assessment of economic impact of electricity supply interruptions in the Sri Lanka industrial sector. *Energy Conversion and Management*, *45*(2), 235–247. https://doi.org/10.1016/S0196-

8904(03)00132-8

Williams, J. (2005). One-Person Households – A Resource Time Bomb? *Ecosystems and Sustainable Development V*, *81*, 409–417.

Williams, Jo. (2002). Shared living: Reducing the ecological footprint of individuals in Britain. *Built Environment*, *28*(1), 57–72.

Williams, Jo. (2007). Innovative solutions for averting a potential resource crisis - The case of one-person households in England and Wales. *Environment, Development and Sustainability*, *9*(3), 325–354. https://doi.org/10.1007/s10668-006-9068-x (Accessed 5 October 2022)

Willis, R. M., Stewart, R. A., Giurco, D. P., Talebpour, M. R., & Mousavinejad, A. (2013). End use water consumption in households: Impact of socio-demographic factors and efficient devices. *Journal of Cleaner Production*, *60*, 107–115. https://doi.org/10.1016/j.jclepro.2011.08.006 (Accessed 5 October 2022)

Woolley, E., Luo, Z., Jellil, A., & Simeone, A. (2021). A Data Driven Approach to Reducing Household Food Waste. *Sustainable Production and Consumption*. https://doi.org/10.1016/J.SPC.2021.11.004 (Accessed 5 October 2022)

World Bank. (2018). *Households and NPISHs Final consumption expenditure per capita growth (annual %) - South Asia, East Asia & Pacific, Sub-Saharan Africa, Latin America & Caribbean, Middle East & North Africa | Data*. 2018. https://data.worldbank.org/indicator/NE.CON.PRVT.PC.KD.ZG?end=2018&locations=8S-Z4-ZG-ZJ-ZQ&start=1977 (Accessed 5 October 2022)

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

World Food Programme. (2017). *National Strategic Review of Food Security and Nutrition Towards Zero Hunger*.

Wu, S., Lei, Y., & Li, S. (2019). CO_2 emissions from household consumption at the provincial level and interprovincial transfer in China. *Journal of Cleaner Production*, *210*, 93–104. https://doi.org/10.1016/j.jclepro.2018.10.356

(Accessed 23 January 2021)

Wulff, M. (2001). Growth and change in one person households: Implications for the housing market. *Urban Policy and Research*, *19*(4), 467–489. https://doi.org/10.1080/08111140108727894

Xu, W., Xie, Y., Cai, Y., Ji, L., Wang, B., & Yang, Z. (2021). Environmentally-extended input-output and ecological network analysis for Energy-Water-CO_2 metabolic system in China. *Science of the Total Environment*, *758*(100), 143931. https://doi.org/10.1016/j.scitotenv.2020.143931 (Accessed 5 October 2022)

Yagita, Y., & Iwafune, Y. (2021). Residential energy use and energy-saving of older adults: A case from Japan, the fastest-aging country. *Energy Research and Social Science*, *75*(July 2020), 102022. https://doi.org/10.1016/j.erss.2021.102022 (Accessed 5 October 2022)

Yang, Q., Guo, S., Yuan, W. H., Shen, Q., Chen, Y. Q., Wang, X. H., Wu, T. H., Chen, Z. M., Alsaedi, A., & Hayat, T. (2015). Energy-dominated carbon metabolism: A case study of Hubei province, China. *Ecological Informatics*, *26*(P1), 85–92. https://doi.org/10.1016/j.ecoinf.2013.10.001 (Accessed 5 October 2022)

Yang, S., Chen, B., Wakeel, M., Hayat, T., Alsaedi, A., & Ahmad, B. (2018). PM2.5 footprint of household energy consumption. *Applied Energy*, *227*(19), 375–383. https://doi.org/10.1016/j.apenergy.2017.11.048 (Accessed 5 October 2022)

Yeung, W. J. J., & Cheung, A. K. L. (2015). Living alone: One-person households in Asia. *Demographic Research*, *32*(1), 1099–1112. https://doi.org/10.4054/DemRes.2015.32.40 (Accessed 5 October 2022)

Yigezu, Z. D., & Jawo, T. O. (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. https://doi.org/10.1080/14786451.2020.1812609 (Accessed 23 January 2021)

Yu, E., & Liu, J. (2007). Environmental impacts of divorce. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(51), 20629–20634. https://doi.org/10.1073/PNAS.0707267104 (Accessed 23 January 2021)

Zen, I. S., Al-Amin, A. Q., Alam, M. M., & Doberstein, B. (2021). Magnitudes of households' carbon footprint in Iskandar Malaysia: Policy implications for sustainable development. *Journal of Cleaner Production*, *315*(June), 128042. https://doi.org/10.1016/j.jclepro.2021.128042 (Accessed 23 January 2021)

Zhou, X. Y., & Gu, A. L. (2020). Impacts of household living consumption on energy use and carbon emissions in China based on the input–output model. *Advances in Climate Change Research*, *11*(2), 118–130. https://doi.org/10.1016/j.accre.2020.06.004 (Accessed 5 October 2022)

Zou, B., & Luo, B. (2019). Rural household energy consumption characteristics and determinants in China. *Energy*, *182*, 814–823. https://doi.org/10.1016/j.energy.2019.06.048 (Accessed 5 October 2022)

APPENDICES

APPENDIX A

Table A-1: 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, 2017
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, 2017
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, 2017

Table A-2: Input Parameters of Variables of Energy Supply and Transformation 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 A-3: Input Parameters of CO_2 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

APPENDIX B

Table B-1: Results of the desk study of sustainability indicators

Criteria	Indicator	References	Policy Objective
Economic	Energy intensity	2,4,6.8,9,11,12,13, 14,15, 17, 19, 20	Security (Efficiency)
	Energy use per capita	1,3,4,6,8,9,10,11,12,13,15, 16, 17, 19, 20	Security (Efficiency)
	Energy intensity of industrial sector	3,6,9,10,11,12,13,15, 17, 20	Security (Efficiency)
	Energy intensity of domestic and commercial sector	3,6,8,11,12,13,15, 17, 20	Security (Efficiency)
	Energy intensity of transport sector	3,6,8,11,12,13,15, 17, 20	Security (Efficiency)
	Efficiency of electricity conversion and distribution	6,8,11,12,13, 19, 20	Security (Efficiency)
	Energy self-sufficiency	6,8,12,13, 17, 19	Security (Self-Reliance)
Social	Share of household income spent on electricity	5,9,10,11, 17, 18, 19, 20	Equity (Optimum Cost)
	Energy consumption per household	1,6,8,9,10,11,14,15, 16, 19	Equity (Optimum Cost)
	Share of population without electricity (%)	7,9,10,11,13, 16, 17, 18, 20	Equity (Access)
Environmental	CO_2 emissions per capita	1,3,4,5,7,8,9,10,11, 12,13,14,15, 16, 17, 19, 20	Sustainability (Environment)
	Emission intensity	1,3,4,5,7,8,9,11,12, 13,14, 17	Sustainability (Environment)
	Renewable energy share in energy (%)	2,8,9,11,12,13,16, 18, 20	Sustainability (Renewable Energy)

1.European Foundation (1998); 2.Kemmler & Spreng (2007); 3.Organisation for Economic Co-operation and Development (1998); 4.The Urban China Initiative (2010); 5.Kostevšek et al. (2015); 6.Chrysoulakis et al., 2013) 7.Afgan & da Graça Carvalho (2000); 8.Kilkiş (2016); 9.González et al. (2013); 10.Kennedy et al.(2014); 11.Tongsopit et al. (2016); 12.Patlitzianas et al. (2008); 13.Sahabmanesh & Saboohi

(2017); 14.Boggia & Cortina (2010); 15.Sözen & Nalbant (2007); 16.Sheinbaum-Pardo et al.(2012); 17.Hannan et al. (2018); 18.Angelis-Dimakis et al. (2012); 19.Iddrisu & Bhattacharyya (2015); 20.Vera & Langlois (2007)

Table B-1: Questionnaire

Evaluation and Future Scenarios for Sustainable Urban Metabolic System in Sri Lanka

Respondents' Details:

Name (Optional):

Age:

Educational qualifications:

Name of the organization:

Please indicate which criterion in the pair is more important to sustainability of energy metabolic system in Sri Lanka. If one criterion is more important than the other, please indicate the magnitude of its importance over the other criteria.

The scale for magnitude is as follows.

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two criteria are equally important in evaluating the building performance.
3	Moderate Importance	One of the criteria is slightly more important than the other
5	Strong Importance	One of the criteria is strongly more important than the other
7	Very Strong Importance	One of the criteria is very strongly favoured than the other and its dominance demonstrated in practice
9	Extreme Importance	The evidence importance of one criterion over another is of the highest possible order of affirmation which cannot being comparable

Example 1: If Economic Criterion is judged as strongly more important (5 times more important) than Social Criterion in evaluating sustainability of energy metabolic system in Sri Lanka, please indicate as follows.

Comparison Pair			More Important A or B		Level of Importance				
A	Vs	B							
Economic	Vs	Social	A	B	1	3	5	7	9

Example 2: If Economic Criterion is judged as equally important (level of importance = 1) to the Social Criterion in evaluating sustainability of energy metabolic system in Sri Lanka, please indicate as follows.

Comparison Pair			More Important A or B		Level of Importance				
A	Vs	B							
Economic	Vs	Social	A	B	1	3	5	7	9

Part 1: Evaluating sustainability criteria

Please indicate which criterion in the pair is more important to evaluate the sustainability of energy metabolic system in Sri Lanka. Please indicate the magnitude of importance of each criterion.

Comparison Pair			More Important A or B		Level of Importance				
A	Vs	B							
Economic	Vs	Social	A	B	1	3	5	7	9
Economic	Vs	Environmental	A	B	1	3	5	7	9
Social	Vs	Environmental	A	B	1	3	5	7	9

Part 2: Evaluating Sustainability Indicators of Each Criteria

Economic Indicators

Please indicate which indicator in the pair is more important than the other in evaluating the economic aspect of sustainability of energy metabolic system in Sri Lanka. Please indicate the magnitude of importance of each performance indicator.

Comparison Pair			More Important A or B	Level of Importance
A	Vs	B		
Energy intensity	Vs	Energy use per capita	A B	1 3 5 7 9
Energy intensity	Vs	Energy intensity of industrial sector	A B	1 3 5 7 9
Energy intensity	Vs	Energy intensity of domestic and commercial sector	A B	1 3 5 7 9
Energy intensity	Vs	Energy intensity of transport sector	A B	1 3 5 7 9
Energy intensity	Vs	Efficiency of electricity conversion and distribution	A B	1 3 5 7 9
Energy intensity	Vs	Energy self-sufficiency	A B	1 3 5 7 9
Energy use per capita	Vs	Energy intensity of industrial sector	A B	1 3 5 7 9
Energy use per capita	Vs	Energy intensity of domestic and commercial sector	A B	1 3 5 7 9
Energy use per capita	Vs	Energy intensity of transport sector	A B	1 3 5 7 9
Energy use per capita	Vs	Efficiency of electricity conversion and distribution	A B	1 3 5 7 9
Energy use per capita	Vs	Energy self-sufficiency	A B	1 3 5 7 9
Energy intensity of industrial sector	Vs	Energy intensity of domestic and commercial sector	A B	1 3 5 7 9
Energy intensity of industrial sector	Vs	Energy intensity of transport sector	A B	1 3 5 7 9
Energy intensity of industrial sector	Vs	Efficiency of electricity conversion and distribution	A B	1 3 5 7 9
Energy intensity of industrial sector	Vs	Energy self-sufficiency	A B	1 3 5 7 9
Energy intensity of domestic and commercial sector	Vs	Energy intensity of transport sector	A B	1 3 5 7 9
Energy intensity of domestic and commercial sector	Vs	Efficiency of electricity conversion and distribution	A B	1 3 5 7 9

Energy intensity of domestic and commercial sector	Vs	Energy self-sufficiency	A B	1 3 5 7 9
Energy intensity of transport sector	Vs	Efficiency of electricity conversion and distribution	A B	1 3 5 7 9
Energy intensity of transport sector	Vs	Energy self-sufficiency	A B	1 3 5 7 9
Efficiency of electricity conversion and distribution	Vs	Energy self-sufficiency	A B	1 3 5 7 9

Social Indicators

Please indicate which indicator in the pair is more important than the other in evaluating the social aspect of sustainability of energy metabolic system in Sri Lanka. Please indicate the magnitude of importance of each performance indicator.

Comparison Pair			**More Important A or B**	**Level of Importance**
A	**Vs**	**B**		
Share of Population without Electricity (%)	Vs	Share of Household Income Spent on Electricity	A B	1 3 5 7 9
Share of Population without Electricity (%)	Vs	Energy consumption per Household	A B	1 3 5 7 9
Share of Household Income Spent on Electricity	Vs	Energy consumption per Household	A B	1 3 5 7 9

Environmental Indicators

Please indicate which indicator in the pair is more important than the other in evaluating the environmental aspect of sustainability of energy metabolic system in Sri Lanka. Please indicate the magnitude of importance of each performance indicator.

Comparison Pair			More Important A or B		Level of Importance				
A	Vs	B							
GHG Emissions per Capita	Vs	Emission intensity	A	B	1	3	5	7	9
CO_2 Emissions per Capita	Vs	Renewable Energy Share in Energy (%)	A	B	1	3	5	7	9
Emission intensity	Vs	Renewable Energy Share in Energy (%)	A	B	1	3	5	7	9

Table B-3: Pair-Wise Comparison of Social Criteria

Social Indicators	Share of Population without Electricity (%)	Share of Household Income Spent on Electricity	Energy consumption per Household
Share of Population without Electricity (%)	1.000	0.297	0.248
Share of Household Income Spent on Electricity	3.365	1.000	1.533
Energy consumption per Household	4.038	0.652	1.000
SUM	8.404	1.949	2.781

TableB-4: Normalise Comparison of Social Criteria

Social Indicators	Share of Population without Electricity (%)	Share of Household Income Spent on Electricity	Energy consumption per Household	SUM	Sustainability Score
Share of Population without Electricity (%)	0.119	0.152	0.089	0.360	0.120
Share of Household Income Spent on Electricity	0.400	0.513	0.551	1.465	0.488
Energy consumption per Household	0.481	0.335	0.360	1.175	0.392

Table B-5: Consistency Comparison Social Criteria

Social Indicators	Share of Population without Electricity	Share of Household Income Spent on Electricity	Energy consumption per Household	SUM	SUM / Sustainability Score
Share of Population without Electricity	0.120	0.145	0.097	0.362	3.014
Share of Household Income Spent on Electricity	0.404	0.488	0.600	1.493	3.058
Energy consumption per Household	0.485	0.318	0.392	1.195	3.052

λ max=3.042 CI=0.021 CR=0.036

Table B-6: Pair-Wise Comparison of Environmental Criteria

Environmental Indicators	CO_2 Emissions per Capita	Emission intensity	Renewable Energy Share in Energy (%)
CO_2 Emissions per Capita	1.000	1.533	3.200
Emission intensity	0.652	1.000	4.200
Renewable Energy Share in Energy	0.313	0.238	1.000
SUM	1.965	2.771	8.400

Table B-7: Normalise Comparison of Environmental Criteria

Environmental Indicators	CO_2 Emissions per Capita	Emission intensity	Renewable Energy Share in Energy (%)	SUM	Sustainability Score
CO_2 Emissions per Capita	0.509	0.553	0.381	1.443	0.481
Emission intensity	0.332	0.361	0.500	1.193	0.398
Renewable Energy Share in Energy (%)	0.159	0.086	0.119	0.364	0.121

Table B-8: Consistency Comparison of Environmental Criteria

Environmental Indicators	CO_2 Emissions per Capita	Emission intensity	Renewable Energy Share in Energy (%)	SUM	SUM / Sustainability Score
CO_2 Emissions per Capita	0.481	0.610	0.388	1.479	3.074
Emission intensity	0.314	0.398	0.510	1.221	3.071
Renewable Energy Share in Energy (%)	0.150	0.095	0.121	0.366	3.019

λ max=3.055 CI=0.027 CR=0.047

APPENDIX C

Table C-1: Conversion factors and carbon emission factors for different types of fuels in Sri Lanka (UNFCC, 2000)

Fuel Type	Net calorific value (TJ/kt)	Carbon emission factor (tC/TJ)
FOSSIL FULES		
Crude Oil	42.16	20
Gasoline	44.8	18.9
Jet Kerosene	44.59	19.5
Kerosene	44.75	19.6
Gas/Diesel Oil	43.33	20.2
Residual Fuel Oil	40.19	21.1
LPG	47.31	17.2
Naphtha	45.01	20
Bitumen	40.19	22
Lubricant	40.19	20
Other Oil	40.19	20
Other Bituminous Coal	25.75	25.8
SOLID BIOMASS		
Wood (Air dried)	15.5	29.9
Charcoal	29	29.9
Bagasse (Air dried)	16.2	29.9
Agricultural Waters	15	29.9

Table C-2: Prices of Petroleum and Diesel Fuel (Ceylon Petroleum Corporation, 2020)

Fuel Type	2016	2013	2010	2007	2002
Petroleum (Rs.)	117	162	115	105	49.5
Diesel Oil (Rs.)	95	121	73	65.8	28.2

Table C-3: Tariff plans for electricity usage in private residences (Ceylon Electricity Board, 2020)

Monthly Consumption kWh	2016		2013		2010		2007		2002	
	Unit Charge (Rs./kWh)	Fixed Charge (Rs./month)	Unit Charge (Rs./kWh)	Fixed Charge (Rs./month)	Unit Charge (Rs./kWh)	Fixed Charge (Rs./month)	Unit Charge (Rs./kWh)	Fixed Charge (Rs./month)	Unit Charge (Rs./kWh)	Fixed Charge (Rs./month)
0-30	2.5	30	3	30	3	60	3	60	3	30
31-61	4.85	60	4.7	60	4.7	90	4.7	90	3.7	30
0-60	7.85	N/A		N/A						
61-90	10	90	12	90	7.5	120	7.5	120	4.1	30
91-120	27.75	480	26.5		16	180	14	180	10.6	30

Table C-4: Grid emission factor (Sri Lanka Sustainable Energy Authority, 2017)

Year	2002	2007	2010	2013	2016
Grid emission factor (Kg CO_2 /kWh)	0.3451	0.3451	0.3158	0.5077	0.5845

Table C-5: Water tariff plan for households, other than those of Samurdhi recipients and residing

in tenement gardens (National Water Supply and Drainage Board, 2020)

No. of units (m^3)	2013		2010	
	Usage Charge Rs./Uni	Monthly Service Rs.	Usage Charge Rs./Uni	Monthly Service Rs.
0-5	12	50	12	50
5-10	16	65	16	65
10-15	20	70	20	70

Table C-6: Estimated/assumed waste percentages for each commodity group in each step of the FSC for South and Southeast Asia (Food and Agriculture & Organization of the United Nations (FAO), 2011)

Food category	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	7%	3.5%	2%	3%
Roots and tubers	6%	19%	10%	11%	3%
Oilseeds and pulses	7%	12%	8%	2%	1%
Fruits and vegetables	15%	9%	25%	10%	7%
Meat	5.1%	0.3%	5%	7%	4%
Fish and seafood	8.2%	6%	9%	15%	2%
Milk	4%	6%	2%	10%	1%

APPENDIX D

Table D-1: Cross-mapping of FIES consumption expenditure data with 3EID emissions intensity categories

Item names (FIES)	**Item names (3EID)**
Rice	Grain
Plain Bread	Bread
Other Bread	Bread
Raw Udon / Soba	Noodles
Dried Udon Noodles	Noodles
Spaghetti	Noodles
Chinese Noodles	Noodles
Cup Noodles	Noodles
Instant Noodles	Noodles
Other Noodles	Noodles
Flour	Milling
Mochi	Grain
Other Cereals Other	Grain
Tuna	Marine fishing
Taste	Marine fishing
Sardines	Marine fishing
Bonito	Marine fishing
Karei	Marine fishing
Salmon	Marine fishing
Mackerel	Marine fishing
Saury	Marine fishing
Want	Marine fishing
First Time	Marine fishing
The Squid	Marine fishing

Octopus	Marine fishing
Shrimp	Marine fishing
Crab	Marine fishing
Other Fresh Fish	Marine fishing
Assorted Sashimi	Marine fishing
Clams	Marine fishing
Shijimi	Marine fishing
Oyster (Shellfish)	Marine fishing
Scallop	Marine fishing
Other Shellfish	Marine fishing
Salted Salmon	Salt / dried / kun products
Tarako	Salt / dried / kun products
Dried Whitebait	Salt / dried / kun products
Dried Aji	Salt / dried / kun products
Other Salted Seafood	Salt / dried / kun products
Fried Kamaboko	Fish-paste Product
Chikuwa	Fish-paste Product
Kamaboko	Fish-paste Product
Other Fish Meat Products 練	Fish-paste Product
Skipjack And Sharpener	Other seafood
Seafood Pickles	Other seafood
Tsukudani With Seafood	Other seafood
Canned Seafood	Other seafood
Other Processed Seafood Products	Other seafood
Beef	Beef cattle
Pork	Pig
Chicken	Chicken
Goat Meat	Other livestock
Other Fresh Meat	Other livestock
Ham	Processed meat

Sausage	Processed meat
Bacon	Processed meat
Other Processed Meat	Processed meat
Milk	Dairy products
Powdered Milk	Dairy products
Yogurt	Dairy products
Butter	Dairy products
Cheese	Dairy products
Other Dairy Products	Dairy products
Egg	Chicken eggs
Cabbage	Vegetables
Spinach	Vegetables
Hungry	Vegetables
Green Onions	Vegetables
Lettuce	Vegetables
Broccoli	Vegetables
Sprout	Vegetables
Other Leafy Vegetables	Vegetables
Sweet Potato	Potatoes
Potatoes	Potatoes
Sweet Potato	Potatoes
Radish	Vegetables
Carrots	Vegetables
Burdock	Vegetables
Onion	Vegetables
Lotus Root	Vegetables
Bambooshoot	Vegetables
Other Root Vegetables	Vegetables
Soybean	Vegetables
Pumpkin	Vegetables

Cucumbers	Vegetables
Eggplant	Vegetables
Tomato	Vegetables
Green Pepper	Vegetables
Raw Mushroom	Vegetables
Other Mushrooms	Vegetables
Shimeji muchroom	Vegetables
Other muchroom	Vegetables
Other Vegetables	Vegetables
Beans	beans
Dried Shiitake	Vegetables
Dried Seaweed	Marine aquaculture
Seaweed	Marine aquaculture
Konbu	Marine aquaculture
Other Dry Matter / Seaweed	Marine aquaculture
Tofu	Other food products
Deep Fried / Ganmodoki	Other food products
Natto	Other food products
Other Soy Products	Other food products
Konjac	Other food products
Salted Plum	Agricultural preserved foods (excluding bottles and canned foods)
Radish Pickles	Agricultural preserved foods (excluding bottles and canned foods)
Hakusai Pickles	Agricultural preserved foods (excluding bottles and canned foods)
Pickles Of Other Vegetables	Agricultural preserved foods (excluding bottles and canned foods)
Boiled Konbutsu	Other food products
Tsukudani Of Other Vegetables And	Agricultural preserved foods (excluding

Seaweed	bottles and canned foods)
Other Processed Vegetable And Seaweed Products	Agricultural preserved foods (excluding bottles and canned foods)
Apple	Fruit
Mandarin Orange	Fruit
Grapefruit	Fruit
Orange	Fruit
Other Citrus	Fruit
None	Fruit
Grape	Fruit
Oyster (Fruit)	Fruit
Peaches	Fruit
Watermelon	Fruit
Melon	Fruit
Strawberry	Fruit
Banana	Fruit
Kiwi Fruit	Fruit
Other Fruits	Fruit
Processed Fruit	Agricultural preserved foods (excluding bottles and canned foods)
Cooking Oil	Animal and vegetable fats and oils
Margarine	Animal and vegetable fats and oils
Salt	Seasoning
Soy Sauce	Seasoning
Miso	Seasoning
Sugar	Seasoning
Vinegar	Seasoning
Source	Seasoning
Ketchup	Seasoning
Mayonnaise / Mayonnaise Style	Seasoning

Seasoning	
Dressing	Seasoning
Jam	Seasoning
Curry Roux	Seasoning
Dried Soup	Seasoning
Flavor Seasonings	Seasoning
Sprinkle	Seasoning
Soup And Sauce	Seasoning
Other Seasonings	Seasoning
Yokan	Confectionery
Steamed Bun	Confectionery
Other Japanese Sweets	Confectionery
Castella	Confectionery
Cake	Confectionery
Jelly	Confectionery
Pudding	Confectionery
Other Western Confectionery	Confectionery
Rice Cracker	Confectionery
Biscuit	Confectionery
Snacks	Confectionery
Candy	Confectionery
Chocolate	Confectionery
Chocolate Candy	Confectionery
Ice Cream Sorbet	Confectionery
Other Sweets	Confectionery
Lunch Box	Sona, sushi, bento
Sushi (Lunch Box)	Sona, sushi, bento
Onigiri / Others	Sona, sushi, bento
Cooking Pan	Bread
Other Staple Foods	Sona, sushi, bento

Other Cooked Food	Sona, sushi, bento
Grilled Eel	Sona, sushi, bento
Salad	Sona, sushi, bento
Croquette	Sona, sushi, bento
Cutlet	Sona, sushi, bento
Tempura / Fry	Sona, sushi, bento
Shower	Sona, sushi, bento
Gyoza	Sona, sushi, bento
Yakitori	Sona, sushi, bento
Hamburger	Sona, sushi, bento
Frozen Cooked Food	Frozen cooked food
Sozai Material Set	Sona, sushi, bento
Other Cooking Food Other	Sona, sushi, bento
Green Tea	Tea / Coffee
Black Tea	Tea / Coffee
Other Tea Leaves	Tea / Coffee
Tea Beverage	Tea / Coffee
Coffee	Tea / Coffee
Coffee Drink	Tea / Coffee
Cocoa And Cocoa Drinks	Tea / Coffee
Fruit And Vegetable Juice	Soft drink
Soda Drink	Soft drink
Lactic Acid Bacteria Drink	Soft drink
Milk Beverage	Soft drink
Mineral Water	Soft drink
Sports drink	Soft drink
Other Of Other Beverages	Soft drink
Sake	Sake
Baking	Sake
Beer	Beer

Whisky	Whiskeys
Wine	Other alcoholic beverages
Happoshu / Beer-Style Alcoholic Beverages	Other alcoholic beverages
Cocktail of Japanese spirits	Other alcoholic beverages
Other Sake	Other alcoholic beverages
Japanese Soba / Udon	Food service
Chinese Noodles	Food service
Other Noodles Eating Out	Food service
Sushi (Eating Out)	Food service
Japanese Food	Food service
Chinese Food	Food service
Western Food	Food service
Grill	Food service
Hamburger	Food service
Other Staple Eating Out	Food service
Coffee Bill	Food service
Drinking Fee	Food service
School Lunch	School lunch (public)
Private Rent	Housing rent
Public Rent	Housing rent
Salary Housing Rent	Housing rent
Rent	Housing rent
Other Rent Rent	Housing rent
Equipment	Other electric machinery
Repair Materials	Architectural metal products
Tatami Mat	Other personal services
Water Supply And Drainage Related Construction Costs	Building services
Construction Costs For Exterior Walls	Building services

And Fences	
Gardening And Garden Care	Building services
Other Construction Costs	Building services
Fire And Earthquake Insurance Premiums	Non-life insurance
Midnight Electricity Bill	Commercial power
Other Electricity Bills	Commercial power
City Gas	City Gas
LPG	Compressed gas / liquefied gas
Kerosene	Petroleum products
Other Light Heat Other	Heat supply industry
Sewerage fee	River, sewerage system and other public projects
Microwave	Consumer electrical equipment (excluding air conditioners)
Cooking Appliances	Consumer electrical equipment (excluding air conditioners)
Gas Appliances For Cooking	Gas / oil equipment / heating kitchen equipment
Electric Refrigerator	Consumer electrical equipment (excluding air conditioners)
Electric Vacuum Cleaner	Consumer electrical equipment (excluding air conditioners)
Electric Washing Machine	Consumer electrical equipment (excluding air conditioners)
Air Conditioner	Consumer air conditioner
Stove / Hot Air Heater	Gas / oil equipment / heating kitchen equipment
Other Cooling And Heating Equipment	Consumer electrical equipment (excluding air conditioners)
Chest	Wooden furniture

Dining Table Set	Wooden furniture
Reception Set	Wooden furniture
Cupboard	Wooden furniture
Other Furniture	Other furniture and equipment
Lighting Equipment	Electric lighting equipment
Upholstery	Personal goods
Rug	Carpets and floor coverings
Curtain	Other fiber ready-made products
Other Indoor Equipment	Other furniture and equipment
Bed	Wooden furniture
Futon	bedding
Blanket	bedding
Mattress	bedding
Other Bedding	bedding
Bowl, Plate, Bowl	Plastic products
Other Tableware	Plastic products
Pots And Kettles	Metal containers and metal cans
Other Kitchen Utensils	Other glassware
Light Bulbs And Fluorescent Lamps	Light bulbs
Towel	Other fiber ready-made products
Other Household Goods	Plastic products
Tissue Paper	Paper sanitary materials and supplies
Toilet Paper	Paper sanitary materials and supplies
Kitchen And Residential Detergents	Oil and fat products, soaps, synthetic detergents, surfactants
Laundry Detergent	Oil and fat products, soaps, synthetic detergents, surfactants
Plastic Bag / Wrap	Plastic products
Insecticide And Insect Repellent	Pesticide
Fabric softener	Oil and fat products, soaps, synthetic

	detergents, surfactants
Deodorant	Oil and fat products, soaps, synthetic detergents, surfactants
Other Household Consumables	Other chemical end products
Housekeeping Fee	Building services
Cleaning Fee	Building services
Furniture And Household Goods Related Services	Building services
Men's Kimono	Woven clothing
Women's Kimono	Woven clothing
Women's Belt	Woven clothing
Other Women's Kimono	Woven clothing
Kimono For Children	Woven clothing
Suit Suit	Woven clothing
Men's Outerwear	Woven clothing
Men's Pants	Woven clothing
Men's Coat	Woven clothing
School Uniforms For Boys	Woven clothing
Other Men's Clothes	Woven clothing
Women's Clothing	Woven clothing
Women's Outerwear	Woven clothing
Skirt	Woven clothing
Women's Slacks	Woven clothing
Women's Coat	Woven clothing
School Uniform For Girls	Woven clothing
Other Women's Clothes	Woven clothing
Children'S Wear	Woven clothing
Baby Clothes	Woven clothing
Shirt	Woven clothing
Other Men's Shirts	Woven clothing

Men's Sweaters	Knitted clothing
Women's Shirts And Sweaters	Woven clothing
Blouse	Woven clothing
Other Women's Shirts	Woven clothing
Women's Sweater	Knitted clothing
Children's Shirts	Woven clothing
Children'sSweaters	Knitted clothing
Men's Underwear	Woven clothing
Men's Sleepwear	Woven clothing
Women's Foundation	Woven clothing
Other Women's Underwear	Woven clothing
Women's Sleepwear	Woven clothing
Underwear For Children	Woven clothing
Children'S Sleepwear	Woven clothing
Kijyakuji / Fabric	Knitted fabric
Other Fabrics And Yarns	Other textile products
Hat	Other clothing and personal items
Tie	Other clothing and personal items
Muffler Scarf	Other clothing and personal items
Gloves	Other clothing and personal items
Men's Socks	Other clothing and personal items
Women's Stockings	Other clothing and personal items
Women's Socks	Other clothing and personal items
Kids Socks	Other clothing and personal items
Other Clothing Other	Other clothing and personal items
Sports Shoes	Rubber and plastic footwear
Sandals	Rubber and plastic footwear
Men's Shoes	Leather footwear
Women's Shoes	Leather footwear
Kids Shoes	Leather footwear

Other Footwear	Rubber and plastic footwear
Washing Fee	Laundry industry
Clothing Rent	Goods rental business (excluding rental cars)
Other clothing services	Other personal services
Cold Medicine	Medicine
Gastrointestinal Drug	Medicine
Nutritional Supplement	Medicine
Trauma / Dermatological Drugs	Medicine
Other Topical Drugs	Medicine
Other Medicines	Medicine
Ingestion For Maintaining Health	Medicine
Paper Diapers	Paper sanitary materials and supplies
Consumables For Health	Medicine
Glasses	Other manufactured industrial products
Contact Lens	Other manufactured industrial products
Other Healthcare Supplies And Equipment	Other manufactured industrial products
Medical Treatment Fee	Medical care (out-of-hospital care)
Dental Care Fee	Medical (Dental practice)
Maternity Hospitalization Fee	Medical care (hospital care)
Other Hospital Charges	Medical care (hospital care)
Osteopath (Bone Graft) / Acupuncture	Medical (Dental practice)
Massage Fee, Etc.	Health and hygiene (industry)
Medical checkup	Health and hygiene (industry)
Other Health Care Services	Health and hygiene (industry)
Rail Fare	Railway passenger transport
Railway Commuter Pass	Railway passenger transport
Rail Commute	Railway passenger transport
Bus Fare	bus
Bus Commuter Pass	bus

Bus Commute	bus
Taxi Fare	Higher taxi
Airfare	Air transport
Toll Road Fee	Provision of road transport facilities
Other Traffic	Private transportation (passenger car)
Car Purchase	Passenger car
Purchase Of Transportation Equipment Other Than Automobiles	Other transport equipment
Bicycle Purchase	bicycle
Gasoline	Petroleum products
Automotive Parts	Auto parts
Automobile Related Goods	Auto parts
Car Maintenance Costs	Mechanical repair
Transportation Equipment Maintenance Costs Other Than Automobiles	Mechanical repair
Annual And Monthly Parking Rent	Real estate brokerage and management
Other Parking Rent	Real estate brokerage and management
Car Rental Fee	Car rental business
Other Automobile Related Services	Car maintenance
Car Insurance (Committee Liability)	Non-life insurance
Car Insurance Premium (Optional)	Non-life insurance
Transportation Equipment Insurance Premiums Other Than Car Insurance Premiums	Non-life insurance
Postage	Postal and letter service
Landline Telephone Charges	Fixed telecommunications
Mobile Phone Communication Charges	Mobile telecommunications
Freight Charges	Cargo transportation
Mobile Phone	Wireless telecommunications equipment (excluding mobile phones)

Other Communication Equipment	Other telecommunications equipment
National Public Elementary School	School education (national public)
Private Elementary School	School education (private)
National Public Junior High School	School education (national public)
Private Junior High School	School education (private)
National Public High School	School education (national public)
Private High School	School education (private)
National And Public Universities	School education (national public)
Private University	School education (private)
Kindergarten	School education (national public)
Vocational School	School education (national public)
Textbook	Printing, plate making, bookbinding
Learning Reference Materials	Printing, plate making, bookbinding
Infant And Elementary School Supplementary Education	Other educational and training institutions (industry)
Junior High School Supplementary Education	Other educational and training institutions (industry)
High School Supplementary Education And Prep School	Other educational and training institutions (industry)
Tv Set	Radio / TV receiver
Portable Music And Video Equipment	Electroacoustic equipment
Video Deck	Video equipment and digital cameras
Personal Computer	Personal computer
Camera	Video equipment and digital cameras
Video Camera	Video equipment and digital cameras
Musical Instrument	Musical instrument
Study / Study Desk / Chair	Wooden furniture
Other Educational And Durable Goods	Other entertainment
Repair Fee For Durable Goods For Education And Recreation	Various repair businesses (excluding separate listings)

Writing And Painting Tools	Writing and stationery
Notebook And Paper Products	Other pulp, paper and processed paper products
Other Learning Consumables	Other manufactured industrial products
Other Learning Stationery	Writing and stationery
Other Stationery	Writing and stationery
Golf Equipment	Exercise equipment
Other Exercise Equipment	Exercise equipment
Sports Equipment	Exercise equipment
Video Game Console	Gun tool
Game Software, Etc.	Information service
Other Cancer Gear	Gun tool
Cut Flowers	Flowers and trees
Media Containing Music And Video	Information record
Unused Media For Music And Video	Information record
Pet Food	Feed
Other Loved Animals And Supplies	Other personal services
Garden Plant	Flowers and trees
Garden Products	Other manufactured industrial products
Handicraft And Craft Materials	Other manufactured industrial products
Battery	battery
Other Educational And Recreational Supplies	Other personal services
Animal Hospital Charges	Veterinary services
Other pet related services	Other personal services
Education And Recreation Supplies	Various repair businesses (excluding separate listings)
Newspaper	newspaper
Magazines And Weekly Magazines	Publication
Books	Publication

Other Printed Matter	Publication
Accommodation Fee	Accommodation business
Domestic Package Travel Expenses	Travel and other transportation-related services
Foreign Package Travel Expenses	Travel and other transportation-related services
Language Awards	Individual teaching
Other Educational Monthly Fees	Individual teaching
Music Monthly Fee	Individual teaching
Other Liberal Monthly Fees	Individual teaching
Sports Monthly Fee	Individual teaching
Car Training Fee	Other educational and training institutions (industry)
Monthly Chores	Other personal services
Other Monthly Fees	Other personal services
Nhk Broadcast Reception Fee	Public broadcasting
Cable Tv Reception Fee	Cable broadcasting
Other Receiving Fees	Private broadcast
Entrance Fees For Movies And Theaters	Movie theater
Sports Viewing Fee	Other personal services
Golf Play Fee	Sports facility provider / park / amusement park
Sports Club Fee	Sports facility provider / park / amusement park
Other Sports Facility Fee	Sports facility provider / park / amusement park
Cultural Facility Entrance Fee	Other personal services
Amusement Park Entrance And Vehicle Fee	Other personal services
Other Admission / Game Fees	Other personal services

Fees	Other personal services
Development Baking Allowance	Other personal services
Education And Recreation Rent	Other personal services
Internet Connection Fee	Other communication services
Other Of Other Cultural And Entertainment Services	Other personal services
Hot Spring And Public Bathing Fee	Bath business
Hairdressing	Barber business
Permanent Fee	Cosmetics / Toothpaste
Cut Fee	Beauty business
Other Hairdressing Fees	Beauty business
Hairdressing Appliances	Consumer electrical equipment (excluding air conditioners)
Toothbrush	Plastic products
Other Hairdressing Supplies	Consumer electrical equipment (excluding air conditioners)
Bath And Face-Wash Soap	Cosmetics / Toothpaste
Shampoo	Cosmetics / Toothpaste
Hair Rinse And Hair Treatment	Cosmetics / Toothpaste
Dentifrice	Cosmetics / Toothpaste
Hair Styling And Hair Restorer	Cosmetics / Toothpaste
Makeup Cream	Cosmetics / Toothpaste
Lotion	Cosmetics / Toothpaste
Latex	Cosmetics / Toothpaste
Foundation	Cosmetics / Toothpaste
Lipstick	Cosmetics / Toothpaste
Hair coloring	Cosmetics / Toothpaste
Other Cosmetics	Cosmetics / Toothpaste
Umbrella	Other manufactured industrial products
Handbag	Bags, bags, and other leather products

School Bag	Bags, bags, and other leather products
Travel Bag	Bags, bags, and other leather products
Other Bags	Bags, bags, and other leather products
Jewelry	Personal goods
Watches	clock
Other Personal Items	Personal goods
Personal Care Related Services	Other personal services
Cigarette	Cigarette

,

Table D-2: Indirect emissions of one-person household consumption

Indirect emissions of One-person household ($MtCO_2$)	**2015**	**2011**	**Indirect emissions of One-person household ($MtCO_2$)**	**2015**	**2011**
Rice	0.1061	0.1213	Gas cooking appliances	0.0013	0.0034
White bread	0.0073	0.0073	Refrigerators	0.0049	0.0056
Other bread	0.0212	0.0209	Vacuum cleaners	0.0021	0.0027
Non-dried “Udon”&“Soba”	0.0026	0.0030	Washing machines	0.0019	0.0028
Dried “Udon”&“Soba”	0.0029	0.0026	Sewing machines	N/A	0.0011
Spaghetti	0.0008	0.0008	Other durable goods assisting housework	0.0027	0.0029
Chinese noodles	0.0028	0.0033	Air conditioners	0.0099	0.0097
Cup noodles	0.0053	0.0049	Stoves & fan heaters	0.0041	0.0044
Instant noodles	0.0019	0.0017	Other heating & cooling appliances	0.0016	0.0043
Other noodles	0.0003	0.0002	Chests of drawers	0.0001	0.0001
Wheat flour	0.0004	0.0003	Dining tables & chairs	0.0004	0.0006
“Mochi”, rice-cakes	0.0024	0.0021	Drawing room suites	0.0004	0.0024
Others	0.0027	0.0014	Sideboards	0.0005	0.0010
Tuna fish	0.0104	0.0118	Other furniture	0.0006	0.0009
Horse mackerel	0.0022	0.0029	Lighting appliances	0.0016	0.0019
Sardines	0.0014	0.0013	Interior decorations	0.0034	0.0046
Bonito	0.0034	0.0037	Floor coverings	0.0025	0.0067
Flounder	0.0018	0.0023	Curtains	0.0023	0.0045
Salmon	0.0071	0.0078	Other interior furnishings	0.0021	0.0034
Mackerel	0.0017	0.0020	Beds	0.0002	0.0003
Saury	0.0019	0.0021	Quilts	0.0009	0.0023
Sea bream	0.0021	0.0024	Blankets	0.0003	0.0004

Yellowtail	0.0053	0.0072	Sheets	0.0003	0.0004
Cuttlefish	0.0039	0.0046	Other bedding	0.0019	0.0045
Octopus	0.0026	0.0024	Bowls & dishes	0.0017	0.0017
Shrimps & lobsters	0.0036	0.0043	Other tableware	0.0034	0.0033
Crabs	0.0037	0.0037	Pans & kettles	0.0041	0.0033
Other raw fish	0.0129	0.0149	Other kitchen utensils	0.0042	0.0036
“Sashimi”, mixed set	0.0106	0.0123	Electric bulbs & lamps	0.0013	0.0016
Shellfish	0.0071	0.0075	Towels	0.0032	0.0029
Short-necked clams	0.0014	0.0016	Other domestic utensils	0.0194	0.0215
Fresh water clams	0.0009	0.0009	Polyethylene bag & food wrap	0.0040	0.0039
Oysters	0.0018	0.0019	Facial tissue	0.0034	0.0041
Scallops	0.0019	0.0022	Rolled toilet paper	0.0052	0.0054
Other shellfish	0.0011	0.0009	Detergent for house & kitchen	0.0032	0.0036
Salted salmon	0.0019	0.0020	Detergent, laundry	0.0043	0.0053
Salted pollock roe	0.0024	0.0036	Insecticide & moth repellent	0.0030	0.0045
“Shirasu-boshi”, dried young sardines	0.0015	0.0014	Others	0.0159	0.0180
Dried horse mackerel	0.0007	0.0009	Domestic help	0.0013	0.0014
Other salted & dried fish	0.0069	0.0078	Sewage disposal charges	0.0010	0.0014
“Agekamaboko”, fried fish-paste patties	0.0021	0.0023	Services related to furniture & domestic utensils	0.0013	0.0022
“Chikuwa”, baked fish-paste bars	0.0012	0.0013	Men's Japanese clothing	0.0003	0.0000
“Kamaboko”, steamed fish-paste cakes	0.0026	0.0024	Women's “Kimono”	0.0012	0.0065

Other fish-paste products	0.0009	0.0010	Women's “Obi”	0.0010	0.0012
Bonito fillets & fish flakes, dried	0.0007	0.0009	Other women's Japanese clothing	0.0002	0.0002
Pickled fish	0.0036	0.0032	Children's Japanese clothing	0.0015	0.0001
Fish prepared in soy sauce	0.0018	0.0021	Men's suits	0.0074	0.0049
Canned fish	0.0033	0.0025	Men's jackets	0.0028	0.0019
Others	0.0043	0.0037	Men's slacks	0.0042	0.0069
Beef	0.0633	0.0670	Men's coats	0.0036	0.0013
Pork	0.0347	0.0341	Other men's clothing	0.0075	0.0110
Chicken	0.0142	0.0115	Women's dresses, ready-made	0.0097	0.0126
Mixed ground meat	0.0013	0.0011	Women's jackets	0.0043	0.0087
Other raw meat	0.0034	0.0028	Skirts	0.0030	0.0032
Ham	0.0050	0.0059	Women's slacks	0.0072	0.0100
Sausages	0.0053	0.0054	Women's coats	0.0059	0.0089
Bacon	0.0022	0.0021	Other women's clothing	0.0155	0.0148
Other processed meat	0.0021	0.0019	Children's clothing	0.0022	0.0028
Fresh milk	0.0350	0.0376	Men's business shirts	0.0020	0.0025
Powdered milk	0.0003	0.0010	Other men's shirts	0.0076	0.0090
Yogurt	0.0309	0.0238	Men's sweaters	0.0013	0.0023
Butter	0.0016	0.0016	Women's blouses	0.0051	0.0081
Cheese	0.0092	0.0085	Other women's shirts	0.0088	0.0117
Other dairy products	0.0008	0.0010	Women's sweaters	0.0120	0.0114
Eggs	0.0109	0.0119	Children's shirts & sweaters	0.0004	0.0006
Cabbage	0.0055	0.0044	Men's underwear	0.0030	0.0054
Spinach	0.0035	0.0037	Men's underwear	0.0027	0.0048

Chinese cabbage	0.0021	0.0021	Men's nightwear	0.0003	0.0006
Welsh onions	0.0047	0.0052	Women's underwear	0.0080	0.0118
Lettuce	0.0042	0.0033	Women's underwear for body foundation	0.0009	0.0017
Broccoli	0.0031	0.0025	Other women's underwear	0.0060	0.0085
Bean sprouts	0.0014	0.0016	Women's nightwear	0.0011	0.0015
Other leafy vegetables	0.0111	0.0102	Children's underwear	0.0002	0.0003
Sweet potatoes	0.0020	0.0021	Cloth, "Kimono" width & others	0.0009	0.0011
White potatoes	0.0035	0.0043	Other cloth & thread	0.0010	0.0014
Taros	0.0015	0.0016	Hats & caps	0.0029	0.0032
Radishes	0.0031	0.0032	Neckties	0.0011	0.0009
Carrots	0.0040	0.0040	Mufflers & scarves	0.0023	0.0027
Burdocks	0.0017	0.0017	Gloves	0.0008	0.0015
Onions	0.0050	0.0046	Men's socks	0.0018	0.0018
Lotus roots	0.0013	0.0013	Women's stockings	0.0007	0.0008
Bamboo shoots	0.0012	0.0012	Women's socks	0.0024	0.0027
Other root vegetables	0.0059	0.0057	Others	0.0032	0.0039
String beans	0.0039	0.0044	Canvas shoes	0.0035	0.0026
Pumpkins	0.0027	0.0028	Sandals	0.0006	0.0004
Cucumbers	0.0054	0.0056	Men's shoes	0.0039	0.0039
Eggplants	0.0031	0.0034	Women's shoes	0.0069	0.0064
Tomatoes	0.0148	0.0144	Children's shoes	0.0000	0.0001
Green peppers	0.0031	0.0028	Other footwear	0.0025	0.0019
“Shiitake”, Japanese mushrooms, fresh	0.0029	0.0032	Tailoring charges	N/A	0.0004
Other mushrooms	0.0071	0.0068	Washing charges	0.0031	0.0037
Others	0.0070	0.0064	Clothing & footwear repair charges	N/A	0.0005

Beans	0.0022	0.0029	Charges for clothing rent	0.0001	0.0001
“Shiitake”, Japanese mushrooms, dried	0.0007	0.0010	Other services related to clothing	0.0010	N/A
Dried laver	0.0160	0.0160	Medicines for cold	0.0011	0.0012
Bean curd	0.0063	0.0073	Gastrointestinal medicines	0.0008	0.0009
Fried bean curd	0.0031	0.0036	Eutrophic compound	0.0027	0.0039
“Natto”, fermented soybeans	0.0045	0.0048	Medicines for external wound & skin disease	0.0003	0.0003
Other soybean products	0.0011	0.0010	Other external remedies	0.0017	0.0019
“Konnyaku”, devil's-tongue jelly	0.0014	0.0016	Other drugs	0.0107	0.0119
“Umeboshi”, pickled plums	0.0013	0.0017	Health fortification	0.0139	0.0137
Pickled radishes	0.0010	0.0011	Paper diapers	0.0007	0.0009
Pickled chinese cabbage	0.0006	0.0007	Medical supplies	0.0031	0.0033
Other pickled vegetables	0.0052	0.0070	Spectacles	0.0064	0.0101
Tangle prepared in soy sauce	0.0011	0.0015	Contact lenses	0.0030	0.0033
Other vegetables & seaweeds prepared in soy sauce	0.0005	0.0006	Other medical supplies & appliances	0.0056	0.0050
Others	0.0014	0.0011	Medical treatment	0.0166	0.0173
Apples	0.0117	0.0109	Dental treatment	0.0094	0.0052
Mandarin oranges	0.0102	0.0128	Osteopathic, acupunctural & moxibustic services	0.0011	0.0015
Grapefruits	0.0009	0.0014	Massage Fee, Etc.	0.0020	0.0026

Oranges	0.0011	0.0019	Fees for complete medical checkup etc.	0.0010	N/A
Other citrus fruits	0.0055	0.0052	Other medical services	0.0035	0.0042
Pears	0.0034	0.0041	Railway fares	0.0670	0.0496
Grapes	0.0044	0.0063	Commuters' season tickets, railway	0.0190	0.0227
Persimmons	0.0029	0.0039	Bus fares	0.0140	0.0205
Peaches	0.0027	0.0031	Commuters' season tickets, bus	0.0036	0.0058
Watermelons	0.0030	0.0034	Taxi fares	0.0195	0.0256
Melons	0.0022	0.0052	Airplane fares	0.0478	0.0443
Strawberries	0.0054	0.0070	Highway fares	0.0028	0.0041
Bananas	0.0108	0.0107	Others	0.0029	0.0036
Kiwi fruits	0.0033	0.0022	Automobiles	0.0219	0.0750
Other fruits	0.0109	0.0116	Other vehicles	0.0036	0.0035
Processed fruits	0.0034	0.0023	Purchase of bicycles	0.0024	0.0048
Edible oil	0.0033	0.0025	Maintenance of vehicles	0.1298	0.1432
Margarine	0.0006	0.0006	Gasoline	0.0743	0.0804
Salt	0.0004	0.0004	Automotive parts	0.0124	0.0168
Soy sauce	0.0015	0.0018	Articles related to private transportation	0.0096	0.0091
“Miso”, soybean paste	0.0016	0.0018	Automotive maintenance & repairs	0.0147	0.0128
Sugar	0.0010	0.0013	Vehicular maintenance & repairs (except cars)	0.0008	0.0008
Vinegar	0.0008	0.0011	Yearly & monthly rent, for park	0.0061	0.0084
Worcester sauce	0.0003	0.0005	Other rent, for park	0.0012	0.0017
Tomato ketchup	0.0003	0.0003	Charges for rental car	0.0011	0.0010

			& carsharing		
Mayonnaise & mayonnaise flavor seasoning	0.0008	0.0009	Other services related to private transportation	0.0054	0.0075
Dressing	0.0015	0.0014	Automotive insurance premium (compulsion)	0.0020	0.0018
Jam	0.0009	0.0011	Automotive insurance premium (option)	0.0094	0.0092
Instant curry mix	0.0006	0.0008	Vehicular insurance premium (except cars)	0.0001	0.0005
Instant dried soup	0.0034	0.0032	Postage	0.0023	0.0023
Soup stock	0.0014	0.0013	Telephone charges	0.0158	0.0258
"Furikake", granular flavor seasonings	0.0008	0.0009	Mobile telephone charges	0.0356	0.0382
"Tsuyu" & "Tare", liquid seasonings	0.0028	0.0028	Forwarding charges	0.0057	0.0034
Other seasonings	0.0082	0.0082	Mobile telephone	0.0017	0.0043
"Yokan", sweet bean jelly	0.0010	0.0011	Other communication equipments	0.0014	0.0024
"Manju", bean-jam cakes	0.0018	0.0014	Education	0.0000	0.0001
Other fresh Japanese cakes	0.0111	0.0113	TV sets	0.0028	0.0150
"Kasutera", sponge cakes	0.0012	0.0009	(b)Portable Music And Video Equipment	0.0006	0.0014
Cakes	0.0053	0.0056	Video recorders & players	0.0005	0.0029
Jelly	0.0018	0.0019	Personal computers	0.0061	0.0126
Puddings	0.0015	0.0014	Cameras	0.0010	0.0028
Other fresh cakes	0.0079	0.0067	Musical instruments	0.0001	0.0001
"Senbei", Japanese	0.0063	0.0054	Desks & chairs for	0.0002	0.0000

crackers			students & office workers		
Biscuits	0.0037	0.0035	Other recreational durable goods	0.0036	0.0068
Fried & salted snack crackers	0.0039	0.0032	Repair charges of recreational durable goods	0.0013	0.0010
Candies	0.0023	0.0022	Stationery	0.0072	0.0071
Chocolate	0.0062	0.0044	Sporting goods	0.0142	0.0226
Chocolate snacks	0.0009	0.0008	Golf goods	0.0021	0.0042
Ice cream & ice sherbet	0.0067	0.0060	Other sporting goods	0.0028	0.0063
Other cakes & candies	0.0202	0.0223	Sport outfits	0.0093	0.0121
Packed lunch	0.2030	0.0531	Toys	0.0069	0.0086
"Sushi", packed	0.0169	0.0192	Cut flowers	0.0582	0.0726
"Onigiri"& others	0.0135	0.0140	Unrecorded recording media	0.0015	0.0025
Bread like sandwiches put cooked food between bread	0.0102	0.0104	Pre-recorded recording media	0.0065	0.0149
Other cooked food with rice, bread or noodles	0.0217	0.0194	Pet food	0.0078	0.0066
"Kabayaki", broiled eels	0.0015	0.0030	Veterinary services	0.0028	0.0017
Salad	0.0111	0.0104	Pet purchase, supplies & medicine	0.0018	0.0023
Croquettes	0.0023	0.0023	Other services related to pets	0.0012	N/A
Cutlets	0.0018	0.0018	Garden plants & gardening goods	0.0200	0.0375
Fried food	0.0136	0.0141	Materials for handicrafts & technical art	0.0010	0.0005

Shao-mais	0.0011	0.0012	Dry battery	0.0028	0.0038
Jiao-zi	0.0025	0.0029	Other recreational goods	0.0039	0.0049
“Yakitori”, grilled chickens	0.0026	0.0028	Repair charges of recreational goods	0.0001	0.0002
Hamburg steak	0.0013	0.0012	Newspapers	0.0410	0.0572
Frozen food	0.0034	0.0036	Magazines (including weekly magazines)	0.0057	0.0099
Food stuff for cooking	0.0016	0.0033	Books	0.0137	0.0222
Others	0.0509	0.0534	Other reading	0.0015	0.0032
Green tea	0.0055	0.0076	Accommodation services	0.0513	0.0404
Black tea	0.0008	0.0013	Package tours	0.0117	0.0186
Other tea leaves	0.0011	0.0018	Lesson fees, language	0.0002	0.0010
Tea beverages	0.0124	0.0146	Lesson fees, other educational	0.0008	0.0011
Coffee	0.0070	0.0069	Lesson fees, music	0.0018	0.0026
Coffee beverages	0.0130	0.0151	Lesson fees, other recreational	0.0032	0.0038
Cocoa & cocoa beverages	0.0005	0.0005	Lesson fees, sporting	0.0039	0.0027
Fruits & vegetable juice	0.0120	0.0154	Lesson fees, driving school	0.0002	0.0008
Carbonated beverages	0.0061	0.0047	Lesson fees, homemaking	0.0003	0.0005
Fermented lactic beverages	0.0044	0.0040	Other private lesson fees	0.0022	0.0030
Lactic beverages	0.0030	0.0027	Charges for NHK TV license	0.0109	0.0114
Mineral water	0.0060	0.0070	Charges for cable TV license	0.0038	0.0057

Sports drinks	0.0018	N/A	Charges for other TV license	0.0008	0.0011
Others	0.0080	0.0116	Admission fees for movies, plays, etc.	0.0213	0.0253
"Sake"	0.0085	0.0107	Admission fees for sports	0.0004	0.0009
"Shochu", distilled spirits	0.0089	0.0097	Charges for playing & practicing golf	0.0121	0.0125
Beer	0.0072	0.0098	Gym charges	0.0075	0.0049
Whisky	0.0018	0.0009	Other charges for sports facilities	0.0026	0.0028
Wine	0.0024	0.0025	Admission fees for cultural establishments	0.0019	0.0018
Low-malt beer & beer-flavored alcoholic beverages	0.0041	0.0048	Admission fees for amusement parks	0.0011	0.0009
Other alcoholic beverages	0.0027	0.0028	Other admission fees & game charges	0.0207	0.0246
"Soba"& "Udon", Japanese noodles	0.0112	0.0105	Membership dues	0.0052	0.0056
Chinese noodles	0.0129	0.0135	Photography & photographic processing charges	0.0006	0.0009
Other noodles	0.0035	0.0037	Hire of recreational goods	0.0010	0.0015
"Sushi", eating out	0.0154	0.0188	Internet connection charges	0.0128	0.0140
Japanese meals	0.0502	0.0437	Others	0.0073	0.0089
dddddf	0.0082	0.0072	Admission fees for hotspring & public baths	0.0204	0.0308

Western meals	0.0324	0.0233	Charges for barbers' services	0.0049	0.0054
Hamburgers	0.0036	0.0053	Permanent wave charges	0.0045	0.0059
Other meals	0.1028	0.1092	Haircut charges	0.0048	0.0047
Other refreshments	0.0139	0.0113	Other personal care charges	0.0167	0.0166
Drinking	0.1012	0.1090	Electric appliances for personal care	0.0015	0.0024
Charges for board	0.0049	0.0052	Toothbrushes	0.0019	0.0016
Rents for dwelling, private	0.0624	0.0973	Other personal care goods	0.0044	0.0030
Rents for dwelling, public	0.0022	0.0078	Bath & facial soap	0.0039	0.0050
Rents for dwelling, issued houses	0.0061	0.0098	Shampoo	0.0026	0.0035
Rents for land	0.0013	0.0009	Hair rinses & treatments	0.0021	0.0028
Other rents for dwelling & land	0.0011	0.0007	Toothpaste	0.0026	0.0028
Tools for repairs & maintenance	0.0181	0.0190	Hair dressing preparations & tonics	0.0023	0.0034
Materials for repairs & maintenance	0.0175	0.0137	Skin cream	0.0066	0.0076
"Tatami" reupholstering	0.0003	0.0002	Skin lotion	0.0052	0.0063
Plumbing	0.0012	0.0014	Liquid cream	0.0023	0.0033
Outer wall & fence	0.0033	0.0085	Makeup foundation	0.0028	0.0042
Gardening	0.0035	0.0027	Lipsticks	0.0011	0.0015
Other charges for repairs & maintenance	0.0062	0.0073	Hair color	0.0015	N/A
Fire & earthquake	0.0039	0.0034	Other cosmetics	0.0173	0.0249

insurance premium					
Electricity	1.9487	1.9560	Umbrellas	0.0010	0.0010
Gas, manufactured & piped	0.0367	0.0398	Bags	0.0098	0.0087
Liquefied propane	0.1866	0.2233	Accessories	0.0048	0.0072
Kerosene	0.0212	0.0275	Wrist watches	0.0018	0.0022
Others	0.0037	0.0031	Other personal effects	0.0048	0.0062
Water & sewerage charges	0.0645	0.0743	Services related to personal effects	0.0004	0.0003
Microwave ovens	0.0024	0.0010	Tobacco	0.0066	0.0076
Electric cooking appliances	0.0041	0.0028			