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Energy System Transformation to Net Zero CO_2 Emissions 2050 in Selected GMS Countries

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ABSTRACT

The energy sector in the selected Greater Mekong Subregion (GMS) countries, namely Cambodia, Lao PDR, Thailand, and Vietnam, was responsible for around 84% of total CO_2 emissions (equivalent to 423.16 $MtCO_2$) in 2015. Without the intervention of climate change mitigation actions, the emissions of CO_2 from energy systems would be tremendously increased. Nevertheless, only Thailand appears to have clear targets for reaching carbon neutrality by the mid-21st century. This study investigates the possibility of energy system transformation to reach net-zero CO_2 emissions in 2050 in the selected nations. The Net-Zero-Emission (NZE) scenario is built as a CO_2 mitigation countermeasure to the reference scenario. Results show that to reach the goal of decarbonized energy systems in the NZE scenario, efficient and advanced technologies must be used on both the demand and supply sides to reduce around 41% of the final energy demand, and at least 81% of all electricity must be generated by renewable energy. Additionally, the application of advanced low-carbon technologies, including carbon capture and storage in the coal, natural gas, and bioenergy industries and power generation in cooperation with the utilization of electric vehicles in the transport sector, are the key measures for attaining carbon neutrality.

1. INTRODUCTION

Climate change causes widespread impacts on ecosystems, including the scarcity of water and agricultural products, the increase of sea levels, effects on human health and other aspects of life, and damage to infrastructure. The main driving force behind global warming is anthropogenic greenhouse gas (GHG) emissions. Owing to the drastic increase in energy consumption, the total net human induced GHG emissions between 1990 and 2019 increased from 38 gigatons of carbon dioxide equivalent ($GtCO_2eq$) to 59 $GtCO_2eq$, based on the "6th Assessment Report (AR6)" of the "Intergovernmental Panel on Climate Change (IPCC)". The main causes of emissions, which make up about 78% of all emissions, are the combustion of fossil fuels and industrial processes [1].

Looking into the energy systems in the selected Greater Mekong Subregion (GMS) countries, the report of final energy consumption clearly shows that the consumption of energy increased by 4.20% annually from 97.75 million tons of oil equivalent (Mtoe) in 2005 to 138.66 Mtoe in 2015. Of the amount of energy demand in 2015, the consumption of fossil fuel sources (petroleum products, natural gas, and coal) accounted for 58%, while biomass and electricity supply were 23% and 19%, respectively [2]–[5]. Besides this, the selected GMS countries generated a total power generation of around 186.81 TWh in 2005, and it increased twice as much to around 356.28 TWh in 2015. In 2015, electricity generation mainly relied on natural gas as the main source, which accounted for 49.22%, followed by coal (26.35%), and hydro (21.21%), while electricity production from other renewable energy sources (RE) was very low and reported to be 2.88%, and the remaining share came from petroleum products (0.34%). [3], [6]–[8]. The four countries emitted CO_2 emissions, excluding the land use, land-use change, and forestry (LULUCF) sector, into the atmosphere from 345 $MtCO_2$ to 504 $MtCO_2$ between 2005 and 2015, with a 4.61% annual average growth rate [9]–[12]. In 2015, the energy sector alone produced around 84% of total CO_2 emissions. This is due to countries' steadfast reliance on fossil fuels for demand-side energy requirements and electricity generation. Without the intervention of energy policies and climate mitigation actions, CO_2 emissions would be tremendously elevated in the next few decades. Hence, the four selected countries' energy systems should have been transiting to mitigate the emissions to align with the Paris Agreement's target.

Outside the selected nations, there are numerous studies that mention the pathway to decarbonize the energy system for attaining the Paris Agreement as well as reaching carbon neutrality by the middle of the

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twenty-first century. Zhou *et al.* [13] investigated how the energy transition pushes China to line with Paris Agreement's objective via RE utilization in final energy consumption and RE electricity generation. Vats and Mathur [14] conducted research relative to the decarbonization of India's energy sector to reduce carbon emissions through significant increases in the use of electricity, improvements in energy efficiency, and a transition to cleaner fuel sources such as green hydrogen and bioenergy. Furthermore, Oshiro, Masui, and Kainuma studied the rapid transition in the structure of energy in Japan and succeeded in reaching zero cumulative emissions by 2050 [15].

In the ASEAN region, many scholarly articles have discussed the plausibility of reaching 2050 net-zero emissions of greenhouse gas in the energy system, particularly in the power sector [16]–[18]. An article from Lau [19] found that to decarbonize the energy system ASEAN countries would require transitions on both the demand and supply sides, including switching from conventional fossil fuel-based to RE-based power plants, the industrial and power sectors integrating carbon capture and storage technology, and utilizing electric vehicles (EVs) in transportation.

There have been several research studies investigated in the individual selected GMS countries with a focus on reducing energy sector emissions. In Cambodia, Lyheang and Limmeechokchai investigated the potential CO_2 reduction in the power sector with the integration of domestic RE sources and the application of CCS in coal-based generation [20]–[21]. In Lao PDR, Phoualavanh and Limmeechokchai determined how electric vehicles (EVs) and biofuels help reducing consumption of energy in the transport sector and mitigate emissions of CO_2 in Lao PDR towards 2030 [22]. For Thailand, many research studies examined the possibility of reaching carbon neutrality in the mid-21st century by greatly promoting the deployment of RE and considerably reducing the energy demand [23]–[24]. As a result, Thailand would be able to attain carbon neutrality by 2050 with an increase in RE in the final energy demand of around 33.5%. In the case study of Vietnam, research has been conducted to illustrate the emissions pathway to reach a neutral level of emissions by mid-century [25].

There are some scientific papers that propose exploration in the selected GMS countries regarding energy system transformation to alleviate GHG emissions. Recently, Dul and Limmeechokchai [26] conducted a study regarding the possibility of achieving the NDC in the chosen four countries located in the Greater Mekong Subregion through the integration of domestic renewable energy sources. Furthermore, the decarbonized power sector in the four selected nations through the application of RE and energy efficiency (EE) improvements is investigated by [27]. The study further illustrated the emissions gap between the four selected nations to accomplish the Paris Agreement's objective. In addition, another study looked at how electric vehicles (EVs) and biofuels could help reduce CO_2 in road transportation by 2030 in the same countries [28]. In the high-ambition EV scenario, 148.25 $MtCO_2$ could be saved by using EVs and biofuels.

Most previous research articles carried out in the chosen GMS nations focus exclusively on sub-sectors of the energy systems and primarily analyze the individual nations and achieving the "Nationally Determined Contribution" levels. Additionally, none of these have discussed the co-benefit analysis and energy security of the reduction of greenhouse gas or carbon dioxide emissions. On the other hand, the potential of achieving zero carbon emissions in the energy sector by 2050 was only mentioned in a case study of Thailand. The other three chosen nations remain in question. Therefore, this research article provides the new ideas of transforming the energy systems to attain net-zero CO_2 for the chosen GMS countries in 2050 by enhancing the ambition of renewable energy (RE) promotion and energy efficiency (EE) improvement above. The LEAP model is being used to build a countermeasures scenario, known as the "Net-Zero-Emission (NZE)" scenario, to examine the outcome of future energy demand, electricity generation mix, and carbon dioxide emissions between 2015 and 2050. The co-benefits and energy security are also considered in this article of research.

2. ENERGY POLICIES AND CLIMATE CHANGE MITIGATION POLICIES IN THE FOUR CHOSEN COUNTRIES

2.1 Energy Policies

To succeed in the sustainability of energy usage and supply, the governments of the four nations cooperated with policymakers and other organizations to construct their respective energy master plans for enhancing energy efficiency and improving renewable energy utilization based on their domestic potential.

The Cambodia's government formulated the energy conservation master plan known as the "National Policy, Strategy, and Action Plan on Energy Efficiency," which aims to cut down 25% of total energy consumption in 2035 compared to the baseline scenario. Electricité du Cambodge developed the power development plan for 2030. The target for installed RE capacity for electricity generation (excluding hydropower) would be 12.85% in 2030, while the capacity of hydropower plants would be 11.36% [29]–[30].

The government of Lao PDR set the goal of elevating the consumption of RE in the energy sector up to 30% by 2025. Furthermore, the power development plan of Lao PDR indicates that the country would achieve 100% electrified households in 2030 and promote the application of RE (excluding hydropower) to generate at least 5% of total power generation in 2030, whereas the electricity generated by hydropower would be 65%, with the remaining coming from coal-based power plants [31].

In Thailand, the "Alternative Energy Development Plan 2018–2037 (AEDP2018)" aims to promote the utilization of RE up to 30% of the total final energy demand in 2037 [32]. Inclusively, the new target for installed RE capacity in the "Power Development Plan

2018–2037 (PDP2018)" would increase from 17.29% in 2019 to 34.23% in 2037 [33]. Furthermore, under the energy conservation master plan, known as the "Energy Efficiency Development Plan (EEP2018)", the total energy intensity is expected to be reduced by 30% in 2037 compared to the 2010 level [34].

The Ministry of Industry and Trade developed the Vietnam renewable energy master plan with the goal of achieving 32.3% of RE in the total primary supply in 2030 and 44% of RE in 2050 [35]. In addition, the electricity generation from RE (including hydropower) would increase by up to 32% in 2030 and by 43% by 2050. Besides this, the national program on energy efficiency between 2019 and 2039 indicated that the total cross-national energy demand would decrease by 8–10% in 2030 compared to the baseline case [36].

2.2 Climate Change Mitigation Policies

2.2.1 Nationally Determined Contributions (NDCs)

The government of Cambodia developed an updated version of the NDC by strengthening the reduction targets for GHG emissions towards 2030 [37]. According to the NDC scenario, there would be a 64.5 $MtCO_2eq$ reduction in greenhouse gases by 2030 when compared to the baseline scenario's cumulative emissions.

Lao PDR set up the new GHG mitigation plan through the updated version of the NDC. In the new climate mitigation report, there are two countermeasure scenarios, such as unconditional (U-NDC) and conditional (C-NDC) scenarios, which aim to decrease 41.5 $MtCO_2eq$ and 80.7 $MtCO_2eq$ of GHG emissions compared to the BAU scenario in 2030, respectively [38].

In the latest updated NDC of Thailand, the overall 2030 GHG emissions of the country are estimated to reach 555 $MtCO_2eq$ in the baseline scenario [39]. Compared to the baseline scenario's emissions, the unconditional NDC would reduce total GHG emissions by 166.50 $MtCO_2eq$ and the conditional NDC by 222 $MtCO_2eq$.

The latest edition of GHG mitigation in Vietnam submitted to the UNFCCC in 2022 indicates the new level of GHG reduction would be increased to around 146 $MtCO_2eq$ under the unconditional NDC, while the GHG mitigation target increases up to 404 $MtCO_2eq$ compared to the BAU scenario [40].

Table 1. GHG mitigation in 2030 in the updated NDC.

Sector	Cambodia	Lao PDR	Thailand	Vietnam
Agriculture	6.2	1.28	2.88-3.84	12.4-50.9
Energy	13.7	28.8-34.0	163-217	64.8-227
IPPU	5.9	-	0.9-1.2	27.9-49.8
Waste	0.6	0.4	-	8.7-29.4
LULUCF	38.1	11.0-45.0	-	32.5-46.6
Sub-Total	64.5	41.5-80.7	167-222	146-404
Total	419-771			

Unit: $MtCO_2eq$
Note: IPPU = Industrial Process and Product Use. LULUCF = Land-Use, Land-Use-Changed, and Forestry.

2.2.2 Long-term low emissions development strategies

The latest GHG mitigation communication from Cambodia, which is submitted to the UNFCCC, is known as the "Long-term Low Emissions Development Strategies (LT-LEDS)". To achieve "net zero" emission levels by the middle of the century, the energy sector's emissions must be diminished by around 54.30 $MtCO_2eq$ compared to the BAU scenario. Also, the non-energy sector, including the IPPU, waste, and agriculture sectors, must eliminate a great deal of GHG emissions, around 30 $MtCO_2eq$, in 2050. Additionally, the LULUCF sector in this country would provide at least 50 million tons of carbon dioxide sequestration [41].

Besides this, the Ministry of Environment and Natural Resources of Thailand, in cooperation with policymakers, has built a long-term strategy for GHG mitigation, namely LT-LEDS. The report indicates that Thailand would be able to achieve net-zero CO_2 emissions by 2050 if and only if the energy sector and the non-energy sector cut down the CO_2 emissions of around 438.70 $MtCO_2$ together and the LULUCF sector delivers 120 $MtCO_2$ removal by 2050 [42].

Table 2. GHG mitigation in 2050 in Cambodia's LT-LEDS.

Sector	Emissions reduction in LT-LEDS scenario	Emissions remaining in LT-LEDS scenario
Agriculture	15.60	19.30
Energy	54.30	28.20
IPPU	9.10	1.60
Waste	5.30	1.20
LULUCF	71.40	-50.20
Total	155.6	0.30

Unit: $MtCO_2eq$

Table 3. CO_2 mitigation in 2050 in Thailand's LT-LEDS.

Sector	Emissions reduction in LT-LEDS scenario	Emissions remaining in LT-LEDS scenario
Agriculture	0.21	0.50
Energy	436.19	95.50
IPPU	1.20	23.80
Waste	0.11	10.80
LULUCF	20.00	-120.00
Total	458.70	0.00

Unit: $MtCO_2$

3. METHODOLOGY

3.1 Structure of LEAP Model in the Study

Low Emissions Analysis Platform (LEAP) is an energy and environment analysis tool created by the Stockholm Environmental Institute [43]. Figure 1 identifies the general configuration of the LEAP software. The resources branch contains different types of fuels. Energy consumption is clearly associated with socio-economic aspects such as GDP, population, household numbers, *etc*. Inside the technological data hierarchy, there are end-use technologies (lighting, electric motors, boilers, etc.) that consume different types of fuels (electricity, gasoline, liquid petroleum gas, etc.) at different energy intensities. The transformation consists of oil refining, coal mining, electricity generation, etc. The electricity generation area comprises the installed capacity of different types of power plants, merit order, load factor, loss, historical data, and others. The demand side includes different sectors such as residential, commercial, industrial, transport, and others. Three types of results, including energy demand, electricity generation, and CO_2 emissions, are being focused on in this research work.

The energy consumption in the LEAP analysis tool is calculated as indicated in Equation 1 [43].

$$E = EI \times ActivityData \tag{1}$$

The CO_2 emission in this analysis software is determined by the product of energy consumption (E) with the emission factor (EF) as shown in Equation 2 [43].

$$CO_2 Emissions = E \times EF \tag{2}$$

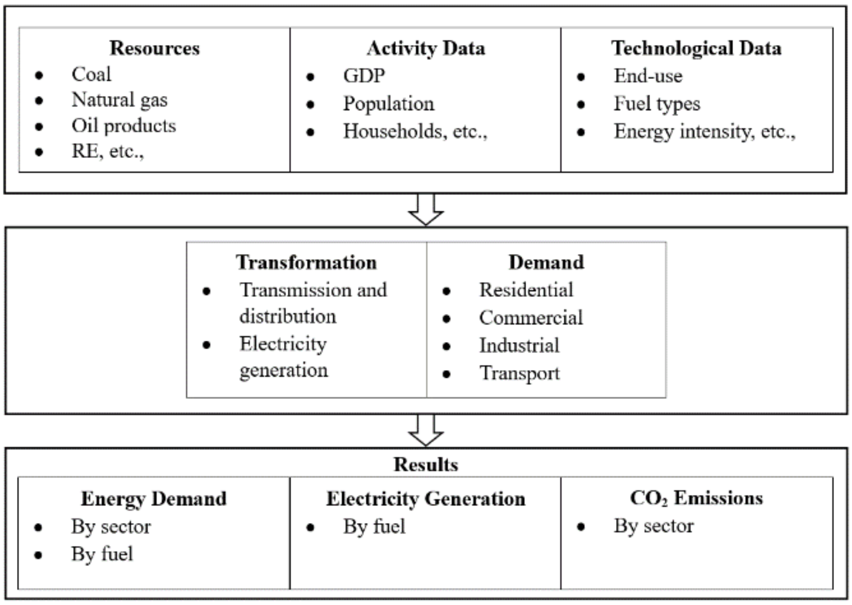

Fig. 1. General structure of the LEAP Model in this study.

3.2 Data and Assumption

The important data and information are collected from various sources, as shown in Table 4.

Due to some limitation of information, there are key assumptions to be made, such as 2015 is selected as the base year due to the data availability of the four countries; the study analyzes only the energy sector; the results indicate only final energy demand, power generation, as well as CO_2 emissions; the energy consumption in the Business-as-Usual (BAU) scenario is estimated by using GDP elasticity as presented in Equation (3) [26]; the GDP elasticity is determined by the log-linear regression model as shown in Equation (4) [26]; and the CO_2 emissions and CO_2 sequestration from other sectors (agriculture, IPPU, waste, and LULUCF sector) are taken and assumed from the NDC and LT-LEDS reports in each selected country.

$$E_t = \left(\frac{GDP_t}{GDP_{2015}}\right)^{\beta} \times E_{2015} \quad (3)$$

$$log(E_t) = \beta \times log(GDP_t) + \alpha \quad (4)$$

Where the energy demand in year t is E_t, the GDP in year t is GDP_t, GDP elasticity of energy consumption is β, and constant elasticity is α.

Table 4. Data and sources of information.

Type of data	Sources of data
Historical data of population, household, and GDP	World Bank, National Institute of Statistics (NIS) of Cambodia, Laos Statistics Bureau, National Statistics Office (NSO) of Thailand, General Statistics Office (GSO) of Vietnam
Historical energy consumption (by sectors and by fuel types)	Ministry of Mines and Energy (MME) of Cambodia, Ministry of Energy and Mines (MEM) of Laos, Department of Alternative Energy Development and Efficiency (DEDE) of Thailand, and Ministry of Industry and Trade (MoIT) of Vietnam
Historical of electricity generation and installed capacity	Electricity Authority of Cambodia (EAC), Electricité du Laos (EDL), Energy Policies and Planning Office (EEPO) of Thailand, and Electricity of Vietnam (EVN)
Energy policies	Ministry of Mines and Energy (MME) of Cambodia, Ministry of Energy and Mines (MEM) of Laos, Department of Alternative Energy Development and Efficiency (DEDE) of Thailand, and Ministry of Industry and Trade (MoIT) of Vietnam
Climate change mitigation policies	Ministry of Environment of Cambodia, Ministry of Natural Resources and Environment of Laos, Thailand, and Vietnam
GDP projections	International Macroeconomic Data Set. Economic Research Service, U.S. Department of Agriculture.
Population projections	United Nations.

3.3 *Description of the Business-As-Usual Scenario*

- **Population:** In 2015, the total population in the four countries was 183.65 million people, whereas the population in Cambodia, Lao PDR, Thailand, and Vietnam was 15.52 million, 6.74 million, 68.71 million, and 92.68 million, respectively. In 2050, the total population is projected to be 20.35 million in Cambodia, 9.75 million in Lao PDR, 70.06 million in Thailand, and 107 million in Vietnam (see Table 5). From 2015–2050, the annual average growth rate of the population of Cambodia would be 0.78%, Lao PDR (1.06%), Thailand (0.06%), and Vietnam (0.41%) [44].

Table 5. Projection of population.

Country	2015	2030	2050	CAGR [%]
Cambodia	15.52	18.30	20.35	0.78
Lao PDR	6.74	8.28	9.75	1.06
Thailand	68.71	71.85	70.06	0.06
Vietnam	92.68	102.48	107.00	0.41
Total	183.65	200.91	207.16	0.35

Unit: million people

Note: CAGR = Compound Average Growth Rate

- **GDP growth:** In the base year, Cambodia had a total GDP of 18.05 billion USD, Lao PDR had 14.43 billion USD, Thailand had 401.30 billion USD, and Vietnam had 239.26 billion USD. The compound average GDP growth rates from 2015 to 2050 for Cambodia is 5.34%, Lao PDR is 5.10%, Thailand is 3.47%, and Vietnam is 5.38% [45]. In 2050, the total GDP is projected to be 111.01 billion USD for Cambodia, 82.12 billion USD for Lao PDR, 1,316.60 billion USD for Thailand, and 1,494.85 billion USD for Vietnam. Table 6 shows the projection of GDP for the four selected countries.

Table 6. Projection of GDP.

Country	2015	2030	2050	CAGR [%]
Cambodia	18.05	39.99	111.01	5.34
Lao PDR	14.43	29.99	82.12	5.10
Thailand	401.30	618.48	1,316.60	3.47
Vietnam	239.26	579.36	1,494.85	5.38
Total	673.03	1,267.82	3,004.57	4.38

Unit: billion USD

- **Household numbers:** In 2015, the number of households in Cambodia was around 3.31 million; in Lao PDR it was 1.18 million; in Thailand it was 22.17 million; and in Vietnam it was 25.05 million [46]–[49]. The household numbers of each country are extrapolated from the historical data by using a linear regression model with household numbers as the dependent variable and population as the independent variable. As a result, in 2050, the total number of households in the four countries would be 6.07 million, 2.43 million, 35.02 million, and 36.29 million, respectively.
- **GDP elasticity:** By using historical data between

2005 and 2015 of energy consumption and the total GDP of the four countries to evaluate a log-log linear regression model, the calculated GDP elasticity would be 1.34 for Cambodia, 0.80 for Lao PDR, 0.85 for Thailand, and 0.88 for Vietnam.

3.4 Description of the Net-Zero-Emission Scenario

This scenario aims to significantly lower CO_2 emissions from the energy system. In this scenario, all economic sectors are prioritized by improving energy efficiency (EE) and the potential for renewable energy (RE) sources. This scenario gathers the most recent information on existing technologies to lower CO_2 emissions. In addition, this scenario will combine advanced technology, such as the integration of industries and power plants with carbon capture and storage (CCS) in the industrial and power sectors, with the utilization of electric vehicles (EVs) to replace internal combustion engine vehicles.

3.4.1 NZE scenario in the residential sector

The NZE scenario implementation in this sector is shown as follows:

- The penetration of efficient end-uses such as LED, COP-8 refrigerators and air conditioners, improved biomass cookstoves, and other technologies will increase to 50% in 2030 and 100% in 2050.
- In 2050, the utilization of biogas cookstoves will gradually increase by 25% in Cambodia, Lao PDR, and Vietnam, and will increase to 30% in Thailand.
- In 2050, the application of electric cooking will be greatly increased, reaching 40% in Cambodia and Lao PDR and 50% in Thailand and Vietnam.

3.4.2 NZE scenario in the commercial sector

The NZE scenario in this sector is illustrated as follows:

- Inefficient technologies (lighting, space cooling, and others) will be replaced by efficient ones up to 50% in 2030 and fully replaced in 2050.
- In 2050, the application of biogas in heating services will gradually increase by 25% in Cambodia, 30% in Lao PDR, 35% in Thailand, and 35% in Vietnam for all commercial buildings.
- In 2050, the utilization of solar heating in commercial buildings will increase to 10% in Cambodia and Lao PDR, 30% in Thailand, and 20% in Vietnam.

3.4.3 NZE scenario in the industrial sector

The description of the NZE scenario in the industrial sector is indicated as follows:

- 50% of conventional technologies (electric motors, lighting, boilers) will be replaced by efficient end-uses in 2030 and fully replaced in 2050.
- In 2050, the utilization of other RE (biomass and solar) for heating services will increase to 55% in Cambodia, 40% in Lao PDR, 60% in Thailand, and 70% in Vietnam.
- The deployment of CCS technology in the coal, natural gas, and bioenergy-based industries will start in 2030. In 2050, coal and natural gas-based industries will be installed with CCS technology up to 30%, while bioenergy-based industries will be fully equipped. The efficiency of CCS in capturing the CO_2 emissions is said to be 90% [50].

3.4.4 NZE scenario in the transport sector

The energy transformation in the transport sector under the NZE scenario is shown as follows:

- Fuel economy efficiency for internal combustion vehicles will gradually improve by 50% in 2050.
- The application of EV in road passenger transportation in Cambodia will increase to 50%, Lao PDR to 50%, Thailand to 80%, and Vietnam to 85% in 2050.
- In 2050, the utilization of EV in road freight transportation will be 10% in Cambodia, 5% in Lao PDR, 20% in Thailand, and 30% in Vietnam.
- In 2050, shifting from road to rail transportation modes in Cambodia will increase by up to 10%, in Lao PDR by 15%, in Thailand by 20%, and in Vietnam by 25%.

3.4.5 NZE scenario in the power sector

The implementation of the NZE scenario in the power sector is denoted as follows:

- The losses in transmission and distribution (T&D) system in all selected nations will gradually decline to 5% in 2050.
- The installed capacity of RE (biomass, solar, and wind) in the four countries will significantly increase to 30% in Cambodia, 14% in Lao PDR, 69% in Thailand, and 74% in Vietnam by 2050.
- Coal-based power generation in Cambodia, Thailand, and Vietnam will be phased out in 2050.
- CCS technology will be implemented in coal, natural gas, and bioenergy-based power plants by 2030. In 2050, coal and natural gas-based power generation will be installed with CCS technology up to 30%, while bioenergy-based power generation will be fully equipped.

4. RESULTS AND DISCUSSION

4.1 Energy Demand

4.1.1 Energy demand in Cambodia

According to the results of the BAU scenario, Cambodia's total final energy consumption (TFEC) would be nearly sevenfold and increase from 3.53 Mtoe in 2015 to 23.77 Mtoe in 2050, as shown in Figure 2. The TFEC in residential, commercial, industrial, transportation, and other sectors is expected to reach roughly 3.63 Mtoe, 2.70 Mtoe, 5.36 Mtoe, 10.77 Mtoe, and 1.31 Mtoe, respectively, in 2050. In the NZE scenario, overall energy consumption would be conserved during the study period due to the use of highly efficient technology across sectors. In 2050, Cambodia's TFEC would be 38.71% lower than in the baseline scenario. The TFEC in 2050 is expected to be 14.57 Mtoe, with the transportation sector consuming most of it (41.90%), followed by the industrial (24.40%), the residential (14.26%), the commercial (12.15%), and other sectors (6.28%).

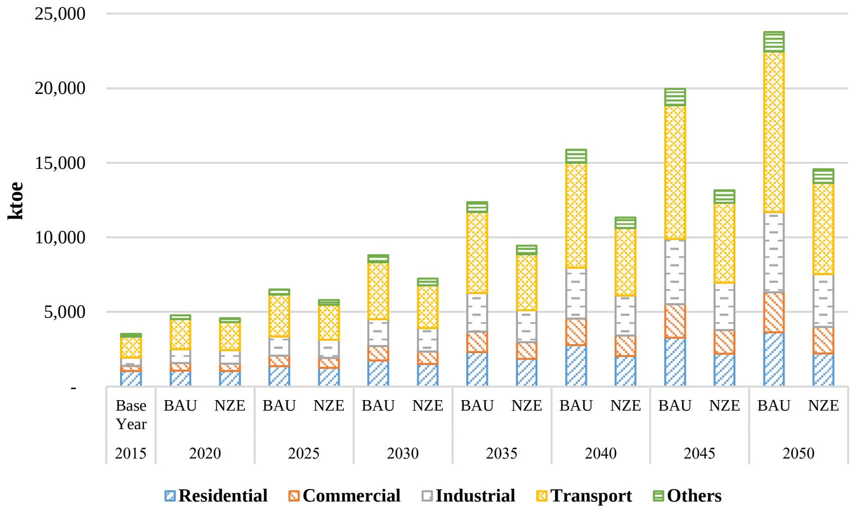

Fig. 2. Sectoral energy consumption in Cambodia.

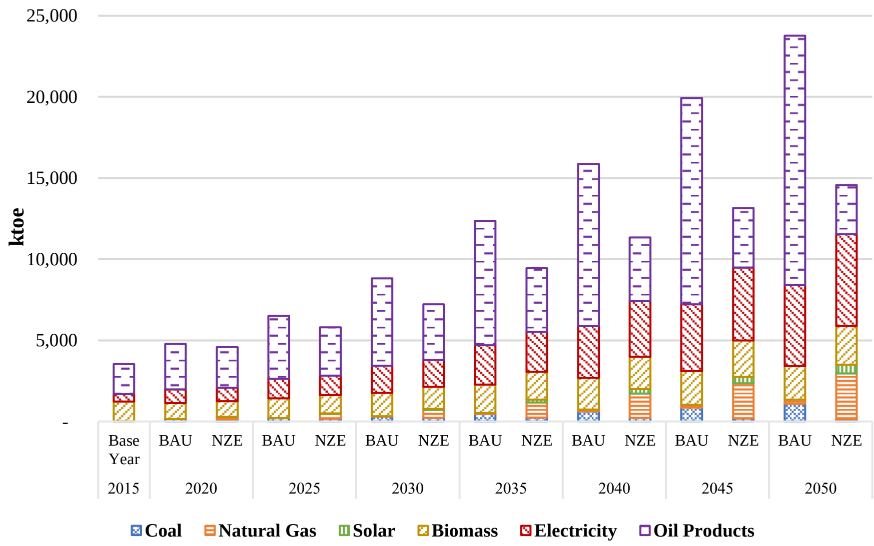

Fig. 3. Energy consumption in Cambodia by fuel type.

The results show that the structure of energy system in Cambodia is primarily dependent on oil products, with electricity, biomass, coal, and natural gas coming in the second and the third, respectively, under the BAU scenario in terms of final energy consumption by type of fuel. In 2050, the requirements for petroleum oil, electricity, biomass, coal, and natural gas are projected to be 15.36 Mtoe, 5.00 Mtoe, 2.06 Mtoe, 1.08 Mtoe, and 0.27 Mtoe, respectively (see Figure 3). Conversely, in the NZE scenario, the final energy demand from petroleum oil would be heavily reduced because of the utilization of EV in the transport sector, increasing the electrification rate across sectors, and transiting to utilize RE. Of the amount of TFEC in 2050 in the NZE scenario, the share of oil products, electricity, biomass, solar, natural gas, and coal is estimated to be 20.83%, 38.77%, 16.45%, 3.61%, 19.54%, and 0.81%, respectively.

4.1.2 Energy demand in Lao PDR

The energy consumption in Lao PDR shows a remarkable increase under the BAU scenario. Between 2015 and 2050, the TFEC would grow from 3.12 Mtoe to 10.55 Mtoe. The transport sector would consume about 39% of the total energy demand in 2050, with industrial (32%), residential (21%), commercial (7%), and other sectors (1%) following. However, under the NZE scenario, with the introduction of energy efficiency improvement technologies in all energy systems together with other advanced technologies such as EV, overall energy demand in the country would be reduced to 6.31 Mtoe in 2050, coming from the residential sector (1.42 Mtoe), commercial sector (0.48 Mtoe), industrial sector (2.22 Mtoe), transport sector (2.11 Mtoe), and other sectors (0.07 Mtoe) (see Figure 4).

By 2050, regarding the share of fuel in the final energy demand, Lao PDR's TFEC in the BAU scenario would consume 47% petroleum products, 26.22% electricity, 14.57% coal, and 12.21% biomass. Looking into the results in the countermeasures scenario, the demand of electricity would grow to 39.86%, followed by biomass (20.06%), oil products (16.39%), natural gas (16.02%), coal (5.46%), and solar (2.21%). The energy consumption by fuel type in Lao PDR in both scenarios is demonstrated in Figure 5.

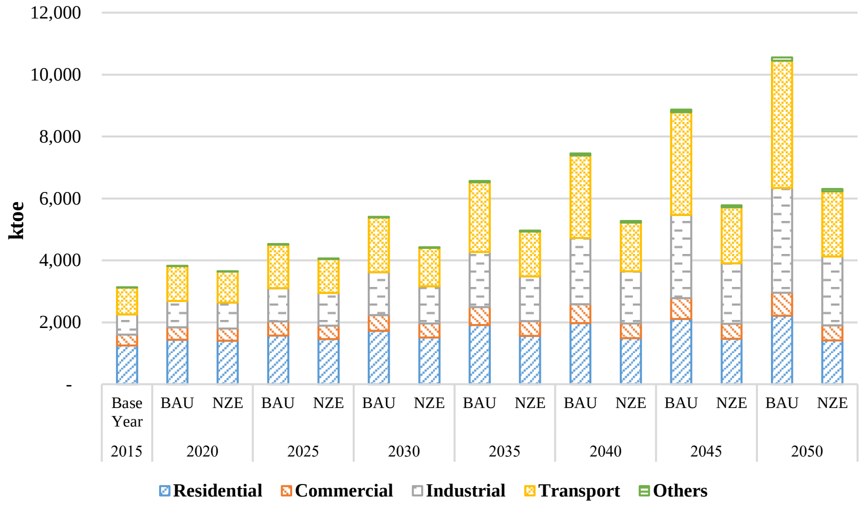

Fig. 4. Sectoral energy consumption in Lao PDR.

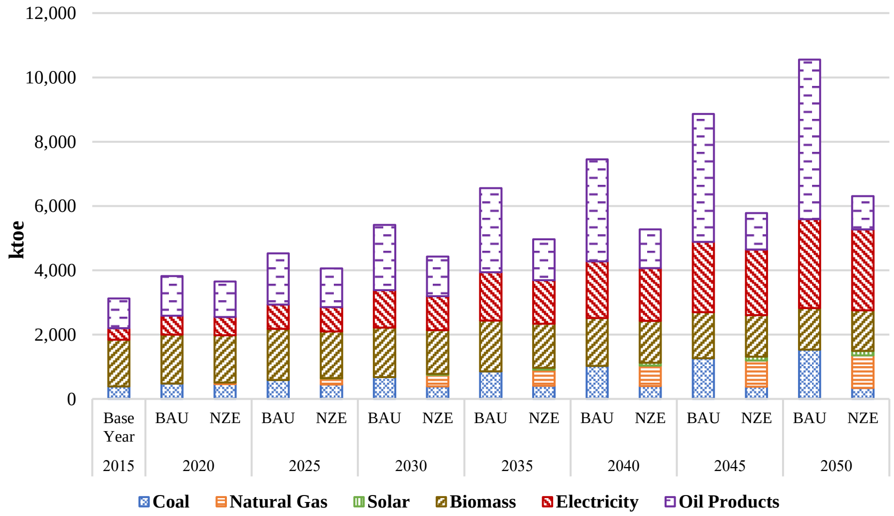

Fig. 5. Energy consumption in Lao PDR by fuel type.

4.1.3 Energy demand in Thailand

Under the BAU scenario, the TFEC in Thailand is estimated to increase from 77.88 Mtoe in 2015 to 201.48 Mtoe in 2050. In 2050, the sectoral energy demand illustrates that the industrial sector, transport, residential, commercial, and other sectors would consume 80.59 Mtoe, 74.55 Mtoe, 24.18 Mtoe, 16.12 Mtoe, and 6.04 Mtoe, consecutively (see Figure 6). Nevertheless, the TFEC in Thailand would be heavily reduced in the NZE scenario. In 2050, overall energy consumption is estimated to be 108.99 Mtoe, which is a 46% reduction compared to the BAU scenario. The energy demand by sector shows that the share of energy consumption in the industrial, transport, residential, commercial, and other sectors would be 43.26%, 30.99%, 12.95%, 8.94%, and 3.85%, respectively.

The results of the BAU scenario demonstrate that petroleum products (45.93%), electricity (26.57%), biomass (10.84%), coal (10%), natural gas (6.65%), and solar (0.01%) would supply most of the Thailand's energy needs in 2050. In the NZE scenario, the utilization of petroleum in the final energy consumption would decrease to 4.83% because of the increase of EV in the transport sector and the increasing electrification rate and RE in other sectors, especially in the industrial sector (see Figure 7). The share of electricity consumption would greatly increase to 48.63%, the share of biomass in the TFEC would grow to 21.49%, the TFEC from natural gas would jump up to 18.90%, and the TFEC from solar would make up 6.15%. Furthermore, the consumption of coal would drop to zero.

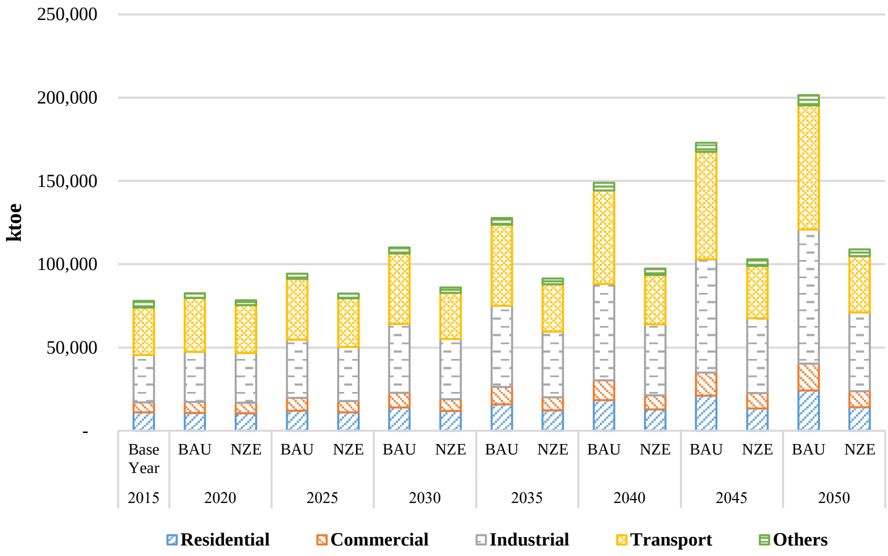

Fig. 6. Sectoral energy consumption in Thailand.

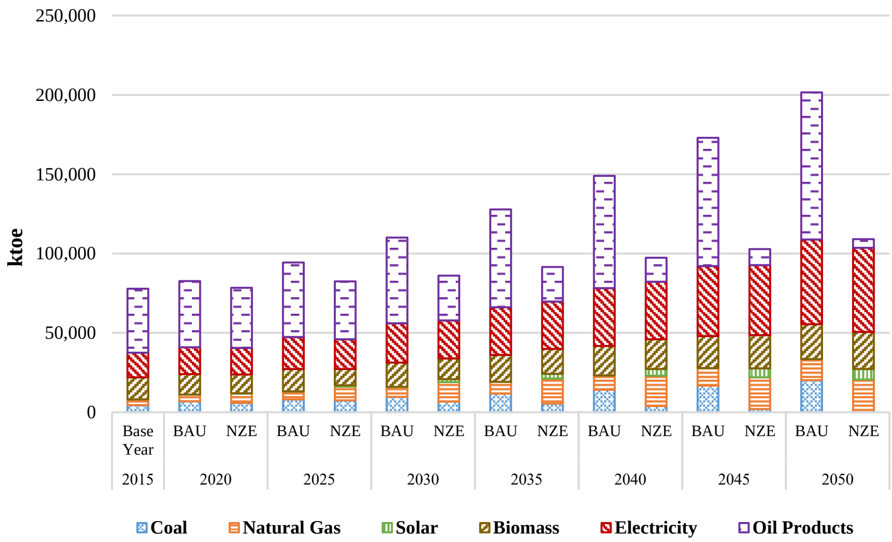

Fig. 7. Energy consumption in Thailand by fuel type.

4.1.4 Energy demand in Vietnam

In the BAU scenario, the TFEC would escalate from 54.13 Mtoe to 213.89 Mtoe between 2015 and 2050. The sectoral energy demand shows that in 2050, the share of energy requirements in different sectors such as the industrial sector, transport, residential, commercial, and other sectors would account for 45.60%, 27.45%, 19.76%, 5.10%, and 2.09%, individually (see Figure 8). Otherwise, the TFEC in the NZE scenario would be gradually decreased following the increase of advanced technology and energy-efficient equipment across the energy system. In 2050, the energy consumption in this country will be reduced by approximately 36.97% compared to the reference scenario. The TFEC is estimated to be 134.81 Mtoe, which is consumed by the industrial sector (56.52 Mtoe), transport sector (43.29 Mtoe), residential sector (25.29 Mtoe), commercial sector (6.58 Mtoe), and others (3.12 Mtoe).

In the BAU scenario, the structure of the energy system in Vietnam is mainly derived from fossil fuels. Individually, in 2050, the proportional consumption of petroleum, electricity, coal, biomass, and natural gas is estimated to be 35.31%, 33.98%, 20.59%, 6.84%, and 3.28%, respectively (see Figure 9). However, under the NZE scenario, the consumption of oil products would significantly fall to 5.02% of the final energy used in 2050. This is because of the switching from the operation of internal combustion engine vehicles to EVs in the transport sector and the improvement of EE and RE utilization in other sectors. In 2050, the proportion of electricity, biomass, natural gas, and solar in the final energy demand would increase significantly to 56.82%, 18.99%, 12.77%, and 6.41%, respectively. Also, the use of coal in energy consumption would be phased out to zero.

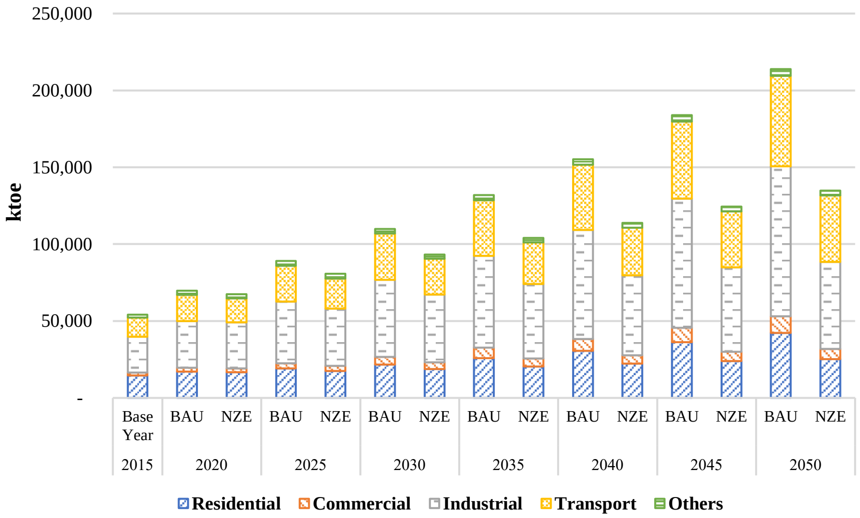

Fig. 8. Sectoral energy consumption in Vietnam.

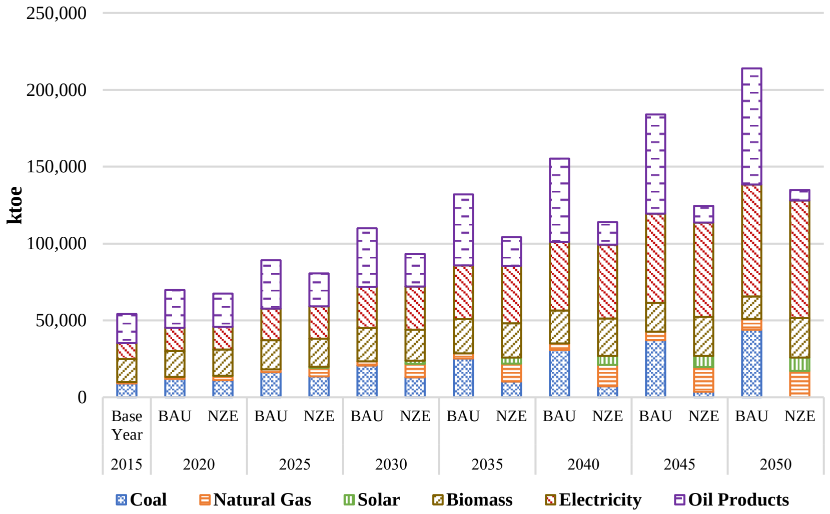

Fig. 9. Energy consumption in Vietnam by fuel type.

4.1.5 Energy demand in the selected GMS countries

Between 2015 and 2050, the combined energy demand in the four nations would increase from 138.66 Mtoe to 449.69 Mtoe, in the BAU scenario. In 2050, Vietnam, Thailand, Cambodia, and Lao PDR would consume 47.56%, 44.80%, 5.29%, and 2.35%, respectively, of the TFEC in this region (see Figure 10). Under the NZE scenario, the TFEC in four selected countries would be reduced by 41.14% compared to the baseline scenario in 2050. The TFEC in 2050 in these selected countries is estimated at 264.67 Mtoe.

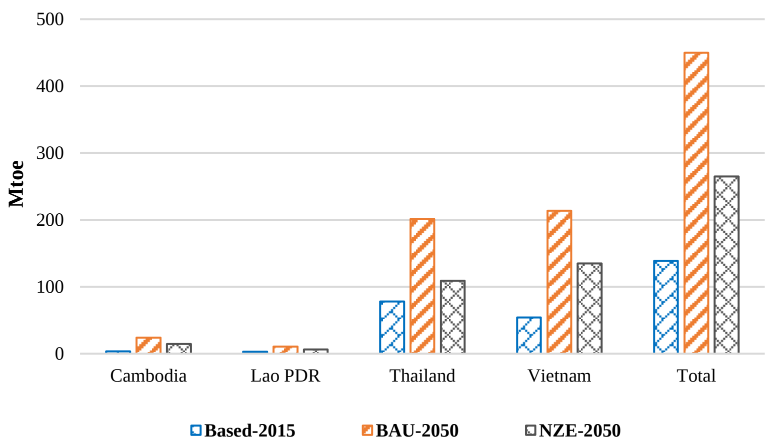

Fig. 10. Energy consumption in the four countries.

Regarding the energy demand by sector, the results in the BAU scenario illustrate that in 2050 the industrial sector in the four countries would consume the most energy, accounting for 186.87 Mtoe, followed by the transport sector (148.15 Mtoe), the residential sector (72.29 Mtoe), the commercial sector (30.47 Mtoe), and other sectors (11.92 Mtoe). By 2050, in the NZE scenario, the energy consumption in the residential, commercial, industrial, transport, and other sectors would be reduced by 40.44%, 39.04%, 41.43%, 42.23%, and 30.25%, compared to the amount of energy demand in the respective sectors in the BAU. Figure 11 indicates the total sectoral energy consumption in the four countries.

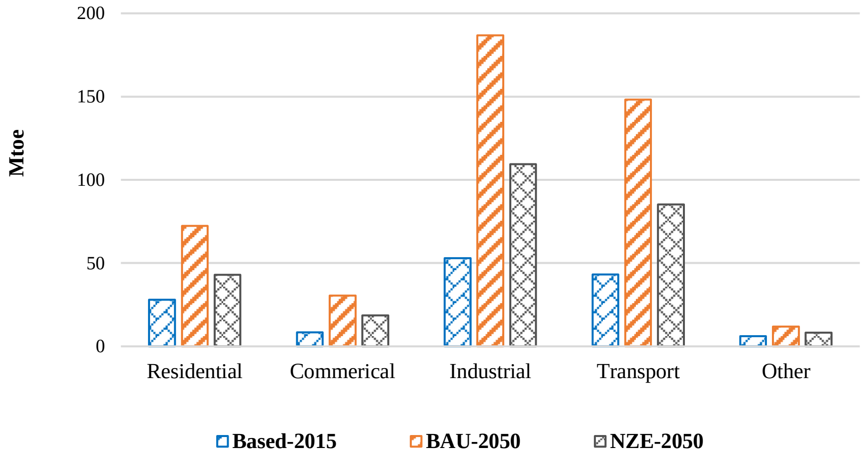

Fig. 11. Energy consumption in the four countries by sector.

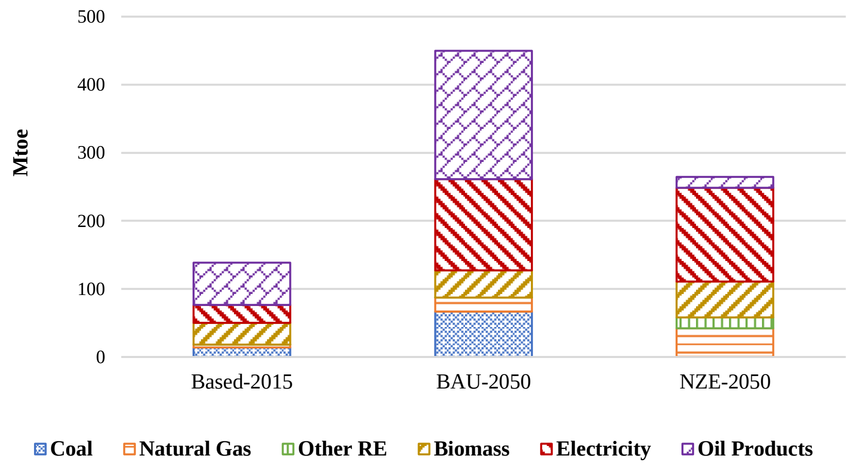

Fig. 12. The TFEC in selected GMS countries by fuel type.

In the BAU scenario, oil products in TFEC in 2050 would increase to 188.38 Mtoe, electricity would be 133.98 Mtoe, coal was reported to be 66.81 Mtoe, natural gas would increase to 20.68 Mtoe, and biomass would increase to 39.81 Mtoe. However, in this scenario, the final energy consumption from other RE sources such as solar would remain extremely low, at 0.02 Mtoe. In contrast, under the NZE scenario, the TFEC in 2050 (264.67 Mtoe) would consist of electricity (52.05%), biomass (19.90%), natural gas (15.74%), solar (6.05%), and oil products (6.08%), while coal use in final energy demand would drop to 0.17% of the TFEC (see Figure 12).

4.2 *Electricity Generation*

4.2.1 Electricity generation in Cambodia

From the results in the reference scenario, total power generation in Cambodia would considerably escalate to 66.88 TWh in 2050, which is 11.12 times compared to the total generation in 2015. Hydropower, coal, natural gas, imports, other RE (biomass, solar, and wind), and fuel oil would account for 32.30%, 30.13%, 16.47%, 11.91%, 7.98%, and 1.20% of the total generation in 2050, respectively (see Figure 13). Under the NZE scenario, despite the extremely high application of efficient technologies, electricity generation in 2050 would still be higher than in the BAU scenario due to the penetration of the electric vehicle fleet in the transport sector and the increased utilization of electrical energy across sectors. As indicated in Figure 13, RE including hydropower would account for 70.89% of total power generation in 2050, with natural gas (18.50%), imported electricity (9.13%), and oil products (1.49%) following.

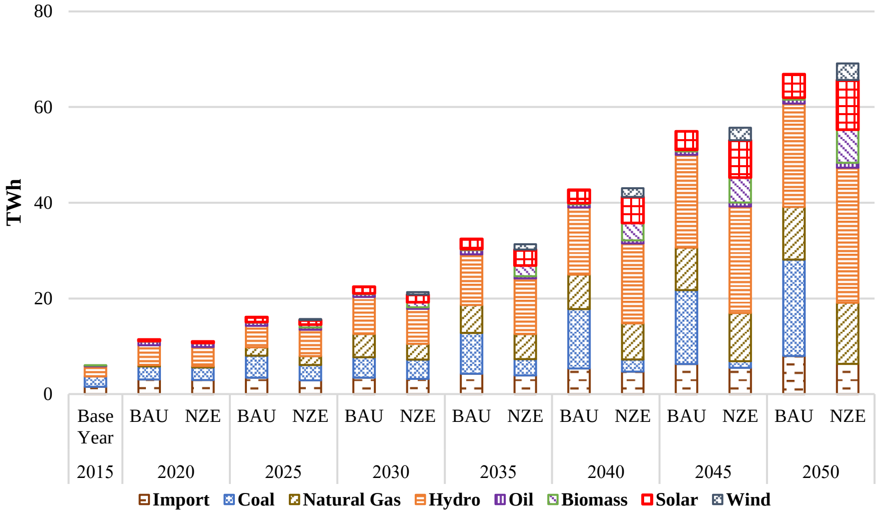

Fig. 13. Electricity generation mix in Cambodia.

4.2.2 Electricity generation in Lao PDR

The Lao PDR's BAU scenario estimates that electricity generation in 2050 will be 12 times higher than in 2015. In 2050, hydropower would generate 81% of total 196.68 TWh of power, coal 12%, and other RE the rest (biomass, solar, and wind) (see Figure 14). In the NZE scenario, even if the electricity demand in the energy systems would be reduced in 2050, the electricity generation in Lao PDR would remain the same. This is because of the high employment of electric vehicles as well as the electric train in the transport sector. However, the structure of the power sector would be changed by reducing the generation from coal and replacing it with other RE sources besides hydropower. As a result, the share of other RE (excluding hydropower) would increase to 13.09% in 2050, while the share of coal power would decrease to 6.06%. The rest of the electricity generation would come from hydropower plants.

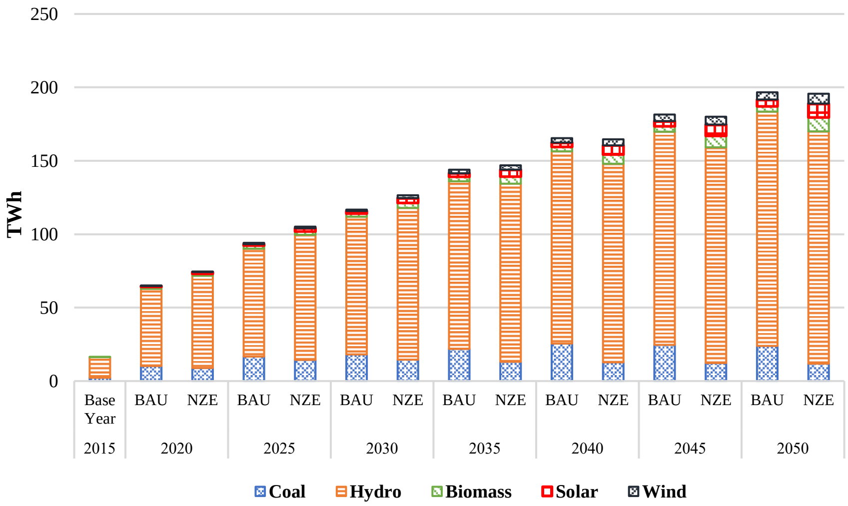

Fig. 14. Electricity generation mix in Lao PDR.

4.2.3 Electricity generation in Thailand

In 2050, total electricity generation in Thailand would be increased by 3.47 times compared to 2015. In 2050, of total 668.00 TWh generated, natural gas would remain the highest source of electricity production, generating 56.02% of total electricity, followed by coal (22.21%), other RE (10.55%), hydropower (5.91%), imports (5.00%), and fuel oil (0.30%). Besides this, under the countermeasure scenario, total power generation in Thailand would slightly decrease to 648.88 TWh in 2050. In the NZE scenario, the power generation from RE, including hydropower, solar, wind, and biomass, would generate 7.77%, 33.99%, 19.42%, and 14.57%, respectively, of the total generation in 2050. Besides this, power production from natural gas would largely decrease to 12.60% of total generation. Further, there will be no more electricity generation from coal power plants in 2050 (see Figure 15).

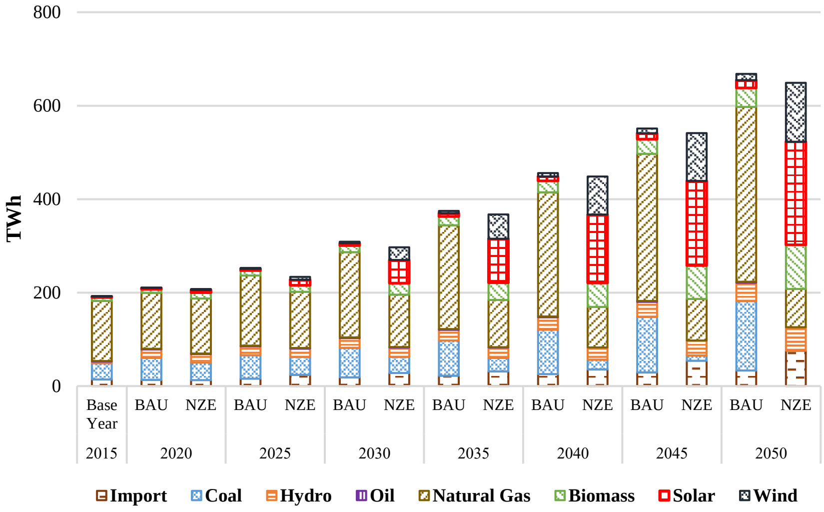

Fig. 15. Electricity generation mix in Thailand.

4.2.4 Electricity generation in Vietnam

The BAU scenario's results show that Vietnam's total generation would be increased by 5.80 times, from 158.42 TWh in 2015 to 918.18 TWh. In 2050, electricity generation will be mainly generated from coal, natural gas, and hydropower, with a share of around 56%, 27%, and 8%, respectively. However, the generation from other RE is reported to be only 7.75% in total, while the remaining is imported. In the NZE scenario, the power generation would increase more than in the BAU because of the high use of EVs in the transport sector and the increased electrification of all economic sectors. In 2050, the overall generation would be 937.67 TWh, consisting of RE (biomass, solar, and wind) of 73.28%, followed by hydropower (11.45%), imported electricity (9.54%), and natural gas (5.73%), while the coal power plants are set to be retired in 2050 (see Figure 16).

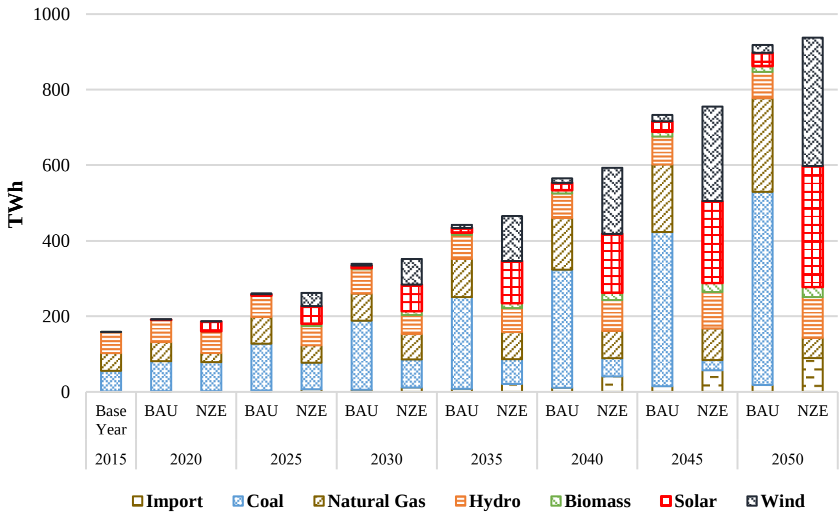

Fig. 16. Electricity generation mix in Vietnam.

4.2.5 Electricity generation in the selected GMS countries

In 2050, following the results from the BAU scenario, the four countries would generate a total of 1,849.75 TWh, which is 4.96 times the total generation in 2015. Vietnam would make up 49.64% of the entire generation in 2050, followed by Thailand (36.11%), Lao PDR (10.63%), and Cambodia (3.62%). As seen in Figure 17, under the NZE scenario, despite the high operation of energy-efficient technologies, total generation in the four countries would slightly increase above the total generation in the reference scenario. This is the result of the high penetration of EVs in the transport sector and the increase in electrification in other economic sectors. In 2050, the total generation in these selected countries is estimated to be around 1,851.35 TWh, where the shares of generation in Cambodia, Lao PDR, Thailand, and Vietnam account for 3.73%, 10.57%, 35.05%, and 50.65%, respectively.

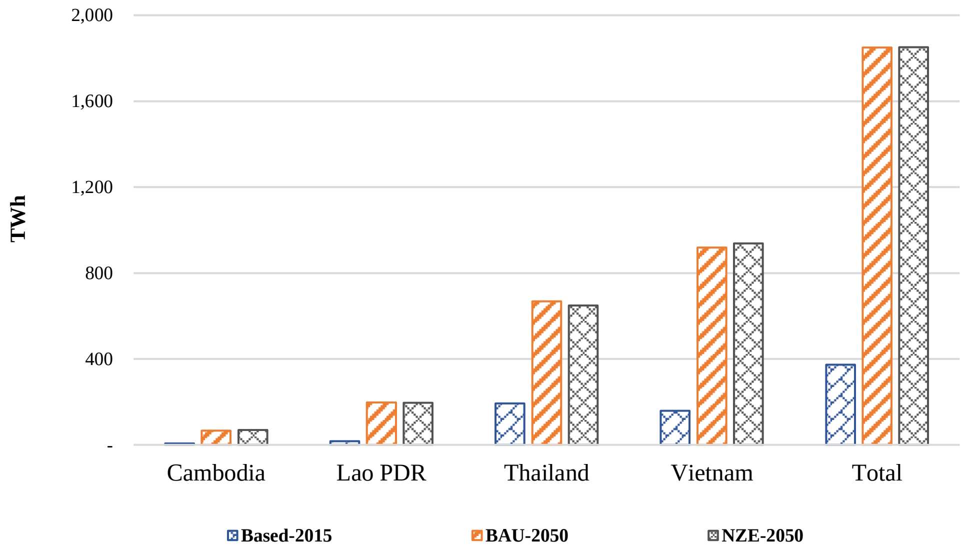

Fig. 17. Electricity generation in the four countries.

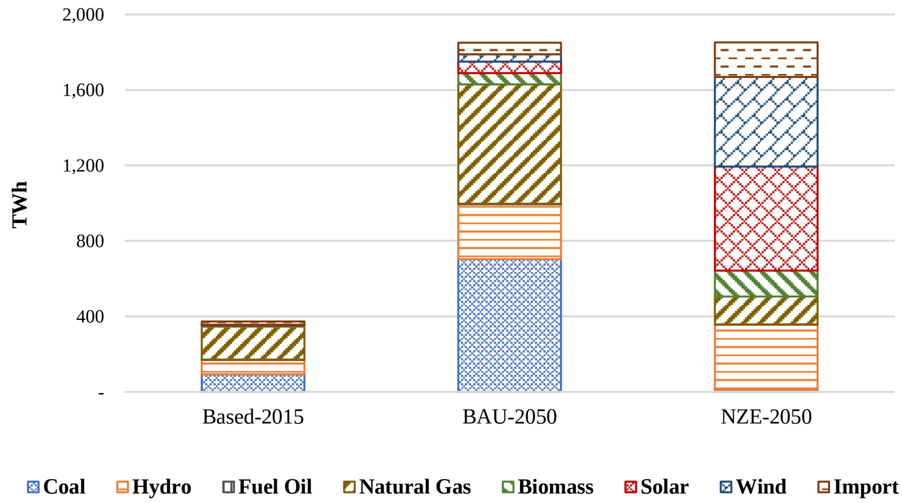

Fig. 18. Electricity generation in the four countries by fuel type.

In 2050, the electricity generation mix in the four countries demonstrates that in the reference scenario, total electricity would be generated by coal, natural gas, hydropower, other RE (biomass, solar, and wind), imports, and fuel oil, which account for 38.05%, 34.21%, 15.69%, 8.66%, 3.23%, and 0.15%, respectively. In contrast, the structure of power production in the four countries in the NZE scenario would be highly transformed from fossil fuel-based to renewable energy-based. As a result, in 2050, the share of total generation from RE, including hydropower, biomass, solar, and wind, would be 18.58%, 7.44%, 29.72%, and 25.72%, respectively. Besides this, the electricity generation from natural gas, coal, and fuel oil would be massively decreased to 18.59%, 0.64%, and 0.06%, respectively. The remaining generation would be imported from other countries (see Figure 18).

4.3 Carbon Dioxide (CO_2) Emissions

4.3.1 CO_2 emissions in Cambodia

Results in the reference scenario show that overall CO_2 emissions in Cambodia's energy sector would drastically increase from 8.02 $MtCO_2$ to 74.91 $MtCO_2$ between 2015 and 2050. However, in the NZE scenario, CO_2 emissions would be massively decreased by 53.5 $MtCO_2$ compared to the emissions in 2050 under the reference scenario (see Figure 19). The CO_2 emissions in the energy sector in Cambodia would reach its peak in 2040 with an amount of 22.54 $MtCO_2$. In 2050, the country's CO_2 emissions would decrease to 21.44 $MtCO_2$, where the transport sector would emit 10.17 $MtCO_2$, followed by the power sector, industrial, commercial, residential, and other sectors would produce 5.13 $MtCO_2$, 1.66 $MtCO_2$, 0.71 $MtCO_2$, and 5.13 $MtCO_2$, respectively.

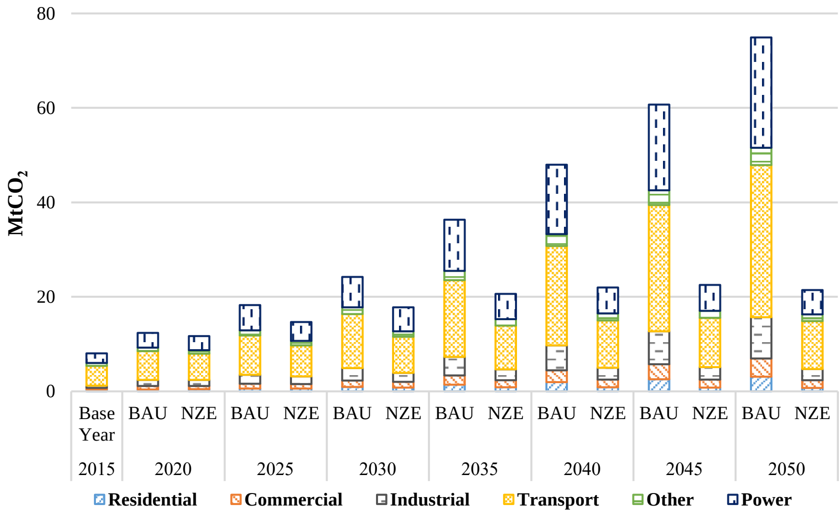

Fig. 19. CO_2 emissions in Cambodia by sector.

To estimate the net CO_2 emissions in Cambodia, the amount of CO_2 emitted by the Industrial Process and Product Use (IPPU), agriculture, waste, and carbon sink from the LULUCF sectors is collected from the LT-LEDS of Cambodia [41]. Therefore, the results illustrate that Cambodia's CO_2 emissions would peak in 2030 at 19.61 $MtCO_2$. This country would reach the goal of net-zero carbon emissions by 2050 with the energy sector, IPPU, agriculture, and waste sectors reducing CO_2 emissions to around 21.44 $MtCO_2$, 1.28 $MtCO_2$, 0.02 $MtCO_2$, and 0.05 $MtCO_2$, respectively, while the LULUCF sector should provide carbon sequestration of around 25 $MtCO_2$.

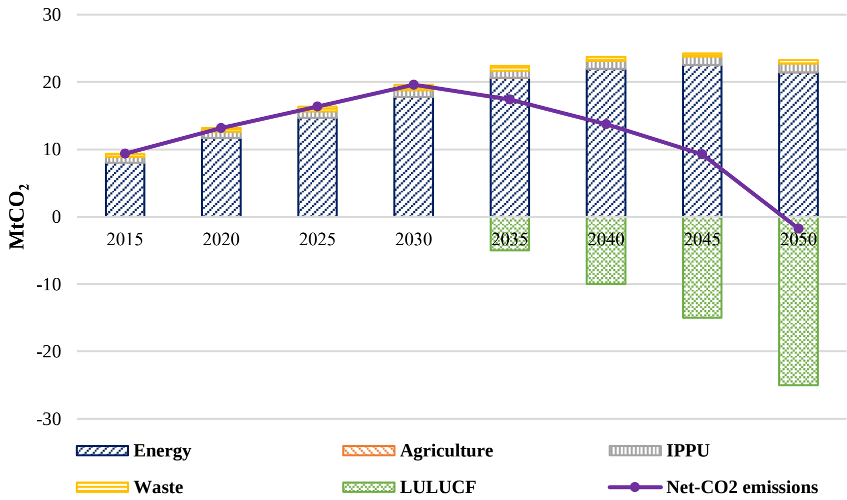

Fig. 20. Net CO_2 emissions in Cambodia in the NZE scenario.

4.3.2 CO_2 emissions in Lao PDR

In 2015, the Lao PDR's energy sector emitted 6.72 $MtCO_2$. In 2050, the total emissions in this sector would be increased by 6.30 times compared to the amount in 2015 under the BAU scenario. The power sector would emit 21.18 $MtCO_2$, followed by the transport sector (12.31 $MtCO_2$), the industrial sector (6.73 $MtCO_2$), the residential sector (1.54 $MtCO_2$), the commercial sector (0.42 $MtCO_2$), and other sectors (0.16 $MtCO_2$) (see Figure 21). Looking into the results in the NZE scenario, overall CO_2 emissions in the energy sector in Lao PDR would be reduced by 64.22% compared to the amount of emissions in 2050 in the baseline scenario. Therefore, in 2050, the total CO_2 emissions in Lao PDR would be approximately 15.15 $MtCO_2$, coming from the power sector (54.80%), transport (24.23%), industrial (15.82%), residential (3.26%), commercial (1.43%), and other sectors (0.45%).

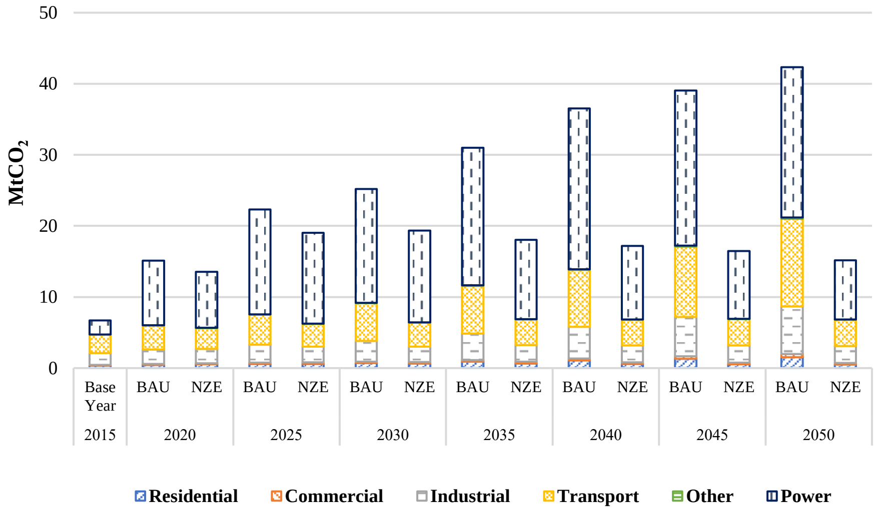

Fig. 21. CO_2 emissions in Lao PDR by sector.

The amount of emissions from non-energy sectors, including the IPPU, agriculture, waste, and carbon stocks from the LULUCF sector, is collected from the Lao PDR's NDC to estimate the net CO_2 emissions in this country [38]. Results show that with the results of emissions from the NZE scenario, this country would be able to achieve carbon neutrality by 2050, when the CO_2 emissions in the energy sector, IPPU, agriculture, and waste sectors would decrease to 15.15 $MtCO_2$, 1.86 $MtCO_2$, and 0.10 $MtCO_2$, 0.01 $MtCO_2$, respectively, while 18 million tons of carbon dioxide would be removed from the LULUCF sector, as seen in Figure 22.

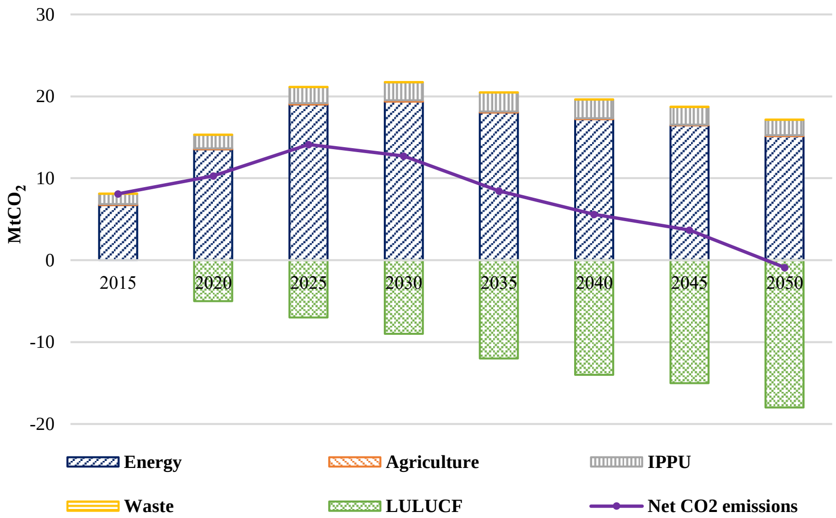

Fig. 22. Net CO_2 emissions in Lao PDR in the NZE scenario.

4.3.3 CO_2 emissions in Thailand

In 2050, the results from the reference scenario demonstrate that the energy sector in Thailand would emit 695.83 Mt of CO_2, which is 2.89 times compared to the CO_2 emissions in 2015. Under the NZE scenario, CO_2 emissions would substantially decline. In 2050, CO_2 emissions in the power sector, transport, industrial, residential, commercial, and other sectors would be reduced to 29.19 $MtCO_2$, 35.46 $MtCO_2$, 18.93 $MtCO_2$, 2.04 $MtCO_2$, 0.84 $MtCO_2$, and 3.91 $MtCO_2$, respectively. Figure 23 shows CO_2 emissions by sector in Thailand.

Thailand's net CO_2 emissions are calculated by adding the energy sector's emissions in the NZE scenario to the CO_2 emissions from the IPPU, agriculture, waste, and LULUCF sectors in the LT-LEDS of Thailand [42]. Results indicate that Thailand's CO_2 emissions would peak at 191.30 $MtCO_2$ in 2025, where the energy, IPPU, agriculture, and waste sectors would emit 250.90 $MtCO_2$, 41.50 $MtCO_2$, 1.50 $MtCO_2$, and 0.30 $MtCO_2$, respectively. Additionally, the LULUCF sector in Thailand would provide carbon removal stocks of approximately 103 $MtCO_2$ in 2025. In 2050, CO_2 emissions in Thailand would drop to zero as the emissions in the energy, IPPU, agriculture, and waste sectors would be decreased to 90.37 $MtCO_2$, 23.80 $MtCO_2$, 0.50 $MtCO_2$, and 0.20 $MtCO_2$, respectively, while the LULUCF sector would increase the amount of carbon sink to 120 $MtCO_2$ (see Figure 24).

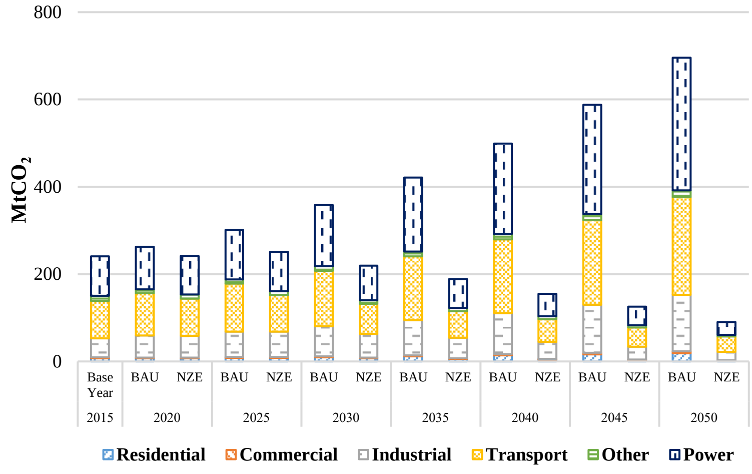

Fig. 23. CO_2 emissions in Thailand by sector.

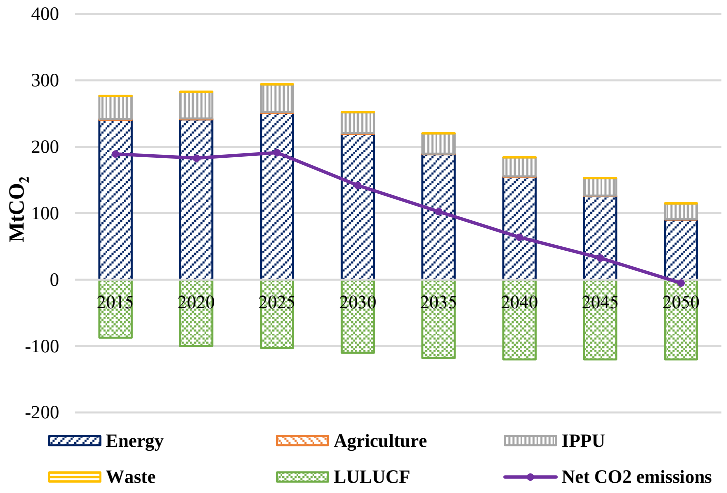

Fig. 24. Net CO_2 emissions in Thailand in the NZE scenario.

4.3.4 CO_2 emissions in Vietnam

In Vietnam's BAU scenario, the energy sector's overall CO_2 emissions in 2050 which is equivalent to 983.67 $MtCO_2$ would be sixfold compared to the emissions in 2015. The power sector would be the largest emissions contributor, emitting 57.36% of total CO_2, followed by the industrial sector (19.22%), transport sector (18.07%), residential (3.39%), commercial (1.27%), and others (0.69%), respectively. Under the NZE scenario, total CO_2 emissions in 2050 would be 907 $MtCO_2$ lower than in the reference scenario. In this case, the total CO_2 emissions in 2050 would be emitted from the transport sector (28.04 $MtCO_2$), the industrial (19.16 $MtCO_2$), the power (18.45 $MtCO_2$), the residential (4.63 $MtCO_2$), the commercial (3.38 $MtCO_2$), and others (2.91 $MtCO_2$). The sectoral CO_2 emissions in Vietnam are illustrated in Figure 25.

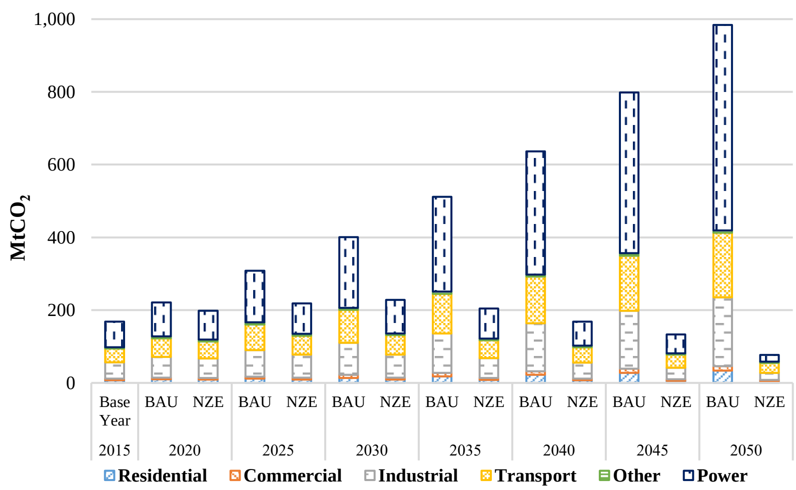

Fig. 25. CO_2 emissions in Vietnam by sector.

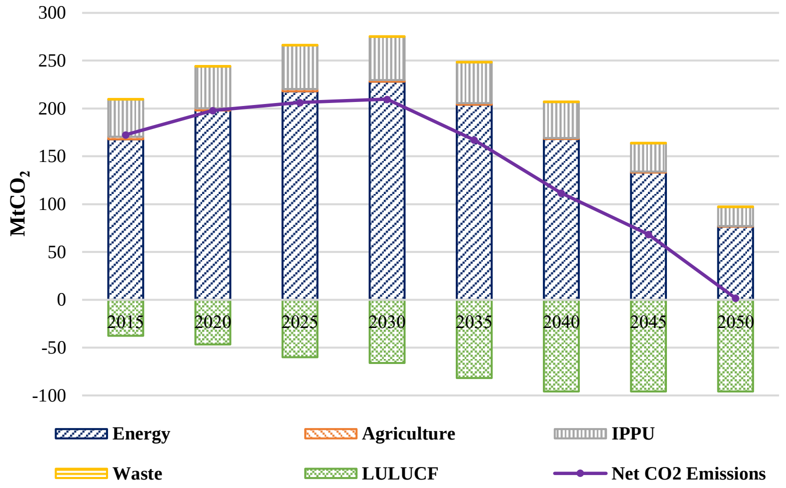

Fig. 26. Net CO_2 emissions in Vietnam in the NZE scenario.

Based on the amount of CO_2 emissions and CO_2 sequestration from the non-energy sectors (IPPU, agriculture, waste, and LULUCF sectors) in Vietnam's NDC [40] combined with the CO_2 emissions from the NZE scenario, this country could reach zero carbon emissions by around 2050, where the LULUCF sector would provide 98 $MtCO_2$ of carbon absorption, together with the CO_2 reduction in energy sector, IPPU, agriculture, and waste sectors to 76.57 $MtCO_2$, 19.50 $MtCO_2$, 0.74 $MtCO_2$, and 0.73 $MtCO_2$, respectively (see Figure 26).

4.3.5 CO_2 emissions in the selected GMS countries

In the four nations, around 423.16 $MtCO_2$ emissions were emitted from the energy sector in 2015. In this Subregion, Thailand was responsible for 56.83% of total emissions, followed by Vietnam (39.69%), Cambodia (1.89%), and Lao PDR (1.59%), respectively. In the reference scenario, CO_2 emissions in these nations are projected to reach approximately 1,796.74 $MtCO_2$ by 2050. In 2050, Vietnam would contribute the most CO_2 emissions, followed by Thailand, Cambodia, and Lao PDR, which share the total emissions of 54.75%, 38.73%, 4.17%, and 2.36%, respectively (see Figure 27). On the other hand, in the NZE scenario, total CO_2 emissions in these nations would be massively decreased owing to the high penetration of efficient technologies in the energy system, the transition from fossil fuel-based to RE-based on both the supply and demand sides, the application of EVs in the transport sector, and the operation of CCS technologies in natural gas-based, coal-based, and bioenergy-based power plants. Therefore, in 2050, overall CO_2 emissions from the four countries' energy sectors are estimated to be 203.53 $MtCO_2$, which is equivalent to a reduction of 88.67% compared to the reference scenario. Of the total emissions in 2050, Thailand would share 44.40%, followed by Vietnam (37.62%), Cambodia (10.54%%), and Lao PDR (7.44%).

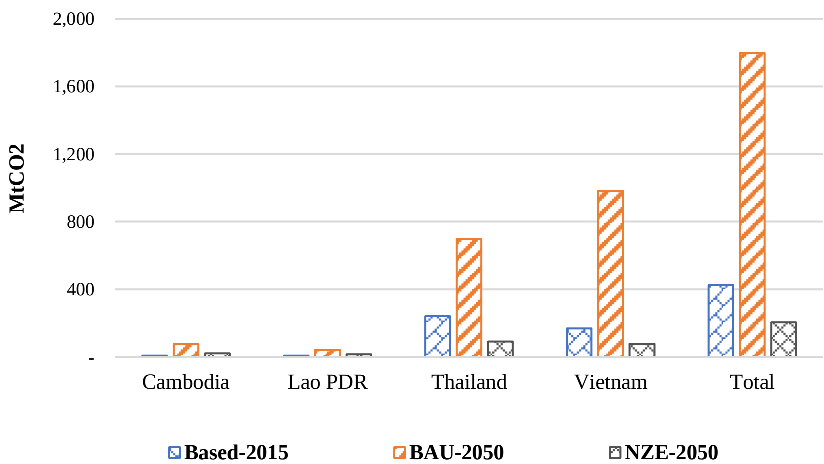

Fig. 27. CO_2 emissions in the four countries.

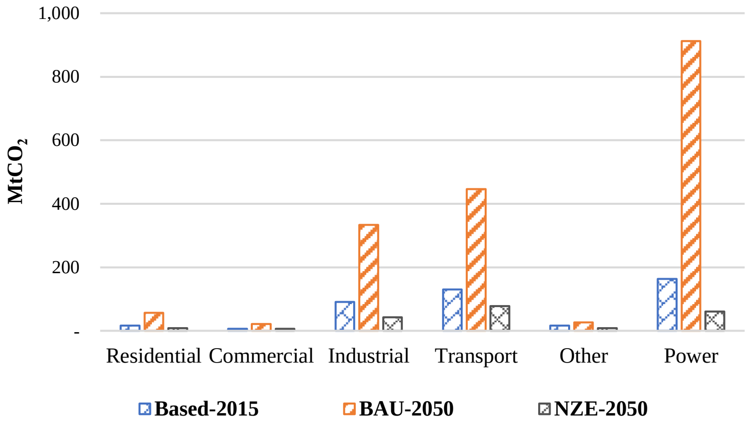

Fig. 28. CO_2 emissions in the four countries by sector.

In 2050, CO_2 emissions by sector in the four countries illustrate that in the reference scenario, the power sector would be the highest CO_2 emitter (912.73 $MtCO_2$), followed by the transport sector (446.07 $MtCO_2$), industrial sector (333.74 $MtCO_2$), residential sector (57.05 $MtCO_2$), commercial sector (20.97 $MtCO_2$), and other sector (26.17 $MtCO_2$). However, the amount of CO_2 emissions in all sectors would be highly mitigated in the NZE scenario. By 2050, the percentage reduction of CO_2 in the residential, commercial, industrial, transport, power, and other sectors is calculated to be 86.18%, 70.93%, 87.17%, 93.31%, and 68.26%, respectively, compared to the reference scenario (see Figure 28).

The net CO_2 emissions in the four nations are calculated by combining the energy sectors' CO_2 emissions in the NZE scenario with the amount of CO_2 emissions from the non-energy sectors (IPPU, agriculture, and waste sector) and subtracting the amount of CO_2 sequestration from the four countries' LULUCF sector. Hence, the results illustrate that the selected GMS nations' CO_2 emissions would peak in 2025 at 428.29 $MtCO_2$. The energy sector alone generates 464.67 $MtCO_2$ of this total, while non-energy sector CO_2 emissions would be 91.63 $MtCO_2$. In addition, LULUCF would provide 151.50 million tons of carbon sinks in 2025 to absorb the remaining emissions. The selected GMS countries would possibly achieve the carbon neutrality goal in the mid-century based on the results of net CO_2 emissions (see Figure 29). To reach net-zero CO_2 emissions, the energy sector, and the non-energy sectors of the four countries would reduce the emissions to 203.53 $MtCO_2$ and 49.38 $MtCO_2$, while the LULUCF sector would deliver at least 256.80 $MtCO_2$ for CO_2 absorption.

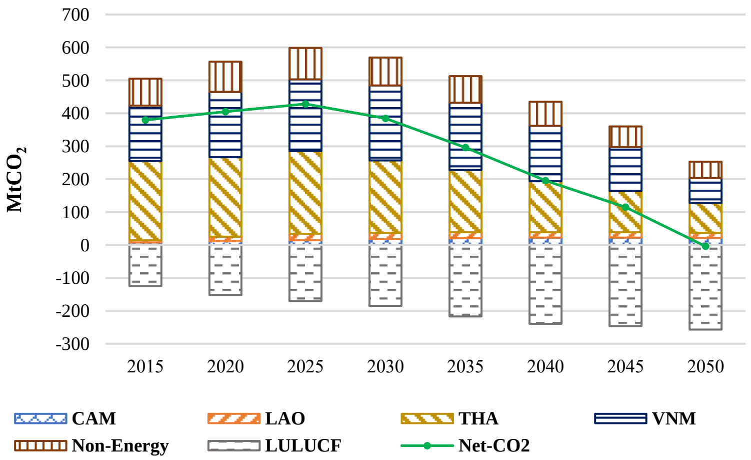

Fig. 29. Net-CO_2 emissions in the four countries in the NZE scenario

Table 7. Energy security and co-benefits analysis.

Indicators	2015	BAU-2050	NZE-2050
Economic			
EI of GDP (toe/million USD)	206.0	149.7	88.1
Social			
EI of people (toe/thousand people)	755.0	2,170.8	1,277.6
Environment			
CO_2 emissions of GDP ($kgCO_2$/thousand USD)	628.7	598.0	67.7
CO_2 emissions per capita ($kgCO_2$/person	2,304.1	8,673.3	982.5

4.4 Energy Security and Co-benefits

Table 7 presents the results of the energy security and the co-benefits analysis in the four GMS countries.

Economic: According to the economic indicator, energy intensity in the four countries in 2050 under the BAU scenario would be 27% lower than in the base year due to significant GDP growth from 2015 to 2050. Energy intensity would continue to fall to around 88.09 toe/thousand USD under the NZE scenario, with the implications of energy savings.

Social: The BAU of the selected nation's per capita energy intensity increased from 755.01 toe/thousand people in 2015 to around 2,170.77 toe/thousand people in 2050, owing to the slower increase in population compared to the increase in energy consumption. Nonetheless, the energy intensity per capita in the NZE scenario would be 41% lower in 2050 than in the BAU.

Environment: Carbon intensity would slightly decrease in the BAU scenario (30.73 kgCO_2/thousand USD from the base year), and it would be decreased by 9 times in the NZE scenario compared to the BAU level in 2050. In the BAU, per capita CO_2 emissions would be increased from 2,304.09 kg-CO_2/person in 2015 to 8,673.29 kg-CO_2/person in 2050. By 2050, CO_2 emissions per capita would be decreased by 57% compared to 2015 in the NZE scenario.

5. CONCLUSION AND POLICY IMPLICATION

This study examines the feasibility of achieving deep decarbonized energy systems in the selected GMS countries through analyses of increasing energy efficiency and renewable energy, as well as advanced technology such as CCS technology. The key findings indicate that by 2050, total CO_2 emissions from the energy sectors of the four countries would be tremendously mitigated by around 200 MtCO_2. This target can be achieved by improving energy efficiency and conservation to reduce around 40% of the final energy demand by 2050. Besides this, the penetration of EVs in the road transport and the modal shift to mass transport would play a crucial role in CO_2 mitigation in the transport sector. In the industrial sector, a transition from high-carbon-intensity fuels to renewable energy would be required. In the power sector, solar, wind, and biomass would generate 65% of electricity in 2050. The biomass-based power plant would be equipped with CCS technology to store CO_2 emissions. Furthermore, to achieve carbon neutrality by the mid-century, this amount of CO_2 emissions would be sequestered from the LULUCF sectors. In addition, the analysis of energy security and co-benefits of CO_2 reduction show that, the energy intensity of the chosen countries would roughly drop to 88.09 toe/million USD with EE implemented in the NZE scenario. The energy consumption per thousand people would fall to 1,277.62 toe/thousand people in the NZE scenario. Under the reference scenario, the carbon intensity in these nations would slightly increase from 628.73 kg CO_2/thousand USD in 2015 to 598 kg CO_2/thousand USD in 2050, while it would decrease to 67.74 kg CO_2/thousand USD in the countermeasure scenario. In 2050, the NZE scenario's per capita CO_2 emissions would be 7,690.82 kgCO_2/person lower than the BAU scenario.

Regarding the results of the study, there are some important policy suggestions for the four countries indicated as follows:

- Increasing energy efficiency awareness and energy-efficient technologies: sharing knowledge of energy savings and the proper use of technology.
- Reconstructing the energy master plan: recreate the new renewable energy as well as energy efficiency plans by promoting the application of domestic renewable energy resources to their optimum capacity and setting a clear target for energy savings.
- Promoting the application of CCS: implement the CCS technology in highly CO_2-emitting power plants and industries such as coal, natural gas, and bioenergy.
- Smart grid technology development: improving the smart grid utilities to reduce transmission and distribution losses and improve the electrification of other services, for instance, heating.
- Promoting the utilization of electric vehicles: switching from internal combustion vehicles to electric vehicles would result in a heavy reduction of GHG emissions and air pollution.
- Modal shift to mass transportation: shifting from individual transport modes to public services such as buses and trains would help in decreasing both energy consumption and GHG emissions.

In further research, the feasibility of utilizing nuclear power plants, green hydrogen power plants, and hydrogen fuel cell vehicles will be integrated to observe the outcome. Additionally, the abatement cost of CO_2 mitigation should be addressed.

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REFERENCES

[1] IPCC., 2022. *Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY, USA: Cambridge University Press.

[2] MME., 2022. *Cambodia Energy Statistics 2000-2019*. Jakarta, Indonesia: Economic Research Institute for ASEAN and East Asia (ERIA).

[3] MEM., 2018. *Lao PDR Energy Statistics 2018*. Jakarta, Indonesia: Economic Research Institute for ASEAN and East Asia (ERIA).

[4] DEDE. 2022. Energy consumption by economic sector. *Ministry of Energy* [Online serial], Retrieved October 15, 2022, from the World Wide Web: https://www.dede.go.th/ewt_news.php?nid=42079
[5] MoIT., 2017. *Vietnam Energy Outlook Report 2017*. Hanoi, Vietnam: Ministry of Industry and Trade (MoIT).
[6] EAC., 2016. *Report on Power Sector of the Kingdom of Cambodia*. Phnom Penh, Cambodia: Electricity Authority of Cambodia (EAC).
[7] EGAT., 2016. *Annual Report 2015*. Bangkok, Thailand: Electricity Generating Authority of Thailand (EGAT).
[8] EVN., 2016. *Vietnam Electricity Annual Report 2015*. Hanoi, Vietnam: Vietnam Electricity (EVN).
[9] MoE., 2020. *First Biennial Updated Report of the Kingdom of Cambodia*. Phnom Penh, Cambodia: Ministry of Environment (MoE).
[10] MONRE., 2020. *The First Biennial Update Report of the Lao PDR*. Vientiane, Lao PDR: Ministry of Natural Resources and Environment (MONRE).
[11] MoNRE., 2022. *Thailand's Fourth Biennial Update Report*. Bangkok, Thailand: Ministry of Natural Resources and Environment (MoNRE).
[12] MNRE., 2020. *Vietnam Third Biennial Update Report*. Hanoi, Vietnam: Ministry of Natural Resources and Environment (MNRE).
[13] Zhou S., Tong Q., Pan X., Cao M., Wang H., Gao J., and Ou X.., 2021. Research on low-carbon energy transformation of China necessary to achieve the Paris agreement goals: A global perspective. *Energy Economics* 95: 105137.
[14] Vats G. and R. Mathur., 2022. A net-zero energy system in India by 2050: An exploration. *Journal of Cleaner Production* 352: 131417.
[15] Oshiro K., Masui T., and Kainuma M., 2018. Transformation of Japan's energy system to attain net-zero emission by 2050. *Carbon Management* 9(5): 493-501.
[16] Lau H.., 2023. Decarbonization of ASEAN's power sector: A holistic approach. *Energy Reports* 9: 676-702.
[17] Phoumin H., Kimura F., and Arima J., 2021. Asean's energy transition towards cleaner energy system: Energy modelling scenarios and policy implications. *Sustainability (Switzerland)* 13(5): 1-29.
[18] Handayani K., Anugrah P., Goembira F., Overland I., Suryadi B., and Swandaru A., 2022. Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050. *Applied Energy* 311: 118580.
[19] Lau H., 2022. Decarbonization roadmaps for ASEAN and their implications. *Energy Reports* 8: 6000-6022.
[20] Lyheang C. and B. Limmeechokchai., 2018. The role of renewable energy in CO_2 mitigation from power sector in Cambodia. *International Energy Journal* 18(4): 401-408.
[21] Chhay L. and B. Limmeechokchai., 2020. CO_2 mitigation in the power sector in Cambodia: Analysis of cleaner supply-side options beyond INDC. *International Energy Journal* 20(1): 1-14.
[22] Phoualavanh S. and B. Limmeechokchai., 2016. Energy saving and CO_2 mitigation of electric vehicle (EV) technology in Lao transport sector. *Engineering Journal* 20(4): 101-109.
[23] Pradhan B., A. Chaichaloempreecha, Chunark P., Rajbhandari S., Pita P., and Limmeechokchai B., 2022. Energy system transformation for attainability of net zero emissions in Thailand. *International Journal of Sustainable Energy Planning and Management* 35: 27-44.
[24] Chaichaloempreecha A., Chunark P., Hanaoka T., and Limmeechokchai B., 2022. Thailand's mid-century greenhouse gas emission pathways to achieve the 2 degrees Celsius target. *Energy, Sustainability and Society* 12(1): 1-20.
[25] Dang P. and B. Baruah., 2022. An evaluation of Vietnam's pathway to net-zero by 2050: Reconciling the developmental state and civil society. London, Canada: University of Ontario.
[26] Dul D. and B. Limmeechokchai. 2020. Potential of renewable energy in selected Greater Mekong Subregion (GMS) countries to achieve NDCs in 2030. *2020 International Conference and Utility Exhibition on Energy, Environment and Climate Change (ICUE)*. Pattaya, Thailand, 2020.
[27] Limmeechokchai B. and D. Dul., 2023. Achievement of Paris Agreement in selected Greater Mekong Sub-region countries: Analyses of renewable electricity and emissions gap. *GMSARN International Journal* 17(3): 253-261.
[28] Dul D. and B. Limmeechokchai., 2021. Greenhouse gases mitigation in the road transport toward 2050: Analyses of selected greater mekong sub-region (GMS) countries. *International Energy Journal* 21(3): 305-322.
[29] MME., 2013. *National Policy, Strategy and Action Plan on Energy Efficiency in Cambodia*. Phnom Penh, Cambodia: Ministry of Mines and Energy.
[30] EDC., 2019. *Development of Power Sector in Cambodia*. Phnom Penh, Cambodia: Electricité du Cambodge.
[31] MEM., 2020. *Lao PDR Energy Outlook 2020*. Jakarta, Indonesia: Economic Research Institute for ASEAN and East Asia (ERIA).
[32] EPPO., 2020. *Alternative Energy Development Plan 2018-2037*. Bangkok, Thailand: Ministry of Energy.
[33] EPPO., 2020. *Power Development Plan 2018-2037*. Bangkok, Thailand: Ministry of Energy.
[34] EPPO., 2020. *Energy Efficiency Plan 2018-2037*. Bangkok, Thailand: Ministry of Energy.
[35] MoIT., 2020. Decision: *Approving the Viet Nam's Renewable Energy Development Strategy up to 2030 with an Outlook to 2050*. Hanoi, Vietnam: Ministry of Industry and Trade (MoIT).
[36] MoIT., 2018. *National Program: Vietnam-National Energy Efficiency Program 2019-2030*. Hanoi, Vietnam: Ministry of Industry and Trade (MoIT).

[37] MoE., 2020. *Cambodia's Updated Nationally Determined Contribution*. Phnom Penh, Cambodia: Ministry of Environment (MoE).

[38] MONRE., 2021. *Nationally Determined Contribution (NDC)*. Vientiane, Lao PDR: Ministry of Natural Resources and Environment (MONRE).

[39] MoNRE., 2022. *Thailand's 2nd Updated Nationally Determined Contribution*. Bangkok, Thailand: Ministry of Natural Resources and Environment (MoNRE).

[40] MNRE., 2022. *Nationally Determined Contribution (NDC) (Updated in 2022)*. Hanoi, Vietnam: Ministry of Natural Resources and Environment (MONRE).

[41] MoE., 2021. *Long-Term Strategy for Carbon Neutrality*. Phnom Penh, Cambodia: Ministry of Environment (MoE).

[42] MoNRE., 2022. *Thailand's Long-Term Low Greenhouse Gas Emission Development Strategy (Revised Version)*. Bangkok, Thailand: Ministry of Natural Resources and Environment (MoNRE).

[43] Heaps C.G.. 2022. LEAP: The Low Emissions Analysis Platform. [Software Version: 2020.1.101] *Stockholm Environment Institute*. Somerville, MA, USA. https://leap.sei.org

[44] UN. 2022. World Population Prospects 2022. *Department of Economic and Social Affairs Population Division, United Nation* [Online serial], Retrieved October 10, 2022, from the World Wide Web: https://population.un.org/wpp/

[45] USDA. 2022. International Macroeconomic Data Set. *Economic Research Service, U.S. Department of Agriculture* [Online serial], Retrieved December 15, 2022 from the World Wide Web: https://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx

[46] NIS., 2019. *General Population Census of the Kingdom of Cambodia 2019*. Phnom Penh, Cambodia: National Institute of Statistics of Cambodia.

[47] LSB., 2015. *Results of Population and Housing Census 2015*. Vientiane, Lao PDR: Laos Statistics Bureau.

[48] NSO., 2015. *The 2015 Household Socio-Economic Survey in a Whole Kingdom*. Bangkok, Thailand: National Statistics Office of Thailand.

[49] GSO., 2020. *Results of the Viet Nam Population and Housing Census of 00:00 Hours on 1 April 2019*. Hanoi, Vietnam: General Statistics Office of Vietnam.

[50] Brandl P., Bui M., Hallett J., and Dowell N.M., 2021. Beyond 90% capture: Possible, but at what cost?. *International Journal of Greenhouse Gas Control* 105: 103239.