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Decarbonizing Building and Transport Sectors in Thailand towards Net Zero Emissions 2050

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Abstract

The building and transport sectors in Thailand are two major GHG emissions contributors in terms of direct and indirect emissions through energy use. Accelerating the transition to low-emissions technology is necessary to mitigate the rise in global temperatures. This study explores three scenarios, the Reference (REF), the Existing Policy (EXP), and the Deep Decarbonized (DDC) scenarios, using the LEAP-NEMO analysis tool. The REF scenario is formulated under a business-as-usual assumption without considering any policy or mitigation implementation. The EXP scenario is developed by the adoption of the latest government energy and climate change mitigation policies. The DDC scenario is constructed by increasing the ambition of the climate policies regarding energy efficiency improvement in the building sector, increasing battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (HFEVs) in the transport sector, and fully integrating renewable energy in electric power generation through the optimization method in LEAP-NEMO. The outcomes illustrate that, in the EXP scenario, total energy consumption in 2050 for both the building and transport sectors would be reduced by 26.04% compared to the REF scenario, and GHG emissions would be reduced by 31.16%. Under the DDC scenario, energy saving and GHG emissions mitigation in 2050 would be around 41.46% and 86.85%, respectively, compared to the REF scenario. The DDC scenario shows that the net zero emissions target in 2050 is feasible for Thailand. However, to avoid carbon lock-in, policy measures on decarbonized building and transport sectors are critical in this decade to achieve net zero emissions in 2050.

Keywords

Decarbonized building and transport sectors; Energy efficiency; Electric vehicles; Hydrogen; Net zero emissions

1. Introduction

1.1 Background

Global climate change has been considered a major challenge due to its serious effects on every living thing on our planet. The global average temperature is expected to increase by up to 2 degrees Celsius above the pre-industrial level in the next decades due to the extremely high emissions of anthropogenic greenhouse gases (GHG) (Intergovernmental Panel on Climate Change, 2023). In 2019, total global GHG emissions increased to 59 gigatonnes of carbon dioxide equivalent (GtCO2eq) with the energy sector responsible for three-quarters of the total. Of those total energy-related emissions, the building and transport sectors accounted for 21% and 23%, respectively (Cabeza et al., 2022; Jaramillo et al., 2022).

Thailand, a country highly vulnerable to climate change, has put significant efforts into the mitigation of medium- and long-term GHG emissions. The Thai government has formulated and updated its nationally determined contributions (NDCs) to cut the country's emissions by about 30% using domestic resource utilization and 40% with support from the international community (Ministry of Natural Resources and Environment, 2022a). Additionally, Thailand has communicated a long-term strategy to the UNFCCC for carbon neutrality by 2050 and GHG neutrality by 2065, respectively (Office of Natural Resources and Environmental Policy, 2022).

In 2018, the total final energy consumption (TFEC) in Thailand was 83.95 million tonnes of oil equivalent (Mtoe), where the building sector and the transport sector accounted for 20.90% and 31.86%, respectively (Department of Alternative Energy Development and Efficiency, 2021). Electricity, liquefied petroleum gas (LPG), and traditional biomass (wood and charcoal) are the main sources of energy in the building sector, whereas petroleum products dominate the transport sector's energy utilization.

GHG emissions in the building and transport sectors come from both direct and indirect emissions. Direct emissions refer to onsite combustion for heating such as cooking in buildings through the application of fossil fuels and biomass, while indirect emissions are associated with electricity consumption generated by solid, liquid, and gas fuels. In 2018, Thailand's GHG emissions in the building sector reached 65 million tonnes of carbon dioxide equivalent ($MtCO_2eq$), consisting of 15% direct emissions and 85% indirect emissions from electricity consumption (Ministry of Natural Resources and Environment, 2022b). In the transport sector, overall emissions in 2018 reached 98.64 $MtCO_2eq$ with total emissions primarily coming from the direct emissions of internal combustion engine (ICE) vehicles.

1.2 Objective, Scope, and Limitation of the Study

The main objective of this study is to determine the potential energy-saving and GHG mitigation in the building and transport sectors through the implementation of low-carbon technologies, as well as analyze the future cost of electricity production in Thailand. Our analysis incurred certain assumptions, as follows:

- Emissions from construction of buildings and transport infrastructure were excluded.
- GHG emissions were estimated according to the IPCC 2006 guideline.
- Emissions from power generation were converted to the emission intensity of electricity production.
- The Low Emissions Analysis Platform (LEAP) with the Next Energy Modeling System for Optimization (NEMO) was employed as a tool for analysis between 2018 and 2050.

2. Review of Existing Related Research Studies

Numerous research articles have investigated energy conservation and GHG emissions mitigation in Thailand's building sector. Promjiraprawat et al. (2014) indicated that by 2050, the adoption of efficient lighting technology, efficient cooling appliances, efficient heating devices, other efficient equipment, and the building energy code could minimize the total energy consumption in Thailand's building sector (including residential and commercial buildings) by up to 42.7% while reducing CO_2 emissions by 35%. Kusumadewi and

Limmeechokchai (2015) conducted a comparative study between Indonesia and Thailand, focusing on CO_2 mitigation and energy savings in the household sector. Their findings indicated that when compared to the business-as-usual (BAU) scenario, the residential sector in Indonesia and Thailand would achieve energy savings of 27.6% and 15.5%, respectively, in 2050, through replacement by energy-efficient technologies. Furthermore, Chaichaloempreecha et al. (2017) found that the successful implementation of Thailand's 2015 Energy Efficiency Plan (EEP2015) in the building sector would lessen the total energy consumption and GHG emissions in 2036 by 19.1% and 31.2%, respectively, compared to the BAU scenario.

A few studies have recommended different GHG mitigation measures to reduce emissions in Thailand's transport sector. Chunark et al. (2015) explored the combination of fuel switching, modal shift, and advanced vehicle technology implementation between 2005 and 2050 to investigate emissions reduction in land transportation in Thailand. They showed that energy demand in passenger transport would decrease by 33.63% and CO_2 emissions would decline by 38.21% in 2050, compared to the baseline in 2005, while for freight transport, total energy consumption and GHG emissions would decrease by 47.96% and 13.2%, respectively. Pita et al. (2017) conducted research on reducing carbon emissions in Thailand's transport sector in the NDC context. Under the NDC scenario, the application of the Energy Efficiency Plan 2015 (EEP2015) and the Alternative Energy Development Plan 2015 (AEDP2015) in the transport sector would mitigate approximately 41 $MtCO_2eq$ of GHG in 2030, compared to the BAU scenario. According to Limmeechokchai et al. (2022), Thailand's transport sector would be able to achieve the global climate goal of holding average temperature growth at 1.5°C, based on the use of electric vehicles (EVs) and biofuel in proportions of 75:25.

The above studies examined the different pathways to reducing GHG emissions in Thailand's building and transport sectors through the adoption of various strategies. Those studies mainly focused on the reduction of direct emissions from onsite combustion for heating such as cooking in buildings; however, none of the studies considered the indirect emissions from electricity generation to support electricity consumption in particular sectors. In addition, the above research papers did not address the optimal electricity generation cost with a full utilization of the country's maximum renewable energy resources, as well as the full implementation of low-emissions technologies and other advanced technologies such as hydrogen fuel and carbon capture utilization and storage (CCUS) in the building, transport, and power sectors. This article fills these gaps from previous research, illustrates a solution to decarbonize the building and transport sectors, and provides insightful results for policymakers to consider regarding emissions reduction. There are three different scenarios constructed in this study, namely Reference (REF), Existing Policy (EXP), and Deep Decarbonized (DDC) scenarios. The REF scenario considers the current situation of energy generation and utilization in Thailand, mainly in the building, transport, and power sectors. The EXP scenario is developed by following the existing government policies regarding energy efficiency improvement and alternative fuel utilization. The DDC scenario is formulated with the application of advanced low-carbon technologies to replace conventional ones. This study establishes all three scenarios to compare the results, explore possible changes in the structure of energy consumption in the building and transport sectors, and estimate the mitigation of GHG emissions towards 2050.

3. Energy and GHG Emissions Situation in the Building and Transport Sectors

3.1 Energy Consumption in the Building and Transport Sectors

The building sector is divided into residential and commercial sub-sectors. In this paper, the industrial and traditional commercial buildings such as retail and wholesale buildings are not included. The total energy consumption in Thailand's residential sub-sector increased by 2.28% per year from 2000 to 2018 (see Figure 1). The Department of Alternative Energy Development and Efficiency (2021) reports that total final energy consumption (TFEC) in 2018 was 11,001 thousand tonnes of oil equivalent (ktoe), with biomass (wood and charcoal) accounting for 47.37% of the TFEC, followed by electricity (35.15%) and LPG (17.48%).

Figure 2 illustrates energy demand in the commercial sector, which grew from 3,113 ktoe in 2000 to 6,549 ktoe in 2018. Electricity had the highest share in the TFEC, accounting for almost 90% in this period, followed by LPG, while other fuel use was low.

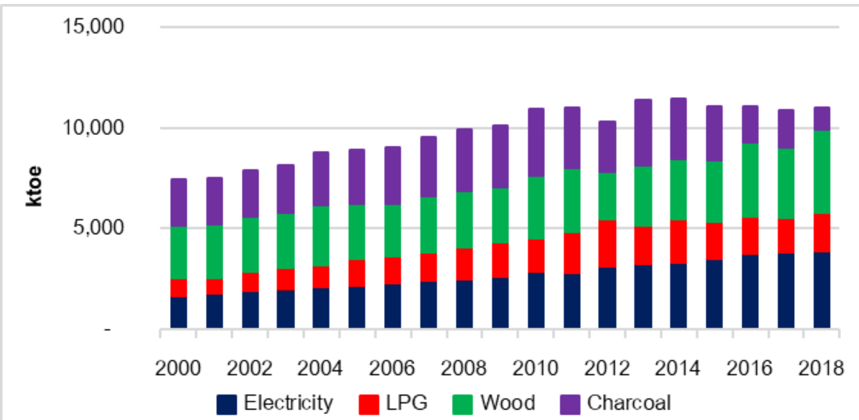

Figure 1. Final energy consumption in the residential sub-sector, 2000–2018.

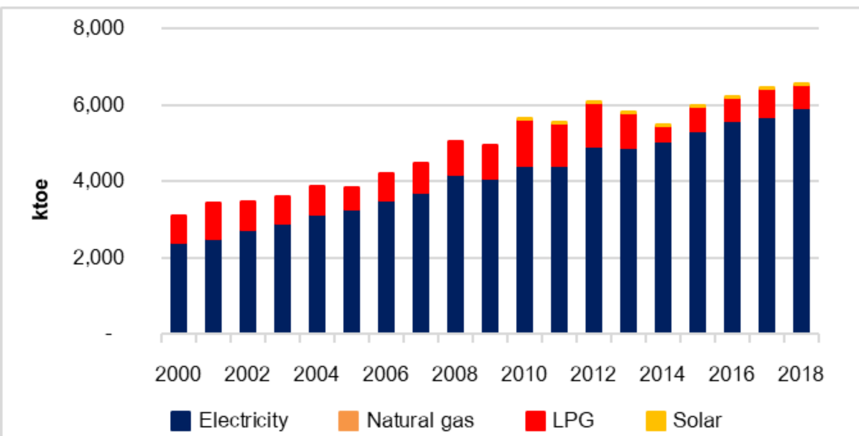

Figure 2. Final energy consumption in the commercial sub-sector, 2000–2018.

The transport sector had the largest energy consumption compared to other sectors. In 2018, the TFEC in this sector was 33,087 ktoe, an 83.59% increase compared to the 2000 TFEC (Department of Alternative Energy Development and Efficiency, 2021). The trends of fuel consumption are shown in Figure 3. Diesel and gasoline represent the largest fuel demand, followed by jet fuel and other fossil fuels, while electricity consumption in the transport sector was negligible.

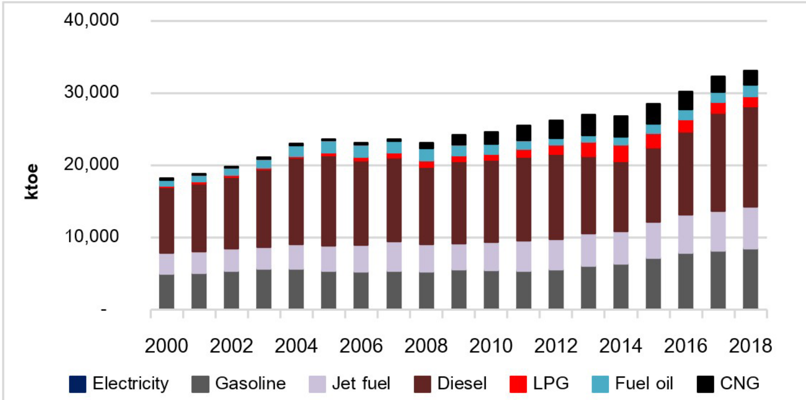

Figure 3. Final energy consumption in the transport sector, 2000–2018.

3.2 GHG Emissions in the Building and Transport Sectors

The latest Biennial Updated Report of Thailand (BUR4) submitted to the UNFCCC provides information regarding the total GHG emissions in Thailand (Ministry of Natural Resources and Environment, 2022b). The total emissions in the building and transport sectors together increased from 87.88 $MtCO_2eq$ in 2000 to approximately 163.66 $MtCO_2eq$ in 2018. In 2018, the transport sector accounted for 98.64 MtCO2eq of total emissions, followed by the commercial sub-sector (35.28 $MtCO_2eq$) and the residential sub-sector (29.71 $MtCO_2eq$). The combined amount of GHG emissions from the three sectors is shown in Figure 4.

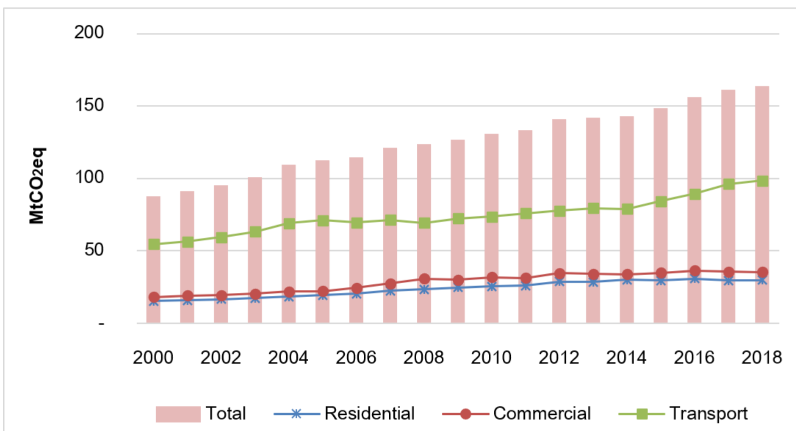

Figure 4. GHG emissions trend in the building and transport sectors, 2000–2018.

4. Thailand's Existing Policies on Energy and Climate Change Mitigation

4.1 Climate Change Mitigation Policies

Thailand, as a member of the United Nations Framework Convention on Climate Change (UNFCCC), has submitted the second updated NDC in November 2022 (Ministry of Natural Resources and Environment, 2022a). There are two scenarios developed in the updated NDC, namely the unconditional and conditional scenarios. Results of the unconditional and conditional NDCs indicate countrywide emissions mitigation on the order of 166.50 $MtCO_2eq$ and 222 $MtCO_2eq$ in 2030, respectively, with the energy sector alone accounting for 97.75% of the total reduction in both scenarios.

Thailand submitted the Long-Term Low Emissions Development Strategy (LT-LEDS) to the UNFCCC (Office of Natural Resources and Environmental Policy, 2022). This long-term climate vision has two main goals: first, Thailand aims to reach carbon neutrality in the mid-21st century; second, it aims to become a net zero GHG emissions country fifteen years later.

4.2 Energy Development Policies

To assist in climate change mitigation actions, several types of energy development policies have been established to reduce energy intensity, transition to cleaner fuels, maintain energy security, and mitigate GHG emissions. The details of these development policies are illustrated as follows:

Energy Efficiency Plan 2018 (EEP2018): The EPP2018 aims to save up to 30% of the 2037 energy intensity compared to 2010 levels (Department of Alternative Energy Development and Efficiency, 2020b). The EEP2018 projected that in 2037 the energy efficiency implementation would save 49,064 ktoe of TFEC. The savings come from the industrial sector (21,137 ktoe), the transport sector (17,682 ktoe), the building sector (9,718 ktoe), and the agriculture sector (527 ktoe).

Alternative Energy Development Plan 2018 (AEDP2018): By 2037, the AEDP2018 policy promotes up to 30% of renewable energy for the final energy consumption in the form of biofuel, heating, and electricity generation (Department of Alternative Energy Development and Efficiency, 2020a).

Power Development Plan 2018 (PDP2018): The PDP2018 aims to promote renewable energy (RE) in electricity generation, secure low-cost electricity supply, and reduce emissions. This policy would increase the total installed capacity of RE to 47% by 2037, with 37% coming from domestic sources and the remaining 10% of electricity supply coming from neighboring countries (Energy Policy and Planning Office, 2020).

5. Methodology

5.1 Overview of Analysis Framework

Figure 5 summarizes the analytical framework of this study. Firstly, this study collected related data, such as socioeconomic information, building sector data, transport sector data, and power generation data. Then, these data were analyzed in the current account of the LEAP, as well as with multivariable regression for future projections. The low-carbon technologies were reviewed in different scholarly articles, official reports, and experiments. After that, the data and information were input into the LEAP with NEMO model. Finally, three scenarios were developed under the different policy and technology trajectories for generating the results, including energy demand, GHG emissions, and electricity production cost. Furthermore, results from the three scenarios were compared and then the discussion, conclusion, and policy implications are presented.

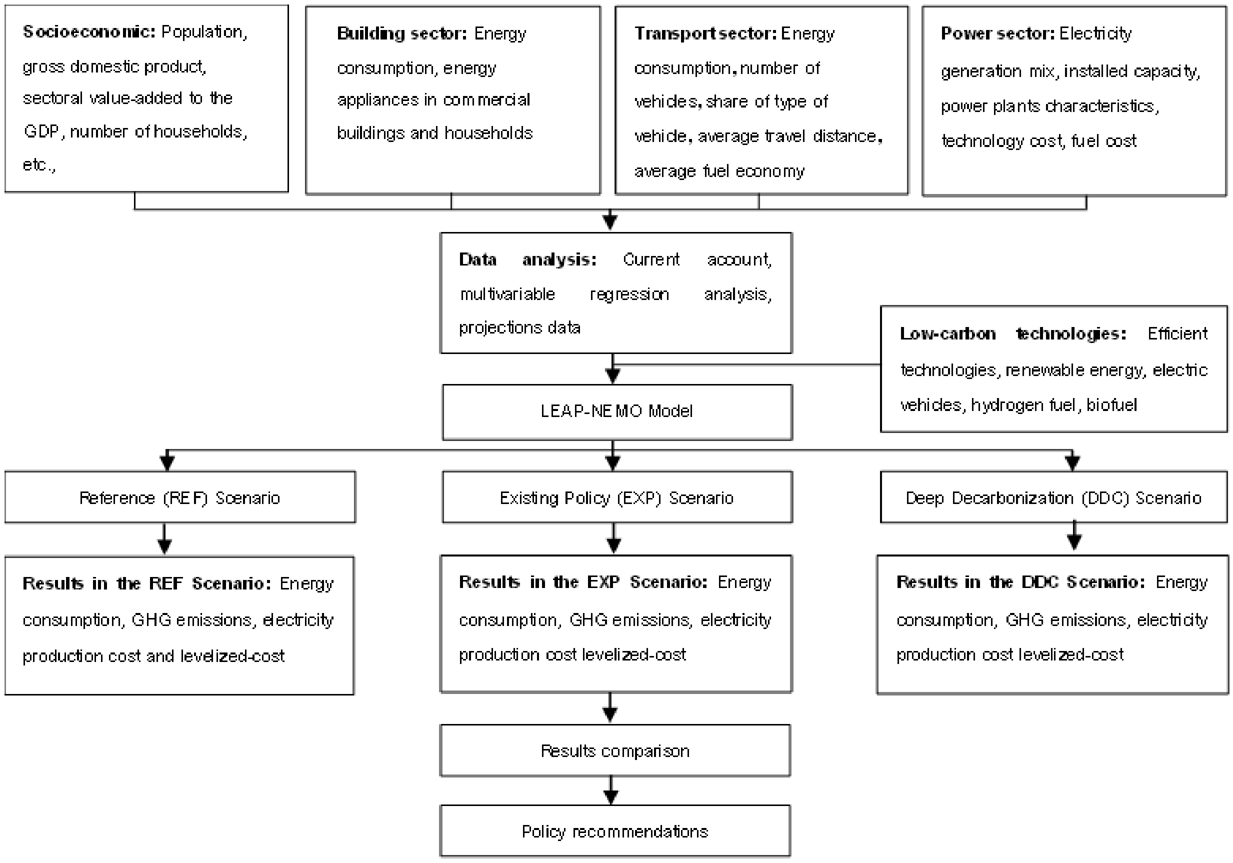

Figure 5. Framework of the analysis.

5.2 LEAP and NEMO

The Low Emissions Analysis Platform (LEAP) was developed by the Stockholm Environmental Institute (SEI) to be an energy-environmental planning tool (Heaps, 2020). The structure of LEAP allows users to construct multiple scenarios to determine the energy structure and GHG emissions. The tool can be applied to create different energy system models in various timeframes of up to 50 years. LEAP has been integrated with built-in tools that make it possible to generate and calculate complex models with less initial data. Additionally, LEAP contains multiple approaches for solving accounting problems and least-cost optimization. More recently, the SEI developed an optimization module, named “NEMO,” to integrate with the LEAP to determine the optimum electricity generation options (Stockholm Environment Institute, 2021). In this integration tool, users can add emission limitations and set the target of renewable energy. Additionally, this program has a variety of prominent optimization calculation solvers.

LEAP has been used globally as an energy-environmental analysis tool because of its ease of use and flexibility (Heaps, 2020). Based on the popularity of the software, many articles have been produced on energy and climate change mitigation projections from country-level to regional-level in the context of achieving the NDCs (Dul & Limmeechokchai, 2021; Limmeechokchai & Dul, 2023).

5.2 Data Assumptions on Energy Consumption-Driven Factors

Numerous data and information for conducting the analysis in this study were collected from multiple reliable and official sources including the government statistical reports and databases, international organization reports and databases, and other scientific and technical reports. To forecast future energy consumption in the building and transport sectors, there are many important driving factors which are illustrated in Table 1 and Table 2. The assumptions and projections of these energy drivers are demonstrated as follows:

Demographics: Thailand's total population increased by an annual growth rate of 0.67% between 2000 and 2018 (National Statistical Office, 2023; World Bank, 2024). The Department of Economic and Social Affairs (2022) of the United Nations has made a projection of the world population, illustrating that Thailand is an aging society and the total population would decline to 68.08 million by 2050.

Macroeconomics: In 2018, Thailand's total GDP was approximately 1,256.76 billion $PPP (constant 2017 USD), where the service sector contributed 57.06% (World Bank, 2024). The GDP projection from the International Institute for Applied Systems Analysis (2018) shows that Thailand's GDP will increase at an average growth rate (AGR) of 3.12% between 2018 and 2050. The service sector will contribute approximately 61.73% of the total 2050 GDP.

Table 1. Historical and Projected Demographics and Macroeconomics

Factor	Historical		Projection				AGR [%]
	2000	2018	2020	2030	2040	2050	
Population [million]	63.07	71.13	71.48	72.07	71.02	68.08	-0.14
Households [million]	16.21	26.25	27.18	30.03	30.88	30.94	0.52
Urbanization growth [%]	31.39	49.95	51.43	58.42	64.45	69.46	1.05
GDP [billion $PPP]	617.54	1,256.76	1,205.50	1,792.90	2,520.30	3,298.40	3.12
GDP per capita [thousand $PPP]	9.79	17.67	16.87	24.88	35.49	48.45	3.24
Service sector value added [%]	54.83	57.06	55.46	57.64	59.69	61.73	–

Remark: AGR = average growth rate between 2018–2050, $PPP = purchasing power parity in USD
Source: (Department of Economic and Social Affairs, 2018; Department of Economic and Social Affairs, 2022; International Institute for Applied Systems Analysis, 2018; National Statistical Office, 2023; World Bank, 2024;)

Transport: In 2018, the total number of vehicles in Thailand was around 39.55 million (Ministry of Transport, 2020). The projected transport demand shows that the total number of vehicles will increase to around 60.33 million by 2050. In the rail transport mode, total passenger and freight transport are estimated to increase by an annual rate of 3.22% and 3.08%, respectively, between 2018 and 2050. In the domestic air transport mode, by 2050, passenger and freight transport would increase to 147.61 million passenger-km per year and 4,319 million tonne-km per year, respectively. In the water transport mode, the total passenger and freight transport will increase to approximately 12.47 million passenger-km/year and 36,798 million tonne-km/year by 2050, respectively.

Table 2. Historical and Projected Transport Demand in Thailand

Parameter	Historical		Projection			
	2000	2018	2020	2030	2040	2050
Road transport						
Total vehicles [million]	20.80	39.55	38.60	45.55	53.70	60.33
Bus share [%]	0.59	0.41	0.50	1.00	1.50	2.00
Car share [%]	28.61	41.71	45.00	51.67	58.33	65.00
Motorcycle share [%]	66.66	53.35	50.00	42.67	35.33	30.00
Truck share [%]	4.14	4.53	4.50	4.66	4.84	5.00
Rail transport						
Passenger [million pass-km/year]	5,907	6,473	5,638	8,316	11,862	16,197
Freight [million metric tonne-km/year]	2,247	2,769	2,656	3,950	5,553	7,268
Air transport						
Passenger [million pass-km/year]	56.33	89.14	87.10	105.77	126.33	147.61
Freight [million metric tonne-km/year]	1,713	2,666	2,611	3,185	3,776	4,319
Water transport						
Passenger [million pass-km/year]	3.02	5.85	5.65	7.57	9.87	12.47
Freight [million metric tonne-km/year]	16,302	17,846	17,297	23,295	30,073	36,798

Remark: pass-km/year = passenger-kilometer per year, tonne-km/year = tonne-kilometer per year
Source: (Ministry of Transport, 2020; World Bank, 2024)

5.4 Description of Reference (REF) Scenario

The Reference (REF) scenario is designed to be a frozen scenario. There is no energy efficiency technology utilization, no renewable energy application, and no other climate policy intervention in this scenario. The share of future technology applications will remain the same as in the base year. On the other hand, in the electricity generation sector, the installed capacity is assumed to increase based on the current trend of installed capacity while keeping the same share of each technology. The future energy consumption in the building and transport sector is forecast using the following equations (ASEAN Centre for Energy, 2022):

$$EC_R = H_{urban} \sum_i (EI_i) + H_{rural} \sum_i (EI_i) \quad (1)$$

Where EC_R refers to the residential subsector's energy consumption, H is the total number of households, and EI_i is the energy intensity of service type *i*.

$$EC_C = EI \times GVA \quad (2)$$

Where EC_C refers to the commercial subsector's energy consumption, *EI* is the energy intensity per gross value added [toe/USD], and GVA refers to the GDP's gross value added from the commercial sector [USD].

$$EC_T = \sum_i (V_i \times FE_i \times AD_i) \quad (3)$$

Where EC_T refers to transport's energy consumption, V_i is the number of type *i* vehicles, AD_i is the average travel distance by type *i* vehicle [vehicle-kilometer/year], and *FE* refers to average fuel economy [liter/km] or [joule/km] of type *i* vehicles.

5.5 Description of Existing Policy (EXP) Scenario

The Existing Policy (EXP) scenario in this study is formulated by following the government's existing policies on energy efficiency (EEP2018) and renewable energy (AEDP2018 and PDP2018).

5.5.1 Building Sector

The Department of Alternative Energy Development and Efficiency (2020b) sets the total energy savings in the building sector under the EEP2018 to be 22% by 2037 compared to the baseline scenario's level of TFEC. This scenario assumes a 1% annual increase in energy savings towards 2050.

5.5.2 Transport Sector

For the transport sector, the total final energy conservation would be 15%, as reported in the EEP2018, compared to the baseline scenario in 2037 (Department of Alternative Energy Development and Efficiency, 2020b). It is assumed that a 1% annual improvement in energy savings will be achieved until the end of the study period. In addition, the policy on EV promotion in Thailand aims to increase the share of EVs in the passenger transport mode to 30% by 2030 and 35% by 2035 (Theparat, 2021). The annual growth rate of EVs would be 1% per year after 2030. Therefore, this scenario assumes 1% annual growth in the share of EVs from 2030 until 2050.

5.5.3 Power Sector

In the power sector, the PDP2018 utilizes RE installed capacity from the AEDP2018 plan until 2037 (Energy Policy and Planning Office, 2020). The EXP scenario assumes that the installed capacity of RE in power generation will remain unchanged from 2037 until 2050.

5.6 Description of Deep Decarbonized (DDC) Scenario

Thailand's LT-LEDS suggests that the country can achieve net zero GHG emissions by 2065 through deployment of low-emission technologies in the building, transport, and power sectors within the 2020-2065 timeline (Office of Natural Resources and Environmental Policy, 2022). However, the LT-LEDS did not discuss the amount and share of those technologies' replacement and utilization for attaining the climate mitigation goal. Therefore, this study implements the DDC scenario by leveraging the placement of the best available low-emissions technologies and the future potential of advanced technologies, which experts and scientists have thoroughly examined to assess the potential of attaining GHG neutrality earlier than the target in the LT-LEDS. Furthermore, the assumptions and choice of technologies in the DDC scenario are made in consideration of the recommendations from the global scenario developed by the International Energy Agency (IEA) towards the mid-21st century.

5.6.1 Building Sector

The IEA has constructed a 2050 net-zero emissions scenario for the building sector through efficient energy technology utilization (International Energy Agency, 2021). The scenario shows that all the best available efficient appliances, including refrigerators and air conditioners, will lead to an 80% share in 2030 and increase to 100% by 2050. Furthermore, LED lamps will replace all lightbulbs by 2050 in all regions. The case study in India made similar assumptions (Vat & Mathur, 2022). The authors also assumed that electric cooking would replace all cooking fuels by 2050. Therefore, the DDC scenario in the building sector (residential and commercial buildings) assumes a share of efficient appliances based on the aforementioned studies (see Table 3).

Table 3. Description of the DDC Scenario Assumptions in the Building Sector

Services	- Mitigation measures
Lighting[1]	- By 2050, all households and commercial buildings will gradually switch to 100% LED lighting.
Cooling[2]	- All households and commercial buildings will gradually transition from non-inverter air-conditioner and refrigerator to the label number 5 of inverter air-conditioner and refrigerator by 2050.
Household cooking[3]	- The share of efficient electric cooking devices will increase up to 25% by 2030 and 75% by 2050 across the country. - The improved biomass cookstoves (wood and charcoal) will replace the traditional biomass cookstoves by up to 10% from 2030 to 2050. - The traditional biomass cookstoves will be phased out by 2050.
Heating in commercial buildings[4]	- The share of solar heating services will gradually increase to 15% by 2050.
Entertainment and office equipment[5]	- By 2050, efficient appliances will completely replace all conventional technology.

Source: [1, 2, 3, 4, 5](International Energy Agency, 2021; Vats & Mathur, 2022)

5.6.2 Transport Sector

The ASEAN fuel economy roadmap has stated that in 2050, average fuel economy efficiency will be improved by 50% (Gesellschaft fur Internationale Zusammenarbeit [GIZ], 2018). Regarding the penetration of electric vehicles (EVs) and hydrogen fuel cell electric vehicles (HFEVs), the IEA has conducted a study to identify the pathways that attain zero carbon emissions in the transport sector, indicating that the 2050 share of EVs in different types of vehicles will significantly increase to 75% in light-duty vehicles (LDVs), 100% for two/three-wheelers, and 65% for heavy trucks (International Energy Agency, 2021). Furthermore, HFEV by type possibly will have a share of 10% for LDVs and 25% for heavy trucks. In addition, the IEA has illustrated the pathway for the rail sector by doubling the share of passenger rail transport and increasing the electric train share to 65% by 2050. By adopting the above studies as references, the DDC scenario in this sector can be assumed as shown in Table 4.

Table 4. Description of the DDC Scenario in the Transport Sector

Components	Mitigation measures
Fuel economy[1]	- Internal combustion engine vehicle fuel economy will improve by 25% by 2025 compared to 2018, and by 50% by 2050.
Promotion of electric vehicles[2]	- In passenger road transport, the share of EVs will be 30% by 2030 and 70% by 2050. - By 2030, the share of EV trucks in freight road transport will be 15%, and 50% by 2050. - Electric passenger and freight train locomotives will gradually increase their share up to 50% by 2050.
Promotion of public transport[3]	- Rail passenger transport (passenger kilometers) is assumed to have double growth compared to the REF scenario. - By 2050, the share of public buses in passenger transport will increase by 10%.
Promotion of hydrogen fuel cell vehicle[4]	- Hydrogen fuel cell vehicles will start to penetrate passenger cars and passenger buses in 2030 and their share will gradually increase to 5% and 10%, respectively, by 2050. - Hydrogen trucks will start in 2030 and their share in the road freight transport will increase to 15% by 2050.

Source: [1](GIZ, 2019), [2, 3, 4](International Energy Agency, 2021)

5.6.3 Power Sector

The installed capacity and electricity generation is calculated by the LEAP-NEMO analysis tool using the least-cost optimization method. However, there are several assumptions that need to be clarified:

- **Potential and possible capacity:** International Renewable Energy Agency & ASEAN Centre for Energy (IRENA & ACE, 2022) estimate the total potential capacity of renewable energy in Thailand (see Table 5). Limitations of deployment of renewable energy in Thailand are not considered by IRENA & ACE. When plantation area and yield of biomass are considered, the maximum possible or realistic capacity is estimated. For hydropower, large scale storage type is excluded. The limitations of land/site for solar and wind in Thailand result in lower possible capacity. In addition to the estimate of Pradhan et al. (2022), the possible installed capacity of these RE resources in Thailand is limited, as shown in Table 5.
- **Installed capacity of diesel and coal power plants:** Diesel and coal power plants will be phased out by 2025 and 2050, respectively (Office of Natural Resources and Environmental Policy, 2022).
- **Advanced electricity generation:** Hydrogen electricity generation and carbon capture and storage (CCS) technology in natural gas generation will be introduced in 2030 (International Energy Agency, 2021).
- **Power plant characteristics:** The technical characteristics, technology costs, and fuel costs of each type of power generation are retrieved from Lorm & Limmeechokchai (2024).

Table 5. Thailand's Renewable Energy Potential and Maximum Possible Installed Capacity

Renewable energy technology	Biomass	Hydropower	Solar PV	Wind
Potential [MW]	18,000	15,000	3,509,000	63,000
Possible installed capacity [MW]	15,000	8,000	65,000	45,000

Remark: MW = Megawatts, Solar PV = Solar Photovoltaic
Source: (IRENA & ACE, 2022; Pradhan et al., 2022)

6. Results and Discussion

6.1 Residential Sub-sector

6.1.1 Final Energy Consumption

Between 2018 and 2050, the LEAP-NEMO for the REF scenario predicts that the growth of the number of households, urbanization, and per capita income in Thailand will drive the total final energy consumption (TFEC) in the residential sub-sector to increase by 1.45% per year. Electricity consumption shows a remarkable expansion to around 8,806 ktoe by 2050 (see Figure 6), while non-electricity demand such as LPG, wood, and charcoal is estimated to have a slight change over the study period. The TFEC shows a decrease in the EXP scenario compared to the REF scenario over the study period thanks to the successful adoption of the government energy efficiency development plan, making a one-quarter reduction in overall energy demand in 2050 relative to the REF scenario. Results from the DDC scenario demonstrate that fully adopting efficient appliances across every household in Thailand would increase further energy savings over the existing government plan. Additionally, non-electricity fuel consumption in the DDC scenario would drop due to the expansion of electric cooking to replace biomass and LPG fuels towards 2050. Regarding fuel utilization in the DDC scenario in 2050, electricity would account for 8,887 ktoe, followed by wood (887 ktoe), LPG (259 ktoe), and charcoal (163 ktoe).

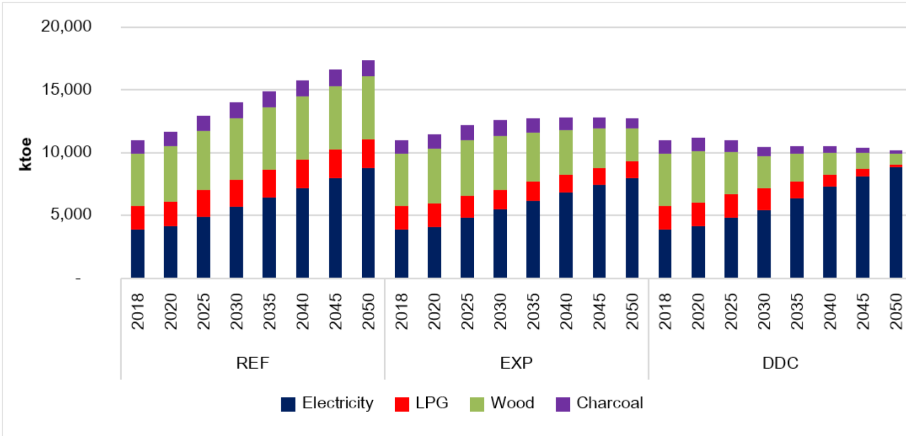

Figure 6. Final energy consumption in the residential sub-sector by fuel type.

6.1.2 GHG Emissions

The REF scenario estimates total emissions from electricity consumption alone to be 48.76 $MtCO_2eq$ by 2050 due to growth in electricity demand and high fossil fuel utilization on the generation side. The total emissions from LPG and biomass in 2050 would increase by 1.01 $MtCO_2eq$ and 0.44 $MtCO_2eq$, respectively, compared to the base year (see Figure 7). The EXP scenario, on the other hand, estimates the energy savings from the government's energy efficiency plan and the renewable energy promotion from the power development plan would help to manage the rate of increase in the total emissions for the residential sub-sector resulting in a slower pace than the REF scenario. It is estimated that the 2050 total emissions would be 42.21 $MtCO_2eq$. The DDC scenario predicts that household GHG emissions would peak at approximately 32.02 $MtCO_2eq$ by 2025 as a result of the remaining high utilization of fossil fuels in power plants to generate electricity. Results from the LEAP-NEMO model show that despite having an increased electricity demand, the total emissions after 2025 would decrease due to the increase in renewable electricity generation and the decline in fossil fuel-based generation through the least-cost optimization method. Total emissions in the residential sub-sector would decrease to around 4.01 $MtCO_2eq$ by 2050.

6.2 Commercial Sub-sector

6.2.1 Final Energy Consumption

Under the REF scenario, with the current state of technology used and the need for energy to support the growth of GDP contributed by the commercial sector, the TFEC is projected to grow up to 18,377 ktoe in 2050, which is almost three times the TFEC in 2018 (see Figure 8). Electricity remains on top in terms of energy consumption in this sector, followed by LPG and natural gas. Results in the EXP scenario show that by adopting the government's energy efficiency plan, the TFEC is forecast to have a decrease and be approximately 11,511 ktoe in 2050. In the DDC scenario, the demand for energy in 2050 would be decreased further to 9,419 ktoe with the full penetration of efficient technologies such as LED lighting, efficient air-conditioners, and other efficient electric equipment.

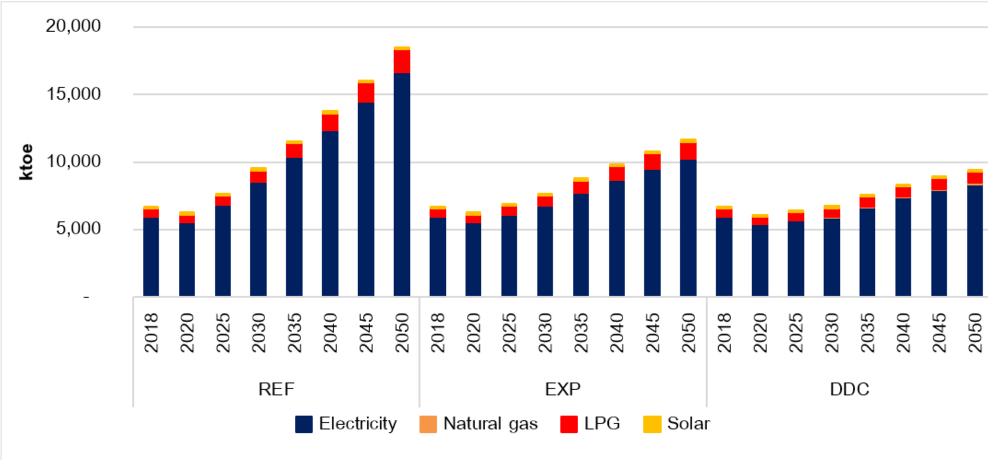

Figure 8. Final energy consumption in the commercial sub-sector by fuel type.

6.2.2 GHG Emissions

GHG emissions in commercial buildings primarily stem from electricity use. The REF scenario projects an annual increase in these emissions of 3.25% from 2018 to 2050, reaching 97.42 $MtCO_2eq$. LPG and natural gas fuel consumption in heating services primarily drive the direct emissions in this sector, contributing around 5.21 $MtCO_2eq$ (see Figure 9). In the EXP scenario, emissions decrease compared to the REF scenario, particularly in electricity-related emissions. This decrease results from the energy savings based on the implementation of the EEP2018 plan and the transition towards cleaner supply side from the adoption of the PDP2018 plan. By 2050, GHG emissions from electricity consumption in this sector are projected to drop by about 45 $MtCO_2eq$ compared to REF scenario emissions. Under the DDC scenario, even though the demand for electricity in the commercial sub-sector is relatively high, the total emissions show a substantial drop because of the transition to cleaner electricity production utilizing the least-cost optimization method. The results show total emissions dropping to 5.66 $MtCO_2eq$ by 2050.

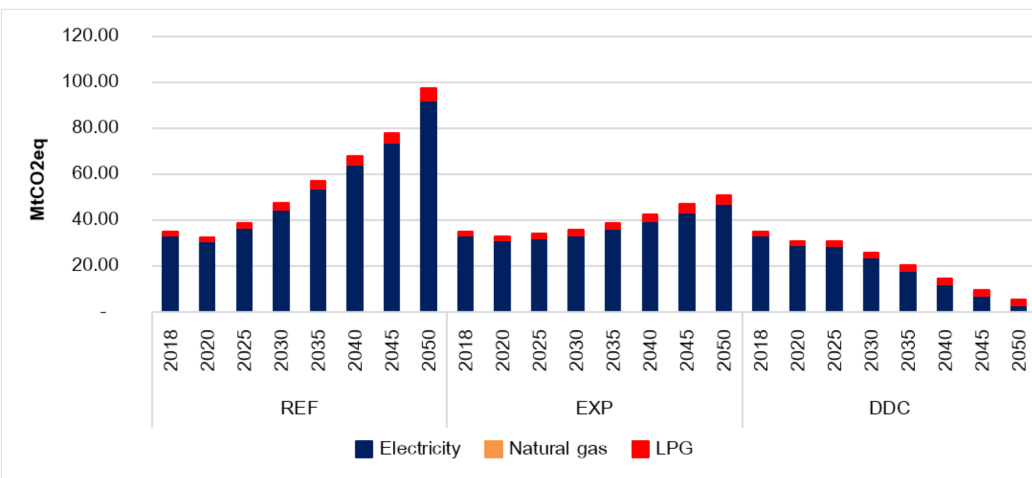

Figure 9. GHG emissions in the commercial sub-sector by fuel type.

6.3 Transport Sector

6.3.1 inal Energy Consumption (FEC)

In the REF scenario, the results show that the 2050 TFEC in this sector would grow by almost twice as much as the energy consumption in 2018, equivalent to 63,517 ktoe (Figure 10). Three principal fuels, including diesel, gasoline, and jet fuel, are expected to be the main sources of energy consumption in the study timeline. On the other hand, the 2050 TFEC in this sector shows a considerable drop to approximately 49,200 ktoe under the EXP scenario. The successful adoption of energy savings stated in the government energy efficiency development plan is the primary driving factor to reduce energy demand in this sector. The implementation of the government's alternative fuel development plan would swing from diesel and gasoline dominance to cleaner fuels such as electricity, compressed natural gas (CNG), and biofuel. Under the DDC scenario, the implementation of fuel economy improvement to its highest efficiency together with a modal shift to rail and the high applications of zero-emission vehicles (BEVs and HFEVs) would reduce the TFEC in this sector to approximately 38,527 ktoe by 2050. Electricity and hydrogen will become the two dominant sources of fuel consumption in this sector due to the high utilization of EVs and HFEVs.

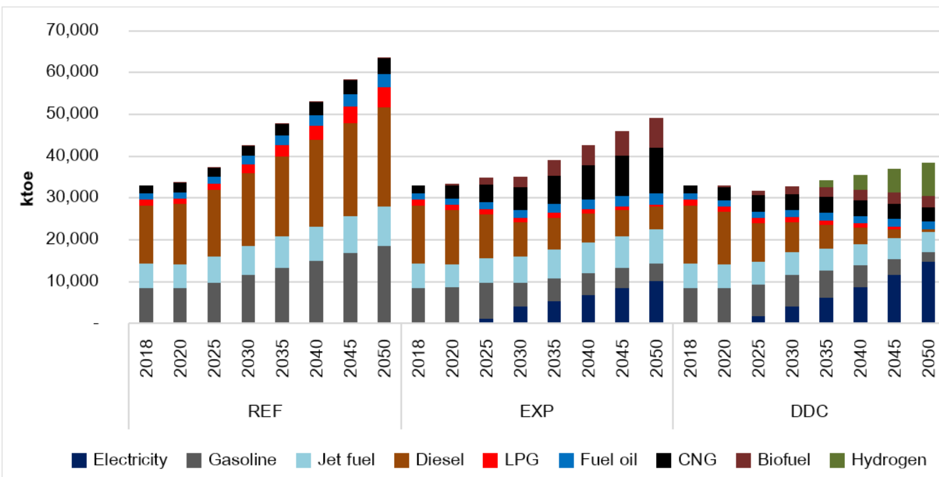

Figure 10. Final energy consumption in the transport sector by types of fuel.

6.3.2 GHG Emissions

By 2050, the total transport sector's emissions will increase to 189.08 $MtCO_2eq$ in the REF scenario, almost twice the total emissions in 2018. In 2050 total emissions, diesel and gasoline consumption will account for 38.73% and 28.10%, respectively, as shown in Figure 11. The total emissions of GHG under the EXP scenario will decrease to 143.94 $MtCO_2eq$ owing to energy savings and use of alternative fuels. However, electricity-related emissions surprisingly will increase to have the highest share of emissions in 2050, approximately 32.49%, due to the increase in EVs. In the DDC scenario, the total GHG emissions in 2050 are projected to be 35.69 $MtCO_2eq$, with 85.65% coming from the direct use of petroleum products in the transport sector and 14.34% coming from electricity-related GHG emissions utilization.

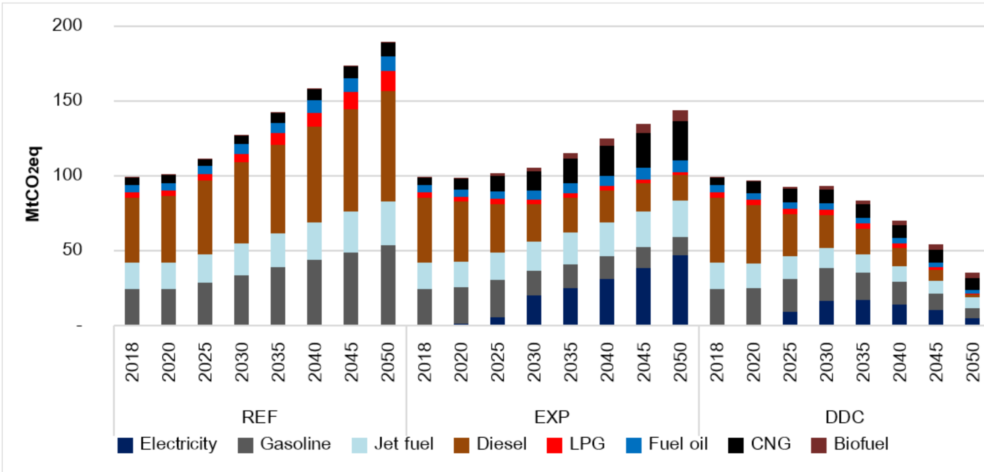

Figure 11. GHG emissions in the transport sector by types of fuel.

6.4 Cost of Electricity Production

In 2018, average cost of electricity production in Thailand was approximately 8.02 cent/kWh, based on the calculation in the LEAP-NEMO model. The modelling simulation in the REF scenario shows that the price of electricity generation would increase slightly to around 8.51 cent/kWh in 2030 due to the increase in fossil fuel prices; however, it decreases to 7.69 cent/kWh by 2050 because of a minor increase in renewable energy electricity generation.

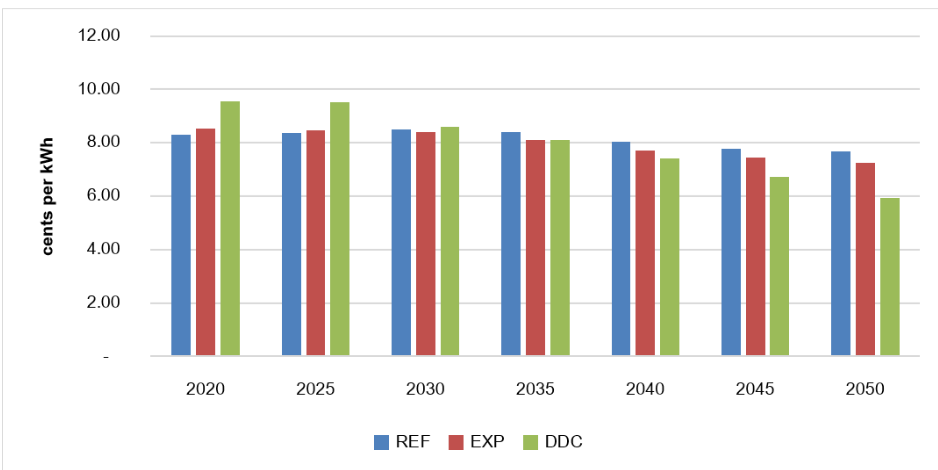

Figure 12. Cost of electricity production in Thailand.

In the REF scenario, despite having zero cost for fuel use with renewable energy, the cost of renewable energy technology was relatively high compared to other fossil fuel-based power plants. This would make the production cost of electricity grow in proportion to the growth of electricity production from renewable energy. Likewise, in the EXP and DDC scenarios, the cost of electricity generation is estimated to increase to approximately 8.54 cent/kWh and 9.57 cent/kWh in 2020, respectively. However, the future cost of renewable energy installed capacity (solar, wind, biomass, and biogas) will drop based on the 2023 Annual Technology Baseline (ATB) (The National Renewal Energy Laboratory [NREL], 2023). Therefore, the long-term planning for electricity generation illustrates that the increasing portion of renewable energy in electricity generation would minimize the cost of electricity generation. Results demonstrate that by 2050, the average production cost of electricity under the EXP and DDC scenarios would decrease by 0.42 cent/kWh and 1.76 cent/kWh, respectively, compared to the REF scenario.

6.5 GHG Emissions in Deep Decarbonized Scenario

The results from the study demonstrate that the total direct emissions in the building and transport sectors are projected to increase from 108.43 $MtCO_2eq$ in 2018 to 202.45 $MtCO_2eq$ in 2050 under the REF scenario. Combined with electricity-related emissions, the amount of GHG emissions in 2050 will be approximately 344.64 $MtCO_2eq$. Under the EXP and DDC scenarios, overall emissions in the building and transport sectors would be reduced by 31.16% and 86.84%, respectively, compared to the 2050 emissions in the REF scenario. According to the LT-LEDS (Office of Natural Resources and Environmental Policy, 2022), the GHG emissions in the manufacturing industry sector are projected to be 15 $MtCO_2eq$ by 2050. Other non-energy sectors, including industrial process and product use (IPPC), agriculture, and the waste sector, together will generate approximately 60 $MtCO_2eq$ of GHG emissions in 2050. The land-use, land use change, and forestry (LULUCF) sector, on the other hand, provides an emission sink of 120 $MtCO_2eq$. By adding the total emissions from the building and transport sectors under the DDC scenario together with the emission sources from other sectors with the offset from the LULUCF sector, Thailand will be able to achieve the deep decarbonization goal or GHG-neutrality by 2050.

7. Challenges to the Deep Decarbonization in the Building and Transport Sectors

Attaining deep decarbonized of the building and transport sectors in Thailand would require the combination of energy efficiency improvement, battery electric vehicles (BEV) and hydrogen vehicles, increasing public transportation, and supply-side renewable energy electricity generation with natural gas CCS technology. However, the involvement of community members in terms of behavior change and perception, together with the engagement from different stakeholders towards climate change mitigation, would be the force pushing the mitigation implementation to become visible.

In the building sector, switching to 100% efficient technologies, increasing electric cooking to replace conventional biomass and LPG stoves, and promoting solar for heating services are key roles not only to reduce the energy consumption and direct GHG emissions but also to reduce the emissions from the supply side and electricity cost. However, the achievement of these implementation measures would require great encouragement and individual contribution in terms of behavior changes towards energy savings in the building sector (Bastini et al., 2023; Jareemit & Limmeechokchai, 2017). The building architecture also would play an important role in energy savings due to the direct effect on heating, ventilation, and air conditioning (HVAC) systems, as well as lighting in the buildings (Aghimien et al., 2022). In addition, the deep decarbonized building sector is directly linked with climate resilience and adaptation actions, which are needed to transform the building sector to climate resilience (Limmeechokchai et al., 2024). For instance, as heatwaves increase, cleaner and green cooling systems in the building are required to avoid the health impacts and GHG emissions.

Transitioning from diesel/gasoline internal combustion engine vehicles towards BEVs and HFEVs and shifting from private to public transport mode are the key measures for the decarbonized transport sector. Nevertheless, increasing security in the community and public areas could be one of the key factors in promoting public transportation use (Nordfjærn & Rundmo, 2018). EVs and hydrogen vehicles are considered to be eco-friendly transportation vehicles; however, increasing durability, safety, and providing sufficient fuel supply are important considerations that shape people's perceptions of utilizing these technologies (van Bree et al., 2010).

8. Conclusion and Policy Recommendation

This study developed three scenarios to assess potential future energy consumption and GHG emissions in Thailand's building and transport sectors towards 2050. Under the REF scenario, the TFEC in the building and transport sectors would increase to 35,785 ktoe and 63,517 ktoe, respectively, by 2050. Besides this, the 2050 total GHG emissions (direct and indirect emissions) in these two sectors would increase to approximately 344.64 MtCO_2eq. In the EXP scenario, the successful implementation of the EEP2018 would lead to a decline in energy consumption in the building and transport sectors by 11,541 ktoe and 14,317 ktoe, respectively, compared to the REF scenario. Additionally, the collaborative implementation of the EEP2018 and the AEDP2018 aims to reduce energy consumption and enhance the use of renewable energy, resulting in a reduction of greenhouse gas emissions by 62.26 MtCO_2eq in the building sector and 45.14 MtCO_2eq in the transport sector by 2050. Furthermore, in the DDC scenario, the ambition of increasing the utilization of energy-efficient technologies together with advanced low-carbon technologies in the building and transport sectors, as well as in the power sectors, would result in the 2050 energy consumption reduction of around 45% in the building sector and 39% in the transport sector, respectively, compared to the TFEC in the REF scenario. Moreover, the total GHG emissions from both sectors would be reduced to around 45.35 MtCO_2eq. This is the lowest emission level that could assist Thailand in achieving GHG neutrality, when combined with emissions from other sectors and the LULUCF sector's carbon sequestration estimates.

In conclusion, deep decarbonization in Thailand's building and transport sectors is achievable under the highly ambitious level of low-emissions technology deployment as indicated in the DDC scenario development. However, the goal of the 2050 net zero emissions would not be possible without the collaboration of citizens, public and private organizations, and support from the international community.

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Author Contributions

Conceptualization, B.L., and R.L.; methodology, B.L., and R.L.; formal analysis, B.L., and R.L.; investigation, B.L., and R.L.; writing-original draft preparation, B.L., and R.L.; writing-review and editing, B.L. and R.L.; visualization, B.L., and R.L. All authors have read and agreed to the published version of the manuscript.

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