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Thailand Net Zero Emissions 2050: Analyses of Decarbonized Energy System Beyond the NDC

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ABSTRACT

The energy sector in Thailand has shared most of the total country's greenhouse gas (GHG) emissions for decades. This sector needs accelerating decarbonization targets to push the country's net emissions to a neutral level. Thailand's current energy system has not fully utilized renewable energy, energy efficiency enhancements, and electric vehicles to their full potential. Carbon capture and storage (CCS), as a great technology for capturing and storing carbon emissions, has not been integrated into fossil fuel-based power plants. Furthermore, hydrogen fuel has not yet reached a large-scale implementation level in the decarbonized energy system, despite being recognized as a promising choice for a zero-GHG emissions energy carrier. This article evaluates the combination of technology deployments to assess the possibility for Thailand to reach the climate target of net-zero emissions by 2050. The LEAP-NEMO analysis tool is used to implement the Reference, More Ambitious, and Net Zero Emissions 2050 (NZE) scenarios. In the NZE scenario in 2050, renewable energy accounts for 25% of final energy consumption and 71% of electricity production, while electric vehicles account for 80% of the total vehicle fleet in road transportation, whereas natural gas-based power plants equipped with CCS technology play an important role in decarbonized power generation.

1. INTRODUCTION

Anthropogenic greenhouse gas (GHG) emissions are the main driving factors of global warming, which are mainly caused by the utilization of fossil fuels for generating energy to boost economic growth, support urbanization development, and improve the quality of lives. Global human-induced GHG emissions in 2019 were around 59 $GtCO_2eq$ [1], increasing by 12% and 54%, respectively, in comparison to the net emissions in 2010 and 1990. If this trend in emissions continues, the global average temperature would increase over 2°C compared to the pre-industrial era [1]. To tackle the current threats of global warming, every nation adopted the Paris Agreement which aims to minimize the growth of the earth's average temperature to under 2°C and increase the target to 1.5°C above the pre-industrial level [2]. Therefore, global net carbon dioxide (CO_2) emissions must be zero in the early 2050s, and the energy sector is the major challenge to the emissions mitigation plan [3].

The higher the reliance on fossil fuels in energy systems, the greater the amount of GHG emissions released. In Thailand, the total final energy consumption (TFEC) in 2018 was approximately 83.95 Mtoe, where petroleum products accounted for 49%, followed by electricity, biomass, coal, and natural gas, which accounted for 20%, 17%, 8%, and 7%, respectively [4]. Furthermore, total electricity generation in 2018 was 208.14 TWh, and natural gas stood at the top of the generation, accounting for 56.7%, followed by coal and electricity imports, which generated 17.9% and 12.8%, respectively, while the electricity produced by renewable energy is 12.6% of the total electricity in Thailand [5]. In terms of massive dependence on fossil fuels, it is reported that the energy sector emitted 257 $MtCO_2eq$ of GHG emissions, or 69% of the nation's emissions (excluding the LULUCF sector) in 2018 [6]. There is ample evidence that the current energy structure will eventually cause enormous volumes of GHG emissions; therefore, climate change mitigation actions and Thailand's energy system transition must be carefully considered.

As a developing country and highly vulnerable to climate change, Thailand has considered the Paris Agreement by mitigating GHG emissions through the implementation of the Nationally Determined Contribution (NDC) and the Long-Term Low Emissions Development Strategy (LT-LEDS) accordingly. In the updated Thailand's NDC report [7], the total emissions in 2030 can be reduced by 30% using domestic resources compared to the BAU. The funding and technology support from international communities would increase the reduction targets by up to 40% by 2030. Furthermore, the LT-LEDS [8] mentioned that

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Thailand aims to attain the neutrality level of CO_2 emissions by 2050 and GHG emissions by 2065. To assist in the reduction of GHG emissions and improve energy security in the country, the Ministry of Energy launched new energy development plans. In those plans, the government set a target to increase renewable energy share in various economic sectors by up to 30% in 2037 [9]. Furthermore, the energy intensity in 2037 would be minimized by up to 30% compared to 2010 level [10]. In addition, the energy policy aims to increase electricity generation from renewable energy from around 17% to approximately 34% between 2019 and 2037 [11].

This article determines the possibilities of GHG emissions mitigation in Thailand's energy sector toward a climate neutrality by 2050. This study integrates various technologies, including renewable energy, energy-efficient technology, and advanced technology (electric vehicles, hydrogen fuel, hydrogen vehicles, and CCS technology). Furthermore, the integration of the Next Energy Modeling System for Optimization (NEMO) with the Low Emissions Analysis Platform (LEAP) is used as a tool for developing the scenarios and analyzing the results.

2. REVIEW OF DECARBONIZED ENERGY SYSTEM

The study of carbon neutrality and net zero GHG emissions has been carried out in many regions and countries including India, China, Japan, and the United States of America [12]– [17]. Those scientific articles provide clear pathways toward low carbon society through the multiple technologies implementation such as increasing in electrification in demand-side, enhancing of energy efficiency, accelerating renewable energy in electricity generation, retirement of coal in industries and power generation, as well as the utilization of CCS technology. Several studies in the ASEAN region have illustrated the technical pathway to reaching net-zero carbon dioxide emissions in energy systems. Handayani *et al.* [18] conducted an analysis to identify the roadmap for ASEAN's power sector to attain a neutral level of emissions in 2050. Cambodia, Laos, and Myanmar can reach carbon neutrality in the power sector through 100% renewable energy generation [19]. Energy storage and the full utilization of electricity production from renewable energy are the most cost-effective ways to attain zero carbon generation in Indonesia, compared to the adoption of CCS technology [20]. Studies on emissions mitigation in the transport and energy sectors in Cambodia, Laos, Thailand, and Vietnam can be found in [21]– [22].

In the case study of Thailand, many scholarly articles have mentioned different pathways to mitigate emissions. Some scientific articles have studied the effectiveness of low-carbon technology deployment in shaping the energy system and GHG emissions in Thailand in the NDC context [23]– [24]. Rather than this, the demonstration of the GHG mitigation pathway to reach the Paris Agreement's goal of 2ºC and 1.5ºC by 2050 in Thailand has been conducted [25]– [26]. Further research on energy savings and GHG emissions reduction in different economic sectors can also be found, including the building sector [27], transport sector [28], industrial sector [29], and power sector [30]– [31]. However, only one study that assessed the pathway for achieving net zero emissions by 2050 in Thailand's energy system [32].

From those existing research articles, the decarbonization energy sectors in different countries have similar pathways; however, the main differences are the potential of technology deployment, type of technology utilization, and targets of each technology implementation. In Thailand's case study, there are different scholarly articles that contain different approaches to assess and analyze the mitigation of GHG emissions. Some studies have mentioned only sub-sectors of the energy system. A few research studies illustrate the scenario pathways of reaching 2ºC and 1.5ºC in Thailand by 2050, as well as the net zero GHG emissions in the middle of the twenty-first century. Most of those articles used the AIM/Enduse and LEAP models as the analysis tools. There has yet to be an application of NEMO integration in the LEAP model in the case study of Thailand for analyzing the combined GHG reduction with least-cost optimization. Therefore, this article demonstrates the scenario with the high utilization of renewable energy, the application of highly efficient devices, and cutting-edge technologies. Moreover, this study expands the utilization of the framework of LEAP-NEMO analysis for achieving net-zero emissions and presents potential prospects for Thailand and other countries in their journey towards achieving zero emissions through optimal electricity generation.

3. METHODOLOGY

3.1 LEAP and NEMO

The Stockholm Environmental Institute (SEI) implemented LEAP, an energy-environmental planning software, which is utilized as an integrated resource planning tool to develop multiple scenarios for assessing medium- and long-term energy supply and consumption and GHG emissions [33]. Due to its flexibility and ease of use, many researchers have adopted LEAP as an analysis tool for constructing their respective research studies, formulating the NDCs, and developing the LT-LEDS [33]– [35].

The SEI has developed the NEMO for integration with the LEAP model for estimating the least-cost optimization of electricity production [36]. The construction of NEMO in Julia programming enables high-performance determination of the optimization. This integration tool supports multiple regions and allows users to add emission constraints together with renewable energy target settings to meet their maximum potential.

Figure 1 demonstrates the structure of LEAP-NEMO in this study. The input parameters consist of demographics, macroeconomics, energy intensity, sectoral energy consumption, electricity production, etc. These parameters are being utilized for Thailand's energy demand projection and electricity production.

Three scenarios are implemented, namely the Reference (REF) scenario, the More Ambitious (MA) scenario, and the Net Zero Emissions 2050 (NZE) scenario, in the LEAP-NEMO analysis tool to generate results of sectoral energy demand, electricity generation mix, GHG emissions, and the cost of investment and production of electricity.

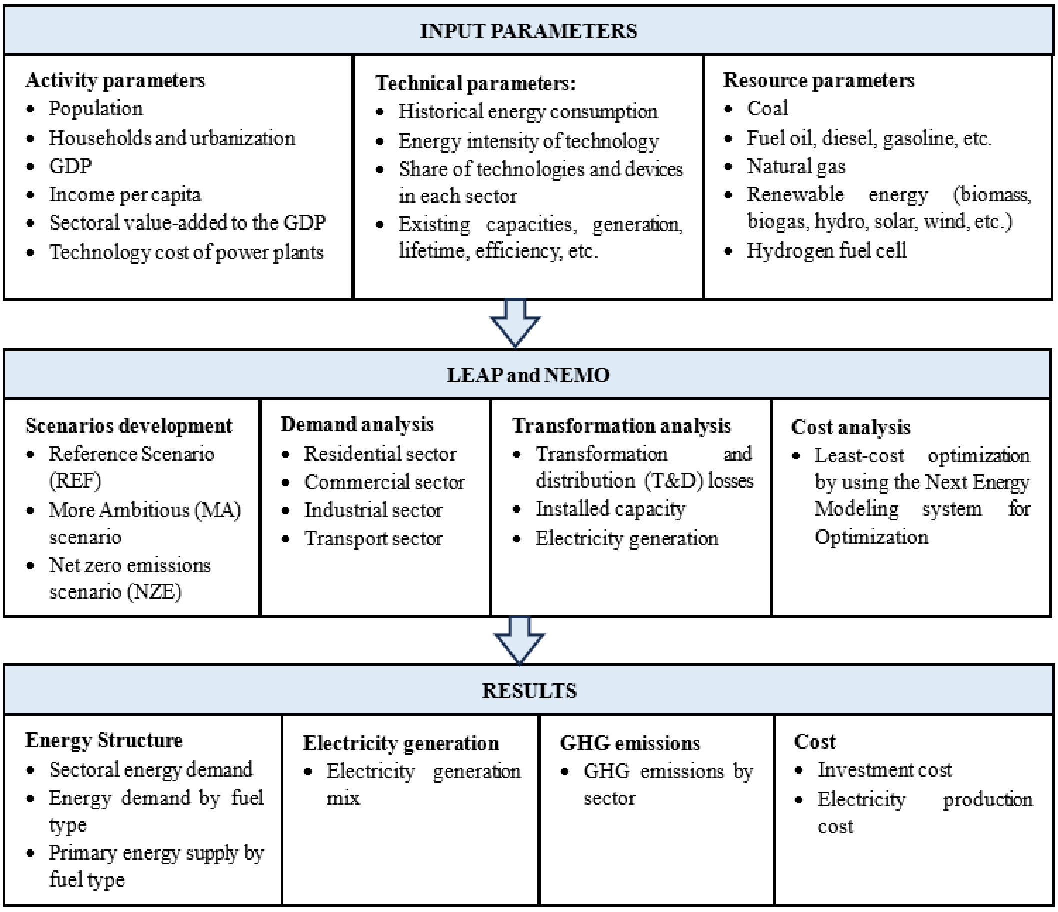

Fig. 1. The LEAP-NEMO framework.

3.2 Assumption of Energy Demand Projection and Electricity Generation

The energy demand in Thailand is growing with the increase in the country's gross domestic product (GDP), population, and urbanization. Table 1 illustrates the projected results of these driving factors, while the assumptions of the projection are detailed as follows:

Economic indicators: Thailand boasts the second-largest economy in the Southeast Asia. In 2018, the total country's GDP was 1,172 billion U.S. dollars in purchasing power parity ($PPP) at a constant 2017 international dollar, and GDP per capita was 16,505 $PPP [37]. Based on the second scenario of the share socioeconomic pathway (SSP) [38], the 2050 total GDP of Thailand will increase to around 3,298 billion $PPP. Additionally, the share of sectoral value-added of the industrial sector, commercial sector, and agricultural sector is gathered from the World Development Indicator (WDI) of the World Bank [37]. The future estimations of these variables are derived from the historical trends of each sectoral share.

Demographics: In 2018, the population of Thailand was 71.03 million people, and the total number of households was approximately 22.13 million households [37], [39]. The projection of the total population of Thailand indicates that in 2050 the populations in Thailand would decrease to 68.08 million people [40]. The number of households in Thailand is projected proportionally to population growth. Thailand's urbanization growth rate, recorded in the WDI of the World Bank database, shows that the urbanization rate increased from 31.39% in 2000 to 49.94% in 2018 [37]. By 2050, the urbanization rate in Thailand would expand to around 69.46% [41].

Number of vehicles: In Thailand, the total vehicles in the road transportation mode increased significantly between 2000 and 2018, from 20.81 million vehicles to roughly 39.89 million vehicles [42]. Regression analysis is used to project the future number of vehicles, with income and population size as the two key independent variables. Therefore, the estimate results show that the total number of vehicles would be 48.31 million by 2050. The share of vehicle types in road transportation is estimated through historical trends, and the results are shown in Table 1.

Characteristics of power plants: The characteristics of power plants are collected from various sources and databases of official organizations, governments, and scientific articles. The details include the technology parameters from the article by Handayani *et al.* [18], the technology cost from the National

Renewable Energy Laboratory [43], fuel cost from the ASEAN Centre for Energy [44], and the technical installed capacity of renewable energy from the International Renewable Energy Agency [45]. The power plants characteristics are shown in Table 2.

Table 1. Projection of driving factors of energy demand.

Parameters	Historical		Projection			
	2000	2018	2020	2030	2040	2050
Economic indicators [37]-[38]						
GDP [billion $PPP]	618	1,172	1,207	1,793	2,520	3,298
Income per capita [$PPP]	9,848	16,505	16,909	24,877	35,486	48,452
Industrial [% share of GDP]	36.63	35.27	35.08	34.00	32.79	31.48
Commercial [% share of GDP]	50.11	55.71	56.30	59.11	61.74	64.19
Residential [% share of GDP]	13.26	9.01	8.62	6.89	5.47	4.33
Demographics [37], [39], [41]						
Population [million people]	62.77	71.03	71.39	72.07	71.02	68.08
Household [million households]	17.88	22.13	22.39	23.41	23.92	23.81
Urban [% share of total household]	31.39	49.94	51.43	58.42	64.45	69.46
Rural [% share of total household]	68.61	50.06	48.57	41.58	35.55	30.54
Number of vehicles [42]						
Total number of vehicles [million vehicles]	20.81	39.55	39.89	43.02	46.00	48.31
Car share [% share of total vehicles]	28.61	41.71	42.53	43.36	44.18	45.00
Motorcycle and three-wheelers share [% share of total vehicles]	66.66	53.35	50.02	46.67	43.34	40.00
Bus share [% share of total vehicles]	0.59	0.41	2.82	5.22	7.60	10.00
Truck share [% share of total vehicles]	4.13	4.53	4.63	4.76	4.88	5.00

Table 2. Characteristics of power plants in Thailand.

Technology	Process efficiency [%][a]	Capacity credit [%][b]	Lifetime [year][c]	Capital cost [Thousand USD/MW][d]	Fixed O&M [Thousand USD/MW][e]	Variable O&M [USD/MWh][f]	Fuel price [USD/MWh][g]
Coal	42	88	30	2,800-3,500	64-78	7.3-8.5	7.1-9.8
NGCT	33	53	30	880-1,100	18-24	6	27.9-28.4
NGCC	56	54	30	970-1,250	22-31	1.5-2.0	27.9-28.4
NGCC-CCS	56	54	30	1,350-1,750	31-53	2.2-3.3	27.9-28.4
Diesel	45	92	30	1,150	35	40	10.2-14.1
Biogas	30	36	25	3,870-5,390	157	5	2.3
Biomass	30	36	25	3,870-5,390	157	5	0.6
Hydropower	100	27	50	6,660	33	0	-
Solar	100	30	25	632-1,290	11-23	0	-
Wind	100	20	30	925-1,360	21-30	0	-
Hydrogen	56	50	30	500-1,600	18	2.5	60-120
Import	80	67	30	6,660	33	0	39-50

Remark: NGCT = natural gas combustion turbine, NGCC = natural gas combined cycle, NGCC-CCS = natural gas combined cycle with carbon capture and storage.

[a, b, c] [18]

[d, e, f] [43]

[g] [44]

3.3 Scenario Description

3.3.1 Reference (REF) Scenario

This scenario is developed based on the current situation of energy structure in Thailand combined with the national energy development plans.

Residential sector: The energy demand in this sector is calculated by the following equation [44]:

$$EDR = HH \times \left(\sum_j \left(TA_j \times EI_j \right) \right) \quad (1)$$

Where *EDR* is energy demand in the residential sector, *HH* is the total number of households, *TA* is the type of appliance per household, *j* is the number of appliances, and *EI* is the energy intensity of each appliance.

Commercial and Industrial sectors: The consumption of energy in these two sectors can be determined by the following equation [44]:

$$ED = GVA \times ECperGVA \quad (2)$$

Where *ED* is energy demand in the commercial/industrial sector, *GVA* is the gross value added to the GDP [USD], and *ECperGVA* is energy intensity per gross value added to the GDP of the commercial/industrial sector [Mtoe/USD].

Transport sector: Energy demand in this sector is estimated as follows [44]:

$$EDT = NV \times VD \times FE \quad (3)$$

Where *EDT* is energy demand in the transport sector, *NV* is number of vehicles by type, *VD* is average of vehicle travel distance [vehicle-kilometer/year], *FE* is fuel economy [liter/km].

Power sector: The projection of the installation capacity of each power plant is made by following the latest power development plan in Thailand, known as the Power Development Plan 2018-2037 (PDP2018) [11]. Additionally, towards 2050, the total installed capacity is linearly increased from 2037, while the share of each type of power plant in total capacity remains the same (see Table 3).

Table 3. Installed capacity in the REF scenario [11]**.**

Technology	2018	2025	2030	2037	2045	2050
Import	3,878	6,235	7,509	8,661	8,796	9,000
Coal	4,637	6,208	6,307	6,505	6,703	7,000
Natural gas	24,836	33,186	33,224	32,112	38,067	47,000
Hydropower	3,281	4,105	4,105	4,105	4,105	4,105
Diesel	355	380	380	65	65	65
Biomass	2,063	2,928	2,590	4,694	6,816	10,000
MSW	193	784	784	828	1,096	1,500
Wind	1,081	1,774	1,774	2,989	4,193	6,000
Solar	2,967	3,608	7,936	14,754	18,852	26,000
Biogas	80	1,165	1,165	1,565	1,939	2,600

Unit: Megawatt (MW)
Remark: MSW = municipal solid waste, Import = imported electricity from neighboring countries (Laos, Malaysia, and Myanmar).

3.3.2 More Ambitious (MA) Scenario

The Energy Policy and Planning Office (EPPO) and the Department of Alternative Energy Development and Efficiency (DEDE) of the Ministry of Energy of Thailand designed the energy plans between 2018 and 2037 with the goal of increasing energy-savings potential and integrating renewable energy. The targets and goals of these plans have been discussed in Section 1. In this study, the More Ambitious (MA) scenario is implemented by boosting the ambitions of the government's energy development plans in both energy efficiency enhancement and renewable energy promotion in the energy sector from 2037 to the end of the study period. The details of this scenario's development are shown in Table 4.

Table 4. Description of MA scenario.

Sector	Technology	Assumption/Description
Residential	Efficient appliances	In 2037 and 2050, conventional technologies will be replaced by efficient technologies, such as lighting, air conditioning, and refrigerators, of around 70% and 90%, respectively.
	Cleaner cooking fuels	By 2050, 25% of households will use electricity for cooking, 5% will use improved biomass stoves, and the rest will use LPG stoves.
Commercial	Efficient appliances	Efficient lighting, air conditioning, refrigerators, and other office equipment will increase to 75% and 90%, respectively, in 2037 and 2050.
	RE promotion	By 2050, solar for heating systems in commercial buildings will increase to 5%.
Industrial	Efficient appliance	Replace conventional end-uses with high-efficiency technologies, such as lighting, space cooling, electric motors, and efficient boilers, by 75% by 2037 and 90% by 2050.
	RE promotion	By 2050, the share of RE in fuel utilization will be 40%.
Transport	Fuel economy	Efficiency will improve by 15% in 2037 and 25% in 2050 compared to the average fuel consumption of vehicles in 2018.
	Electric vehicle	In road transportation, the share of electric vehicles will be 30% in 2030 and 60% in 2050.
	Electric train	By 2050, the share of electric trains for rail passenger transport and rail freight transport will increase to 50% and 25%, respectively.
Power	Share of RE installed capacity	By 2050, the share of RE installed capacity will increase by 1.5 times compared to the share of RE in the PDP2018.

3.3.3 Net Zero Emissions 2050 (NZE) Scenario

This scenario is constructed to mitigate future GHG emissions through the employment of cross-sectoral energy efficiency enhancement and the promotion of optimal RE utilization. Furthermore, the integration of cutting-edge clean technologies, such as green hydrogen and CCS technology, is considered a major part of this scenario.

Green hydrogen is classified as an energy carrier with zero GHG emissions, and it is one of the alternative fuels, aside from renewable energy, to replace conventional fossil fuels in energy supply [47]. The scientific community is gradually acknowledging the role of hydrogen in energy systems, recognizing its potential for use as fuel in transport (light-duty and heavy-duty vehicles), industry (chemical, iron, and steel), and the power sector (co-fired generation with natural gas, fuel cells, and steam turbines) [48]. Therefore, hydrogen provides a promising opportunity for shifting towards clean energy systems. Nevertheless, the application of hydrogen in today’s energy sector is still limited due to the high cost of hydrogen production, particularly for green hydrogen from renewable energy electrolysis [49]. The International Renewable Energy Agency's (IRENA) study on green hydrogen technology and its cost found that this fuel can achieve cost-competitiveness by reducing the cost of renewable energy for electricity production and electrolysers, making green hydrogen an alternative fuel for fossil fuels in the coming decades [50].

CCS technology has been studied and confirmed to be a safe technology to capture, transport, and store carbon dioxide emissions released from fossil fuel-based industrial plants and power plants [51]. This technology has high potential, with a 90% efficiency in capturing CO_2 emissions [52]. Consequently, in the study of global net zero GHG emissions, this technology is essentially needed to offset the CO_2 emissions from industrial processes, fuel production, and power generation [49].

Therefore, the development of the NZE scenario measures is assumed as follows:

- **Residential sector:** By 2050, every household will be fully equipped with efficient appliances, and 80% of households will shift to utilizing electric cooking.
- **Commercial sector:** This sector is expected to fully utilize efficient technology by 2050, with the share of solar in heating systems increasing to 15%.
- **Industrial sector:** Every industry will be fully integrated with efficient technology by 2050. Besides this, coal utilization will be phased out in 2050, while the share of electricity utilization and renewable energy is assumed to increase to 40% and 45%, respectively. Green hydrogen fuel in the

industrial sector is assumed to be 2% in 2050. The rest of the fuel share will come from natural gas and oil products.

- **Transport sector:** The penetration of electric vehicles (EVs) will make up to 80% of the road transportation mode in 2050. Fuel economy efficiency will be assumed to improve by 50% compared to the current average fuel economy for internal combustion engine vehicles. The electric train is assumed to increase its share up to 50% for freight transport and 80% for passenger transport in the rail transportation mode.
- **Power Sector:** Under the NZE scenario, the electricity generation in Thailand will be estimated by using the least-cost optimization approach in the LEAP-NEMO model. Therefore, the installed capacity and electricity generation are simulated by allowing the NEMO to choose. However, there are some constraints that need to be set, such as the following: Renewable electricity sources will be utilized at maximum potential by 2050; coal electricity generation is gradually decreasing towards zero by 2050; green hydrogen in the industrial, transport, and power sectors is being considered after 2030; from 2030 onwards, natural gas-based power plants integrated with CCS technology will be deployed; by 2030, diesel and fuel oil power plants will be phased out; technology cost and fuel cost constraints are considered (see Table 2).

4. RESULTS AND DISCUSSION

4.1 Total Final Energy Consumption (TFEC)

The simulation REF scenario estimates that by 2050, the total final energy consumption (TFEC) would gradually grow to approximately 161 Mtoe, an estimated 2% average annual growth rate from 2018 (see Figure 2). By 2050, the industrial and transport sectors are projected to be the first and second largest energy absorbers of the TFEC, consuming 42% and 39%, respectively. The share of TFEC in the residential and commercial sectors would be 16%, while the other sectors consume the rest of the TFEC.

Energy consumption in the MA scenario shows a considerable drop across the study period in comparison with the REF scenario (see Figure 2) due to the implementation of more efficient technologies throughout energy systems. By 2050, total final energy consumption is estimated to be approximately 122 Mtoe, a 24% reduction compared to the REF scenario.

The full adoption of energy-efficient appliances across all sectors would result in shifting in TFEC across the nation, according to the findings from LEAP under the NZE scenario (see Figure 2). In comparison to the MA and REF scenarios, TFEC in the NZE scenario in 2050 shows an extreme reduction of 22% and 41%, respectively. In 2050, the industrial sector would remain the highest energy consumer, accounting for 49% of the TFEC, followed by the transport sector at approximately 27%. The commercial, residential, and other sectors would require 12%, 9%, and 3%, respectively, of energy use.

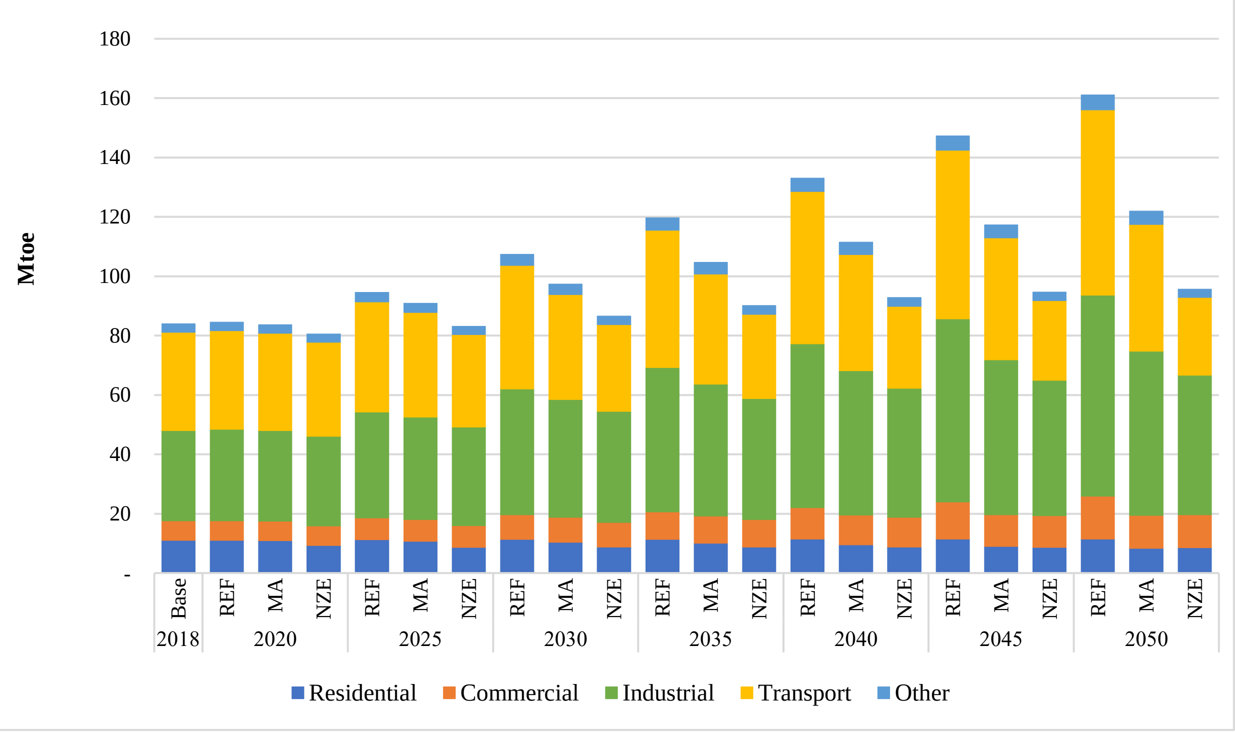

Fig. 2. Final energy consumption by sector.

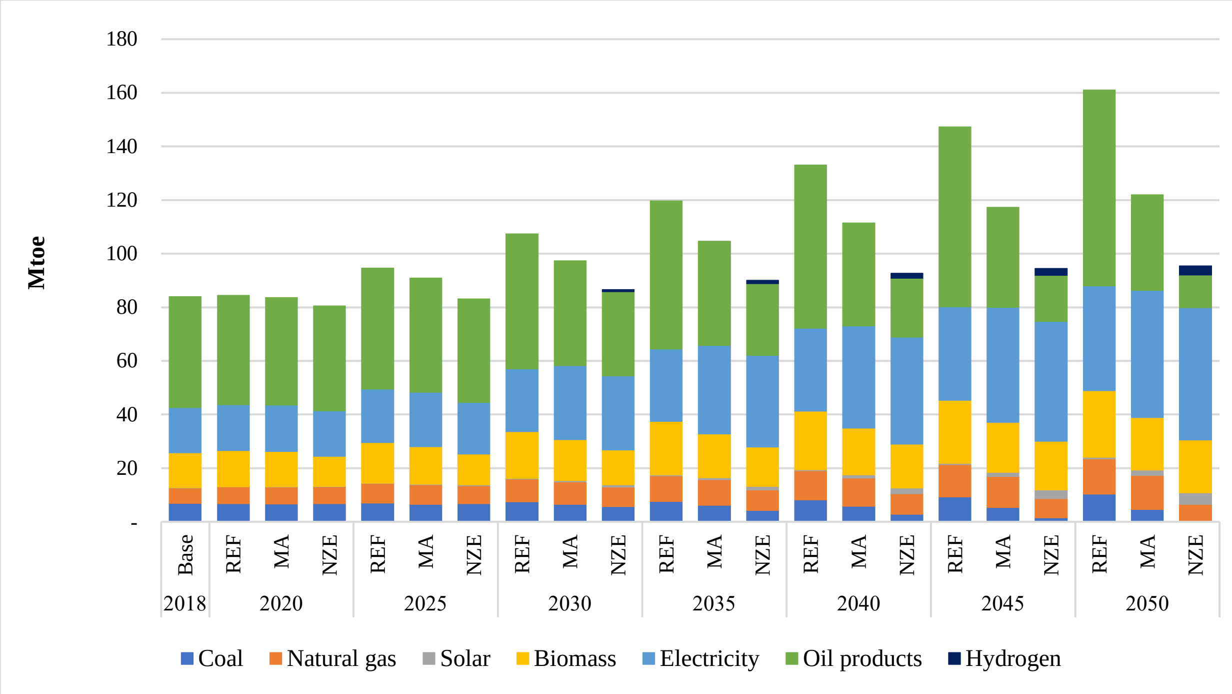

Fig. 3. Final energy consumption by fuel type.

Petroleum products in the REF scenario appear to dominate fuel utilization from 2018 to 2050 (see Figure 3). The increase in fuel consumption in the industrial sector and the growth of passenger and freight transport mainly lead to the substantial consumption of petroleum products. In 2050, oil consumption would account for 45% of the TFEC, whereas electricity, biomass, natural gas, and coal would account for 24%, 16%, 8%, and 6%, respectively. The utilization of other RE sources would be comparatively low.

The simulation results of fuel requirements in the MA scenario show that petroleum product use has a notable drop because of electric vehicle penetration in road transport, together with the increase of electrification use in all sectors (see Figure 3). By 2050, electricity demand is estimated to have the highest share, accounting for 39% of the TFEC, while oil utilization would reduce to 29%. Biomass, natural gas, and coal are expected to share 16%, 10%, and 4%, respectively. Other RE sources would increase to 2% in 2050 TFEC.

The increasing penetration of electric cars and the growth in electrification would cause a large reduction in oil utilization and an enormous increase in the use of electricity. Figure 3 shows that by 2050 electricity consumption in the energy sector would account for around 52% of the TFEC, followed by biomass (21%), natural gas (7%), oil products (13%), other RE (4%), and hydrogen (3%). By 2050, coal consumption would have entirely vanished from the energy mix.

4.2 Total Primary Energy Supply (TPES)

In the REF scenario, the total TPES shows an increase proportional to the increase in the TFEC from 110 Mtoe to 200 Mtoe between 2018 and 2050 (see Figure 4). Fossil fuels are projected to account for the largest proportion of the TPES in 2050, with a contribution from oil (37%), natural gas (23%), and coal (15%). Renewable energy sources in the TPES are estimated to share approximately 23% in 2050, mainly biomass and solar. The remaining share would originate from imported electricity.

The TPES in the MA scenario shows a lagging growth behind the REF scenario due to the higher energy savings (see Figure 4). The 2050 TPES would be 152 Mtoe, comprising natural gas, oil, biomass, solar, coal, imported electricity, and other RE, accounting for 26%, 24%, 18%, 13%, 10%, 4%, and 5%, respectively.

Since energy-efficient technology has been fully integrated into the demand and supply sides in the NZE scenario, the TPES shows slight changes between 2018 and 2050 (see Figure 4). The TPES in 2050 is estimated to be around 43% and 25% lower than that in the REF and MA scenarios, respectively. However, there will be a major shift in the primary fuel supply structure by 2050. With shares of 31% and 26%, respectively, solar and biomass have surpassed oil and natural gas as the two greatest shares in the TPES. 10% of the TPES would be shared by other renewable energy sources, and the use of coal would gradually disappear.

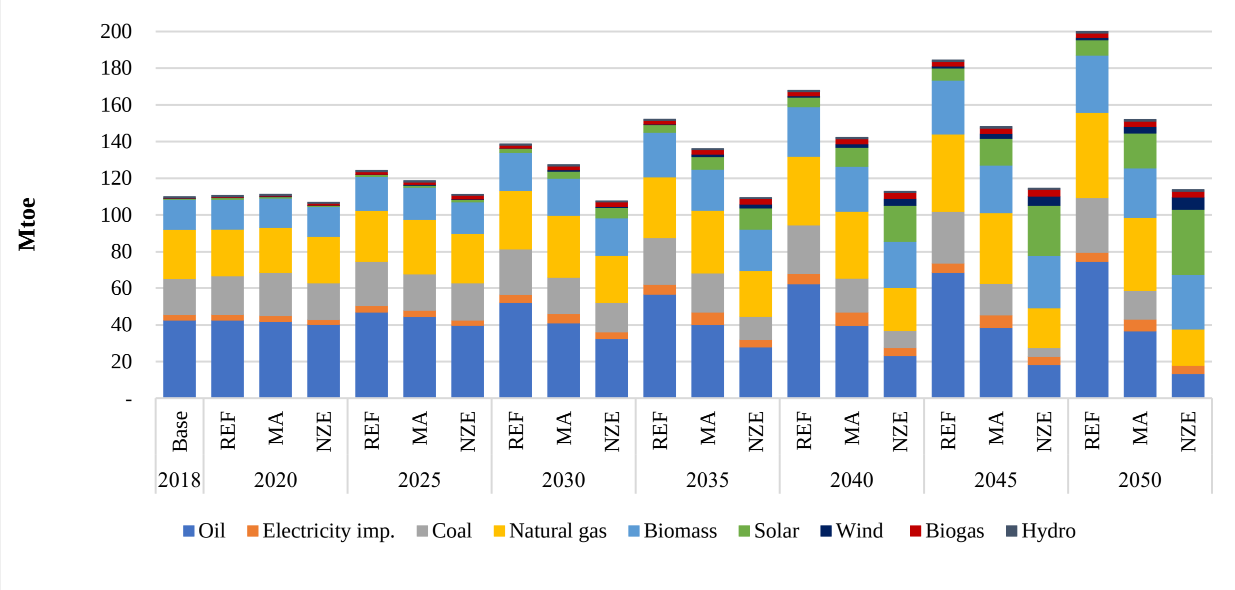

Fig. 4. Primary energy supply projections.

4.3 Electricity Generation

Electricity generation will increase at a rate of 2.74% per year, reaching approximately 485 TWh in 2050 from 208 TWh in 2018 (see Figure 5). 43% of total generation is projected to come from natural gas in 2050, maintaining the highest share of any source. RE sources in electricity production indicate a remarkable increase through the implementation of the PDP2018 plan of the government. In 2050, the share of RE generation will be 35%, while coal shares are expected to be 12%. The rest of the power production would originate from Lao PDR, Malaysia, and Myanmar.

In the MA scenario, total generation would increase greater than the generation in the REF scenario (see Figure 5); this is a result of increasing electricity utilization across sectors. By 2050, the total power generation is estimated to be 577 TWh. The share of RE generation is expected to be 55%, comprising 34% from solar, 9% from biomass, 7% from wind, 3% from biogas, and 2% from hydro. Natural gas and coal shares in electricity production show a steep decline to around 29% and 5%, respectively, in 2050.

Total power generation under the NZE scenario would greatly increase in comparison to the other scenarios (see Figure 5). In 2040 and 2050, total generation would be 2.37 and 3.17 times higher compared to the 2018 level of electricity production, respectively. The structure of the generation mix demonstrates a dramatic transition. Solar power is projected to contribute around 44% to the total generation mix in 2050. Wind, biomass, biogas, and hydro would account for 13%, 9%, 3%, and 2%, respectively, of the total generation in 2050. Natural gas would no longer have the highest share of power production, and coal electricity generation would drop to zero. In 2050, hydrogen-based electricity would account for 5% of the total generation, and 8% of power generation would originate from electricity imports.

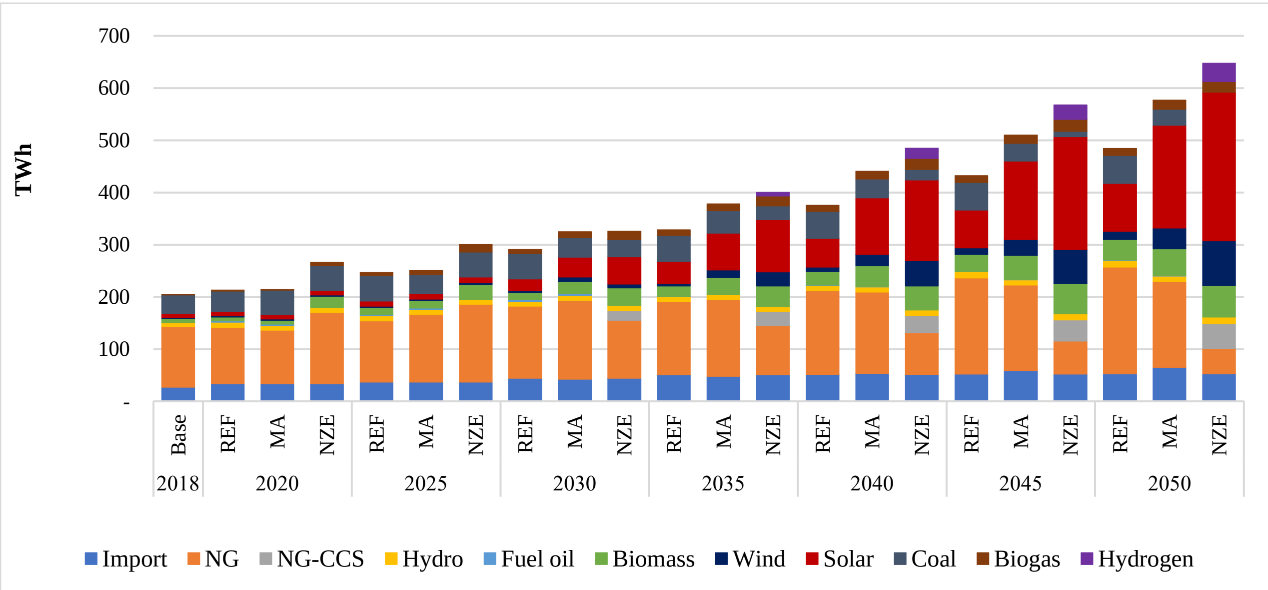

Fig. 5. Electricity generation by fuel type.

Fuel costs and the cost of power plant technology between 2018 and 2050 are the key parameters for determining the cost of electricity production. From the LEAP-NEMO simulation, the total cost of power generation in 2020 shows a significant difference between the NZE scenario and the other two scenarios because of the greater amount of electricity generation in the NZE scenario (see Figure 6). In 2030, the total cost between the NZE and MA scenarios shows a minor difference because the amount of generation is almost the same. By 2050, the total cost of electricity production is estimated to be approximately 38.02 billion USD, 38.54 billion USD, and 38.12 billion USD in the REF, MA, and NZE scenarios, respectively.

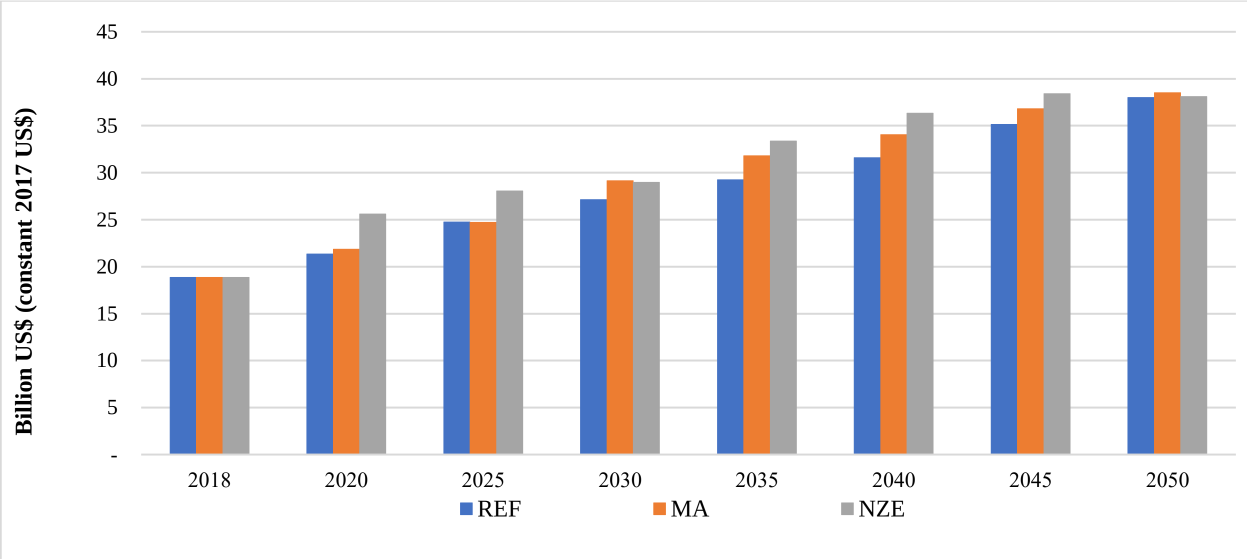

Fig. 6. Cost of electricity production.

4.4 GHG Emissions

Figure 7 illustrates the comparison of emissions levels from the three simulation scenarios. The estimation of GHG emissions employs emission factors from the Fifth Assessment Report (AR5) [46]. Total emissions including CO_2, CH_4 and N_2O in the REF scenario are forecasted to grow from 257 $MtCO_2eq$ in 2018 to 454 $MtCO_2eq$ in 2050. The transport, power, and industrial sectors would be the top GHG emissions contributors by emitting, respectively, 42%, 34%, and 19% of the 2050 total emissions.

In Figure 7, the total emissions in the MA scenario show a slight increase to around 286 $MtCO_2eq$ in 2035, then start slowly declining to around 266 $MtCO_2eq$ in 2050. The power sector is calculated to be the largest emitter of GHG, followed by the transport, industrial, building, and other sectors.

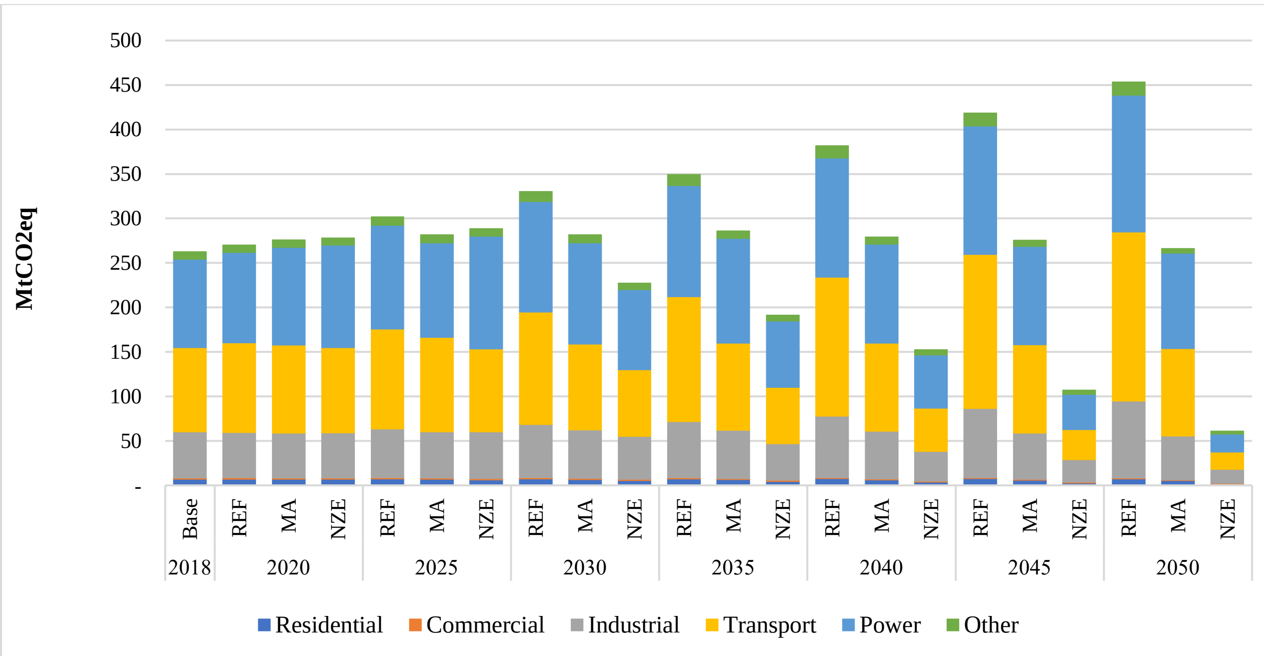

Fig. 7. Projections of GHG emissions.

Under the NZE scenario, the results from LEAP-NEMO calculations illustrate that the amount of GHG emissions would be increased to reach a peak level of 288 $MtCO_2eq$ in 2025. The total emissions are projected to shrink after 2025 to almost 61 $MtCO_2eq$ by 2050. The total emissions would consist of the power sector (33%), transport (32%), industrial (26%), building (3%), and other sectors (6%).

The possibility of reaching the zero level of emissions in Thailand is becoming visible with the combination of GHG emissions in the energy sector under the NZE scenario, together with the emissions projections in the agricultural sector, waste sector, Industrial Process and Product Use (IPPU) sector, and carbon sequestration provided by the Land-Use, Land-Use Change and Forestry (LULUCF) sector. The combined emissions and sinkage of GHG emissions between the agricultural and LULUCF sectors show that in 2050, the total remaining carbon removal is estimated to be 90 $MtCO_2eq$ [32]. The estimation of the waste and IPPU sector's emissions shows a gradual decrease based on the LT-LEDS report [8]. The total emissions from the waste and IPPU sectors would decline to approximately 11 $MtCO_2eq$ and 17 $MtCO_2eq$, respectively. Therefore, the country's net emissions would peak around 2025 at approximately 288 $MtCO_2eq$ and start dropping toward the neutrality level by 2050, as illustrated in Figure 8.

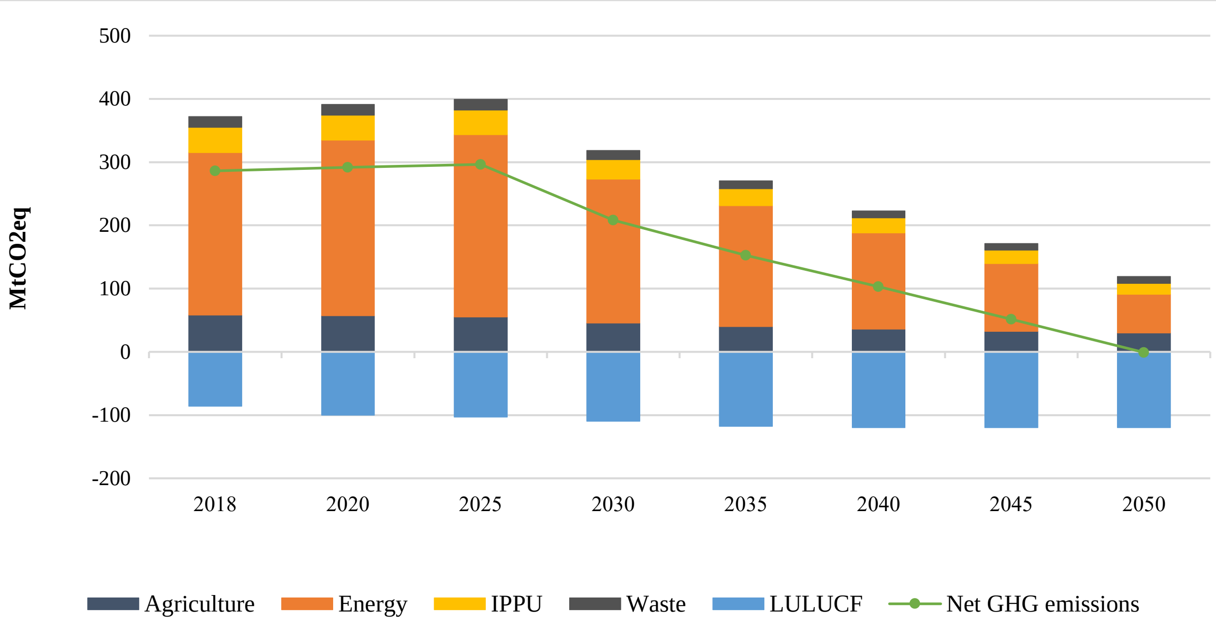

Fig. 8. Net emissions of GHG.

5. CONCLUSION AND POLICY SUGGESTIONS

The structure of energy utilization, GHG emissions, and the cost of electricity production in Thailand between 2018 and 2050 are carefully determined in this article. This study also implements GHG mitigation scenarios across sectors in the country to observe the possibility of GHG emissions elimination through the application of various low-carbon technologies. The key findings clearly indicate that the total emissions of GHG in the NZE scenario in Thailand would be reduced by 392 $MtCO_2eq$ and 266 $MtCO_2eq$, in comparison with the emissions in the REF and MA scenarios in 2050. Therefore, to reach the neutrality level of GHG, the LULUCF sector of the country would have a great impact by offering carbon sequestration to offset the remaining emissions from the atmosphere.

The great reduction of Thailand's total emissions in the NZE scenario would come from sectoral changes through different measures. The building sector contributes the lowest GHG emissions. However, this sector has a crucial impact on power generation based on its great amount of electricity utilization. Fully implementing efficient technology, increasing electrification, and using solar in heating systems could provide significant benefits for saving energy and minimizing GHG emissions. In addition, the industrial sector, which stands as one of the highest GHG emitting sectors, could be transformed by utilizing efficient electric appliances such as motors and boilers for lessening energy use, phasing out of coal as the primary fuel in heating, expanding electrification, increasing the utilization of solar and biomass, and deploying green hydrogen as fuel in industries. Furthermore, the application of electric vehicles, the utilization of clean hydrogen in vehicles, and mode-shifting from private to mass transportation would be the keys to abating not only GHG emissions but also other harmful gases. Moreover, the principal ways to alleviate a great amount of the power sector's emissions would originate from the crucial transformation with the rapid and extensive adoption of renewable energy, the elimination of coal in electricity production, the integration of CCS technology into natural gas-based power plants, and clean hydrogen-based power generation.

In conclusion, achieving net-zero GHG emissions is possible, but it would require a combination of cross-sectoral energy transitions. Therefore, policymakers should strengthen the mitigation strategies for accelerating and promoting clean technologies to their maximum potential. Decreasing use of fossil fuels, eliminating use of coal, and raising carbon prices to increase interest in renewable energy should urgently be considered.

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