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Energy system transformation for attainability of net zero emissions in Thailand

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ABSTRACT

Thailand has a commitment to achieve net zero emissions. The roles of energy service demand reduction and hydrogen in the energy transition have not been sufficiently evaluated. This study analyzed energy and technological implications in the energy sector to attain net zero emissions in Thailand by 2050. This study used the AIM/Enduse model, a bottom-up type energy system model, as an analytical tool. A business-as-usual scenario and a net zero emission scenario are analyzed. Unlike other studies, this paper explored the energy transition in the absence of carbon, capture and sequestration (CCS) technology with a focus on energy service demand reduction and green hydrogen-based technologies. Decarbonization of the energy sector and transition towards net zero emission by 2050 in Thailand would require rapid deployment of renewable energy sources like solar, wind and biomass. In the net zero scenario, installed capacity of solar PV and wind for power generation in 2050 would reach 64 GW and 40 GW, respectively. In addition, green hydrogen will have a crucial role in achieving net zero emission target. The high carbon removals from LULUCF sector in Thailand will aid in reaching net zero emission without CCS technology in the energy sector.

Keywords

AIM/Enduse;
CCS;
Decarbonization;
Net zero emission;
Renewable energy;
Thailand

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1. Introduction

Achieving the net zero emission in line with the 1.5°C target requires net carbon dioxide emission to reach zero around mid-century and concurrent deep reduction in non-CO_2 forcers [1]. In the Paris agreement, participating countries agreed to work jointly on reducing the emissions to keep the global temperature rise within 2°C and put effort to pursue a 1.5°C target. In addition, countries could set their own emission reduction targets in their Nationally Determined Contributions (NDC). Some studies have already analyzed effects of different countries' combined NDC and Intended NDC (INDCs) targets on emissions [2-5]. van den Berg et al. discussed various effort sharing approaches based on allocating national carbon budget and pathway-based effort sharing estimates [6]. The basic idea of effort sharing is to calculate the allowable emission limit over a period. The IPCC's special report on Global Warming of 1.5°C states that the remaining carbon budget is ±420 Gt CO_2 for a two-third chance of limiting global temperature rise to 1.5°C [1]. The bioenergy with CCS (BECCS) and carbon removal from sink are considered as the two potential options for negative emissions i.e., carbon sequestration.

In 2021, Thailand submitted its 'Long-term Low Greenhouse Gas Emission Development Strategy' document to the UNFCCC. Thailand aims to achieve carbon neutrality by 2065 [7]. Thailand, a country with high dependence on fossil fuel to meet its primary energy supply, faces big challenges to comply with the net zero emission target. The combination of theoretical and effective capacity of geological storage sites for

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carbon dioxide storage through CCS technologies in Thailand is 10.3 Gt CO_2 [8, 9]. Thailand has natural forest coverage of 16 million hectares, which accounts for 31.6% of the total land area. In its third biennial update report (BUR3), carbon removal from natural forests, as well as commercial forests such as rubber plantations were taken into account. In 2016, the net sequestration from LULUCF was about 90 $MtCO_2$.

A report by International Energy Agency (IEA) mentioned that behavior change, energy efficiency (including building envelope improvements), end-use sector electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy, and carbon capture, utilization and storage (CCUS) are key pillars of decarbonization. Stafell et al. have conducted a comprehensive review on the potential role of hydrogen in power, heat, industry and transport services; and discusses the versatility and flexibility it offers in power sector and choices it offers in end-use technologies for decarbonization [10]. The stored hydrogen generated from renewables by electrolysis process can also be utilized to balance both seasonal variations in electricity demand and the imbalances occurring between the demand for hydrogen and its supply by off-grid renewable energies.

Demand-side measures such as reduction in the service demand through behavior change and building envelope improvements has not been considered in any of the previous studies of Thailand. While demand side measures are challenging and require innovative solutions and policies as well as behavior change, they are deemed as viable solutions to meet the 1.5°C target [11]. Several studies used integrated assessment models (IAMs) to analyze the role of energy demand reduction [12-15]. van Vuuren et al. in their studies also considered the scenario focusing on the role of lifestyle changes and its impact on less reliance on carbon removal technologies [12]. A study by Levesque et al. found that the adoption of energy saving practices including new behaviors could reduce global energy demand of building by up to 47% in 2050 [16]. The lifestyle changes assume changes in behavior that leads to lower cooling and heating demand, change in transport habits, and the way we eat, etc. Oshiro et al. explored the role of energy service demand reduction through behavioral change and material use efficiency in achieving Japan's decarbonization goal [17].

The existing research in Thailand considers the CCS technologies and renewables in the supply side and energy efficiency improvement and fuel switching in the demand side as the pathway to meet net zero emissions consistent with the 1.5°C target [18, 19]. The existing studies of Thailand have assessed the potential of GHG emissions reduction considering only the technological changes, while leaving aside the impact of behavioral changes and building designs in energy service demand reduction. No studies in the case of Thailand have considered the reduction in energy service demands from behavioral change and building envelope. In addition, the role of hydrogen in energy system transition have been overlooked.

Bioclimatic designs and insulation increase the building envelope performance which reduces the space cooling/heating and lighting demands of the buildings. The use of efficient air-conditioners is included in the earlier studies of Thailand but reduction in cooling demand from improved building design will reduce the cooling service demand and thereby reduces the energy use upstream in supply side as well as GHG emissions. Similarly, in the transport sector, shift to non-motorized transport, car sharing, avoided journeys and modal shift are actions of the behaviors change measures that mitigate GHG emissions from the transport sector [20]. The car sharing concept can be a simple yet effective solution to reduce the number of vehicles significantly.

This study aims to assess the energy and technological transformation needed in Thailand's energy system during 2020-2050 identifying three gaps in the existing literature. First, this study has considered the impacts of energy service demand reduction in the analysis. Second, the role of green hydrogen in the long-term energy transition has been included. Third, the study explores the energy transition needed by mid-century to achieve net zero emission by 2050 in the absence of carbon dioxide removal (CDR) technologies i.e., CCS and BECCS. Furthermore, this study used effort sharing approaches to determine the emission pathways towards net zero emissions by 2050, which also added to the novelty of the research.

This study first estimates the emission allowance pathways of Thailand during 2020-2050 based on the effort sharing approaches following van den Berg et al. This study then uses a bottom-up model based on Asia-Pacific Integrated Model (AIM) framework i.e., AIM/Enduse model to analyze the technological and energy transition needed to achieve net zero emission by 2050. In addition, the study also calculates the carbon budget of Thailand during 2020-2050.

2. Methodology

This section presents the emission pathway calculation, development of energy system model and scenarios description. Energy system models are crucial for assessing the energy transition pathways [21, 22] and its impacts on GHG emissions. Moreover, it provides an insight for energy planners, more than just giving numbers as the outputs [23, 24]. The numerical models for energy system analysis can be generally classified into two types: the model that examines the interaction within the energy system, also called the bottom-up engineering approach, and the model that examines the interaction between the energy sector and rest of the economy, also called top-down macroeconomic approach [22, 25, 26]. Prina et al. classified bottom-up models into static or short-term model and long-term models based on time horizon in which analysis are done. Static models analyze the energy system configuration in a fixed target year. Short-term models make the analysis for one target year and can simulate up to hourly resolution level [27], whereas long-term models analyze the energy system over longer time horizon considering the transformation of the energy system until the target year [22]. This study uses a bottom-up type, long-term energy system model called the "AIM/Enduse" model for the analysis. The AIM/Enduse model is suitable for long-term energy analysis and is capable of quantifying GHG emissions. Various national studies on low carbon scenarios analysis have been done using the AIM/Enduse at sectoral level [28, 29] as well as economy-wide level [30-32].

2.1 Emission pathway calculations

The emission pathways in this study are calculated following van den Berg et al. [6]. Three effort sharing approaches are used for emission pathway estimations; they are grandfathering (GF), immediate per capita convergence (IEPC) and per capita convergence (PCC). The equations for estimating emission allowances using various approaches are available in Table S1 of the supplementary document of van den Berg et al. [6]. The start year is 2018 and the end year is 2100 based on IPCC [1] and van den Berg et al. [6]. The data required for calculation are taken from various sources. Global historical emissions and emissions in year 2018 are taken from CAIT Climate Data Explorer [33]. The LULUCF emissions in 2018 for Thailand has been harmonized with the Third National Communication report of Thailand [34]. Population data projections for Thailand and the world are taken from World Population Prospects 2019 [35]. The global emission pathway in this study are in line with the global 1.5 °C target. The global emission pathway is based on results from the IMAGE (Integrated Model to Assess the Global Environment) model obtained from the Shared Socioeconomic Pathways (SSP) database [36]. The weighting factor in the PCC approach is assumed to be 0.3 [6] and the convergence year is 2050 [1].

2.2 Development of Thailand Energy System Model

The energy system model of Thailand is developed using the AIM/Enduse model. The structure of the AIM/Enduse model is presented in Figure 1. The AIM/Enduse model is a bottom-up type technology selection framework to analyze GHG and local pollutant emissions. The annual end-use energy service demands in future are given exogenously to the model. The energy service demands mean the final services delivered by energy devices or technologies. For example, cooking is the energy service delivered by cookstoves (i.e., energy technology) which can be electric cookstove, biomass cookstoves or LPG cookstove. The types of energy and technology selection in AIM/Enduse model are made by minimizing the total system cost under given constraints using linear optimization. The total cost includes the annualized investment cost, operating cost and maintenance cost. The constraints include energy availability, maximum allowable emissions, etc. The AIM/Enduse is a recursive dynamic model that can simultaneously carry out computation for multiple years. More details on the AIM/Enduse framework can be found in Kainuma et al. [37]. Earlier studies have also used AIM/Enduse model to analyze low carbon development issues in case of Thailand. Shrestha et al. [30] and Chunark and Limmeechokchai [18] forms the basis for the development of AIM/Enduse model in this study. AIM/Enduse model consists of five demand sectors, i.e., the residential, the commercial, the transport, the industry, and the agriculture sectors. In addition, non-energy use of energy has also been considered in the final energy demand sector. The supply side consists of petroleum refineries, natural gas processing plants and the power sector. The study period is 2015-2050. The end-use service demands in various sectors are estimated using GDP and population as the drivers of the end-use services, similar to the methods used in earlier studies of Thailand [18, 19, 30, 38].

The study first analyzes the carbon removal potential of Thailand. In the case of forestry, annual carbon

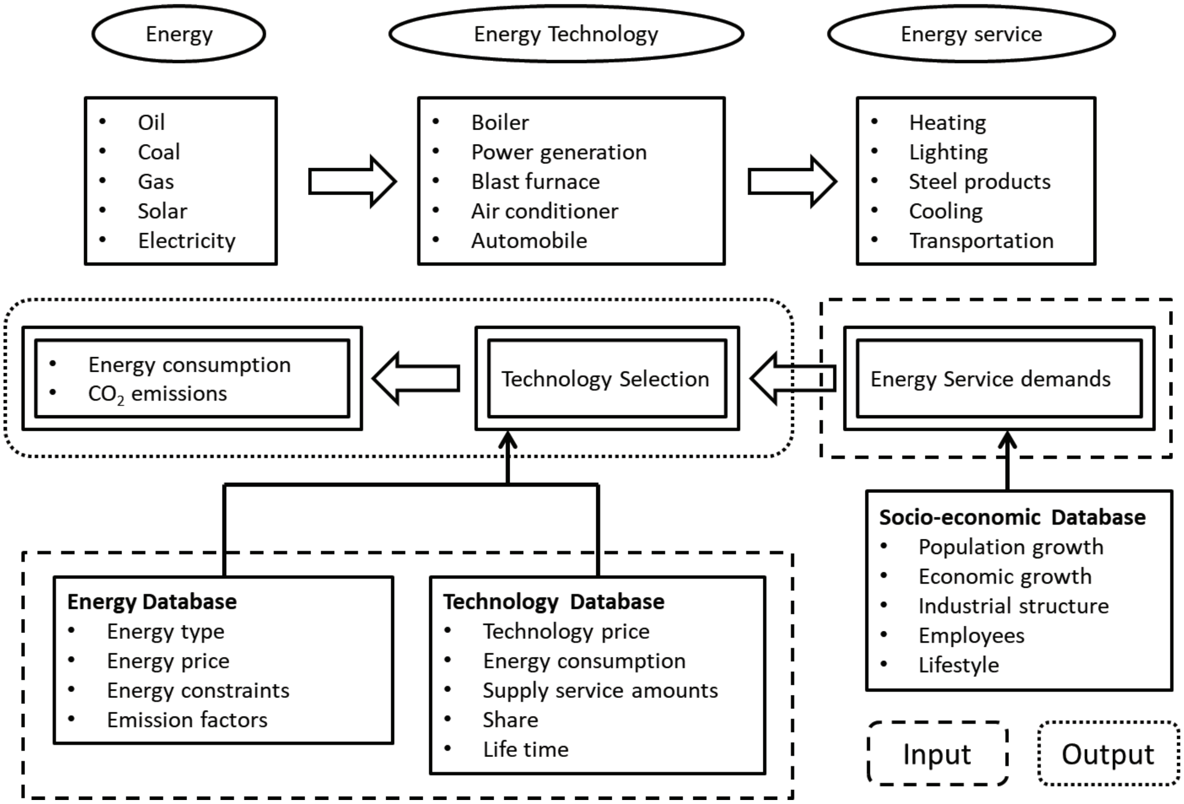

Figure 1: Structure of the AIM/Enduse model (adopted from Kainuma, Matsuoka [37])

removal is assumed to be increasing up to 2050 based on the government's target. It is also assumed that the use of biomass for energy will reduce the carbon removal from the forestry sector. Furthermore, it is assumed that CO_2 emission from biomass burning is canceled out by carbon absorption during the biomass production. In the case of CCS, there is a limit, as once the storage site is filled up it cannot be used. As CCS technology comes into effect, the sequestration potential is assumed to decrease. After estimating the sequestration potential of forests, the emission reduction pathway has been designed. In the analysis, emissions from energy use, agriculture, LULUCF and industrial processes are considered to design emission allowance pathways. The emission reduction in the net zero scenario compared to the BAU scenario will come from conventional mitigation measures such as energy efficiency improvement, fuel-switching and renewable energy. The emissions that cannot be reduced using the aforementioned measures would be offset using forests as natural carbon sink. The technologies and energy sources that would be required to achieve the net zero emission pathway will be identified with the use of the AIM/Enduse model. The reduction in the service demand in the model due to behavior change, improvement in building envelope and material efficiency gains are estimated exogenously to input into the model.

2.3 Scenario Description

This study includes one business-as-usual scenario, and one net zero emissions scenario. The description of each scenario design is as follows:

Business-as-usual scenario: The business-as-usual (BAU) scenario is designed to show the baseline of energy use and GHG emissions when the present energy use and technology continues in the future. In the transport sector, the share of public and private vehicles is constrained to the present share. Likewise, in the case of the agricultural sector, the technology and energy mix are constrained to be the same as in the present scenario. The service demand projection in the BAU is estimated by using a linear regression approach assuming GDP and population as the main drivers following earlier studies in Thailand [7, 18, 19]. The annual average GDP growth rate is assumed to be 3.21% during 2021-2037 and 2.71% during 2037-2050 [7]; and population is assumed to grow on average at 0.19% during 2021-2030 and then decline on average at 0.31% annually during 2030-2050 [7].

Net zero emission scenario: The net zero emission (NZE-GHG) scenario is designed to achieve net zero emission of GHG by 2050. The net GHG emission pathways during 2025 to 2050 are estimated based on various effort-sharing approaches as discussed in the methodology section. NZE-GHG scenario assumes that GHG emissions from all sectors, including agriculture, waste, IPPU and LULUCF, would become near net zero by 2050. This scenario is hereafter referred to NZE-GHG. The NZE-GHG scenario allows the emissions from the energy sector to be offset by carbon removals from the LULUCF. In addition, NZE-GHG also incorporate the reduction in energy service demand due to behavior change, improvement in building envelope and material efficiency. These include a modal shift from car to public vehicles, car sharing, curbing excessive or wasteful energy use and material efficiency measures. These measures will lower energy service demand, thereby lowering the energy use and GHG emissions. IEA stated that net zero CO_2 emission cannot be achieved without people's participation and their willingness to change, as people drive the demand for energy-related goods and services [39].

This study assumes that in the residential and commercial sectors, the lighting and cooling service demands would be lower by 5% compared to the BAU in 2025 and lower by 25% in 2050. The similar approach was also used by Oshiro et al. [17]. The assumptions in this study are made based on existing literature that have estimated the final energy reduction potential from various measures. Reduction in energy consumption by 5 % to 10 % could be achieved by feedback and more informative billing [40]. Ananwattanaporn et al. evaluated the reduction in energy consumption by retrofitting existing buildings in compliance with Thailand's building energy code to achieve a net zero energy building and estimated that energy reduction up to 49.4% could be achieved [41]. Gulati studied the cost effectiveness of HVAC through step-by-step optimization of building orientation, window-to-wall ratio, roof, wall, glass, and shading devices [42]. The estimated heat load reduction through envelope was nearly 71%. In Thailand, the use of low thermal conductance material for the building envelope can save up to 28% of cooling demand [43].

In the transport sector, it is assumed that the demand would be lower by 2.5% from the BAU level in 2025 and by 15% in 2050. This assumption is based on reduction in transport demand due to avoiding unnecessary trips and a shift from motorized transport to non-motorized transport such as cycling and walking. Introducing behavior change in the transport sector by internalizing external costs, investment in transport infrastructure and life style changes, and telecommunication could also reduce the transport service demand [44]. A study concluded from a survey that the modal share of non-motorized transport in Bangkok would increase from the current level of 24% to 42% [45]. In the NZE-GHG, it is also assumed that the occupancy in cars on average would increase to 2.8 by 2050 from the current occupancy rate of 1.4. This would be brought about by the car-sharing concept. Car-sharing can replace four to eight cars [46], increase non-motorized transport such as bicycling and walking [47], reduce car kilometers traveled by 33-50% and increase the use of public transportation [48, 49].

Due to unavailability of reduction in end-use service demand data, this study makes assumptions in the reduction in service demands which can be considered one of the limitations. In the NZE-GHG, it is also assumed that the share of public transport would reach 60% by 2050 compared to 20% in the BAU scenario. The public transport includes regular route public buses, water transport, inter-city trains and intra-city mass rapid transport.

3. Energy and GHG emissions in the BAU scenario

This section presents the primary energy supply, final energy consumption and GHG emissions in the BAU scenario during 2015-2050.

3.1 Primary Energy Supply

Total primary energy supply (TPES) dropped from 5,673 PJ in 2015 to 5,374 PJ in 2020 (see Figure 2). The drop in 2020 was attributed to the COVID-19 pandemic. However, in the future the economy is expected to recover leading to an increasing energy supply. In the BAU, TPES would be increased by more than 40% between 2020 and 2030. In 2050, TPES would reach 12,591 PJ, an increase of 130% from the 2020 level. The increase in TPES in the BAU scenario is led mainly by natural gas and oil. Other energy sources, such as coal,

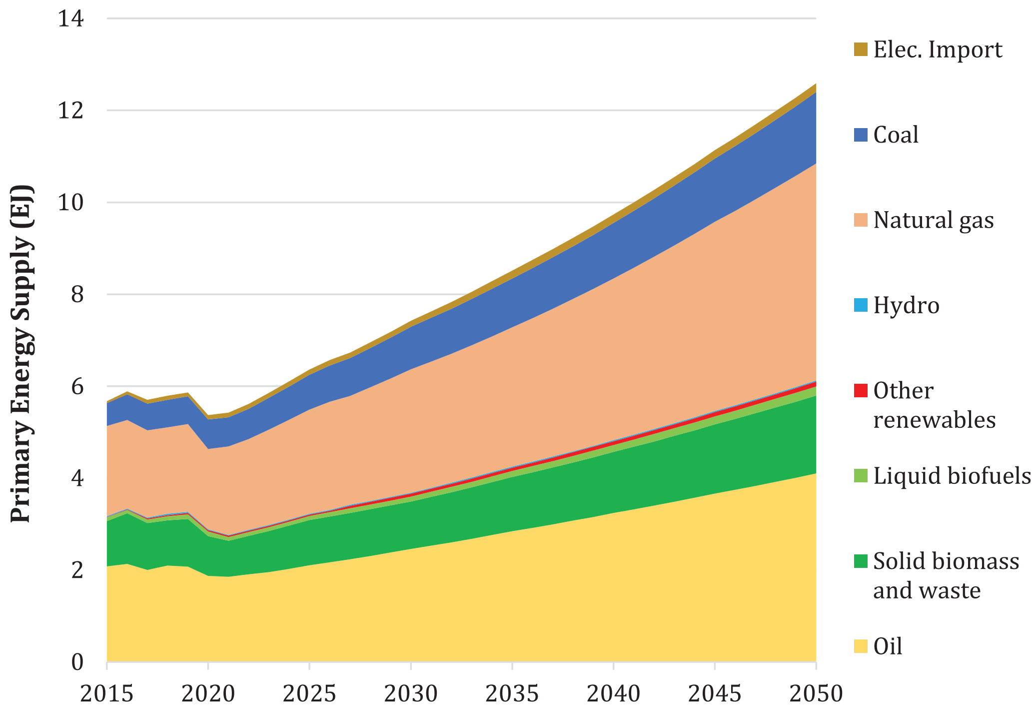

Figure 2: Primary energy supply in Thailand in the BAU scenario during 2015-2050

hydro, biomass, liquid biofuels, and other renewables (solar and wind), would also increase between 2020 and 2050. Oil and natural gas would account for more than a 70% share in TPES during 2020-2050. The share of coal in TPES would increase from 12.0% in 2020 to 12.3% in 2050. The imported electricity from neighboring countries would be increased by 80% between 2020 and 2050. The shares of solid biomass, biofuels, hydro, and other renewables in 2020 were 16.1%, 1.9%, 0.3% and 0.5%, respectively. The use of solid biomass, biofuels and other renewables would more than double between 2020 and 2050; however, their shares in TPES would not increase significantly due to the dominance of natural gas and oil. The share of biomass, biofuels and hydro would drop in 2050; the shares would be 13.4%, 1.6 and 0.2%, respectively. The share of other renewables would increase to 0.8% in 2050.

3.2 Final Energy Consumption

The final energy consumption (FEC) in the BAU scenario was 3,732 PJ in 2015 (see Figure 3). The FEC in 2020 was lower than the 2015 level, like the primary energy supply. The unprecedented pandemic led to a sudden drop in the FEC in 2020 to 3,619 PJ from 4,083 PJ in 2019. The FEC will continue growing in the BAU scenario between 2020 and 2050. In 2030, the FEC would increase by 30% from 2020 level, whereas in 2050 the FEC would be 120% higher than the 2020 level. The FEC in 2020 was dominated by oil followed by electricity, solid biomass, natural gas, coal, liquid biofuels, and other renewables. Petroleum products will account for more than a 45% share in the FEC in 2030, while electricity, solid biomass and coal will account for 19.4%, 9.6% and 9.2%, respectively. The share of biofuels in 2020 was 2.8%, while other renewables accounted for less than 1% in FEC. In 2050, oil would still be the dominant fuel in the final energy accounting with nearly a 40% share. The increase in oil consumption is led mainly by increases in both passenger and freight transport demand. The share of electricity and coal in 2050 would be 17.3%, whereas the share of solid biomass and coal would be attributed to 14.3% and 6.9%, respectively.

Figure 4 presents the sectoral shares in final energy consumption in the BAU scenario during 2015-2050. The transport sector and the industry sector are the two main consumers of final energy use, accounting for 34.2% and 33.4% shares in the final energy mix in 2020. The residential, commercial and agriculture sectors accounted for 11.4%, 7.7% and 2.7%, respectively, in the final energy mix. Non-energy uses also accounted for more than one-tenth of final energy use in 2020. The

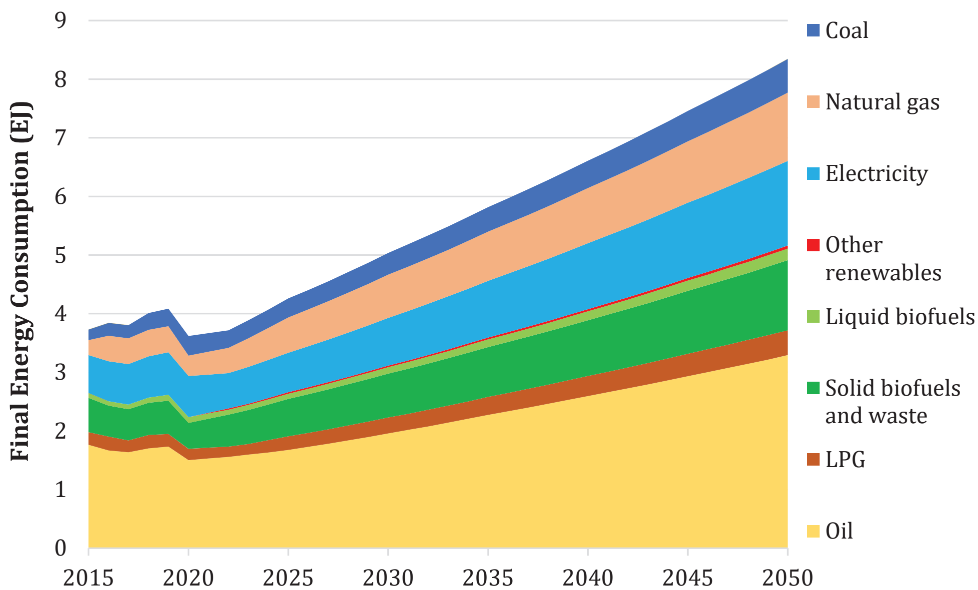

Figure 3: Final energy consumption in Thailand in the BAU scenario during 2015-2050

share of the transport sector in the final energy mix would increase between 2020 and 2050, reaching 44.5% in 2050. The share of the industry sector in 2050 would drop to 29.0% in 2050. In 2050, the share of the residential sector would account for 11.3%, whereas shares of the commercial and the agriculture sector would account for 8.6% and 1.5%, respectively, in the final energy mix. The share of non-energy uses would drop to 5.2% in 2050.

3.3 GHG emissions

The GHG emissions during 2015-2050 are shown in Figure 5. The GHG emissions in 2020 are estimated to be 255.5 $MtCO_2e$ in 2020. The emissions would increase by 149% between 2020 and 2050, reaching 635.0 $MtCO_2e$ in 2050. The increase is driven mainly by energy industries and the transport sector. The emissions from energy industries mainly come from the power sector, while petroleum refineries and natural gas processing plants account for less than one-tenth of emissions in energy industries. In 2050, power sector would emit 248.3 $MtCO_2e$. The industry sector accounted for only a 19.4% share in 2020. Emissions in the agriculture, the commercial and the residential sector would increase by 27%, 51% and 82%, respectively, during 2020-2050. In 2020, GHG emissions in the power sector and the transport sector accounted for 43.3% and 31.3%, respectively, in total GHG emissions, followed by agriculture (2.5%), residential (2.2%) and commercial (0.9%) sectors. In 2050, the share of energy industries in GHG emissions would reach 42.6%, while that of the transport sector would decrease to 36.6%. The industry, residential, agriculture and commercial sectors would contribute 17.3%, 1.6%, 1.4% and 0.6%, respectively, in total GHG emissions in 2050.

Figure 6 presents the decomposition of GHG emissions from the power sector i.e., the emissions are decomposed by electricity consumption corresponding to the end-use sectors and transmission and distribution (T&D) losses. In 2050, industrial and commercial sectors are attributed to the highest emissions in the power sector, both sectors accounting for 85.5 $MtCO_2e$ which is 34.4% of the total emissions. The residential sector would account for 23.3% of the emissions whereas T&D losses would account for 7.7%. The agriculture and transport sectors would contribute to about 0.1% in the GHG emissions from the power sector.

4. Emission Allowance

The GHG emissions allowances during 2018-2050 by different effort-sharing approaches are presented in Figure 7. The GHG emissions allowances are time dependent, and depend on all sectors including emissions and sequestrations from land use, land use change and forestry (LULUCF). It is found that the lowest GHG emission allowances occur in the IEPC approach. The emission allowances would decrease from 2018 until

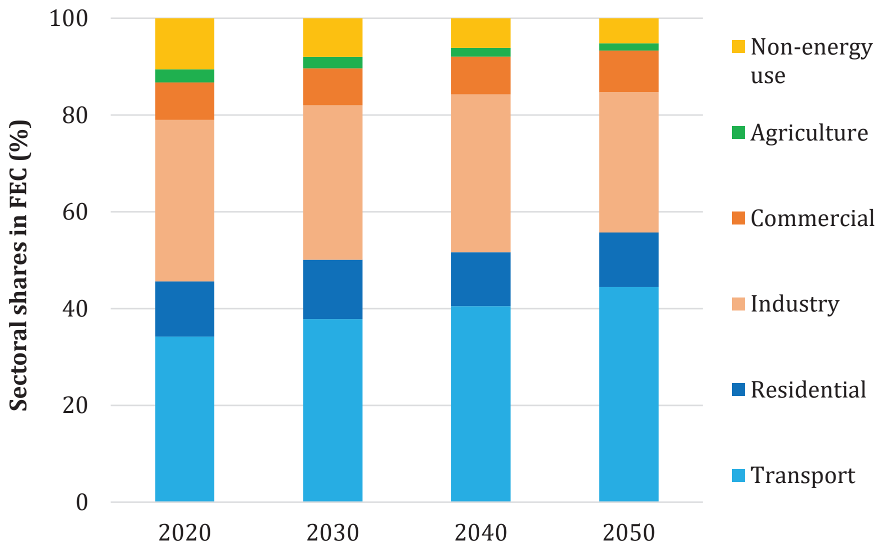

Figure 4: Shares of sectoral final energy consumption in Thailand in the BAU scenario

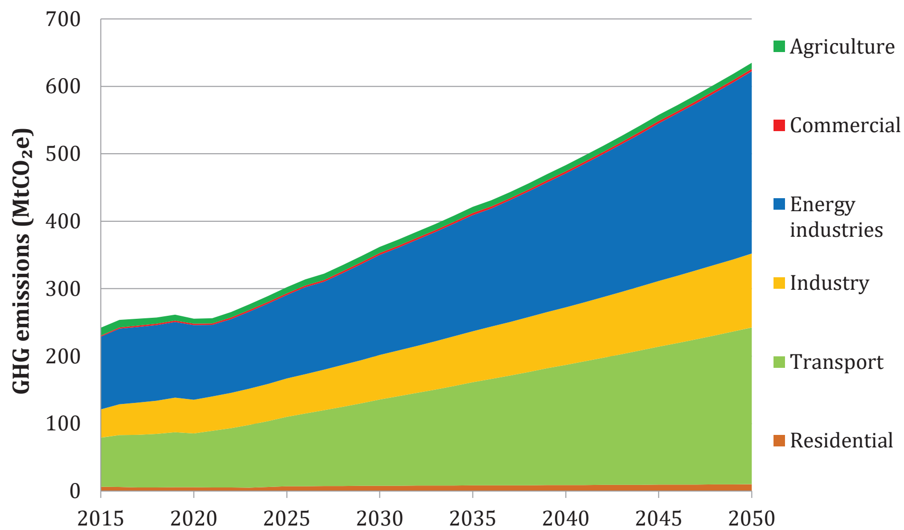

Figure 5: GHG emissions in Thailand in the BAU scenario during 2020-2050

2050. However, in the GF and PCC approaches, the emission would peak in 2020 and would drop continuously until 2050. In the three approaches (i.e., GF, PCC and IEPC), nearly net zero emissions (NZE) will be reached in 2050. It should be noted that Thailand aims to achieve carbon neutrality by 2065 [7]. However, in the COP26, Thailand announced carbon neutrality by 2050 and net zero emission by 2065. According to the effort sharing approaches considered in this study, Thailand will have net GHG emission allowance of less than 1 $MtCO_2e$ by 2050. Therefore, in this study it is assumed that net GHG emission reaches zero by 2050. In the NZE analysis in the subsequent section, the emission allowances in GF are adopted starting from 2025 onwards.

5. Emission pathways in the NZE-GHG

The pathway of GHG emission allowance in the energy sector in NZE-GHG scenario is presented in Figure 8. This pathway represents the GHG emission pathway that is input to the AIM/Enduse model as the emission constraint. GHG emissions would peak in 2020, drop sharply from 2020-2030, and reach net zero emissions in

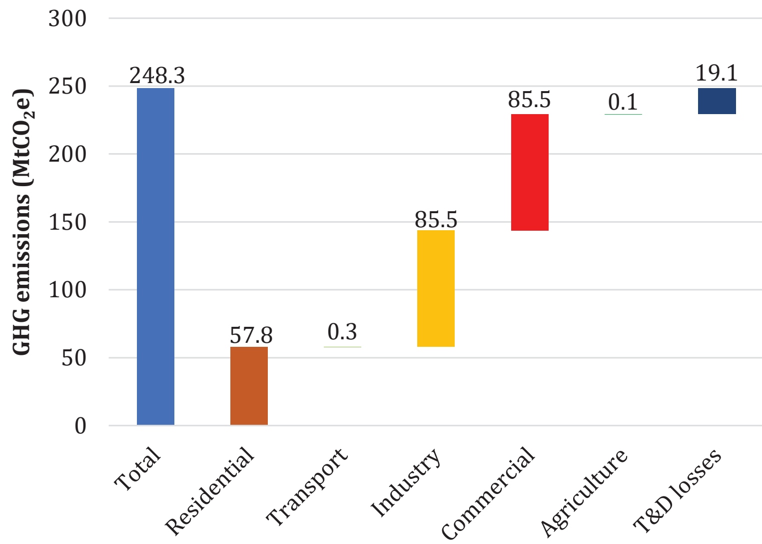

Figure 6: Decomposition of GHG emissions from power sector in Thailand in 2050 in the BAU scenario

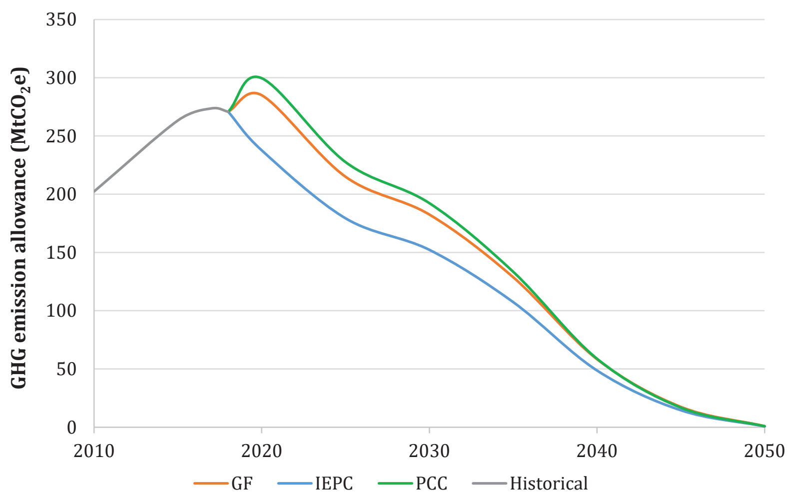

Figure 7: GHG emissions allowances in Thailand in different effort-sharing approaches

2050. In 2020, the GHG emission in the BAU scenario is lower than the emission allowance limit. In NZE-GHG, it is assumed that there would be net zero emission of GHG emissions in the energy, the AFOLU, the IPPU and the waste sectors combined. The removals in the AFOLU sector are estimated to be 90 $MtCO_2e$ in 2050 [50]. The emissions in the IPPU and the waste sector during 2020-2050 are capped to be 19 $MtCO_{2e}$ and 12 $MtCO_{2e}$, respectively, which are based on their historical emissions during 2000-2013 as given in Thailand's third national communication report [34]. There would be net sequestration in the AFOLU sector; therefore, the emissions in the energy sector could be offset partially or completely for the LULUCF. The emissions in the NZE-GHG scenario include the emissions from the AFOLU, the IPPU and the waste sectors, as well as the sequestrations from the forestry sector. The deviation from the emissions pathway derived by the PCC approach is the emission allowance in the energy sector as shown in Figure 8.

6. Energy and GHG emissions in the NZE-GHG scenario

This section presents the GHG emissions by sector, primary energy supply, final energy consumption and

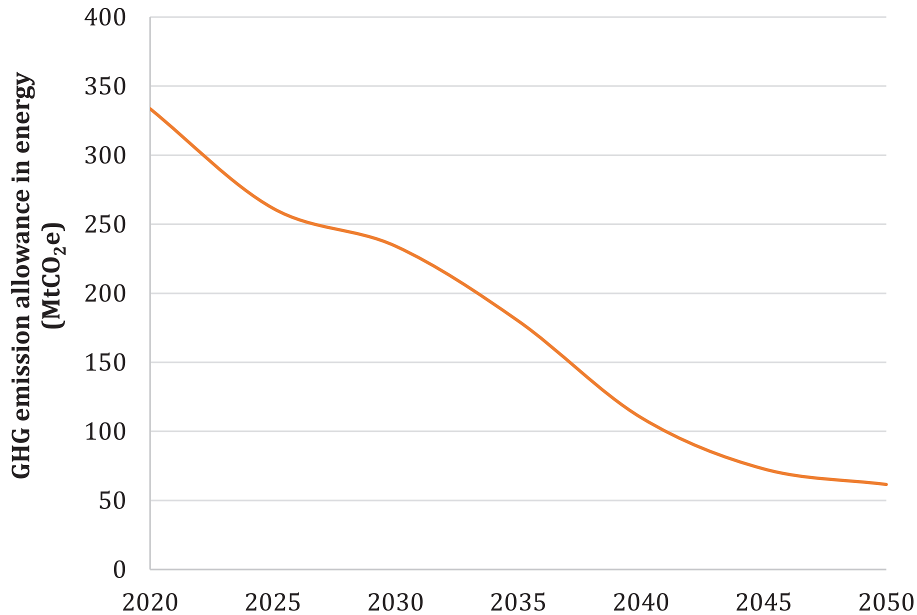

Figure 8: Emission allowances in Thailand in the energy sector in NZE-GHG scenario

power generation by fuel type during 2020-2050 in the NZE-GHG scenario. The GHG emissions reduction by sector in NZE-GHG compared to the BAU scenario has also been presented.

6.1 GHG Emissions

GHG emissions by sector during 2020-2050 in the NZE-GHG scenario are shown in Figure 9. Following the GHG emission allowance limit, the emission would peak in 2024 reaching 265.9 $MtCO_2e$ and then decline to 234.2 $MtCO_2e$ in 2030. The GHG emission from energy sector would drop to 61.6 $MtCO_2e$ by 2050 to achieve net zero emission. The transport sector would account for the highest emissions in 2030 having a share of 38.9%, followed by energy industries (36.6%), industry (20.3%), residential (2.5%), agriculture (1.8%) and commercial (less than 1%) sectors. The emissions reduction achieved is mainly due to energy efficiency improvement and partially due to the improvement in building envelope, reduction in energy service demand due to behavior change, switch from private transport to public transport mode and fuel switching. In 2050, energy service demand reduction and modal shift in the transport sector would reduce about 153 $MtCO_2e$, which represents 27.2% of the total GHG reduction in the NZE-GHG scenario. The post-2030 GHG emissions reduction is mainly due to the fuel switching and the decarbonized power sector. In 2040, the transport sector will account for the highest contribution in GHG emissions, while by 2050 the energy industries, mainly the power sector, would account for more than half of the GHG emissions. In 2050, the share of GHG emissions in the transport sector would be 13.7%, whereas the industrial sector will emit GHG more than the transport sector contributing by nearly 23%. In 2050, the share of GHG emissions from the residential, commercial and agriculture sectors in total emissions would be less than 5%. The emission reductions in all sectors in the NZE-GHG scenario are presented in Figure 10.

6.2 Primary Energy Supply

The primary energy supply (PES) in the NZE-GHG scenarios is shown in Figure 11. The PES would decline from 2025 until 2037 despite the increase in the end-use service demands. The decrease in the PES is mainly due to energy efficiency improvement. Other factors that would contribute to the decrease in PES are reduction in energy service demands from behavior changes and improvement of building envelope, modal shifts in the transport sector, electrification in end-use services and increase in the share of renewable energy in the power sector. The primary energy supply decreases due to a higher share of renewables. The overall efficiency increases because the conversion loss of renewable electricity is not accounted for, and renewable electricity assumes that input energy equals output energy. The PES would increase after 2037 and would reach 5,890 PJ by 2050. The consumption of

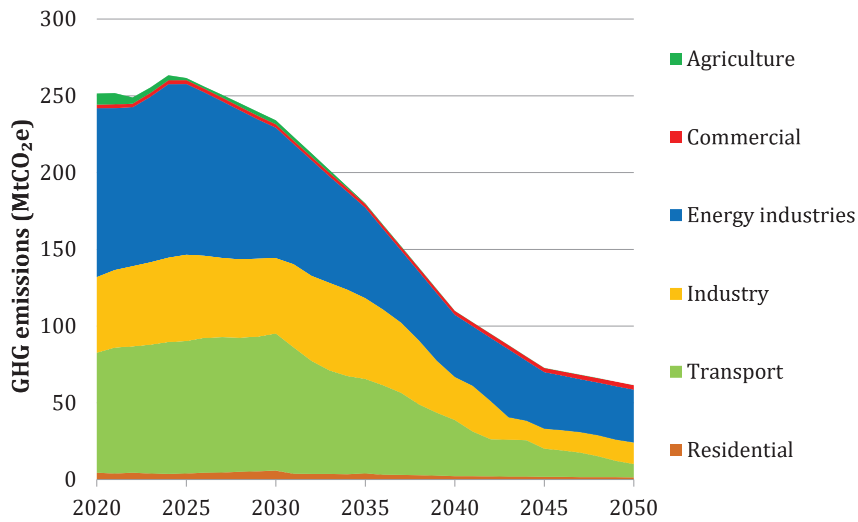

Figure 9: GHG emissions in the energy sector in the NZE-GHG scenario during 2020-2050

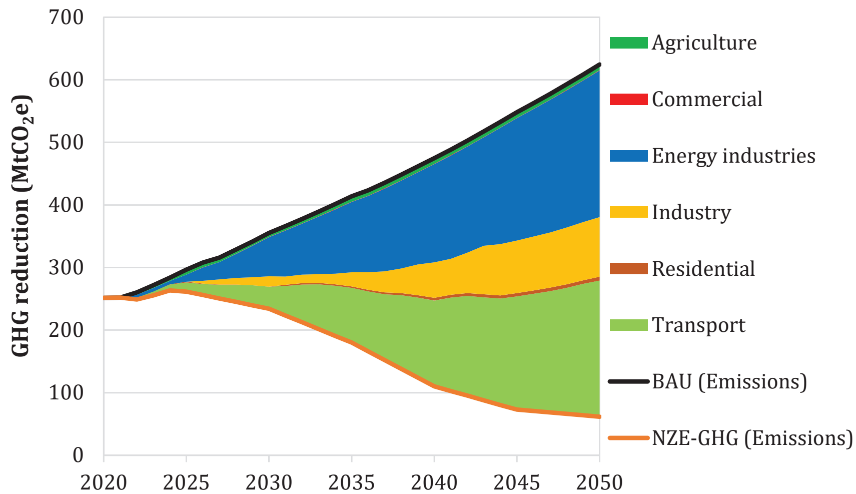

Figure 10: Sectoral GHG emissions reduction in Thailand in the NZE-GHG scenario

coal, natural gas and oil would decrease, whereas the renewable electricity generation would increase dramatically. Solar and biomass (solid biomass and waste) would have significant shares in PES by 2050. Both solar and wind would account for more than 45% of PES by 2050. In the power sector, it is assumed that 10% of the solar PV in power generation is also equipped with battery storage. Equipping intermittent renewable resources with battery storage would result in higher reliability and stability when integrated into the grid. In addition, the solar PV system is also used to produce green hydrogen for use in the industry, transport, and power sectors. The share of biomass in PES would be 27.4% in 2050, whereas biofuels would account for only 3.6% in PES. Among the fossil fuels, the share of natural gas and oil would be nearly 20% and 10%, respectively, in the primary energy supply in 2050, whereas the share of coal would be lower than 1%. The imported electricity would account for 3.3% of the total primary energy supply.

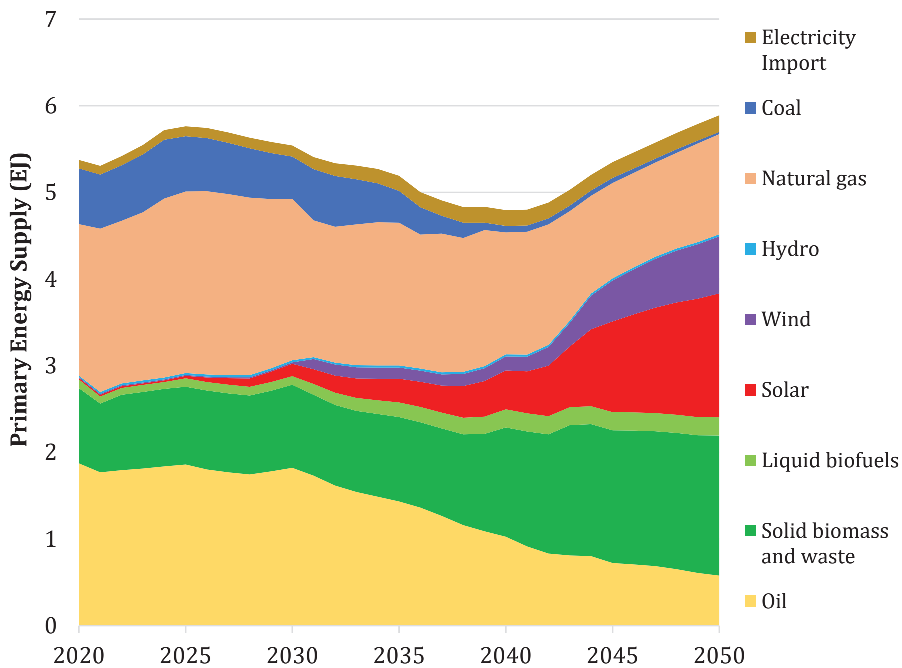

Figure 11: Primary energy supply in Thailand in the NZE-GHG scenario

6.3 Final Energy Consumption

The final energy consumption would increase by 1.5% during 2020-2030 (see Figure 12). After 2030 there would be significant drop in final energy consumption. Then, the FEC will increase after 2040. The decrease in FEC after 2031 in the transport sector is mainly due to a modal shift from private to public transport, reduction in transport demand due to behavior change and car-sharing. In addition, energy efficiency improvement and electrification also will contribute in final energy reduction. Electrification of end-use technologies in the industry and the transport sectors would increase the overall efficiency, which is also attributable to the decrease in final energy consumption. The industrial heat pump technologies would need to be deployed for low- to medium-heat applications in industry. Green hydrogen produced using renewable energy would have a crucial role in FEC to replace coal and other fossil fuels in the industrial sector and the transport sector after 2040. Fuel-cell based technologies would be essential in the transport sector. The fuel mix would notice significant changes during 2020-2050. The share of oil in final energy consumption would drop to 10.8% in 2050 from 41.5% in 2020. By 2050, the shares of coal, LPG and natural gas would be 0.6%, 1.3% and 9.3%, respectively.

The shares of non-fossil energies in final energy mix would increase in the NZE-GHG scenario. In 2050, the shares of electricity and solid fuels (including waste) would be 32.4% and 28.5%, respectively. The share of liquid biofuels would reach nearly 5%. In 2050, the share of hydrogen produced from renewable energy would be 11.3% in final energy consumption.

6.4 Power Generation

Electricity generation mix in the NZE-GHG scenario during 2020-2050 is shown in Figure 13. Electricity generation would increase from 220 TWh in 2020 to 233.2 TWh in 2030, an increase of 6%. In 2040 and 2050, due to high electrification in end-use technologies, the electricity generation requirement would increase by 31% in 2030 from the 2020 level. In 2050, the electricity generation would be 88% higher than the 2020 level. Power generation in 2020 was dominated by natural gas, followed by coal and imported electricity. Thailand has long-term power purchase agreements with neighboring countries; therefore, imported electricity would contribute significantly to power generation. In 2020, electricity generation from natural gas accounted for more than 60% of generation mix, while coal and imported electricity accounted for 16.7% and 12.7%,

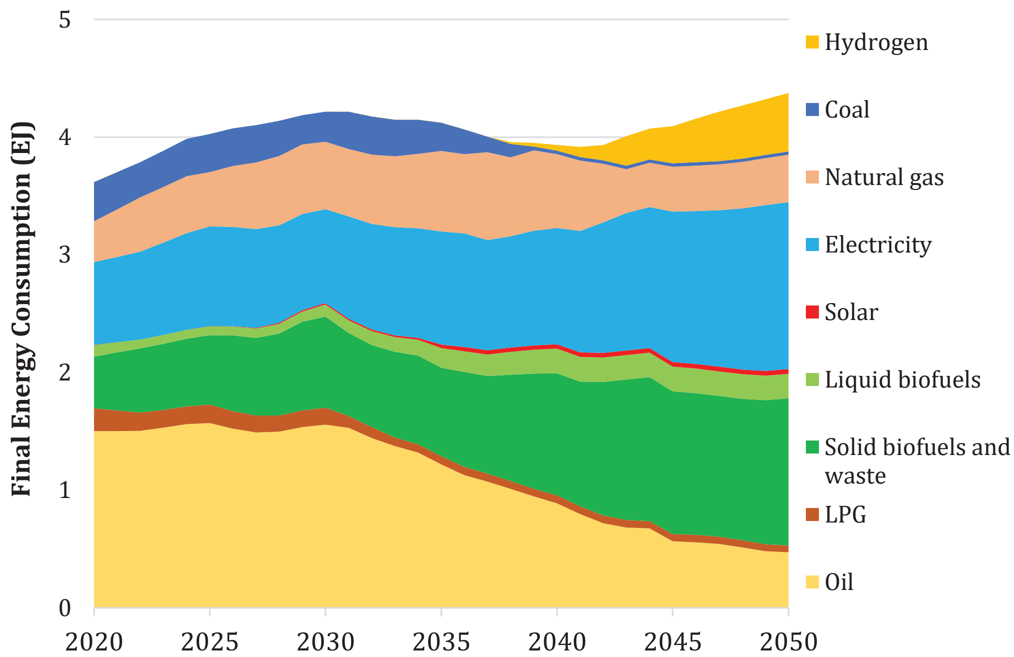

Figure 12: Final energy consumption in Thailand in the NZE-GHG scenario

respectively. Biomass and hydro power accounted for about 5.6% and 2.6%, respectively, in the generation mix in 2020. The generation mix would change dramatically by 2050. Solar would contribute 40% in the power generation mix, while wind and biomass would account for 8.6% and 9.2%, respectively. The installed capacity of solar PV would be 64 GW, while that of wind would be 40 GW. The share of natural gas would drop to 16.4% in 2050. Hydrogen based power generation would account for 10% in the generation mix in the NZE-GHG scenario. The imported electricity would account for 13% in the generation mix in 2050. Shares of coal and oil would be negligible by 2050. The share of solar in power generation is limited to 40% in the energy system model. The solar PV can generate only in the presence of sunlight; consequently, relying on solar PV might be doubtful. Therefore, solar PV equipped with large battery storage is also considered in the model. Stored hydrogen generated from clean renewables by an electrolysis process can also be utilized to balance both seasonal variations in electricity demand and the imbalances occurring between the demand for hydrogen and its supply by off-grid renewable energies. If clean renewables like solar and wind cannot be deployed to the desirable extent, alternative options like bioenergy based powerplants and CCS technologies would need to be employed.

7. Opportunities and Challenges

This study finds that the development of hydrogen using renewable energy can be one of the viable solutions to the deep decarbonized transport and industrial sectors. Hydrogen-based technologies can now replace coal in the steel industry and offers a greener pathway towards steel production. Stored hydrogen generated from clean renewables by an electrolysis process can also be utilized to balance seasonal variations in electricity demand in the power sector. Hydrogen can also be stored to avoid the imbalances occurring between the demand for hydrogen and its supply by off-grid renewable energies. However, there are several challenges that need to be addressed by the policy makers to promote hydrogen. Firstly, new investments are needed to promote renewable energy along with hydrogen production, storage, and transportation infrastructure. Secondly, the technologies in energy intensive industries like cement, iron and steel are long-lived assets with a minimum lifespan of 20 years. These infrastructures, once built, are hard to replace without policy interventions and incentives.

The transition from carbon-intensive electricity generation to low- or zero-emission electricity presents several challenges for the power sector. Recently, the costs of solar PV technology and batteries have rapidly

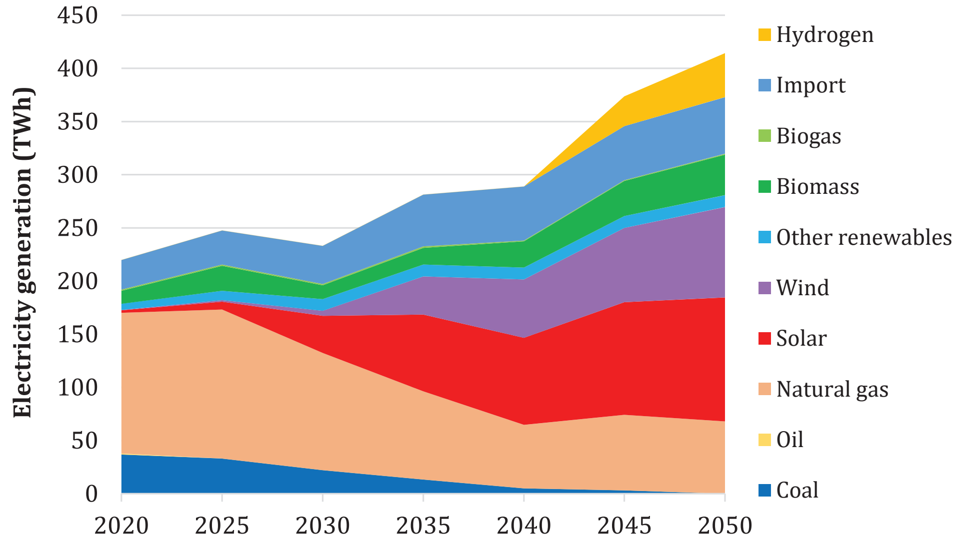

Figure 13: Electricity generation by fuel types in Thailand in the NZE-GHG scenario

decreased. Although the cost of renewables and hydrogen-production is expected to decline further, the switch to renewables would require substantial investment in the power sector. Do et al. used Vietnam's success story in rapid development of wind and solar power to provide policy insights to other member countries of the Association of Southeast Asian Nations (ASEAN) and concluded that strong government commitment and public support are necessary for rapid take-up of renewable energy deployment [51]. The thermal-based power plants are usually long-lived assets with a minimum lifespan of 30 years. Retiring the already built infrastructures in the power sector before their lifespan is over would be one of the challenges and is not possible without policy interventions and financial incentives to the power producers. Incentives such as feed-in-tariff rates and a favorable investment environment would be the key drivers for renewable power development.

The transmission grids must be upgraded and managed beforehand to make them compatible with the intermittency of the renewables like solar and wind. The uncertainty in government policies is one of the main barriers for renewable power development [51]. There are also controversies with the nuclear power development plans in Thailand. Nuclear energy offers higher stability in the power supply system compared to wind- and solar-based generation. Achieving the net zero emission target without nuclear would require higher deployment of other renewable technologies such as biomass-based generation. There are also issues with biomass-based generation. In the net zero emissions scenarios, there is a substantial increase in the use of biomass fuel. Higher dependency on biomass fuels would require more land designated for short-rotation forestry to meet the required biomass supply.

There are issues related to high use of variable renewable energy sources such as solar and wind in the power generation. The uncertainty of variable renewable energy (VRE) sources can be efficiently facilitated by using flexible energy resources such as flexible generation units, energy storage units, interconnectors and demand-side management [52, 53]. The hydrogen-based electricity generation, produced from clean energy, is also considered in the net zero scenario to maintain the reliability of the power system. This paper analyzed the pathway to achieve net zero emissions in an annual basis over a long-time horizon. However, it is important that analyses in daily and hourly basis would be required to have a deeper understanding during the transition to high renewable energy system. Lund et al. presented state-of-the-art cross-sectoral smart energy system concept which would have crucial role in decarbonizing the energy systems [54]. Smart energy systems offer efficient and affordable solutions by identifying the synergies between multiple sectors [54, 55].

8. Final Remarks

This study assessed levels of energy use and GHG emissions in Thailand over the period 2015-2050. The increase in GHG emissions is driven mainly by the power sector, the transport sector, and the industrial sector. This study also assessed the emission allowance pathways using various effort-sharing approaches. Based on the emission allowance pathways, the study assessed the energy implications and the changes in sectoral emissions in the NZE-GHG scenario. In the NZE-GHG scenario, it is assumed that the emission from the energy sector is offset by sequestration from the LULUCF. The study finds that the reduction of energy service demand would complement in achieving the net zero emission target of Thailand. The use of green hydrogen and hydrogen-based technologies can contribute to achieving net zero emission without relying on CCS technologies. Unlike existing literature of Thailand that focuses mainly on CCS technologies in the power sector [18, 19], this study presents an alternative approach to achieve the net zero emissions focusing on energy service demand reduction and the use of hydrogen fuels. As the pathway to achieve net zero emissions is already narrow, it is crucial that deployment of renewable and low-carbon technologies be made immediately at massive scales. In the net zero scenarios, hydrogen fuel and electrification of end-use services using low-carbon electricity would be the game changer as they can substitute fossil fuels in the transport, the industry, and the power sectors.

The power sector, which is currently accountable for the highest share in GHG emissions in Thailand, will require radical changes in the generation mix in NZE-GHG scenario. The transformation of the power generation from emission-intensive fuels to renewable energies is crucial to achieve the net zero emission target. The renewable energy mainly contributes to the decarbonized power sector. Electricity generation from renewables such as solar, biomass and wind would start to emerge in the power sector by around 2025. In the NZE-GHG scenario, net zero emission is also possible for Thailand without nuclear and CCS based generation. As the power sector is driven by end-use sectors, the energy service demand reduction in end-use sectors would lower the GHG emissions in the power sector. Due to reliability and security issues of solar and wind, the study has limited the share of solar energy in power generation to 40%. Green hydrogen-based electricity generation would also have key role in providing reliable and uninterrupted power supply.

Additional measures such as energy efficiency, behavior changes, a modal shift in the transport, and building envelope improvement would also have crucial roles in achieving the net zero emission targets. The behavior changes can play a vital role in reducing the energy demands and cutting CO_2 emissions [39]. This study assumed the reduction in energy service demand from behavior changes and building envelope improvement based on existing literature which is one of the limitations of the study. The role of behavioral change in reduction of energy consumption and GHG emissions are still in the preliminary stages and needs more robust analysis in the future. Moreover, energy service demand reduction in the residential and commercial buildings are dependent on building designs. Architects and building engineers also have crucial role in making the buildings more energy efficient and adopting efficient end-use technologies [56]. Therefore, the net zero emission target needs to be achieved by integration of different fields and professionals. The study also assumed shifting from private vehicles to public modes of transport and non-motorized transport such as walking and cycling. Finally, this study finds that deployment of renewables, and the use of advanced batteries and green hydrogen in end-use technologies and power generation could reduce or avoid the dependency on carbon capture, utilization and storage (CCUS) technology including BECCS.

In conclusion, achieving net zero emissions target would be possible only with combined measures of energy efficiency, behavior change, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy and CCUS. Thailand's government should strengthen the necessary policies to promote and deploy clean energy technologies and disincentivize fossil fuels and fossil fuel-based technologies. Phasing out fossil-fuel subsidies, carbon pricing, subsiding renewable energy and other market reforms would be needed to discourage the use of fossil fuels and shift towards cleaner energy and technologies.

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