Achieving Near-Zero Carbon Dioxide Emissions from Energy Use: The Case of Sri Lanka

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Abstract

Signatories to the Paris Agreement are to achieve net zero Green House Gas (GHG) emissions during the half-century to pursue the efforts limiting global average temperature increase by 2˚C compared to pre-industrial levels. This study models ambitious to challenging scenarios involving energy demand and supply side actions for energy system transition towards net-zero for Sri Lanka. To analyze these scenarios a least cost optimization-based bottom-up type energy system model was developed from 2015 to 2050. A Business-as-usual (BAU) scenario and four countermeasure (CM) scenarios termed Plausible, Ambitious, Challenging, and Stringent were developed. Four different carbon tax rates were used to fathom the level of carbon tax needed to achieve net-zero emissions. The CM scenarios were formulated considering different technology options and policy measures such as the diffusion of efficient technologies, availability of renewable energy sources, use of cleaner fuels, the introduction of nuclear and carbon capture and storage technologies, and green hydrogen for power generation. The result of this study reveals that the stringent scenario which includes aggressive policy measures in both the energy supply and demand sectors, such as nuclear, and renewable energy for power generation, diffusion of efficient Enduse devices, fuel switching, including the introduction of electric cars, and increased share for public transport achieves the near carbon-neutral scenario at a carbon tax trajectory of 32

US$/$tCO_2$ in 2020 and 562US$/$tCO_2$ in 2050. The Net Energy Import Dependency (NEID) of the country decreases to 13% in 2050 compared to that of the BAU scenario (65%) under the near carbon neutral scenario, which is a positive sign from the energy security perspective.

Keywords:

Near Net-zero carbon emissions, energy transition, carbon tax, developing country, energy-economic-environmental modeling

1. Introduction

Sri Lanka has a population of 22.1 million and a GDP of 84.5 billion USD in 2021 (CBSL, 2021). It has historically maintained a low carbon profile of 0.258 kg per 2015 US$ of GDP and 1.09 Mt per capita CO_2 emissions in 2019, well below the global mean of 0.419 kg per 2015 US$ of GDP and 4.4 Mt per capita CO_2 emissions in 2019 (World Bank, 2020). The Sri Lankan economy has faced a recession in recent times. However, the energy demand is expected to increase rapidly with the anticipated growth in the economy in future years.

As a non-annex-I-member country of the Paris Agreement, the country pledged to mitigate 14.5% of GHG emissions by 2030 as compared to 2021 through its Nationally Determined Contributions (NDCs), although it does not have legally binding emissions reduction targets. Furthermore, Sri Lanka is aiming at ambitious yet challenging targets such as reaching carbon neutrality by 2050 and increasing the renewable energy share in electricity generation from 45% in 2021 to 70% in 2030. (MOE, 2021). However, it lacks a pragmatic plan that could lead the country toward a clean energy transition.

According to Rogelj et al., (2015), net-zero carbon emissions should be achieved between 2060 and 2070 to limit the global temperature rise below 2^{o}C by the end of this century. Further, the net zero status between 2045-2060 would keep global warming well below 1.5°C by the end of this century. On the other hand, energy use has been identified as the main cause of GHG emissions (IEA,2021). Hence, achieving carbon neutrality through energy transition in the energy sector is a significant challenge in achieving the Paris targets.

The country has historically maintained a low carbon footprint from energy use due to its significant use of biomass and hydro resources. However, it has almost exhausted its hydro resources and biomass use is challenged by the requirements for large-scale biomass plantations for meeting the energy purposes. As a result, the share of fossil fuels has increased during the past decade. In 2019 alone out of a Total Primary Energy Supply (TPES) of 295 PJ, the share of fossil fuels comprised 56% (44% petroleum and 12% coal) and 44% renewables (33% from biomass, 7% from hydro and 4% of Solar and wind)). Currently, the contribution of wind and solar is very low (SLSEA,2020). Liquified natural gas has been identified as a cleaner alternative to coal and oil. Sri Lanka is also exploring the possibility of alternative energy sources (nuclear) and carriers (green hydrogen) (CEB, 2020). Although nuclear energy remains a feasible clean alternative, green hydrogen is considered as an emerging technology that requires scientific breakthroughs to make it cost-competitive. The country has a significant potential for solar and wind power development with a total potential of up to 5600MW and 6000MW (ADB,2019) But wind and solar are more expensive as compared to some of the fossil fuel alternatives. Therefore, it requires a careful analysis through a systematic approach to developing the energy transition pathways for the optimum use of these renewable sources.

Energy-Economic-Environmental (EEE) Models can play an important role in energy systems planning and climate change mitigation. These Models have been extensively used to develop energy and emission scenarios (Kainuma et al.,2003; Shrestha et al., 2016), analyze the economic and environmental implications of different climate policies (Selvakkumaran & Limmeechokchai, 2015; Chunark & Limmeechokchai, 2018), analyze the co-benefits of climate change mitigation (Selvakkumaran & Limmeechokchai, 2013; Pradhan et al.,2020), and investigate potential climate futures (B. Frame et al., 2018; Chen et al., 2020). However, the development of such models for Sri Lanka and carrying out scientific studies on energy economic and environmental implications of energy use is still in a premature stage. According to Bhattacharyya and Timilsina (2010), the development of EEE models for developing economies has become more challenging due to the lack of data and some of the available data is not suitable for developing such models. However, Shrestha et al., (2013) studied the influence of clean technologies and emission taxes on the Sri Lankan energy sector for the period between 2005 to 2030, This study did not use a comprehensive and disaggregated model due to data limitations. Furthermore, it did not consider energy generation options such as renewable storage, green hydrogen, and nuclear. Nor did consider end-use policies such as increasing public transport. In another study on Sri Lanka, Selvakkumaran & Limmeechokchai (2013) analyzed the impact of energy efficiency improvements in Sri Lanka's power sector and related co-benefits. However, the past studies on Sri Lanka are either limited in scope or have rarely considered all energy-consuming sectors in the economy. The proposed study develops a model that includes both energy supply and energy demand sectors. It also considered a range of existing and potential technologies such as renewable storage, nuclear energy, green hydrogen, and carbon capture and storage (CCS). Nevertheless, no study has been carried out for low-carbon scenarios that could support a smooth energy transition to achieve carbon neutrality in the case of Sri Lanka.

This study explores the potential impact of a range of low-carbon scenarios in achieving carbon neutrality in Sri Lanka by 2050. It uses the AIM/Enduse modeling framework, a least-cost energy system optimization model, developed by the National Institute of Environmental Studies and Kyoto University, Japan (Kainuma et al. 2003), to model the Sri Lankan energy system. This study develops a range of scenarios that could be considered from ambitious to challenging. A Business-as-usual (BAU) scenario and four countermeasure (CM) scenarios termed Plausible, Ambitious, Challenging, and Stringent were developed. The aggressiveness of the policy measures increases from a Plausible scenario to a stringent scenario. The low carbon scenarios include policy measures in both the energy supply and demand sectors, They are nuclear energy, deployment of breakthrough technologies (eg. Battery storage renewable energy options, carbon capturing and storage, green hydrogen), diffusion of efficient endues devices, fuel switching, electric energy using technologies (eg. electric cars and electric locomotives) and increased share for public transport. Moreover, four carbon tax trajectories were used to identify the level of carbon reduction at different tax rates and the most appropriate tax rates for achieving carbon neutrality. The combinations of BAU scenario, four low carbon scenarios, and four carbon taxes developed 25 different scenarios. These scenarios were simulated using the Aim/Enduse model developed for Sri Lanka. The results of the model include energy mix, end use device mix, electricity generation, penetration of new technologies, emissions, and co-benefits.

The rest of the paper is organized as follows: Section 2 presents a brief literature review covering energy system modeling and policy analysis followed by the methodology used in Section 3. Section 4 analyses the results. Finally, Section 5 presents the conclusions and final remarks of the study.

2. Literature Review

Past studies used energy system models for analyzing various climate policy scenarios. According to the literature, there are three main types of modeling frameworks: namely top-down models, bottom-up models, and hybrid models. The top-down models access the consequences of policies in terms of microeconomic impacts. The main drawback of the top-down models is that they do not consider technology characteristics and complex interlinks between the economy and energy sectors (Hourcade et al., 2006). Several studies (Rajbhandari et al., 2019; Ugarte et al., 2021, and Delgado et al., 2020) used top-down type models to investigate energy systems. On the other hand, bottom-up type models consider end-user device characteristics and technological options for energy system analysis. They are very effective in illustrating the possibility for radically different technology futures. Most studies have used bottom-up type models for analyzing different energy and climate change policy options (Chaichaloempreecha et al., 2022; Pradhan et al., 2020; Chunark & Limmeechokchai, 2018). However, The bottom-up type models do not provide a realistic representation of microeconomic decision-making in technology selections and complex behavioral aspects of energy consumption (Hourcade et al., 2006).

To overcome the drawbacks of top-down and bottom-up type models, hybrid energy economic models have been used in several studies (Younis et al.,2021; Lallana et al.,2021). Hybrid models are highly complex and there are challenges in data requirements. For an accurate output, it would require a reasonable representation of feedback effects and interdependencies between sectors and technologies. Furthermore, combining different models may result in additional uncertainties. In absence of data, such models would not produce reliable results.

In general, more than half of the studies on energy system analysis have been carried out using bottom-up type models. These models include TIMES, LEAP, IMACLIM, OSeMOSYS, and

AIM/End-use. They will explicitly use technological characteristics to provide insights as to how emerging technologies could contribute to reducing emissions (Hourcade et al., 2006). Therefore, bottom-up models may provide a reasonable representation of the energy flows in the economy for analyzing policies like low-carbon scenarios for carbon neutrality.

There are low carbon scenarios developed at global levels (Fragkos, 2020; Liu et al., 2018), regional (Ouedraogo, 2020; Altieri et al., 2016), and national levels (Rajbhandari et al., 2019; Pradhan et al., 2020; Chunark & Limmeechokchai, 2018). Among the studies that considered policy analysis for achieving Paris targets, most studies have considered only the energy sector for achieving the net-zero status, and only a few carried out an economy-wide analysis for achieving net-zero emissions in both energy and non-energy sectors (Lallana et al., 2021). Despite this, both energy demand and energy supply sectors were used for developing these models (Chaichaloempreecha et al., 2022; Pradhan et al., 2020; Oshiro et al., 2017). Some studies are sector focused such as the transport sector (Manan et al., 2022; Pita, et al.,2017), the building sector (Xing et al., 2021), and the power sector (Selvakkumaran & Limmeechokchai,2013; Gambhir et al., 2014). These sector-specific studies have failed to capture a holistic picture of the energy demand and supply. Failure to capture cross-sectional dependencies will result in policy misalignment and suboptimal policy outcomes. Table 1 summarizes the literature on studies carried out to investigate the low carbon scenarios and net zero scenarios using EEE models.

Past studies have developed low-carbon scenarios combining a variety of different policy measures for reducing carbon emissions. These policy measures include reducing the use of fossil fuels (Kriegler et al.,2018), breakthrough technologies (Ashina et al., 2012), increased share of renewable energy sources (Chunark & Limmeechokchai, 2018), deployment of carbon capture technologies (Chaichaloempreecha et al., 2022; Selvakkumaran & Limmeechokchai,2013), and introducing taxes for emissions and subsidies for selected energy types and technologies (Chaichaloempreecha et al., 2022; Kriegler et al.,2018). Carbon taxes have been used as a market-based policy instrument to drive the transition from fossil fuel energy sources to cleaner renewable energy alternatives (Chaichaloempreecha et al., 2022; Pradhan et al., 2020). In most of the studies, the selection of carbon tax rates has been made according to the published literature (Shrestha et al., 2013, Selvakkumaran & Limmeechokchai, 2015). However, in recent literature, some studies use carbon tax trajectories proposed by Integrated Assessment Models under the new Shared Socioeconomic Pathways presented in the sixth IPCC assessment report (Chaichaloempreecha et al., 2022; Pradhan et al.,2020)

Achieving net-zero emissions has been primarily focused on the context of major economies in the world (Oshiro et al., 2017; Mittal et al., 2016). There are only a few studies that considered developing countries such as Nepal (Pradhan et al.,2020), and Thailand (Chaichaloempreecha et al., 2022; Chunark & Limmeechokchai, 2018). These studies rarely considered a range of low-carbon scenarios covering both energy demand and supply sectors comprehensively. Low-carbon scenarios in a Sri Lankan context have not been studied in the past. According to the literature each country is unique in terms of energy use and the number of cleaner technologies that could be employed for reducing carbon.

Table 1. Summary of the literature of similar studies.

#	Author/Year of Publication	Geographic focus	Sectors covered	Models used	Scope of the study
1.	Pradhan et al,2020	Nepal	Energy	AIM/Enduse	Investigate the effect of carbon taxes in achieving the 2°C-degree Paris target, Study considered the BAU scenario and three carbon tax scenarios.
2	Oshiro et al,2018	Japan	Energy	AIM/Enduse	Analyses the net zero emissions by 2050 using the emission constraints approach. It considered three Low carbon scenarios and six net zero scenarios. No carbon taxes have been used.
3	Shrestha et al., 2013	South Asia	Energy	MARKAL	Investigate the maximum possible GHG mitigation by 2030 BAU scenario and the carbon tax scenario has been considered.
4	Chaichaloempreecha et al., 2022	Thailand	Energy and Removals	AIM/Enduse	Investigate the low carbon pathways in achieving 2°C and 1.5°C degree Paris targets by 2050. Two low-carbon scenarios and carbon tax scenarios have been considered.
5	Chunark & Limmeechokchai, 2018	Thailand	Energy And Removals	AIM/Enduse	Investigate the effect of low carbon pathways and carbon taxes leading to 1.5°C degree Paris target by 2050. Four Low carbon scenarios and five Carbon tax scenarios were investigated.
6	Zheng et al., 2021	China	Economy	Multiple models	Analyze eight low carbon scenarios leading to net zero emissions combined with the carbon tax to achieve 1.5°C degree Paris target by 2050
7.	Glynn et al., 2019	Ireland	Economy	Irish Times	Investigate six low carbon scenarios and thirty net zero scenarios to achieve 2°C and 1.5°C degree Paris targets by 2050
8	Capros et al., 2019	EU	Economy	PRIMES	Investigate the BAU Scenario six low carbon scenarios and two net zero scenarios to achieve net zero emissions by 2050 and 2070. The study considers the effect of carbon taxes
9	Browning et al. 2023	North America	Economy	Multiple models	Analyze two net zero emission scenarios and the BAU scenario with the introduction of Carbon taxes to achieve net zero emissions by 2050.

3. Methodology

This section describes the methodological approach used to develop the EEE model using a bottom-up approach. It discusses the model structure, inputs used, and assumptions. It also describes the framework for scenario development. These scenarios were analyzed using the model developed.

Modeling framework

Several factors should be considered in selecting an energy modeling tool for policy analysis. It depends on the research objectives, intended research outcomes (Gambhir et al., 2014), computational and technical requirements, and availability of data (Bhattacharyya and Timilsina, 2010). In general, about half of the studies on energy system analysis have been carried out employing bottom-up type models as they will explicitly use technological characteristics providing insights as to how emerging technologies could contribute to reducing emissions (Emenekwe et al., 2022). This study selected AIM/ Enduse which belongs to the Asia Pacific Integrated Modelling (AIM) family as a tool for developing the energy system model in this study. The AIM/Enduse model could be used to capture the integrated reference energy system in an economy considering both energy supply and demand sectors.

The AIM/Enduse considers the flow of energy in an economy from primary energy sources through their conversion into secondary forms and into end use devices that meet the demands for different end use energy services over a planning horizon. It requires detailed device-wise data that includes fixed cost, operation, and maintenance cost, lifetime, the energy required per unit of service output, and the number of devices in the base year. To meet a given service demand, a set of technology options, which include existing and potential technology options, are used as inputs to the model. The energy data used in the model comprise energy, cost, and emissions. Over time, energy service demand is determined exogenously considering socioeconomic and demographic factors (Kainuma et al., 2003). The AIM/End-use model carries out a recursive dynamic, cost optimization to minimize the total system cost of the energy system on a year-by-year basis. The total system cost includes initial investment costs, operating and maintenance costs, energy costs, and taxes. In doing so, it selects an optimum combination of technology options and their usage to meet energy service demands subjected to constraints (technology, energy, environment, and policy). It also provides demand for final energy, primary energy resources, and emissions during the planning period. Moreover, this model can also be used to analyze the effects of policy options, such as taxes and subsidies, as well as constraints on emissions and technology options. (Kainuma et al.,2003).

AIM/End-use is provided as open-source software. It provides a user-friendly interface with Microsoft Excel as the frontend data interface. To solve the optimization problem, GAMS (General Algebraic Modeling System) is used as the solver. Highlights of the AIM/Enduse model are provided in Appendix 1. Further information on AIM/Enduse model could be obtained from Kainuma et al (2003)

AIM/Enduse Model of Sri Lanka

The current study modeled the energy system of Sri Lanka considering both the energy supply and energy demand sectors, for the period of 2015 – 2050. A schematic diagram of the modeling framework is presented in Figure 1. The primary energy sources comprise imported fossil fuels (coal, oil, natural gas) and renewable energy sources (hydro, wind, solar, and biomass). The secondary energy types considered in the study include refinery products (diesel, gasoline, kerosene, LPG, and fuel oil), electricity, biofuels, and hydrogen. The power generation sector was modeled in detail, considering all possible existing and future technological options. Some of the technical parameters used in the Long-Term Generation Expansion Plan (LTGEP) have been used as inputs for modeling the power sector (CEB, 2020). This model considered energy storage for renewable energy sources, which includes battery, pumped hydro, and green hydrogen technologies.

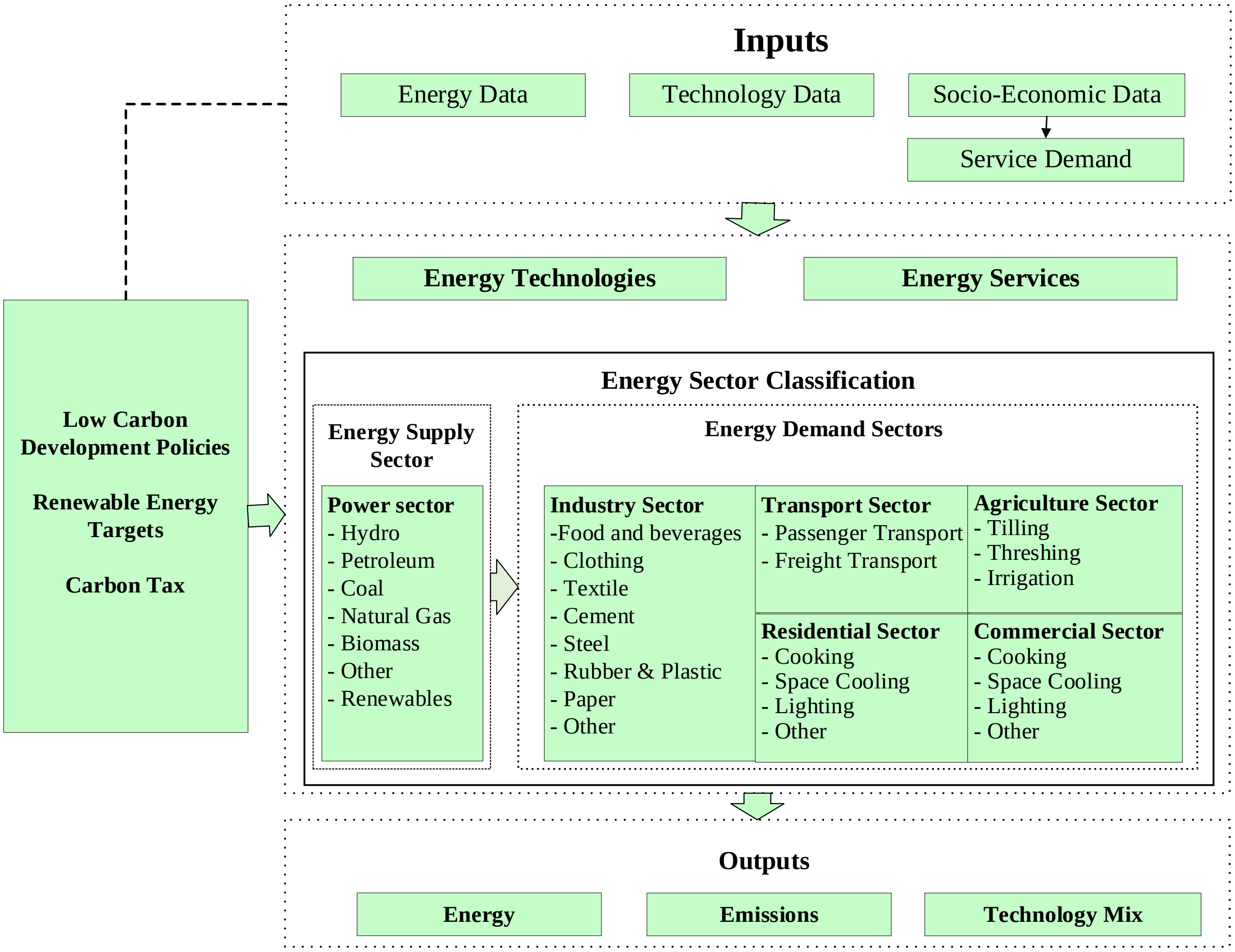


Figure 1: Schematic Diagram of the Proposed Energy Economic Environmental Model for Sri Lanka

For energy end use sectors, sub-sectors as well as end use services were identified based on their relative contribution to total energy consumption provided in government reports and past studies on energy demand analysis. The industrial sub-sectors were further separated into heating and electrical systems (Chunark and Limmeechokchai, 2015).

A bottom-up model requires a more disaggregated representation of the current and emerging technologies. The extent of details or disaggregation of technologies depends on data availability. Acquiring data was rigorous, particularly for a developing country like Sri Lanka. Whenever Sri Lanka-specific data was unavailable, similar data from other countries were adopted. The oil prices of the base year were centered on the average import prices of Ceylon Petroleum Corporation (CPC, 2018). Coal and natural gas prices were obtained from the Sri Lankan LTGPE (CEB, 2016). The cost, including insurance and freight (CIF) based price, was considered for crude oil, coal, and natural gas imports. The future fuel prices were based on the values provided in the World Energy Outlook (IEA, 2017a). The technology data was derived from various national and international sources: Department of Motor Traffic (DMT,2020), National Transport Commission (NTC,2016), Civil Aviation Authority (CAAS,2015), Sri Lankan LTGEP (CEB,2016), and Sri Lankan Energy Balance (SLSEA,2016). The international sources considered for candidate technologies for future power generation and transport sectors were mainly the International Energy Agency (IEA, 2011, 2012, 2013, 2017b, 2017c). Additionally, specific publications based on AIM/Enduse models were used for technology data (Kainuma et al., 2003; Shrestha et al., 2016). A discount rate of 10% was considered in this study, in line with the leading government publications used for future energy planning (CEB,2020). All the price values used in the model were in 2010 US$ constant values.

Emission factors in this study were based on IPCC 2006 guidelines (IPCC,2006). A single emission factor is used for all sub-sectors per the IPCC tier 1 approach. This is mainly because of the non-availability of country-specific emission factors for Sri Lanka. In the energy system model, biomass was considered carbon-neutral assuming that it will be produced sustainably (Shrestha et al., 2016).

The projection of the energy service demand for future years was carried out using an econometric method following Pradhan et al. (2020) and Shrestha et al. (2013). The energy service demand projections were estimated using Population, GDP, and income elasticities. Due to the unavailability of country-specific data, for income elasticity, relevant values were taken from Shrestha et al., (2013). The future GDP and the population projections were adopted from (Riahi et al. 2017; Delink et al.,2017) and (Riahi et al.,2017; Samir and Lutz,2017), respectively. The end-use service demands were estimated based on the data given in key government publications such as the Central Bank of Sri Lanka (CBSL,2021), the Department of Census and Statistics of Sri Lanka (DCS, 2012; DCS,2018), Third National Communication of Sri Lanka (MOE,2022), National Transport Commission (NTC, 2016), Civil Aviation Authority (CAAS,2015) and LTGEP (CEB, 2020).

Scenarios

This study considered a medium-term time horizon as the planning period. Therefore, the scenarios of this study were developed considering possible socioeconomic factors and technological advancements throughout the study period. Since the model used a bottom-up approach, the technology options considered play a major role in reducing emissions. Therefore, special consideration was given to clean energy technologies in developing the scenarios. These technologies include existing, already commercialized but continuously improved and potential technology options in the future.

Business-as-usual scenario

The BAU scenario assumed existing economic, demographic, and social trends throughout the modeling period. The power generation in the BAU scenario considered the policy measures in the Sri Lankan LTGEP (CEB,2018). These policy measures include phasing out petroleum-based power generation and introducing natural gas-based power generation. The BAU had not considered the existing government goal of reaching 70% of the power generation from renewable energy sources (SLSEA,2022). Instead, it assumed a maximum of 50% renewable energy share in the power generation sector in 2050. Furthermore, the BAU scenario did not include nuclear, green hydrogen, and CCS technologies in power generation. According to government energy policies, the transport sector assumed a continuation of existing, efficient, and hybrid technologies along with electric and natural gas penetration (MPEDB,2019). However, the transport sector did not consider biofuels and hydrogen technologies. The industrial sector in BAU assumed a continuation of existing technologies and no significant penetration of efficient and natural gas technologies. The residential and commercial sectors were expected to continue with existing technologies while allowing efficient natural gas technologies to penetrate during the planning period, as per government plans. The model outputs of the base year were calibrated against the SLSEA, (2016) and Shrestha et al. (2013).

To analyze the behavior of the carbon taxes scenario similar to the BAU scenario behavior, this study assumes a reference scenario (abbreviated as REF) which is similar to the BAU scenario except that the technology shares in the future years have not been constrained.

Countermeasure Scenarios

A substantial technological innovation will be required to transform the energy system towards net zero emissions (Steen & Mäkitie ,2023). In developing CM scenarios, existing as well as emerging technologies were considered for carbon mitigation. The technology options considered were switching to cleaner fuels, using new and advanced Enduse technologies, promoting renewable energy sources, using nuclear energy and green hydrogen for power generation, and employing carbon capture and storage technologies. Four CM scenarios namely Plausible, Ambitious, Challenging, and Stringent were developed involving actions from both the demand and supply sides of the economy. The aggressiveness of the policy options was increased gradually from a Plausible to a stringent scenario to check the level of carbon neutralization in Sri Lanka. With these CM scenarios, Carbon tax was used to discourage the use of fossil fuels and promote the use of mitigation options. For each CM scenario, four different carbon tax trajectories were considered. This will help to identify the level of the carbon tax that should be deployed, to achieve the net-zero status. It will also provide holistic feedback on the effect of different carbon tax rates in reducing carbon emissions. This study analyzed a total of twenty-five alternative cases that comprised BAU and CM scenarios. The details of the scenarios used in this study are given in Table 2.

Table 2: Low Carbon Scenarios considered to achieve carbon neutrality in Sri Lanka

	Sectors	Business-as-usual Scenario (BAU)	Plausible Scenario (CM1)	Ambitious Scenario (CM2)	Challenging Scenario (CM3)	Stringent Scenario (CM4)
Power Generation Sector	Renewable Energies (Hydro, Solar P.V. Pumped Storage, Wind, Biomass, Battery Storage, Green Hydrogen)	According to (LTGP,2020)	To be used up to 70%	To be used up to 80%	To be used up to 100%	To be used up to 100%
	Natural gas	According to (LTGP,2020)	Used as a clean fossil fuel	Used as a clean fossil fuel	Used as a clean fossil fuel	Used as a clean fossil fuel
	Coal	According to (LTGP,2020)	A decreasing trend toward 2050	A decreasing trend toward 2050	A decreasing trend toward 2050	Used with CCS
	Nuclear	Not considered	Not considered	Not considered	considered	considered
	Green Hydrogen	Not considered	Not considered	Not considered	Not considered	considered
Energy Demand sector	Transport Sector	1. Continuation of existing technologies. 2. Limited use of efficient and new technologies.	1. Efficient technologies are to be used up to a share of 25%. 2. Public transport is to be used up to a share of 60%.	1. Efficient technologies are to be used up to a share of 50%. 2. Public transport is to be used up to a share of 70%.	1. Efficient technologies are to be used up to a share of 75%. 2 Public transport is to be used up to a share of 80% 3.3% maximum share of biofuels to be used by 2050	1.Efficient technologies are to be used up to a share of 100%. 2. Public transport to be used up to a share of 100% 3.5% maximum share of biofuels to be used by 2050

	Industry Sector	1. continuation of existing technologies 2. No efficiency improvements in technologies 3. Natural penetration according to government Plans	Efficient technology is to be used up to share of 25%	1. Efficient technology is to be used up to share of 50% 2. CHP and CCS technologies to be used up to 20%	1. Efficient technologies are to be used up to share of 75% 2. CHP and CCS technologies to be used up to 60%	1. Efficient technologies are to be used up to a share of 100%. 2. CHP and CCS technologies to be used up to 80%
	Residential and Commercial Sectors	Continuation of existing technologies and efficient versions	Efficient and new technologies are to be used up to 25%	Efficient and new technologies are to be used up to 50%	Efficient and new technologies are to be used up to 75%	Efficient and new technologies are to be used up to 100%
Emission Taxes US$/t CO_2	T1	√	√	√	√	√
	T2	√	√	√	√	√
	T3	√	√	√	√	√
	T4	√	√	√	√	√

Scenario 1

In this Plausible scenario (CM1) the use of fossil fuels continued with a limited use of renewable energy sources. There was also a very minor emphasis on promoting efficient end use devices. It is considered that the maximum allowable share of renewables for power generation would be 70% in 2050. In this scenario, coal will continue as a fuel for power generation. In all end-use sectors, it was assumed that the existing technologies would continue with limited penetration of efficient technologies. Accordingly, the share of these efficient technologies was limited to a maximum share of 25% in the industry, residential, commercial, and transport sectors.

Scenario 2

The second scenario referred to as Ambitious (CM2), considered the use of cleaner fossil fuels, a higher share of renewable energy sources, and much higher use of efficient technologies as compared to the other scenarios. This scenario assumed a target of 80% for power generated using renewable energy sources. It also considered an increase in the share of natural gas cleaner fuel for power generation. The use of coal was expected to continue as proposed, according to the LTGEP (2020). A higher penetration was assumed for efficient technologies. The share of efficient technologies in each sector comprised up to 50% of the total use of technologies in the Enduse sectors. There was also more emphasis on public transport to reduce the carbon emissions. It assumed a 60% share of public transportation.

Scenario 3

The third scenario was referred to as Challenging (CM3) and it had a much higher emphasis on using renewable energy sources, clean options for fossil fuels, and advanced technology options in the end use sectors as compared to previous scenarios. It assumed that the role of breakthrough technologies will be minimum in this scenario. In this scenario, renewable energy sources are expected to play a significant role in reducing carbon emissions. One of the key features of this scenario is the use of nuclear energy for power generation. Renewable energy sources will contribute at least 80% of the total power generation. It is considered the complete elimination of coal from power generation. In this scenario, the use of efficient technologies could increase up to 75%. A higher share of public transport was considered in this scenario. It also considered a limited use of natural gas in the power and transport sectors as a cleaner fossil fuel.

Scenario 4

The Stringent scenario (CM4) had a very aggressive policy approach toward achieving carbon-neutral status. It employed all possible mitigation options for carbon mitigation. Breakthrough technologies like carbon- capture and storage were also considered in this scenario. Under this scenario, the maximum share of renewable technologies available for power generation is assumed to be 100%. It assumed that if fossil fuels are used for power generation, it would integrate carbon capture and storage technologies. It also considered nuclear power as an option for power generation. Since the primary focus of this scenario was emission mitigation it was assumed that all existing technologies will be replaced by efficient and new technologies. Under this scenario, the maximum public transport share is assumed to be 100% to complete carbon mitigation.

Carbon Emission Taxes

Four carbon tax trajectories were proposed to incentivize the transition to cleaner technologies and carbon-free sources. The proposed carbon tax trajectories are denoted as T1, T2, T3, and T4 as shown in Figure 3. These carbon tax trajectories were based on extant literature (Pradhan et al., 2020; Riahi et al.,2017; Shrestha et al., (2013). Under the respective trajectories, the carbon tax would be 56, 140, 280, and 560 US$/t CO_2 by 2050. A total of twenty-five scenarios were developed by applying four different carbon tax rates to the BAU, CM1, CM2, CM3, and CM4 scenarios.

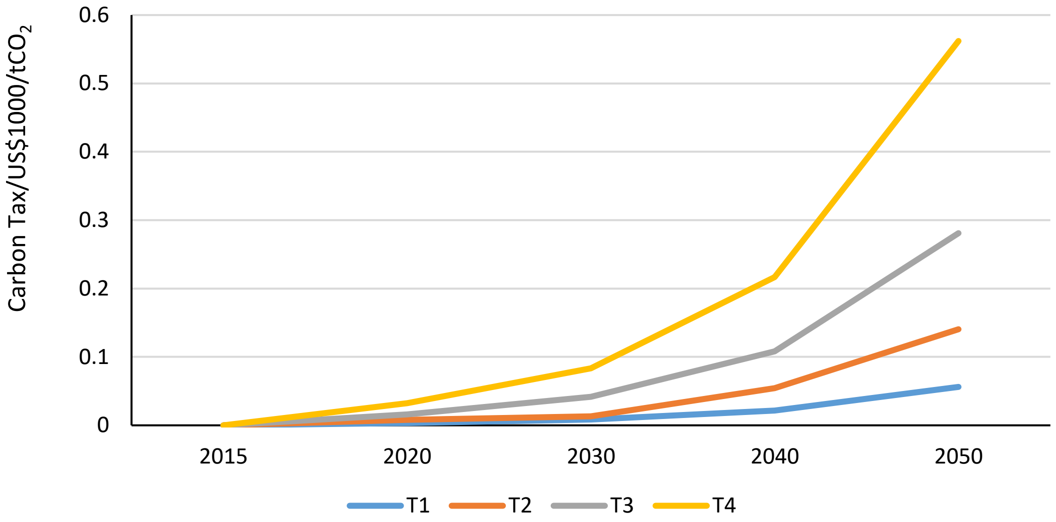


Figure 3. Proposed carbon tax trajectories.

4. Results and Discussion

Energy and Emissions in Business-as-usual Scenario

The TPES, presented in Figure 3, is expected to increase from 11 Mtoe in 2015 to 34 Mtoe in 2050 at an average annual growth rate (AAGR) of 6%. The share of fossil fuels in TPES will increase from 53% in 2015 to 66 % in 2050 due to limitations in hydropower and comparative costs of solar and wind energy compared to fossil fuels. By 2050, Petroleum fuels will have the highest share of 41%, followed by biomass which will account for 28% of the total supply. If the current trends continue petroleum will continue to dominate the energy supply of Sri Lanka. Although the share of petroleum is expected to remain constant, petroleum use in absolute terms is expected to record a threefold increase by 2050. Unless there is a significant reduction in the prices of electric vehicles, petroleum will be used as the primary fuel of the Transport sector. A large share of biomass is attributed to industry for heating and residential for cooking. The reduction of biomass share in TPES is mainly due to limited biomass resource availability in Sri Lanka by 2050. Hydro energy, which was one of the primary conventional renewable energy sources in Sri Lanka, will have a limited role in the future. As all the potential hydro energy has been utilized, the total share of hydro will be 2% in 2050. The use of LPG is also expected to increase as a fuel for residential cooking replacing biomass as a more efficient energy source. Coal is expected to play a significant role in electricity generation due to its cheaper costs. The share of Coal in TPES will increase from 11% in 2015 to 18% in 2050. Natural gas is expected to be introduced as a new fuel to the energy spectrum in 2023. It will be considered a cleaner alternative to coal and oil for electricity generation. The share of natural gas in TPES is projected to increase. However, it will remain limited reaching only 6% of TPES by 2050. Throughout the study period, renewable energy sources such as solar and wind played a minor role. Combined, together the share of solar and wind comprised 5% of the TPES in 2050.

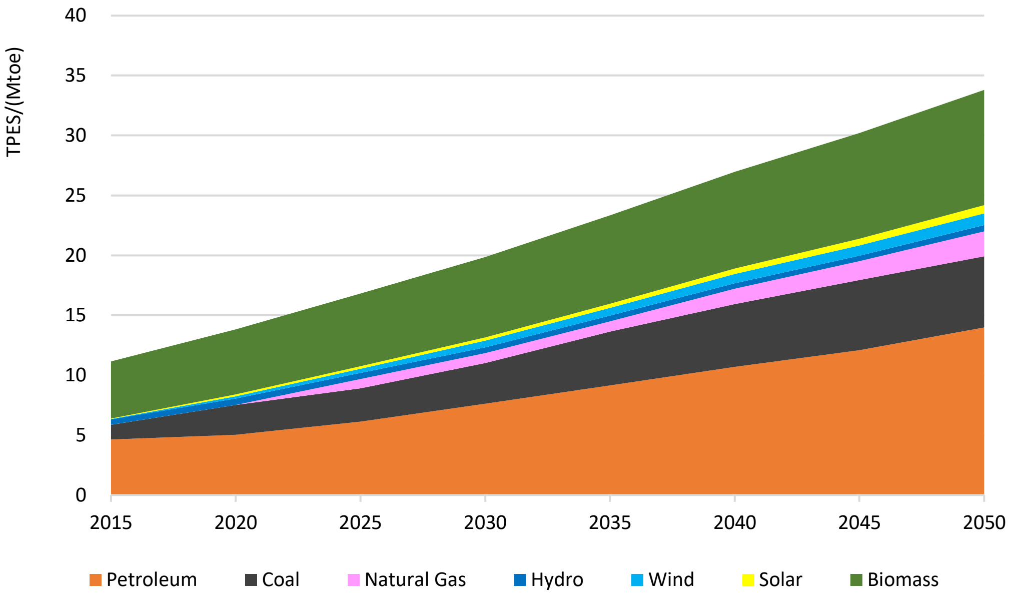


Figure 3: Primary Energy Supply in Business-as-usual Scenario during 2015-2050.

Table 3 presents the Final Energy Consumption (FEC) in the BAU scenario during 2015-2050. The FEC is expected to increase from 10 Mtoe in 2015 to 27 Mtoe in 2050. In the base year, the industrial and transport sectors had the highest share of FEC with 29%, followed by the residential sector with 26% of the FEC. The commercial sector had a lower percentage of 13% compared to other sectors in the base year. If the current trend continues, energy-consuming sectors such as transport and industrial sectors will dominate the energy demand of Sri Lanka. The transport sector will be the primary energy-consuming sector after 2025. The transport sector will account for 37% of the FEC in 2050. In absolute terms, there will be a more than threefold increase compared to the demand in 2015. This is mainly due to the expected increase in personal vehicle usage, as Sri Lanka does not have a sound strategy to improve its public transportation system. By 2050, both the residential and industrial sectors are expected to follow a similar trend, with a share of 25% and 23% respectively. The commercial sector will have a share of 12% in 2050. The share of the agriculture sector will be significantly smaller in 2050.

Table 3: The Final energy demand by sector in the Business -as- usual scenario during 2015-2050

	Final energy consumption/(Mtoe)				
	Agriculture	Commercial	Residential	Transport	Industry
2015	0.2	1.4	2.5	2.8	2.8
2020	0.2	1.6	3.3	3.7	3.0
2025	0.2	1.9	3.8	4.4	3.5
2030	0.3	2.1	4.4	5.5	4.0
2035	0.3	2.4	4.9	6.6	4.5
2040	0.4	2.8	5.6	7.7	5.2
2045	0.5	3.1	6.2	8.7	5.7
2050	0.5	3.4	6.8	10.1	6.3

The contribution to CO_2 emissions by each sector is given in Table 4. The Total CO_2 emissions in the BAU scenario are expected to increase from 19 Mt in 2015 to 66 Mt in 2050 at an AAGR of 7%. In the base year, the transport sector holds the highest share with 45% of CO_2 emissions, followed by the power sector with 38% in the base year. The share of the industry sector contribution is about 10% in 2015. The CO_2 emissions of the commercial, residential, and agricultural sectors account for 7% of the total in the base year. However, the transport sector is expected to continue to dominate as the leading CO_2 emitter. The share of the transport sector in total CO_2 emissions will comprise 41% in 2050. This is mainly due to the increase in transport demand and the dependency on fossil fuels. The total CO_2 emissions from the power sector are increased by 3.7 times as compared to the BAU in 2050. However, the percentage share of CO_2 from the power sector has indicated a slight reduction in share during the planning period. This is mainly due to the increase in the share of natural gas replacing Coal in power generation. The industry sector's CO_2 emissions will record a threefold increase from 2015 to 2050. Commercial, residential, and agricultural sectors combined will record a small growth of 4% growth in CO_2 emissions in 2050 as compared to the base year.

Table 4: The Total CO_2 Emissions by sector in the Business- as- usual scenario during 2015-2030

	CO_2 emissions by sector /(Mt)					
	Power	Agriculture	Commercial	Residential	Transport	Industry
2015	6.9	0.1	0.6	0.4	8.3	1.9
2020	9.7	0.2	1.0	0.6	10.6	1.7
2025	10.2	0.4	1.3	0.7	12.3	2.1
2030	15.3	0.7	1.6	1.0	14.7	2.7
2035	19.1	0.8	2.1	1.2	17.7	3.5
2040	22.4	0.9	2.6	1.5	20.5	4.3
2045	25.1	1.0	3.1	1.8	23.1	5.0
2050	26.2	1.7	3.7	2.2	27.1	5.7

Energy and Emissions in Countermeasure Scenarios

The changes in the primary energy mix from carbon taxes will be discussed in this section. The net difference in the TPES between BAU and each countermeasure scenario is shown in Figure 4.

It shows how carbon taxes contribute to reducing fossil fuel use and increasing the use of renewables and other clean energy types.

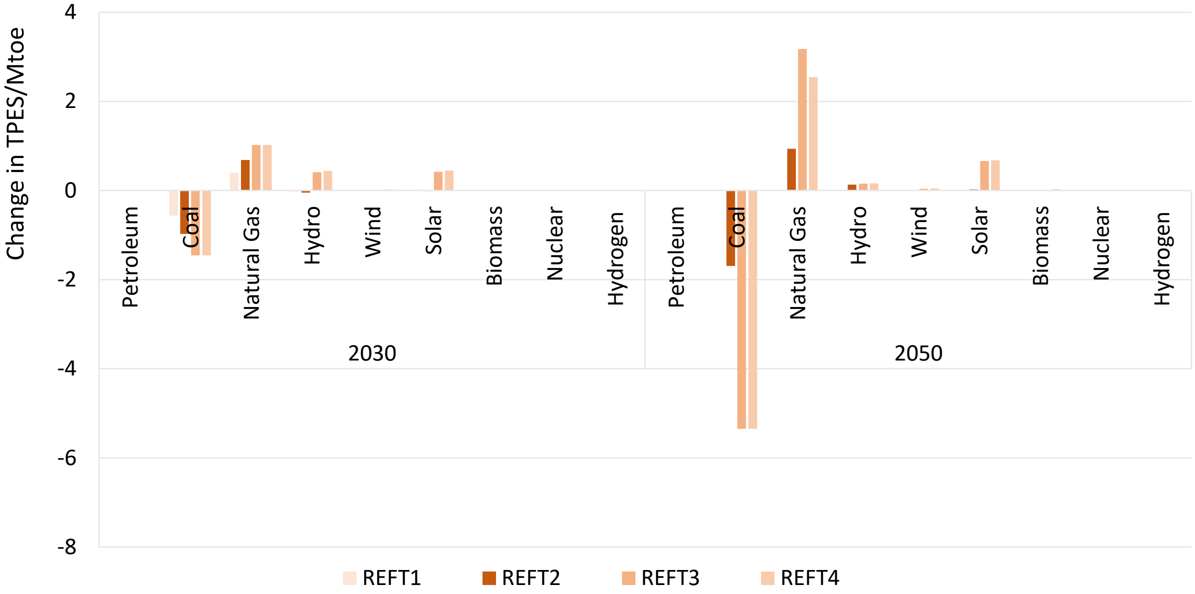
In the reference scenario with carbon taxes, there is a significant reduction in coal use. Natural gas will replace coal. Natural gas use will increase to 3.2 Mtoe by 2050. There is no change in petroleum use. This shows that significant technological interventions are required to reduce petroleum use. There is limited penetration of solar in the reference scenario. This is the lowest penetration as compared to other scenarios.

In the Plausible scenario, under the carbon taxes, petroleum and coal are replaced by natural gas and renewables. In this scenario, at a lower rate of taxes natural gas is used while, at higher tax rates there is a significant penetration of renewable energy sources. There will be a significant penetration of natural gas under carbon tax trajectories T1, T2, and T3 in the plausible scenario. The natural gas use will be highest under T3 with 8.4 Mtoe. The highest increase in wind and solar use is recorded in the carbon tax trajectory of T4 with 2.7 and 2.6 Mtoe, respectively.

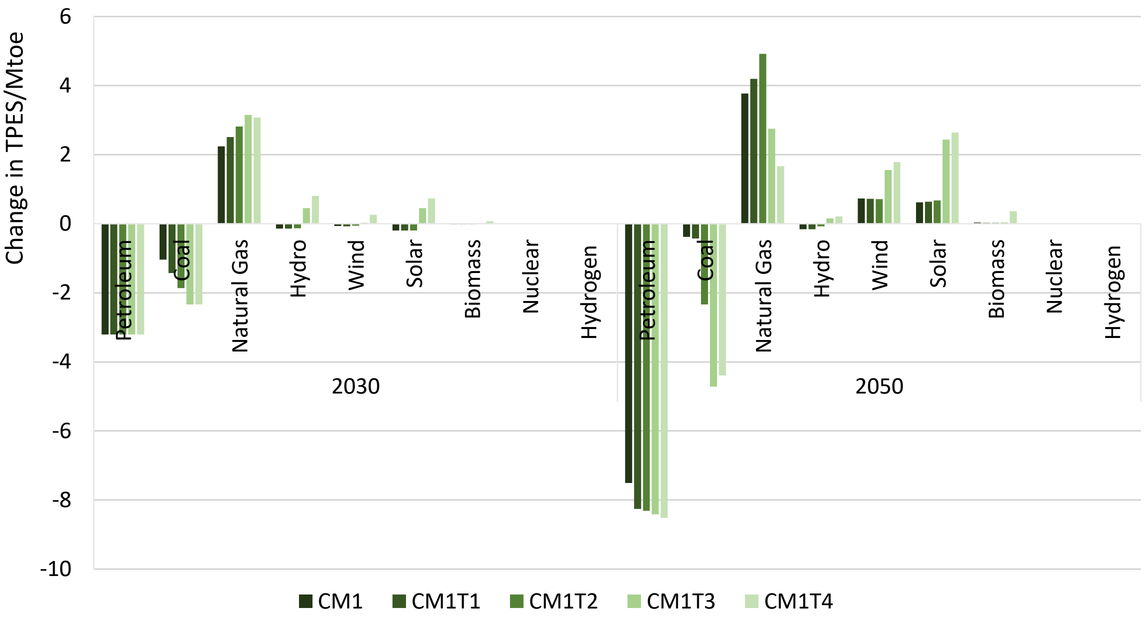
In the Ambitious scenario, there is significant penetration of natural gas under T1, T2, and T3 carbon tax trajectories similar to the plausible scenario. On the other hand, the penetration of renewables is much higher as compared to the plausible scenario for all carbon taxes. Wind and solar use will increase to 2.8 Mtoe and 3.4 Mtoe, respectively by 2050. There is also a very small penetration of biomass, but it is very negligible.

In a Challenging scenario, nuclear energy is selected for power generation at higher carbon taxes (T3 and T4). Nuclear replaces natural gas with high carbon taxes. The nuclear energy use will be 4.3 Mtoe in T4 in 2050. There will also be a much higher penetration of solar and wind with higher carbon taxes as compared to the previous scenarios. The total share of renewables under T4 will be 58% in 2050. In this scenario, a small amount of hydrogen has been selected at higher taxes. Much higher taxes will be required to make an impact on the energy supply.

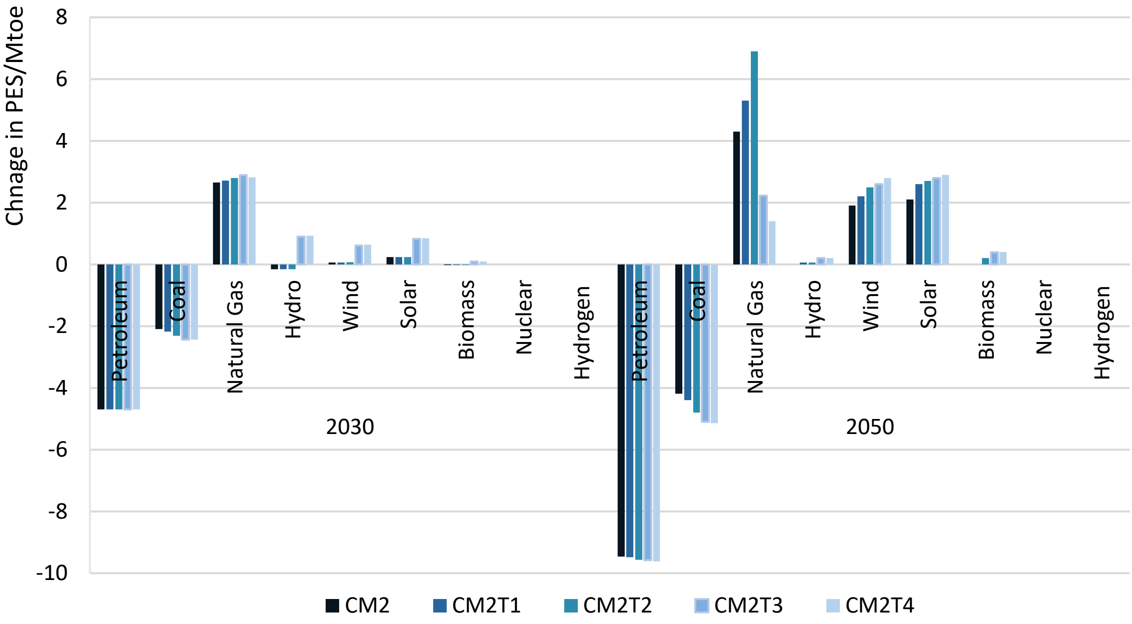
In the Stringent scenario, coal and petroleum will be completely replaced by clean energy sources. There is a significant increase in the use of solar, wind, and nuclear with. Out of all the scenarios, the use of solar, wind, and nuclear will be the highest in the T4 scenario with 5.4, 4.8, and 5.3 Mtoe, respectively in 2050. The role of hydrogen and carbon capture technologies in this scenario is very negligible. To make these attractive much higher taxes are required.



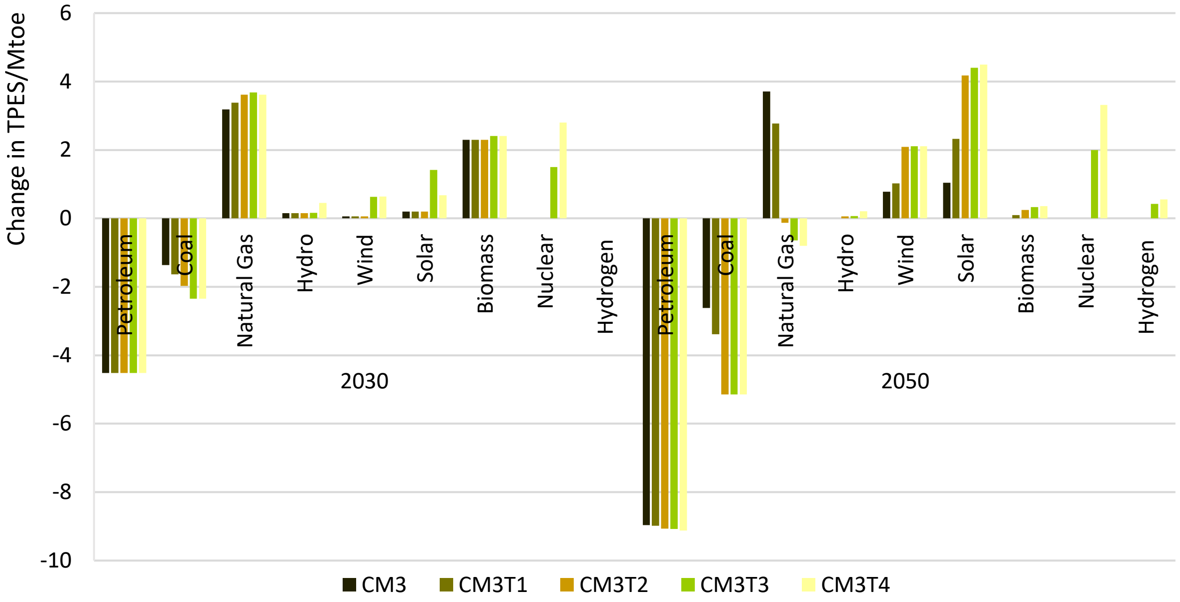
a. Reference scenario



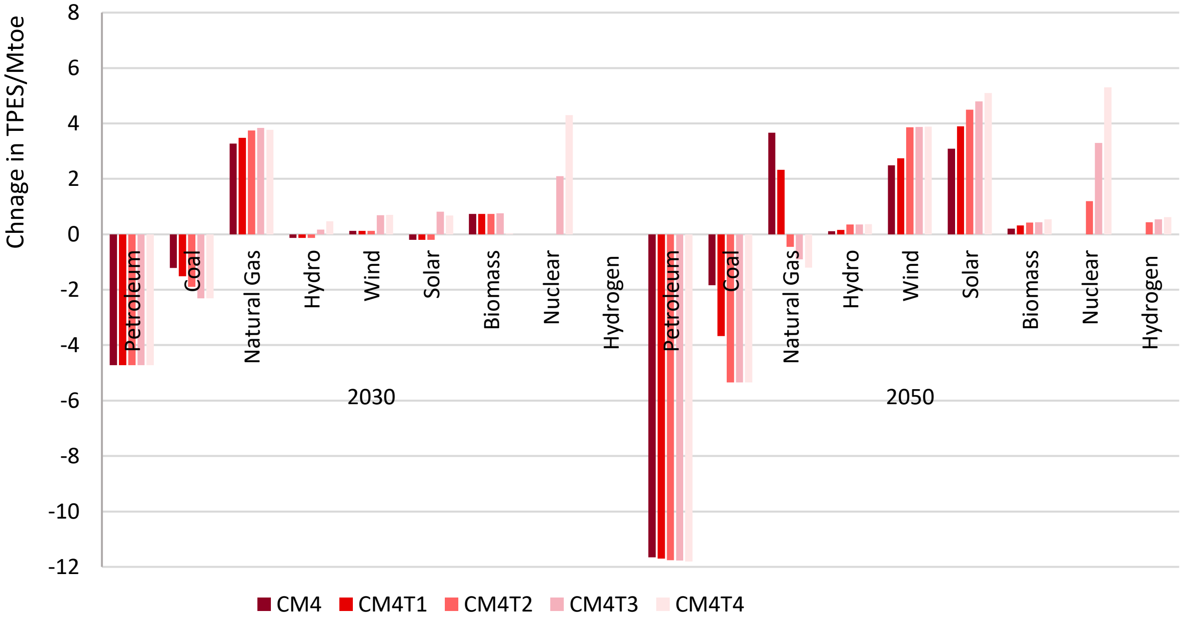
b. Plausible Scenario



c. Ambitious Scenario



d. Challenging Scenario



e. Ambition Scenario

Figure 4: The total primary energy supply in countermeasure scenarios during 2015 -2050 compared to the business-as-usual scenario.

Figure 5 shows the CO_2 emissions in Reference and other CM scenarios. The results show that, even in the absence of carbon taxes, the countermeasure scenarios can lead to significant reductions in total CO_2 emissions. Even without tax, in respective countermeasure scenarios, it could reduce total CO_2 emissions by a quarter (in Plausible) to half (in Stringent) compared to the reference scenario, by 2050. The reference scenario does not show any significant reductions in CO_2 emission. This means that with policy interventions significant CO_2 emissions could be achieved. In Plausible and Ambitious scenarios even at significantly high carbon tax rates, only half of the CO_2 emissions could be reduced. With a carbon tax of T4, up to 61% could be reduced in CM1 while only up to 66% could be reduced in the Ambitious scenario, by 2050. Challenging scenario record higher reductions in CO_2 emissions. At high carbon taxes of T3, it could reduce more than 80% of the emissions. Out of all the scenarios Stringent scenario records the highest reduction of CO_2 emissions. More than 95% of the emissions could be reduced by having a tax of T4. In the Stringent scenario, with carbon taxes, there is a rapid decrease in CO_2 emissions during the latter part of the planning horizon. According to the current results, it is expected that near carbon neutrality would occur around 2050 in the Stringent scenario under the carbon taxes of T4. This is achieved through the help of mainly solar, wind, and nuclear power generation, an increase in public transport, and rapid electrification in-demand sectors.

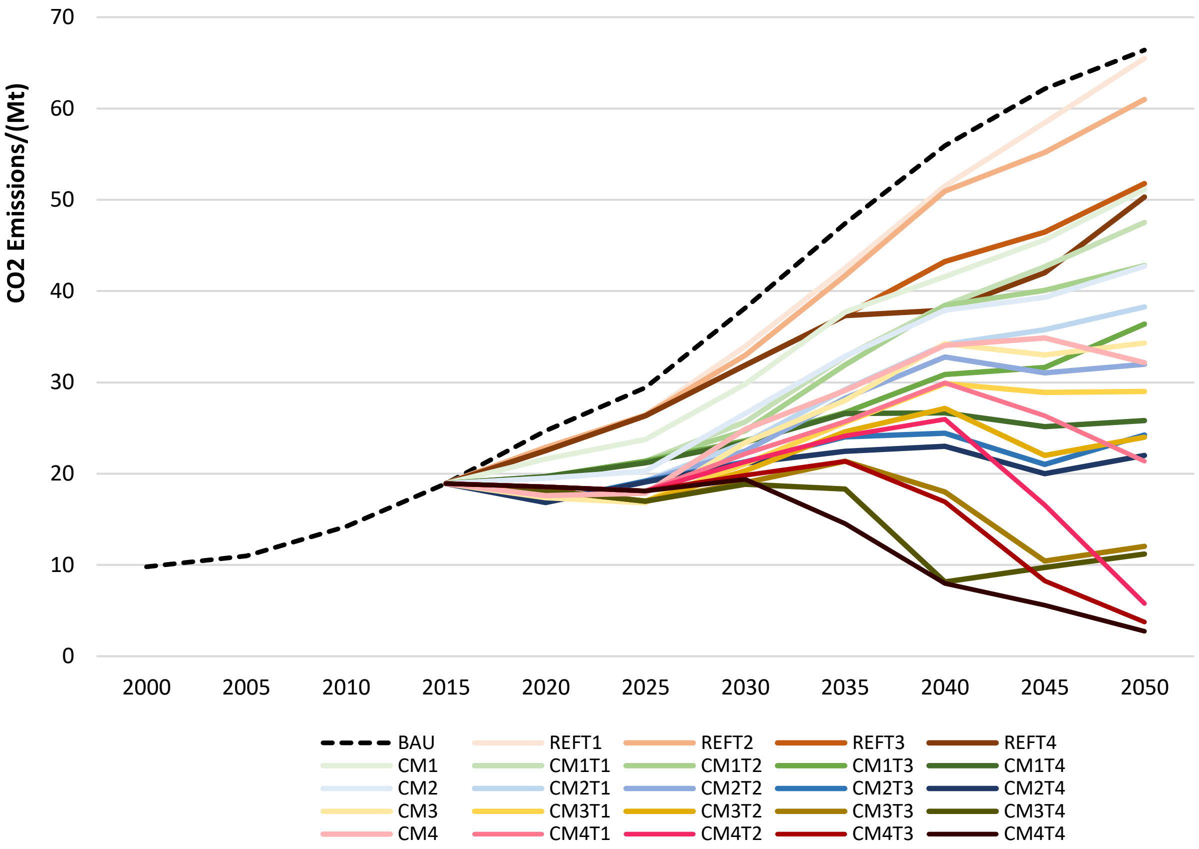


Figure 5: CO_2 Emissions in countermeasure scenarios.

Electricity plays a central role in reducing CO_2 emissions. The electricity generation and the respective fuel mix in electricity generation in the other CM scenarios are shown in Figure 6. There is no change in total electricity generation in the reference scenario. However, the share of coal is decreased with the carbon tax. With a carbon tax trajectory, T4 the share of natural gas increased to 39% while the share of solar and wind increased to 44 %. In the Plausible scenario with a carbon tax of T4 and in other scenarios for a carbon tax above T2 there is a significant increase in electricity generation.

This is because the CO_2 reductions are associated with an increase in electricity generation. This indicates that the end-use sectors are decarbonized mainly through electrification. The electricity consumption in transport, industry, and residential sectors shows significant growth under higher emission taxes in low carbon scenarios.

Up to low to mid-range carbon taxes coal emission reductions are generally achieved through replacing coal with natural gas. However, high CO_2 emission reductions are associated with increasing the use of renewables and nuclear energy.

In the Ambitious scenario with a carbon tax of T4 electricity generation is increased by 73 GWh in 2050. Out of this electricity, only 21% of the share will be from natural gas. The rest of the generation will be carried out through renewable energy sources.

In the Challenging scenario with a carbon tax, electricity generation will further increase. It will be as high as 83 GWh with a carbon tax of T4. Out of this generation, 82% will be from renewable energy sources, 24% will be from nuclear and 4% will be from hydrogen.

The electricity generation will be highest in the carbon-neutral scenario with 110TWh. This generation comprises 68% renewables, 28% nuclear, and 3% hydrogen. The annual generation from nuclear will be 30 TWh, while 36 TWh from wind and 33 TWh from solar.

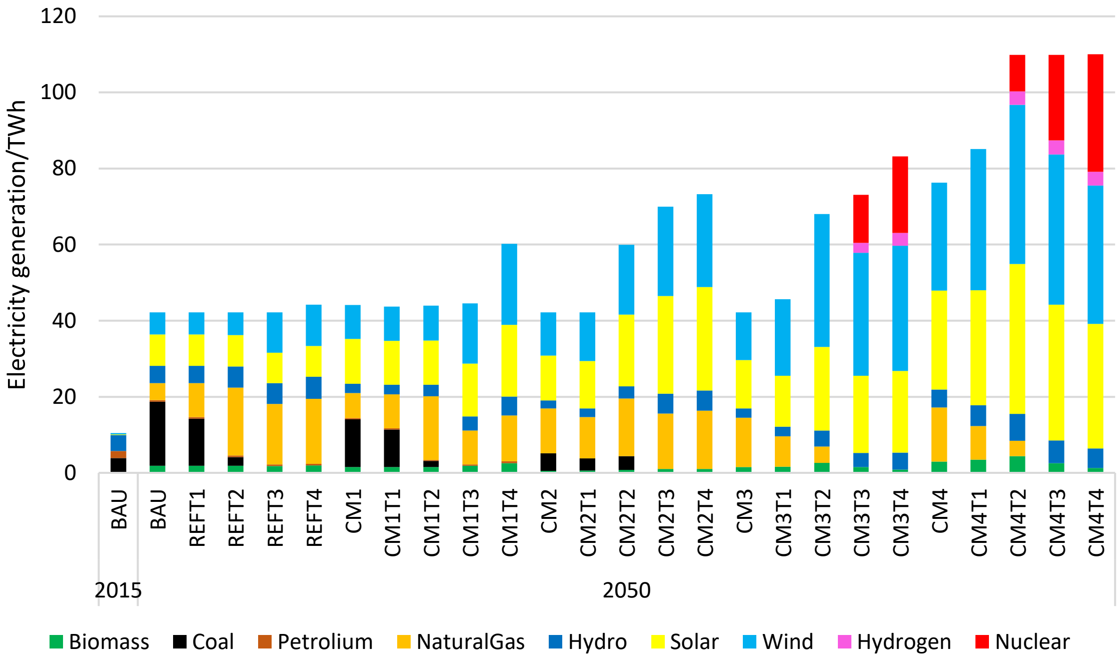


Figure 6: Electricity generation during 2015-2050

The country has no proven economically feasible fossil fuel reserves. High dependency on imports has led to energy shortages at times. Therefore, it would be interesting to see how the near carbon-neutral scenarios would affect the country's energy security. The Net Energy Import Dependency (NEID) is defined as total energy imports as a percentage of the total primary energy supply. The NEID is an indicator of energy security. The government has a plan to improve energy security by promoting renewable energy sources such as solar and wind. It would be interesting to see how these low-carbon scenarios will affect the country's NEID and renewable energy share.

The NEID and renewable energy share for a selected set of CM scenarios during 2015-2050 are presented in Table 5. In the BAU scenario, the NEID increased from 53% in 2015 to 65% in 2050. This is due to the dependency on fossil fuels to meet the increasing energy demand in CM scenarios, with carbon tax NEID is decreases while the share of renewable energy is increased. The results show that the low carbon scenarios result in significant reductions in energy imports resulting in reduced NEID. Such reductions in the NEID are achieved by increasing the share of renewable energy sources. From plausible to stringent scenarios the NEID gradually decreases. This reduction of NEID is achieved through integration of renewable energy sources such as solar and wind. In the plausible to stringent scenario the NEID gradually decreases with the carbon tax. The reduction of NEID is achieved through the integration of renewable energy sources such as solar and wind. In the plausible scenario the renewable energy share will be highest with 61% and the NEID is lowest with 32% in 2050 under a carbon tax of T4. The renewable energy share is highest in the stringent scenario under the T3 carbon tax scenario with 78% in 2050. The lowest NEID is reported in the same scenario under the carbon tax of T4 with 13%. Therefore, low-carbon scenarios have had a positive contribution by improving the energy security of the country as it allows the use of indigenous energy sources such as solar and wind.

Table 5: Net Energy Imports dependency and the renewable energy share of the total primary energy supply in the countermeasure scenarios during 2015- 2050

	Carbon tax Case	Renewable energy share in TPES/ (%)			NEID / (%)		
		2015	2030	2050	2015	2030	2050
Reference	BAU	47	40	35	53	60	65
	T2		41	36		58	63
	T4		44	40		58	57
Plausible	No tax		44	42		50	53
	T2		44	45		48	48
	T4		51	61		47	32
Ambitious	No tax		51	56		39	37
	T2		52	54		39	43
	T4		58	68		38	26
Challenging	No tax		54	49		46	42
	T2		54	71		45	23
	T4		52	64		57	22
Stringent	No tax		48	59		46	36
	T2		49	78		45	14
	T4		43	69		65	13

5. Conclusions

This study explored how large-scale CO_2 emission reductions could be achieved for a developing country that already has a low carbon intensity as compared to other countries. It also studied the role of carbon tax in achieving carbon neutral status. This was done by developing low carbon scenarios that could drive the energy system transition toward achieving net-zero emissions in Sri Lanka. The low carbon scenarios considered clean fuel options, renewable energy sources, nuclear energy, hydrogen, carbon capture energy storage systems, use of efficient and potential technologies. Depending on the level of policy intervention four different scenarios were identified. These scenarios were named plausible, ambitious, challenging, and stringent. It used carbon tax as a policy instrument to promote clean fuels and efficient technologies while discouraging the use of fossil fuels. Four possible tax trajectories were considered under each scenario. A BAU scenario and twenty-four alternative scenarios were developed in this study for analysis.

According to the results of the BAU scenario, Sri Lanka would continue to follow a fossil fuel-based energy pathway in future years. The TPES of Sri Lanka is expected to increase from 11 Mtoe in 2015 to 34 Mtoe in 2050, recording more than a threefold increase. The transport sector (37%) followed by the residential (25 %) and industry sectors (23 %) will be the main energy-consuming sectors in 2050. The resultant total CO_2 emissions will increase by almost 3.5 times from 19 Mt in 2015 to 66 Mt in 2050. The transport sector was found to be the highest emitting sector (41%) followed by power (39%) and industry (9%) in 2050. There was only a limited penetration of solar and wind in the BAU scenario.

In plausible and ambitious scenarios even with high carbon tax rates, only half of the CO_2 emissions could be reduced in 2050. This will be achieved mainly through fuel switching. It will replace coal with natural gas and use renewable energy sources such as solar and wind for power generation. In the challenging and stringent scenarios with carbon taxes as high as 280 US$/tCO_2$, it could reduce more than 80% of the emissions.

The near carbon neutral status could be achieved through the stringent scenario by having a tax of 560 US\$/t CO_2 in 2050. Renewable energies, nuclear and green hydrogen are used in power generation in the near carbon neutral scenario. There was also a considerable increase in the public transport share (68% in the near carbon-neutral scenario) and the transport sector's use of electric buses, trains, and cars. There will also be a significant penetration of efficient electric appliances in residential, commercial, and industry sectors. Therefore, electricity will play a significant role in achieving carbon neutrality in Sri Lanka. In the carbon-neutral scenario, the annual electricity demand was 110 TWh in 2050. This electricity generation will be comprised of renewable energy (69%), nuclear (28%), and hydrogen (3%).

According to this study, a significant policy intervention will be required to reduce petroleum use in the transport sector. It was seen that the role of hydrogen was very limited even in the stringent scenario. At the current prices carbon capture and storage technologies were also not cost-effective.

Low carbon scenarios will play a positive role in improving the energy security of the country by reducing energy import dependency. The low carbon scenarios reduced the NEID to 19% in the challenging scenario by 2050. It also increases the use of renewable energy sources promoting indigenous energy sources. The renewable energy share was highest with 78% in 2050 in the near carbon neutral scenario.

The results show that for large CO_2 reductions, a significant level of technological intervention will be required. It will require access to breakthrough technologies and large capital investments. Furthermore, large-scale use of solar and wind will be required for decarbonization. This will require significant storage and an upgrade of the transmission system. The transmission system requirement is beyond the scope of this study. There will also be a significant amount of nuclear energy. It is a complex technology that is new to the country. In the end use sector, there is a significant use of electric vehicles and other technologies. Practical implementation would require the actual realization of these technologies in future years to come.

The results of this study reveal that for large scale carbon reductions, carbon tax trajectories between 280 US$/t CO_2 and 560 US$/t CO_2 in 2050 are required. A carbon tax trajectory with tax of 560 US$/t CO_2 in 2050 would help in achieving near carbon neutrality by 2050. These taxes are almost comparable with the carbon taxes required in achieving Net zero emissions in countries such as Thailand (500 $/t$CO_2$ to $1000/t$CO_2$), (Chunark & Limmeechokchai, 2018) and Nepal (300 $/t$CO_2$ to $800/t$CO_2$), (Pradhan et al,2020).

However, these carbon taxes are comparatively higher when compared to those considered for achieving the net zero emissions in countries such as USA ($400/t$CO_2$ in 2050), (Browning et al. 2023) and China (81 $/t$CO_2$ to 382$/t$CO_2$), (Zheng et al., 2021).

Sri Lanka is already a country that has a lower carbon intensity as compared to other countries. In addition to that, solar and wind will play a leading role as it has exhausted its hydro resources and availability of limited biomass. Therefore, higher carbon taxes are required for reducing the CO_2 emissions.

The energy-economic-environmental model considered in this study was a bottom-up type model. It considers the energy production and consumption of individual sectors. However, in a complex economy, there could be sector-wide interactions which are not captured by the model. Furthermore, bottom-up models do not consider price elasticities associated with supply and demand. The price of reducing carbon is a key factor in any mitigation study. Therefore, the marginal abatement cost of carbon reduction should be considered in a future study.

ACKNOWLEDGMENT

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Appendix 1

AIM/Enduse model

AIM/Enduse is a bottom-up energy system model with a detailed technology selection framework for energy and climate policy analysis. It belongs to the Asia- pacific Integrated Model family and was developed by the National Institute of Environmental Studies and Kyoto University, Japan.

Structure of the AIM/Enduse model

A schematic diagram of the AIM/Enduse model is shown in Figure 1. The model considers all energy supply and demand sectors of and economy. Energy supply sectors are electricity generation, Oil refineries, and other energy imports. The energy demand sectors are classified into five sectors: the industry sector, the residential sector, the commercial sector, the transport sector, and the agriculture sector. It considered the flows of energy in all energy supply and energy demand sectors from primary energy sources through their conversion into secondary forms of energy to end-use devices that meet the demands for different energy services. It also considered the flow of materials in the case of process industries. The paths for the flow of energy and materials are characterized by technologies involved along the respective paths. The input data of the model can be categorized under energy data, Service demand data based on the country's socioeconomic data. The input data /data required for input data calculation are listed in Table 1. The model is driven by demands for different energy services, which are determined exogenously based on relevant socioeconomic and demographic factors.

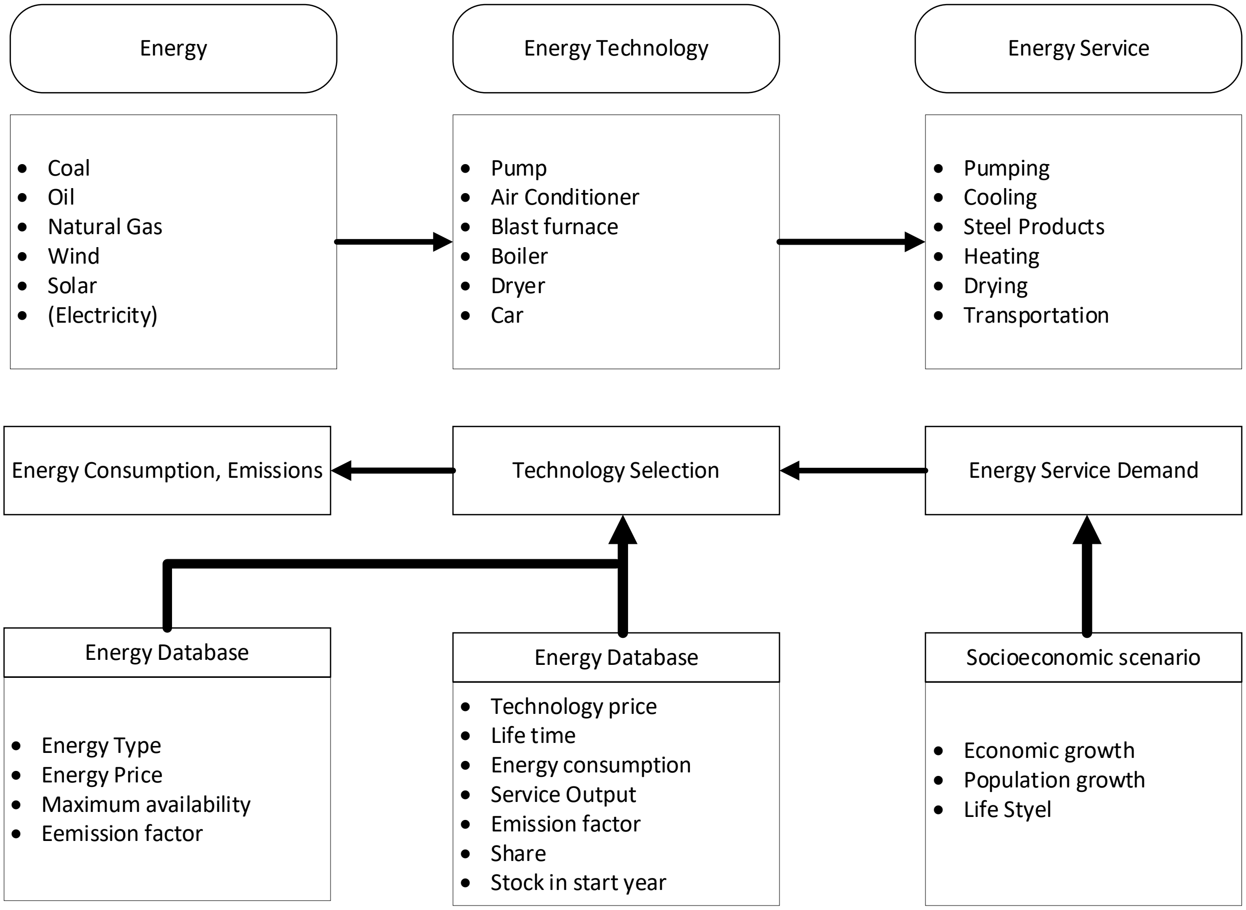

Figure 2.1: A schematic diagram of a BU Energy System Model (AIM/Enduse)

Source: Kainuma et al. (2003),

The framework of the model is designed to determine the cost-effective energy and technology options over the molding time. The technology selection happens on a least cost optimization which optimizes the cost year by year basis during the given period. This model analyses the medium-range scenarios due to future technology and service demand constraints. A comprehensive study of innovative technology advancements and anticipated shifts in service demand across diverse socioeconomic structures will be crucial for the model's application in long-range low-carbon scenario analysis.

This model estimates future energy demand and emissions such as CO_2, CH_4, N_2O, SO_2, and NOx. Further, this model could be used in analyzing the effect of policies such as carbon/energy tax, subsidies, and other regulations. The model framework is designed to determine the cost-effective energy and technology options over the molding time. Further, this model could be used in analyzing the effect of policies such as carbon/energy tax, subsidies, and other regulations.

Table 1: Input data/data required for input calculation of AIM/Enduse model.

Energy Data	Technology Data	Socioeconomic data/ (for Service demand calculation)
Energy Type	Initial Cost	Population growth
Energy Price	Running cost	Economic growth
Energy Constraints	Energy consumptions	Other economic data based on the service demand estimation method used
Emission factors	Emission factors	
	Service supply	
	Lifetime	

AIM Enduse Software Description

AIM/Enduse software integrates Microsoft Excel and General Algebraic Modeling System (GAMS) optimization software. The AIM Enduse setup files and the three Excel files used for data input and output are available on https://www-iam.nies.go.jp/ web page. However, the GAMS optimization software must be purchased to use AIM Enduse software. The software installation procedure, step-by-step process of input data files preparation, and use of model output Excel files are provided in detail in AIM Enduse Manual (NEIS,2015)

Theoretical Formulation of AIM/Enduse Model

The linear programming formulation of the model comprises an objective function to minimize the total system cost subjected to several constraints related to service demands to be met, energy resource availability, existing device stock, the maximum allowable quantity of devices, and emissions. The system cost includes initial investment costs, operating and maintenance costs, energy costs, energy tax, emission tax, and other subsidies. The model considers the annualized investment cost based on the discount rate, which is determined exogenously in its recursive dynamic analysis. Hence the discount rate plays a crucial role in the model analysis. The Enduse service demand and material and energy availability are other constraints considered in the optimization process. The formulation also provides functions to consider the existing device quantities in the starting year of the planning horizon and to calculate the retirement of the devices at the end of their lifetime. The constrained formulations define the service demand calculated by service output per unit device output and the available device quantity stock. The stock calculations per year consider the remaining stock quantity, retired stock quantity, and newly recruited stock per device. The optimization equation represents the total system cost, and the other equations representing the main constraints used in this study are shown below. Further, detailed theoretical and mathematical equations of such a formulation (AIM/Enduse) are provided in Kainuma et al. (2003).

Expression for Emission Quantity Estimation

$$Q_i^m = \sum_{(l,p)\in w_j}\left(X_{l,p,i}.\, e_{l,p,i}^m\right)$$

$$e_{l,p,i}^m = \left(f_{0.l}^m+\sum_k f_{k,l}^m.(1-\varepsilon_{k,l,i}).E_{k,l,p,i}\, .U_{k,l}\right).d_{l,p,i}^m$$

Q_i^m	Emission in gas m in sector i
e_i^m	Emission of gas m from an operating unit of a combination of device *l with* removal process *p* in sector *i*
$X_{l,p,i}$	Operating quantity of combination of device *l* with removal process *p* in sector *i*
$E_{k,l,p,i}$	Energy use of energy kind k per operating unit of a combination of device l with removal process p in the sector I (same as specific energy input)
$f_{0,l}^m$	Emission of gas from operations other than energy combustion of a unit of device l (same as gas m 's emission coefficient of device l)
$f_{k,l}^m$	Emmision of gas m from the combustion of energy kind k by a unit energy use of device l
$\varepsilon_{k,l,i}$	Energy saving ratio due to efficiency improvement in the use of energy kind k by device l in sector i
$U_{k,l}$	Propotion of energy kind k used in device l for combustion operations, or burning rate (Note: 1-$U_{k,l}$ or operation of k used for non-combustion operations in device l is taken as input in database system)
$d_{l,p,i}^m$	Emission rate (1 – removal ratio) of gas m from the combustion of device l with removal process p in sector i

Emission Constraints

$$\sum_{i\epsilon R_z} Q_i^m \leq \hat{Q}_z^m$$

Where,

$\hat{Q}_z^m$: Allowable maximum limit on the emission of gas m in group z

Service demand constraints

$$D_{j,i} \leq \left(1+\phi_{j,i}\right).\sum_{(l,p)\epsilon W_j} A_{l,j,i}\,.X_{l,p,i}$$

$A_{l,j,i}$	Supply output of service *j* per operating unit of device *l* in sector (same as specific service output)

$\phi_{j,i}$	A measure of service efficiency of service type j in the sector I (Note: Negative of $\phi_{j,i}$, a measure of loss of service j, is taken as input in database system; Negative of $\phi_{j,i}$ is the loss incurred during delivery of service j, for example, transmission and distribution loss of electricity supply)
$D_{j,i}$	Service demand quantity of service type j in sector i

Device share ratio constraints

$$\theta_{l,j,i}.\sum_{(\acute{l},p)\acute{\epsilon}W_J} A_{\acute{l},j,i}\,.X_{\acute{l},\acute{p},j} \geq A_{l,j,i}.\sum_p X_{l,p,j}$$

Where;

$\theta_{l,j,i}$	Maximum share og device l in service j

Stock exchange constraints

$$\bar{S}_{l,p,j}.\left(1-\frac{1}{\bar{T}_{l,i}}\right) \geq \sum_{p1} M_{l,p\rightarrow p1,i}$$

Where,

$\bar{S}_{l,p,j}$	Stock of the combination of device l with removal process p in the sector I in the previous year
$M_{l,p\rightarrow p1,i}$	Previous year's stock of combination of device l with removal process p that is replaced in the current year by its combination with removal process p1
$\bar{T}_{l,}$ I	Live of device l in the sector I (this is the average life of stock of device l in the previous year)

Energy supply constraints

$$\sum_{i\epsilon G_i}\sum_j\left[\sum_{(l,p)\epsilon W_j}\left(1-\varepsilon_{k,l,i}\right).E_{k,l,p,i}.X_{l,p,i}\right] \leq \bar{E}_{k,G_i}$$

Where

$\bar{E}_{k,G_i}$	Allowable maximum supply quantity of energy kind k

Annualized initial investment cost (or annualized fixed cost or annualized capital cost)

$$\sum_i \sum_j \sum_{(l,p)\epsilon W_j} \left(C^{\circ}{}_{l,p} . r_{l,p,i} + \sum_{p1} C^{\circ x}_{l,p1\to p} . M_{l,p1\to p,i} \right)$$

$$C^{\circ}{}_{l,p} = B^{\circ}{}_{l,p} . \left(1 - SC_{l,p}\right) . \frac{\alpha(1+\alpha)^{T^{\circ}{}_{l,i}}}{(1+\alpha)^{T^{\circ}{}_{l,i}}-1}$$

Where,

$C^{\circ}{}_{l,p}$	Annualized investment cost of a unit of a combination of device l with removal process p
$C^{\circ x}_{l,p1\to p}$	Annualized investment cost of exchanging a unit of combustion (l,p1) to (l,p)
$B^{\circ}{}_{l,p}$	Initial investment cost or fixed cost of recruiting one unit of a combination of device l with removal process p
α	Discount rate
$SC_{l,p}$	Subsidy rate

$B^{\circ}{}_{l,p}$ is estimated by expressions;

$$B^{\circ}{}_{l,p} = B^{\circ\prime}{}_{l} + b^{\circ\prime\prime}{}_{p} . \sum_i \sum_k E_{k,l,p,i}$$

$E_{k,l,p,i}$ = (1+e_p). $\acute{E}_{k,l,i}$

Where,

$B^{\circ\prime}{}_{l}$	Initial investment cost or fixed cost of recruiting one unit of energy device l
$b^{\circ\prime\prime}{}_{p}$	Initial investment cost or fixed cost of removal process p per energy use of a combination of device l with removal process p
$\acute{E}_{k,l,i}$	Energy use of energy kind k per operating unit of energy device l
e_p	Additional energy use rate of removal process p

Running cost

$$\sum_{(l,p)\epsilon W_j} \left(g^{\circ}{}_{l,p,i} + \sum_k g_{k,i} . (1 - \varepsilon_{k.l.i}) . E_{k,l,p,i} \right) . X_{l,p,i}$$

Where,

$g^{\circ}{}_{l,p,i}$	Operating cost per unit of a combination of device l with removal process p in sector i
$g_{k,i}$	Price per energy kind k in sector i

$g^{\circ}{}_{l,p,i}$ is estimated by expressions;

$E_{k,l,p,i}$ = (1+e_p). $\acute{E}_{k,l,i}$

$g^{\circ}{}_{l,p,i} = \overset{\circ}{g}{}'_{l,i} + \overset{\circ}{g}{}''_{p} . \sum_k E_{k,l,p,i}$

Where

$\overset{\circ}{g}{}'_{l,i}$	Operating cost per unit of energy device l in sector i
$\overset{\circ}{g}{}''_{p}$	Operating cost per unit of removal process p per energy use of a combination of device l with removal process p

Objective Function

$$TC = \sum \left[\sum_{I\ (l,p) \epsilon W_j} \left\{ \overset{\circ}{C}_{l,p} . r_{l,p,i} + \sum_{p1} C^{\circ x}{}_{l,p1\rightarrow p} . M_{l,p1\rightarrow p,l} + \left(\overset{\circ}{g}_{l,p,i} + \sum_k \left(g_{k,i} + \vartheta_{k,i} \right) . \left(1 - \varepsilon_{k,l,i} \right) . E_{k,l,p,i} \right) . X_{l,p,i} \right\} + \sum_m \tau_i^m . Q_i^m \right] \rightarrow min$$

Where,

TC	Total Cost
$\vartheta_{k,i}$	Tax in energy k in sector i
τ_i^m	Emission tax on gas m in sector i

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