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Scenario-based Assessment of Decarbonized Energy System Towards 2050: Analyses of Low Emission Technology in Thailand

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ABSTRACT

Thailand's energy sector has been the dominant contributor to national CO_2 emissions, accounting for approximately 89% of total emissions for decades due to its heavy reliance on conventional fuels across both demand and supply sectors. In response, the country has pledged to become a carbon-neutral economy by 2050, with the energy sector playing a central role in this transition. This study examines sectoral emissions mitigation, energy demand and supply dynamics, and electricity production costs from 2018 to 2050 using the integrated LEAP-NEMO framework. The findings indicate that Thailand can achieve its carbon neutrality target in the early 2050s through the widespread adoption of energy-efficient technologies, reducing 46% of final energy consumption. Additionally, the results highlight a significant shift towards electricity and biomass on the demand side, alongside a substantial increase in renewable energy generation, which must reach at least 67% of total electricity production. To further support decarbonization, natural gas-based power generation will require integration with carbon capture and storage (CCS) technology, while green hydrogen will play a crucial role as a clean fuel alternative across the transport, industrial, and electricity sectors.

1. INTRODUCTION

Anthropogenic greenhouse gas (GHG) emissions have significantly effect on climate change, posing a critical threat to all forms of life on Earth. To mitigate the adverse impacts of climate change, it is imperative to hold the increase in global average temperature to well below 2°C above pre-industrial levels, with an aspirational target of 1.5°C, as outlined in the long-term climate change mitigation goals of the Paris Agreement (PA) [1]. Achieving these targets necessitates a coordinated global effort, requiring all nations to reduce their anthropogenic emissions and strive for carbon neutrality and net-zero emissions by approximately the mid-21st century [2]. As a signatory to the PA, Thailand has undertaken substantial measures to curb its national GHG emissions in mid- and long-term strategies [3]. Given its substantial contribution to national emissions, the energy sector has been identified as a primary focus for GHG reduction efforts.

Between 2010 and 2018, Thailand's total carbon dioxide (CO_2) emissions increased by 1.51% per annum, reaching 272 million tonnes of CO_2 ($MtCO_2$) in 2018, without adding the land use, land-use change, and forestry (LULUCF) sector emissions [4]. During this period, the energy sector accounted for approximately 89% of the country's total carbon emissions. This substantial contribution can be attributed to the extensive reliance on fossil fuels to support economic growth and improve living standards. In 2018, Thailand's final energy consumption reached 83.95 million tonnes of oil equivalent (Mtoe), with fossil fuels constituting 64.34% of total consumption [5]. Additionally, the country generated 204.43 terawatt-hours (TWh) of electricity in the same year, with fossil fuel-based sources contributing 74% of total electricity production [6]. These figures underscore Thailand's dependence on conventional fossil fuel resources, which not only have detrimental environmental impacts but also pose challenges to energy security due to resource depletion and fluctuations in fossil fuel prices.

Thailand has implemented significant measures to mitigate GHG emissions through various key policies. One of its primary mitigation strategies is the Nationally Determined Contribution (NDC), which outlines the country's medium-term emission reduction targets. According to Thailand's latest NDC, the country aims to reduce 30% of emissions relative to the BAU scenario by 2030 using domestic resources. This reduction target could be further increased to 40% with support from the international community [7]. Additionally, Thailand has submitted its "Long-Term Low Greenhouse Gas Emissions Development Strategy (LT-LEDS)," reaffirming its commitment to achieving net-zero carbon

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CO_2 emissions and net-zero GHG emissions by 2050 and 2065, accordingly [3].

A transformation toward carbon neutrality by 2050 is a big challenge task for Thailand. This study demonstrates the implementation of carbon dioxide mitigation measures through the applications of low emissions technologies in Thailand to achieve net zero carbon emissions by 2050. Additionally, this study includes the illustration of least-cost optimization in the power sector to observe the cost of power generation to achieve the net zero CO_2 emissions. This study analyzes further the intensity of energy consumption and CO_2 emissions from the two implemented scenarios. Furthermore, this study compares its key findings with existing government policies on energy and climate change mitigation, providing valuable insights into effective carbon reduction strategies and the deployment of critical technologies. The findings offer policy recommendations for government agencies, researchers, policymakers, and energy utilities to support informed decision-making in advancing Thailand's carbon neutrality objectives.

2. LITERATURE REVIEW

Carbon neutrality is defined as the attainment of net-zero carbon dioxide (CO_2) emissions through the equilibrium between anthropogenic CO_2 emissions and carbon removal over time [8]. In contrast, net-zero emissions encompass all greenhouse gas (GHG) emissions associated with human activities, measured in terms of global warming potential, which are offset by an equivalent amount of GHG removal. In recent years, the increasing focus on achieving net-zero emissions and carbon neutrality, particularly in the energy sector, has garnered significant attention from researchers, scientists, and policymakers. Various scenario pathways and technological combinations have been proposed to facilitate global climate change mitigation efforts. A wide range of low-carbon technologies, including energy-efficient end-use systems, renewable energy (RE) sources, green hydrogen, carbon capture and storage (CCS), electric vehicles (EVs), and fuel cell electric vehicles (FCEVs), have been explored across different economic sectors in case studies conducted in various countries such as China [9], India [10], Ireland [11], Japan [12], Nepal [13], and the United States [14]. Additionally, the International Energy Agency has developed a global net-zero roadmap outlining sector-specific pathways to achieve GHG neutrality by 2050.

In Thailand, there are many scientific articles related to GHG mitigation in Thailand's energy system. The application of energy-efficient appliances, electric cooking, and the building code in Thailand's building sector for analyzing energy-saving potential and GHG emission reduction have been discussed [15]. The successful implementation of government policy in energy savings and renewable sources promotion could reduce 45% of emissions in 2035 [16]. The study of the utilization of electric vehicles (EVs), biofuels, and modal shifts in Thailand's transport sector has been discussed [17]. The study on decarbonized road transportation in Thailand shows that the utilization of 75% of EVs and 25% of biofuel could push the transport sector in the country to reach the global climate change mitigation goal of 1.5ºC by 2050 [18]. In addition, increasing renewable energy electricity generation by up to 65%, integrating CCS technology into efficient natural gas combined-cycle and bioenergy-based power plants, and using green hydrogen electricity generation are the main strategies for achieving carbon neutrality in Thailand's power sector [19]. Moreover, a net-zero energy system in Thailand has been analyzed through the high application of renewable energy and green hydrogen fuel [20].

Existing research on climate change mitigation within Thailand's energy sector has predominantly focused on GHG and CO_2 emission reductions at the individual sector level. However, key aspects such as the optimization of electricity production costs, investment strategies in the power sector, and comprehensive evaluations of energy and environmental indicators have remained largely unaddressed. Moreover, previous articles have not investigated the implementation of carbon capture and storage (CCS) technology or the integration of hydrogen fuel, both of which are recognized by the International Energy Agency (IEA) as critical technologies for mitigating climate change. To address these research gaps, this study systematically examines and incorporates these elements to develop a deep decarbonization scenario for Thailand. By leveraging the Low Emissions Analysis Platform (LEAP) in conjunction with the Next Energy Modelling System for Optimization (NEMO), this study aims to formulate a comprehensive strategy to achieve carbon neutrality in Thailand by 2050.

3. ENERGY SECTOR IN THAILAND

3.1 Situation of Energy Sector in Thailand

3.1.1 Energy consumption

Thailand has transitioned from an agriculture-based economy to a manufacturing-driven economy, leading to a continuous rise in energy demand across the industrial, building, and transport sectors. In 2018, the country's TFEC reached approximately 83.95 Mtoe, reflecting a 2.26% average growth rate since 2010 [5]. The transport sector consumed around 33.09 Mtoe, followed by the industrial sector at 30.86 Mtoe. The building sector, which includes both commercial and household energy use, consumed 11 Mtoe and 6.54 Mtoe, respectively, while the remaining energy demand was distributed among other sectors.

Thailand's energy supply has long been dominated by fossil fuels, which accounted for 64.34% of total energy consumption in 2018 [5]. Among these, oil products contributed the largest share at 49.30%, followed by coal (8.17%) and natural gas (6.87%). In addition to fossil fuels, electricity and biomass played significant roles, representing 20.02% and 15.63% of the 2018 TFEC, respectively. These figures highlight Thailand's reliance on conventional energy sources while also emphasizing the need for diversification and sustainable energy development.

3.1.2 Electricity generation

The electricity sector stands as a backbone of the national energy supply system, playing a vital role in supporting economic growth, as well as commercial and industrial activities. To meet the increase of demand, the total power installed capacity in Thailand has significantly grown from 30,920 MW in 2010 to 43,374 MW in 2018, while the total generation has increased from 165.83 TWh to 204.43 TWh [6]. In 2018, natural gas and coal generation are the two dominant power generation sources, accounting respectively for 56.87% and 17.51% of the total electricity production [6]. Nevertheless, RE-based generation was only 12.48% of the 2018 total electricity production, while the rest of the generation came from the imports from the neighboring countries (13.05%) and diesel/oil (0.09%).

3.2 Climate Change Mitigation Strategies in Thailand's Energy Sector

Thailand possesses substantial renewable energy (RE) resources; however, a significant portion remains underutilized. Thailand has an estimated potential installed capacity of 3,509 GW for solar photovoltaic (PV), 62 GW for wind, 18 GW for biomass, and 15 GW for hydropower [21]. Despite this considerable potential, the total installed RE capacity in 2018 was only 9,667 MW [6], accounting for 22.29% of Thailand's total installed capacity. This included 3,282 MW of solar PV, 2,967 MW of wind, 2,257 MW of biomass, and only 80 MW of hydropower, which are significantly lower than their respective potentials. These figures indicate that Thailand's abundant renewable resources remain largely undeveloped, highlighting the need for greater investment and policy support to maximize their utilization.

Thailand has developed multiple strategic energy policies to facilitate its transformation toward a sustainable and low-carbon energy system. The "Alternative Energy Development Plan 2018 (AEDP2018)" [22] targets promoting the deployment of RE across multiple sectors, including the promotion of modern biomass and solar photovoltaic (PV) technologies in the building and industrial sectors, as well as the expanded utilization of biofuels in the transportation sector. By 2037, AEDP2018 sets a target for 30% of the total final energy consumption (TFEC) to be derived from renewable energy sources. Complementing this effort, the Energy Efficiency Plan 2018 (EEP2018) [23] focuses on improving energy efficiency across all economic sectors, with the goal of reducing energy intensity per unit of gross domestic product (GDP) by 30% by 2037 compared to 2010 levels. Additionally, the Power Development Plan 2018 (PDP2018) [24] outlines the long-term trajectory for Thailand's power sector, emphasizing the expansion of RE-based electricity, including solar, wind, hydropower, and bioenergy. PDP2018 sets to promote the installed renewable energy capacity to 47% by 2037, with 37% sourced from domestic renewable energy resources and 10% from cross-border electricity imports. Collectively, these policies play a crucial role in shaping Thailand's energy transition and its commitment to reducing carbon emissions.

4. METHODOLOGY

4.1 LEAP-NEMO Analysis Tool

The Stockholm Environmental Institute developed sophisticated software, namely "Low Emissions Analysis Platform (LEAP)," for energy and environmental planning analysis [25]. It is a scenario-based modeling framework designed to assess energy demand and supply while evaluating greenhouse gas (GHG) emissions under various alternative scenarios. The energy modeling in LEAP ranges from bottom-up to top-down approaches and can be applied over medium- and long-term timeframes at scales ranging from city-level to national and regional analyses. Additionally, SEI has developed the "Next Energy Modeling System for Optimization (NEMO)," an energy system optimization tool that is integrated within LEAP to facilitate least-cost optimization of energy supply and demand [26]. The NEMO framework incorporates multiple built-in solvers that enable the generation of optimal energy supply scenarios while considering constraints such as emissions limits, renewable energy targets, and installed capacity requirements.

The calculation of energy demand, transformation, and GHG emissions within the LEAP model is represented by the following equations [27]. These equations outline the methodological framework used to estimate energy flows and associated emissions in various scenarios.

$$EC_n = \sum_i \sum_j EI_{i,j,n} \times AL_{i,j,n} \tag{1}$$

Where EC_n is the total energy consumption of fuel type n, $EI_{i,j,n}$ is the energy intensity of technology type j in the sector type i , and AL is the activity level of technology.

$$ET_s = \sum_t \sum_m ETP_{t,m} \times \left(\frac{1}{f_{t,m,s}} - 1 \right) \tag{2}$$

Where ET_s is the net energy consumption for transformation of any s type of primary fuel. $ETP_{t,m}$ is the energy transformation product of any secondary fuel type t, using technology type m. f represents the transformation efficiency.

$$Input_P = \frac{Output_P}{Eff_P} \tag{3}$$

$$Eff_P = 1 - Losses_P \tag{4}$$

Where $Input_P$ represents the feedstock or fuel inject into process P, $Output_P$ refers to the energy output and it can be electricity or other refinery products, Eff_P is the efficiency of power plants or refinery plants.

$$GHG_{EC} = EC_n \times EF_n \tag{5}$$

Where GHG_{EC} indicates greenhouse gas emissions from the final energy consumption for fuel type *n*, *EF* refers to the emission factor.

$$GHG_{ET} = ET_n \times EF_n \quad (6)$$

Where GHG_{ET} is the total energy consumption of fuel type *n*, $EI_{i,j,n}$ is the energy intensity of technology type *j* in the sector type *i* using fuel type *n*, AL is the activity level of technology type *j* in the sector type *i*.

NEMO serves as a computational tool for optimizing power generation dispatch while minimizing the overall cost of electricity production. However, the optimization process must adhere to a set of predefined constraints to ensure that the results accurately represent a feasible future scenario for electricity generation and installed capacity [28]. These constraints encompass various factors, including the type of generation technology employed, the upper and lower capacity limits of individual power plants, the maximum and minimum allowable capacity additions in a given year, operational utilization constraints, renewable energy targets for specific timeframes, as well as the associated technology and fuel costs. By incorporating these constraints, NEMO facilitates a more realistic and reliable assessment of future electricity system configurations.

The structure of LEAP-NEMO in Thailand's energy system is indicated in Figure 1. The resources branch provides several types of energy resources, both renewable and nonrenewable. These resources are used for transforming into electricity through the generation process and being transmitted to the demand side. In this study, the demand side of energy consists of five economic sectors. The demand for energy in these sectors depends on energy demand-driven factors, i.e., population and GDP, and the type of energy technologies used. These data and information are utilized as inputs in the LEAP-NEMO analysis tool to project future demand for energy, electricity generation, carbon dioxide (CO_2) emissions, and the associated electricity production costs.

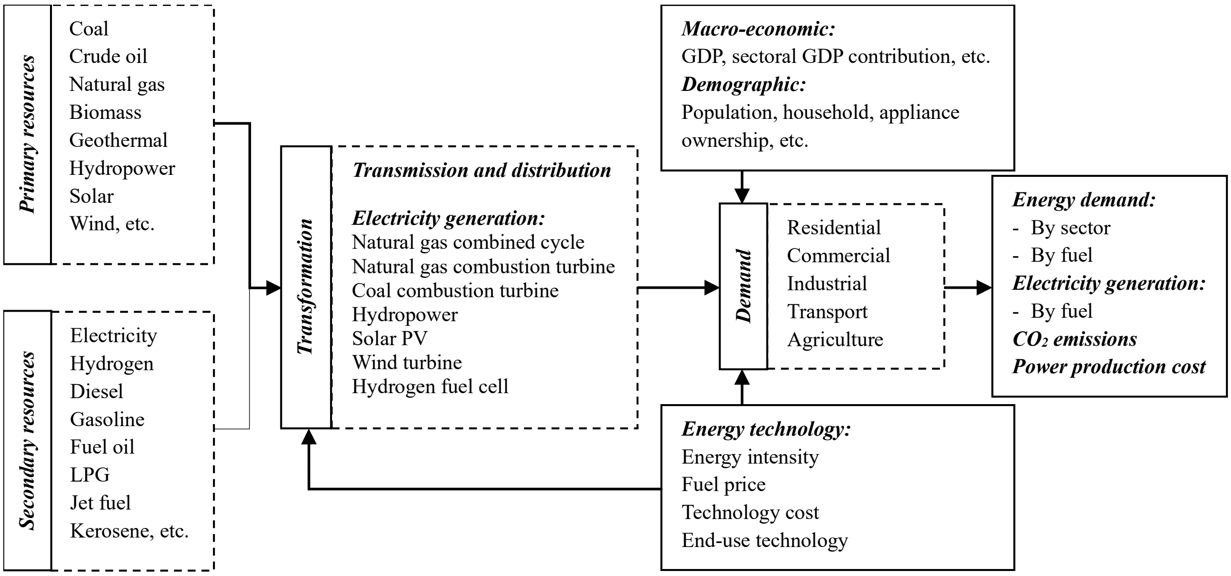

Fig. 1. Structure of LEAP-NEMO of Thailand's energy system.

4.2 Assumption of Energy Consumption Driven Factors

This study identifies demographic trends, macroeconomic factors, sectoral GDP contributions, and transport indicators as the primary drivers of energy consumption. Historical data and future projections for these variables have been sourced from various references, including governmental reports and official organizational databases. The assumptions associated with these data sources are outlined as follows:

1) *Demographic indicators:* In 2018, Thailand consisted of around 71.13 million inhabitants [29]. According to projections by the United Nations, the country's population is projected to grow 0.12% per year between 2018 and 2029 [30]. However, due to trends in population aging, a decline in population is anticipated, with an annual reduction rate of 0.27% between 2030 and 2050. Additionally, the number of households in Thailand was reported to be 26.25 million in 2018 [31]. By 2050, this figure is projected to increase to approximately 30.94 million
2) *Macroeconomic indicators:* In 2018, Thailand's total Gross Domestic Product (GDP) was approximately 1,256 billion US dollars at constant 2021 USD, measured in purchasing power parity (PPP) [29]. Projections from [32] indicate that Thailand's total GDP is expected to increase to approximately 3,298 billion $PPP by 2050. In 2018, the GDP composition by sector was 8.2% from agriculture, 57.1% from the commercial sector, and 26.7% from the industrial sector [29]. Future sectoral contributions to GDP growth have been projected based on historical trends observed between 2000 and 2018. By 2050, the commercial sector is expected to account for 61.7% of GDP,

followed by the industrial sector at 22.2% and the agricultural sector at 8.6%.

3) *Transport Indicators:* In 2018, Thailand had around 39.55 million registered vehicles [33]. Projections indicate that this number could increase at 0.82% per year from 2018 to 2050. The distribution of different vehicle types, including cars, buses, motorcycles, and trucks, is estimated based on historical trends in vehicle usage within the country. Additionally, historical data on passenger and freight transport for other transportation modes, such as air, rail, and water, have been obtained from the Transport Statistics 2018 report [33]. Future trajectories for passenger and freight transport are projected using GDP growth and income per capita as key determinants.

4.3 Business-as-Usual (BAU) Scenario

This scenario is defined as a frozen scenario where energy consumption is forecasted by using energy demand-driven factors. Power generation and installed capacity are increasing proportionally to demand growth, while the share of technology installed capacity will be the same.

Energy demand in different economic sectors is estimated by using the following equation [34]:

1) *Residential sector:*

$$E_R = HH \times \sum_i EC_i \quad (7)$$

Where E_R represents the residential sector energy consumption, HH refers to household number, and EC_i indicates energy demand for service type i.

2) *Commercial, industrial, and agricultural sectors:*

$$E = GVA \times EI_{GVA} \quad (8)$$

Where E refers to energy consumption in each sector, GVA represents the sectoral gross value added, and EI_{GVA} indicates the sectoral energy intensity per gross value added.

3) *Transport sector*

$$E_T = \sum_j \left(TV_j \times FE_j \times ATD_j \right) \quad (9)$$

Where E_T indicates the transport sector energy consumption, TV_j represents the total vehicles type j; FE_j refers to fuel economy; and ATD_j represents the average travel distance.

4) *Power sector*

In the power sector, the total installed capacity in the BAU scenario is assumed to increase in proportion to the demand growth. However, the power installed capacity mix is assumed to remain unchanged from the base year through 2050, representing a frozen-technology scenario. To estimate the cost of electricity production over this period, projected fuel prices are sourced from the 7th ASEAN Energy Outlook report [34] (see Table 1). Key power plant characteristics, including process efficiency, capacity credits, and operational lifespan, are obtained from the study by Handayani et al. [35]. Additionally, data on technology costs, including capital expenditures as well as fixed and variable operation and maintenance costs, are derived from the Annual Technology Baseline 2023 [36] (see Table 2).

Table 1. Projected fuel prices [34].

Type of fuel	Fuel price (USD/MWh)			
	2018	2030	2040	2050
Coal	9.8	7.05	7.05	7.05
Natural gas	28.4	27.9	27.9	27.9
Fuel oil	8.2	14.6	15.8	15.8
Diesel	10.2	13.3	14.1	14.1
Biomass	0.6	0.6	0.6	0.6
Biogas	2.3	2.3	2.3	2.3
Hydrogen (USD/kgH_2) [37]	5.5	3.0	2.0	1.0
Import (USD/kWh) [38]	0.07	0.07	0.07	0.07

4.4 Deep Decarbonized (DDC) Scenario

The Deep Decarbonized (DDC) scenario is developed to analyze the possibility of Thailand reaching the 2050 net-zero emissions target. The assumptions of sectoral mitigation measures in the DDC scenario are developed as follows:

1) *Commercial and residential sectors:* The energy-efficient appliances, including LED lighting, COP-8 air conditioning, refrigerators, and other electrical equipment, are assumed to progressively reach 100%, fully replacing conventional and inefficient alternatives by 2050. A similar assumption has been explored in a case study on India [10]. Additionally, the transition to electric cooking appliances as a substitute for conventional biomass and LPG is expected to contribute to the reduction of both energy consumption and GHG emissions. In this study, it is assumed that household adoption of electric cooking technologies will increase to 85% by 2050. Furthermore, retrofitting existing buildings and ensuring new constructions comply with Thailand's building energy code regulations could lead to a reduction of up to 49.4% in energy

consumption [40]. Based on trends in solar energy adoption in commercial buildings in Thailand, solar energy used in heating services is projected to grow to 25% by 2050.

Table 2. Technology characteristics and technology cost projections for the power sector.

Technology	Characteristics of power plant [35]			Capital cost (1,000 USD/MW) [36]			Fixed O&M cost (1,000 USD/MW) [36]			Variable O&M cost (USD/MWh) [36]		
	Lifetime (years)	Capacity credit (%)	Efficiency (%)	2018	2030	2050	2018	2030	2050	2018	2030	2050
Coal	30	69	42	3,549	3,395	2,824	78	18	13	9	8	8
Diesel oil	25	53	45	1,150	1,150	1,150	35	35	35	40	40	40
NGCC	30	92	56	1,248	1,161	971	31	29	24	2	2	2
NGCC-CCS	30	70	56	2,661	2,255	1,658	64	54	40	3	3	2
NGCT	30	53	33	1,120	1,050	872	24	23	20	6	6	6
Biomass	25	36	31	5,391	4,489	3,871	157	157	157	5	5	5
Biogas	25	92	31	5,391	4,489	3,871	157	157	157	5	5	5
Geothermal	30	70	15	6,750	5,926	5,156	114	107	104	-	-	-
Hydropower	40	27	100	6,660	6,660	6,660	33	33	33	-	-	-
Solar PV	25	30	100	1,219	1,038	500	23	18	13	-	-	-
Wind	27	20	100	1,363	1,150	924	30	27	23	-	-	-
Hydrogen*	30	30	56	2,880	2,697	2,331	206	201	192	68	68	68

Note: NGCC: "Natural Gas Combined Cycle", NGCC-CCS: "Natural Gas Combined Cycle with Carbon Capture and Storage", NGCT: "Natural Gas Combustion Turbine". Hydrogen*: the characteristics and technology cost of hydrogen power generation are gathered from [39].

2) *Industrial sector:* The EEP2018 indicates that energy efficiency improvements in this sector could lead to a 30% savings in energy consumption by 2037 relative to the BAU scenario [23], indicating an energy efficiency growth rate of 1.5% per year from 2018. In the DDC scenario, the annual energy efficiency improvement rate is assumed to remain constant from 2037 to 2050. Additionally, coal utilization in this sector is projected to be completely phased out by 2050, aligning with the LT-LEDS report [3]. Furthermore, the share of renewable energy (RE), specifically biomass and solar, is expected to increase progressively from 25% in 2018 to approximately 45% by 2050.
3) *Transport sector:* It is assumed that fuel economy efficiency for internal combustion engine (ICE) vehicles will increase by 25% in 2030 and 50% in 2050, higher than the 2018 fuel economy efficiency, based on the study of the fuel economy roadmap in ASEAN countries [41]. Furthermore, the electric vehicles (EVs) share will increase to 30% by 2030, according to the EV policy in Thailand mentioned in the LT-LEDS [3]. Towards 2050, the share of EV applications is assumed to be 75%, based on the study in [18]. The average travel distance of private vehicles is assumed to be reduced by 35%–50% as public mass transportation increases [20].
4) *Power sector:* In this scenario, the electric power installed capacity and generation are projected through the application of the least-cost optimization method. However, some constraints need to be defined, such as the RE constraint that is set to be increased up to 65%, similar to the study in [19]; diesel oil generation is set to stop its operation by 2030 while coal-based electricity generation is targeted to retire by 2050, in line with the LT-LEDS [3]; the utilization of hydrogen electricity generation and the incorporation of natural gas combined-cycle with CCS technology will be started in 2030; while the technology costs, fuel costs, and power plant characteristics have been illustrated in Table 1 and Table 2.

5. RESULTS ANALYSIS

5.1 Total Final Energy Consumption (TFEC)

Total TFEC in Thailand is anticipated to have a 2.39% increase per year between 2018 and 2050, reaching approximately 178 Mtoe. Throughout this timeframe, fossil fuels are predicted to remain the dominant energy sources, comprising between 61% and 64% of the total TFEC (see Figure 2). Furthermore, sectoral energy consumption patterns indicate that the industrial and transport sectors will be the primary consumers of final energy, accounting for 44.75% and 30.72% of the TFEC, respectively, by 2050 (see Figure 3).

Under the DDC scenario, Thailand's TFEC is projected to undergo a significant reduction due to the widespread adoption of energy-efficient technologies across various economic sectors. By 2050, the TFEC is projected to be around 97 Mtoe, representing a 45.77% decrease relative to the BAU scenario (see Figure 2). In this scenario, fossil fuel consumption will no longer be the predominant source of energy demand. Instead, electricity and biomass will become the primary energy carriers, accounting for approximately 53.34% and 16.59% of the TFEC, respectively. Additionally, hydrogen is expected to be integrated into the energy system, particularly within the transport and industrial sectors, contributing around 8.49% of the TFEC in 2050.

Sectoral energy consumption patterns (see Figure 3) indicate that in 2050, the industrial and transport sectors will account for 40.78% and 33.88% of the total TFEC, respectively.

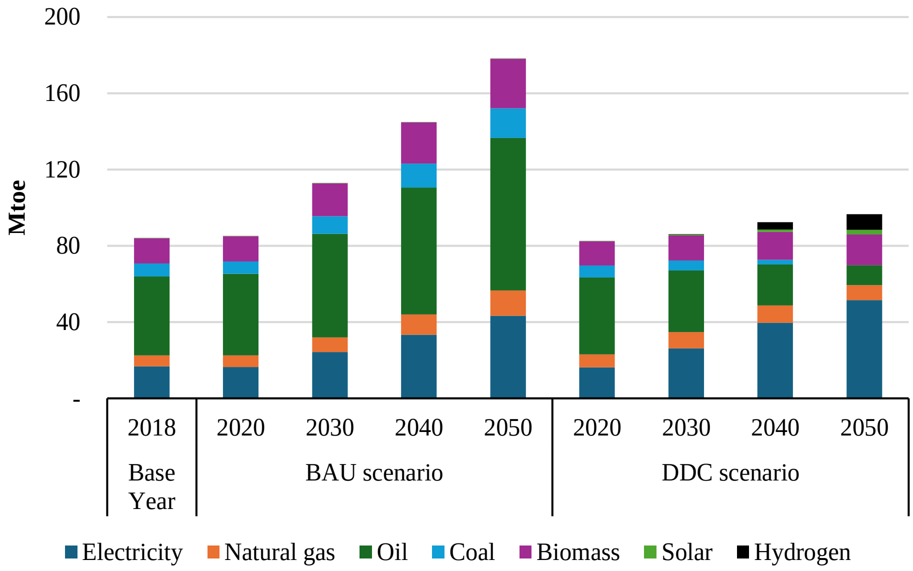

Fig. 2. Final energy consumption by fuel type.

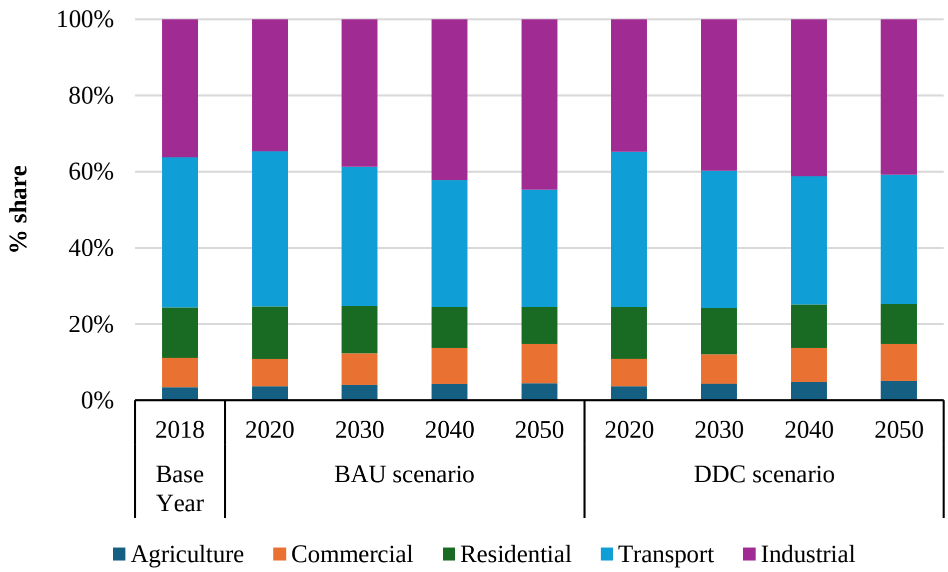

Fig. 3. Share of sectoral energy consumption.

5.2 Total Primary Energy Supply (TPES)

In 2018, the TPES was approximately 107 Mtoe. Under the BAU scenario, this figure is projected to increase significantly, reaching 239 Mtoe by 2050 (see Figure 4). The primary energy mix in 2050 is expected to remain dominated by oil products, natural gas, and coal, accounting for 33.42%, 26.48%, and 21.33% of TPES, respectively. In contrast, biomass and other renewable sources are anticipated to contribute a combined share of 15.57%, while the remaining energy supply will be derived from electricity imports.

However, under the DDC scenario, the TPES is projected to experience a notable decline due to reduced overall energy consumption, with an estimated total of 129 Mtoe in 2050. A significant transition toward renewable energy sources is expected, with solar, biomass, and wind collectively comprising over 48% of the TPES. Additionally, imported electricity from neighboring countries and hydrogen fuel imports are projected to constitute 4.79% and 10.29% of the 2050 TPES, respectively. The supply of natural gas and oil is anticipated to decrease to 23.93% and 8.22%, respectively, while coal will be entirely phased out from Thailand's energy system by 2050.

5.3 Electricity Generation

Under the BAU scenario, Thailand's electricity generation is projected to rise to approximately 539 TWh by 2050 (see Figure 5). The power sector will continue to depend primarily on fossil fuels, with natural gas and coal contributing 366 TWh and 99 TWh, respectively. Renewable energy (RE) will remain limited, accounting for only 13.77% of total generation, indicating a slow transition towards sustainable energy sources.

Despite having a great deployment of energy-efficient appliances on the demand side, the DDC scenario projects a substantial increase in electricity production to 712 TWh by 2050, driven by the widespread adoption of electric vehicles (EVs) in transport and increased electrification in industrial and building sectors to replace conventional fossil fuel-based heating. The power generation mix will shift significantly toward RE, contributing approximately 480 TWh, with 264 TWh from solar, 110 TWh from wind, 90 TWh from biomass, and 16 TWh from hydropower. Meanwhile, electricity generation from natural gas will decline, though CCS-equipped natural gas plants will still contribute 56 TWh. Additionally, hydrogen-based power generation will account for 25 TWh.

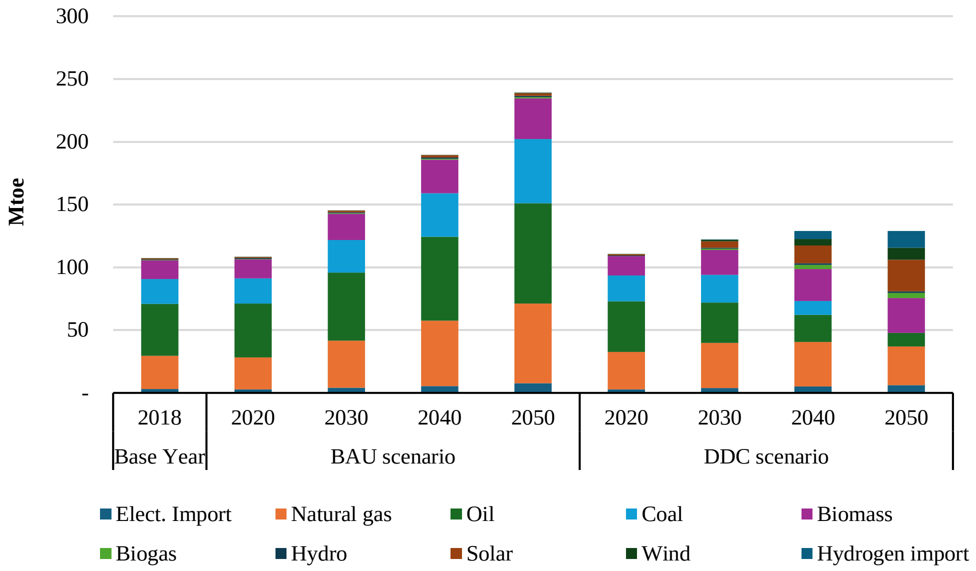

Fig. 4. Primary energy supply under the BAU and DDC scenarios.

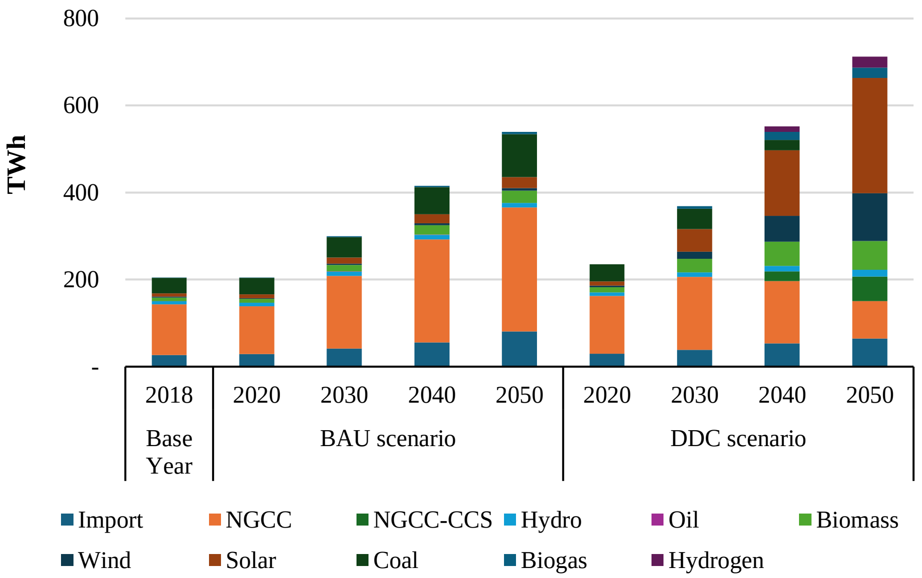

Fig. 5. Power production mix.

Figure 6 illustrates the projected electricity production costs under the BAU and DDC scenarios. In the BAU scenario, electricity production costs are expected to increase slightly from 0.08 cents/kWh (2.56 THB/kWh) in 2018 to 0.085 cents/kWh (2.72 THB/kWh) by 2030 due to the growing reliance on fossil fuel-based electricity and rising fossil fuel prices [36]. However, between 2030 and 2050, production costs are projected to decrease marginally to approximately 0.077 cents/kWh (2.46 THB/kWh), primarily due to declining technology costs, as indicated in the Annual Technology Baseline 2023 [38].

In contrast, under the DDC scenario, electricity generation costs in 2020 are estimated to rise significantly to 0.096 cents/kWh (2.66 THB/kWh), driven by the early deployment of renewable energy technologies, which initially involve high capital costs. However, by 2050, production costs are projected to decline substantially to approximately 0.06 cents/kWh (1.91 THB/kWh). This reduction is attributed to significant decreases in renewable energy technology costs and the negligible fuel costs associated with solar, wind, and hydropower sources, making renewable electricity generation more economically viable in the long term.

5.4 Carbon Dioxide (CO_2) Emissions

Figure 7 presents a comparative analysis of CO_2 emissions within Thailand's energy sector under the BAU and DDC scenarios. The LEAP model projections indicate that total CO_2 emissions in the BAU scenario are anticipated to rise substantially, reaching approximately 591 $MtCO_2$ by 2050, representing a 2.39-fold increase relative to 2018 levels. Among the various subsectors, the power sector is projected to be the predominant source of emissions, contributing 253 $MtCO_2$ by 2050. This is followed by the transport sector, emitting 160 $MtCO_2$, and the industrial sector, with emissions totaling 141 $MtCO_2$. Collectively, the agricultural, commercial, and residential sectors are expected to emit 37 $MtCO_2$ by 2050.

In contrast, the DDC scenario demonstrates a significant reduction in CO_2 emissions due to the adoption of cleaner technologies across both the supply and demand sectors. Under this scenario, emissions from the energy sector are projected to peak at 215 $MtCO_2$ in 2025, followed by a steady decline to approximately 68 $MtCO_2$ by 2050. Sectoral analysis under the DDC scenario indicates that the transport sector will become the largest emissions sector in 2050, accounting for 36.68% of the overall emissions. This is followed by the power sector (34.30%), the industrial sector (21.19%), the building sector (5.44%), and the agricultural sector (2.39%).

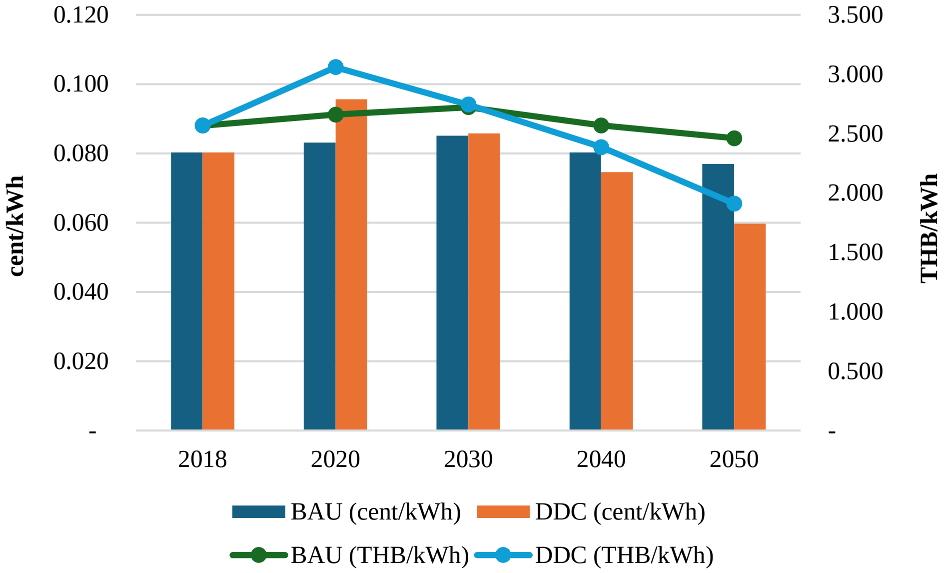

Fig. 6. Electricity production cost.
Note: 1 USD = 31.99 THB using the average exchange rate in 2021 [42]

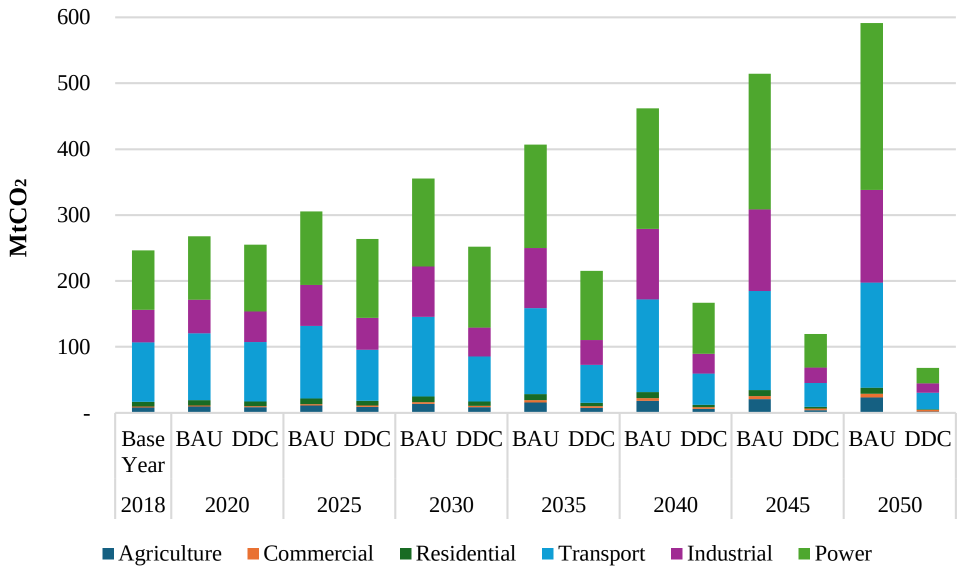

Fig. 7. CO_2 emissions in Thailand's energy sector.

Achieving economy-wide carbon neutrality in a nation necessitates a substantial reduction in carbon emissions across all sectors, removed by carbon sinks from the LULUCF sector. In this study, CO_2 emissions from non-energy sectors were obtained from Thailand's most recent Biennial Transparency Report [4]. The data indicate that, in 2018, CO_2 emissions from other sectors—such as waste, agriculture, and industrial processes and product use (IPPU)—were approximately 0.2 $MtCO_2$, 1.7 $MtCO_2$, and 29 $MtCO_2$, respectively. These emissions are assumed to remain constant from the base year (2018) through the study period ending in 2050. Additionally, Thailand's LULUCF sector has provided significant carbon sequestration, with removals ranging between 89 $MtCO_2$ and 108 $MtCO_2$ between 2018 and 2022. The estimation of net CO_2 emissions in this study integrates the projected emissions under the DDC scenario with the assumed emissions from non-energy sectors and carbon removals from the LULUCF sector. Therefore, Thailand is projected to achieve carbon neutrality by the early 2050s (see Figure 8)

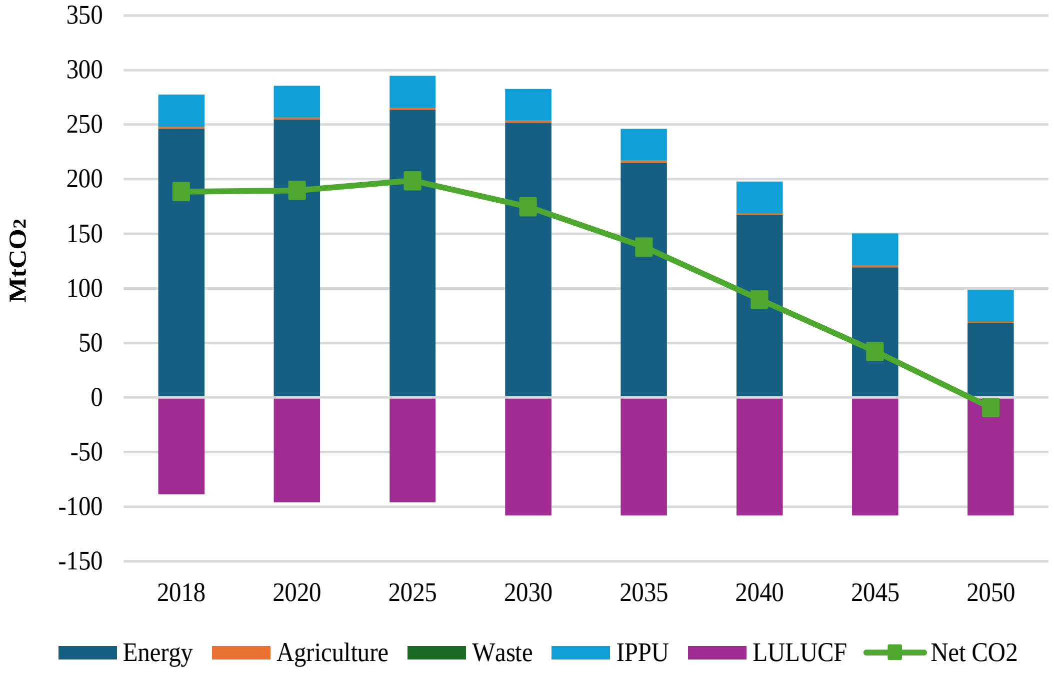

Fig. 8. Net CO_2 emissions in Thailand.

5.5 Energy Efficiency and Environmental Indicators

This study further examines key indicators of energy efficiency and environmental impact, which are critical for monitoring the progress and effectiveness of energy savings and carbon emissions in relation to socioeconomic factors. Energy intensity, defined as the ratio of final energy consumption to gross domestic product (GDP), serves as a key measure of energy efficiency, with a lower energy intensity indicating improved efficiency in producing economic output [43]. Additionally, carbon dioxide emissions intensity quantifies the amount of CO_2 emitted per unit of GDP, offering insights into the environmental sustainability of energy use.

The findings of this study indicate that under the BAU scenario, between 2018 and 2050, overall energy intensity is projected to decline slightly from 0.067/1,000 USD to 0.054 toe/1,000 USD, representing a reduction of 19.14%. However, energy consumption per capita is expected to increase to 1.44 toe/person over the same period. The total reduction in CO_2 emissions intensity by 2050 is estimated to be only 8.63% relative to 2018 levels. Furthermore, per capita CO_2 emissions are projected to increase significantly due to the combined effects of a declining population and persistently high CO_2 emissions from the energy system. In contrast, the DDC scenario demonstrates a substantial decline in both energy intensity and per capita energy consumption, with reductions of approximately 41.27% by 2050 compared to the BAU scenario. This outcome reflects the effectiveness of energy efficiency measures implemented under the DDC scenario in achieving significant energy savings over the study period. Additionally, the widespread adoption of low-carbon technologies in the DDC scenario is projected to lead to a 76.81% reduction in both CO_2 emissions intensity and per capita CO_2 emissions by 2050 compared to the BAU scenario (see Table 3).

Table 3. Energy efficiency and environmental indicators.

Year	2018	2030	2050
Business-as-Usual (BAU) scenario			
Energy intensity (toe/1,000 USD)	0.067	0.063	0.054
Energy consumption per capita (toe/person)	1.180	1.567	2.617
CO_2 emissions intensity ($kgCO_2$/1,000 USD)	0.196	0.198	0.179
CO_2 emissions per capita ($kgCO_2$/person)	3.467	4.929	8.687
Deep Decarbonized (DDC) scenario			
Energy intensity (toe/1,000 USD)	0.067	0.048	0.029
Energy consumption per capita (toe/person)	1.180	1.193	1.419
CO_2 emissions intensity ($kgCO_2$/1,000 USD)	0.196	0.140	0.021
CO_2 emissions per capita ($kgCO_2$/person)	3.467	3.485	0.999

6. DISCUSSION

6.1 Comparing with the Energy and Climate Change Mitigation Policies

The results derived from the LEAP modeling in this study further reveal that energy efficiency enhancement and the transition toward cleaner energy supply on both the supply and demand sides can lead to more ambitious outcomes in energy conservation, RE promotion, and carbon emissions reduction compared to existing government policies. This comparison highlights both alignments and gaps in policy effectiveness. The findings on final energy consumption indicate that, by 2037, energy intensity under the DDC scenario is projected to be 46.16% lower than 2010 levels, exceeding the target set by the national EEP2018 [23], which aims for a 30% reduction relative to 2010 levels. Similarly, the AEDP2018 [22] targets a 30% share of RE and alternative fuels in final energy demand by 2037. However, the results of this study suggest that the share of RE in the TFEC would reach only 20%, falling 10% behind the AEDP2018 target. Notably, electricity consumption is expected to rise substantially, accounting for up to 40% of the TFEC under the DDC scenario. Regarding power generation, the national Power Development Plan (PDP) aims to increase RE-based installed capacity to 47% by 2037, contributing approximately 29.7% to total electricity production [24]. In contrast, the findings of this study indicate that under the DDC scenario, the share of electricity generation from RE could reach 49%, primarily driven by solar and wind energy. In comparison with the recent research article [18], the total generation in the DDC scenario from this study suggests a greater increase due to the increased higher EV penetration as well as higher electrification in the building and industrial sectors.

Regarding economy-wide CO_2 emissions, the findings indicate that net CO_2 emissions in Thailand are projected to peak by 2025, aligning with the government's long-term climate change mitigation objectives [3]. Furthermore, the results suggest a substantial decline in net carbon emissions throughout the mid-21st century, reaching carbon neutrality earlier than the 2050s, as outlined in national targets. The LT-LEDS of Thailand has underlined broad technological pathways and deployment timeframes for emissions reduction; however, specific targets for these technologies remain undefined. In contrast, the DDC scenario in this study explicitly captures the implementation of these technologies, offering a more detailed roadmap for achieving the country's carbon neutrality goals.

6.2 Investment in the Power Sector

The investment in the electricity sector includes all the capital costs of the expansion of each power plant's installed capacity. Figure 9 indicates the cumulative investment in the power sector by different types of technology from 2018 until 2050 in both scenarios. In the BAU scenario, the investment in the power sector continues prioritizing fossil fuel-based power plants, especially natural gas power plants, with moderate growth in RE-based electricity generation. By 2050, the cumulative investment in the power sector under the BAU scenario would reach approximately 71.45 billion USD (at constant 2021 USD), where the investment mainly comes from the expansion of natural gas-based power plants. The three power generation sources with the highest cumulative investment in the BAU scenario consist of natural gas (35.64%), followed by solar (23.36%) and bioenergy (16.57%).

In the DC scenario, the expansion of power generation capacity is significantly greater compared to the BAU scenario, resulting in a substantial increase in total investment for installed power capacity. Under the DDC scenario, the cumulative investment in power generation infrastructure is projected to be approximately 184.79 billion USD. Within this investment, solar PV and wind power account for approximately 31.51% and 26.78%, respectively, of the total cumulative investment throughout the study period.

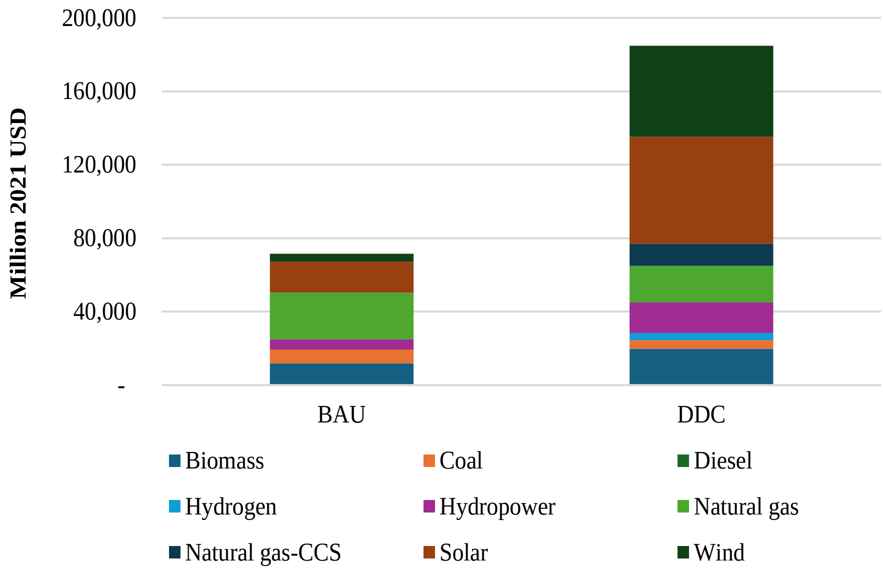

Fig. 9. Cumulative investment in the power sector between 2018 and 2050.

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

This study examines the role of low-carbon technologies in achieving deep decarbonization of Thailand's energy sector. The analysis focuses on the pathway toward attaining carbon neutrality by 2050, assessing the cost of electricity production, the investment in the power sector, and key indicators of energy efficiency and environmental impact associated with deep decarbonization strategies. The findings indicate that Thailand's CO_2 emissions are projected to peak around 2025, with carbon neutrality achievable by the early 2050s. Achieving this mitigation target necessitates a substantial acceleration in energy efficiency improvements and a promotion of cleaner energy supply across both supply and demand sectors. Specifically, energy efficiency enhancements across all economic sectors are expected to achieve a minimum improvement of 46% relative to the BAU scenario by 2050, equivalent to a 56% energy intensity reduction compared to 2018 levels. On the demand side, renewable energy sources—primarily solar and modern bioenergy—are projected to constitute at least 19% of total final energy consumption by 2050. Simultaneously, the electrification is expected to increase to at least 53%, whereas the integration of green hydrogen as a fuel in the transport and industrial sectors contributes approximately 8% of the TFEC. Furthermore, the decarbonization of Thailand's power sector is anticipated to play a crucial role, as this sector has historically been a major contributor to CO_2 emissions. The structure of power generation is expected to shift significantly from fossil fuel- to RE-based sources. Specifically, natural gas-based power generation is projected to decline gradually, while coal-fired power plants are expected to be phased out entirely by 2050, replaced by bioenergy, wind, and solar energy. By 2050, renewable energy is estimated to account for 67.45% of total electricity production in Thailand. Additionally, the implementation of CCS technology in natural gas power plants and the utilization of hydrogen for electricity production are identified as two critical measures for achieving substantial reductions in CO_2 emissions within the power sector.

7.2 Policy Recommendation

Based on the results and discussions presented in this study, the following policy recommendations are proposed to support Thailand's transition toward carbon neutrality:

1) *Early implementation of climate mitigation measures:* Immediate action should be taken to implement climate change mitigation strategies to achieve an early peak in carbon emissions, thereby preventing long-term carbon lock-in effects.
2) *Phase-out of coal-based energy:* The expansion of coal-fired power plants and coal-based energy sources in the industrial sector should be halted, with a strategic decommissioning plan in place to phase out existing coal infrastructure by 2050.
3) *Adoption of advanced carbon mitigation technologies:* The deployment of advanced technologies, such as carbon capture and storage (CCS), should be considered for natural gas- and bioenergy-based power generation to significantly reduce carbon emissions in the power sector.
4) *Integration of green hydrogen technology:* The development and application of green hydrogen as a zero-emission fuel should be prioritized to replace conventional fossil fuels within the energy system.
5) *Electrification and energy efficiency enhancement:* The adoption of electricity-based solutions should be accelerated across demand-side sectors while simultaneously improving the efficiency of end-use technologies to optimize energy consumption.
6) *Energy policy reform for renewable energy expansion:* Existing energy policies should be restructured to enhance the ambition and scale of renewable energy development, ensuring a more sustainable and resilient energy transition.

7.3 Limitation and Future Work

This study primarily focuses on the integration of low-emission technologies within Thailand's energy system to maximize energy savings and achieve deep reductions in CO_2 emissions by 2050. However, it does not incorporate emissions reduction measures from other key sectors, such as agriculture, IPPU, waste management, and LULUCF. Additionally, while the DDC scenario assumes the full applicability of all proposed technologies throughout the study period, this assumption may not fully reflect real-world conditions. Various constraints, including public acceptance, behavioral changes, infrastructure limitations, safety concerns, and government regulations, could influence the feasibility and rate of technology deployment.

Furthermore, this study evaluates investment requirements and electricity production costs exclusively within the power sector, without considering broader macroeconomic impacts such as job creation, economic growth, or gross domestic product (GDP) effects associated with the energy transition. Another key limitation is the study's focus on promoting domestic renewable energy utilization without assessing the role of energy storage systems, which are crucial for ensuring power grid stability.

Future research will address these limitations by incorporating a more comprehensive sectoral analysis, evaluating economic and social impacts, and examining the role of energy storage in grid stability. Such improvements will provide deeper insights into the energy transition pathway necessary for achieving carbon neutrality in Thailand.

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REFERENCES

[1] UNFCCC., 2015. *Paris agreement*. Available: https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf

[2] IPCC., 2018. Summary for Policymakers. In:Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press, 2022, pp.1-24.

[3] ONEP., 2022. *Thailand's long-term low greenhouse gas emission development strategy (revised version)*. Available: https://unfccc.int/sites/default/files/resource/Thailand LT-LEDS %28Revised Version%29_08Nov2022.pdf

[4] DCCE., 2025. *Thailand's first biennial transparency report*. Available: https://unfccc.int/documents/645098

[5] DEDE. 2022. Final energy consumption by economic sectors. *Department of Alternative Energy Development and Efficiency, Ministry of Energy* [Online serial] Retrieved June 15, 2024, from the World Wide Web: https://www.dede.go.th/articles?id=174&menu_id=67

[6] EPPO. 2023. Electricity statistic 2023. *Energy Policy and Planning Office, Ministry of Energy* [Online serial], Retrieved June 15, 2024, from the World Wide Web: https://www.eppo.go.th/index.php/en/en-energystatistics/electricity-statistic

[7] UNFCCC., 2022. *Thailand's 2nd updated nationally determined contribution*. Available: https://unfccc.int/sites/default/files/NDC/2022-11/Thailand 2nd Updated NDC.pdf

[8] IPCC., 2018. Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2018. doi: https://doi.org/10.1017/9781009157940.008.

[9] Zhang S. and Chen W., 2022. China's energy transition pathway in a carbon neutral vision. *Engineering* 14(2022): 64–76.

[10] Vats G. and Mathur R., 2022. A net-zero emissions energy system in India by 2050: An exploration. *Journal of Clean Production* 352: 131417.

[11] Glynn J., Gargiulo M., Chiodi A., Deane P., Rogan F., and Gallachóir B. Ó., 2019. Zero carbon energy system pathways for Ireland consistent with the Paris Agreement. *Climate Policy* 19(1): 30–42.

[12] 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.

[13] Pradhan B.B., Shrestha R.M., and Limmeechokchai B., 2022. Attainability of net zero carbon emission targets in Nepal under different effort-sharing approaches. *Global Environment Research* 26.

[14] Williams J.H., Jones R.A., Haley B., Kwok G., Hargreaves J., Farbes J., and Torn M. S., 2021. Carbon-neutral pathways for the United States. *AGU Advances* 2(1).

[15] Promjiraprawat K., Winyuchakrit P., Limmeechokchai B., Masui T., Hanaoka T., and Matsuoka Y., 2014. CO_2 mitigation potential and marginal abatement costs in Thai residential and building sectors. *Energy and Buildings* 80: 631–639.

[16] Chaichaloempreecha A., Winyuchakrit P., and Limmeechokchai B., 2017. Assessment of renewable energy and energy efficiency plans in Thailand's industrial sector. *Energy Procedia* 138: 841–846.

[17] Chunark P., Thepkhun P., Promjiraprawat K., Winyuchakrit P., and Limmeechokchai B., 2015. Low carbon transportation in Thailand: CO_2 mitigation strategy in 2050. *Springerplus* 4(1).
[18] Limmeechokchai B., Winyuchakrit P., Pita P., and Tatsuya H. 2022. Decarbonizing transport sector in Thailand towards 2050. In *Proceedings of the 2022 International Conference and Utililty Exhibition on Energy, Environment and Climate Change (ICUE)* 2022. Pattaya City, Thailand: 26-28 October.
[19] Chaichaloempreecha A. and Limmeechokchai B. 2022. Transition of Thailand's power sector toward carbon neutrality 2050. In *Proceedings of the 2022 International Conference and Utililty Exhibition on Energy, Environment and Climate Change (ICUE)* 2022. Pattaya City, Thailand: 26-28 October.
[20] Pradhan B.B., Chaichaloempreecha A., 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.
[21] IRENA & ACE., 2022. *Renewable energy outlook for ASEAN towards a regional energy transition*. International Renewable Energy Agency. Available: https://www.irena.org/Publications/2022/Sep/Renewable-Energy-Outlook-for-ASEAN-2nd-edition
[22] DEDE., 2020. *Alternative energy development plan 2018-2037 (AEDP2018)*. Department of Alternative Energy Development and Efficiency, Ministry of Energy. Available: http://www.eppo.go.th/index.php/th/conservation/aedp
[23] DEDE., 2020. *Energy Efficiency Plan 2018-2037 (EEP2018)*. Department of Alternative Energy Development and Efficiency, Ministry of Energy. Available: https://oldwww.dede.go.th/ewt_dl_link.php?nid=54495
[24] EPPO., 2020. *Power Development Plan 2018 (PDP2018)*. Energy Policy and Planning Office, Ministry of Energy. Available: https://www.eppo.go.th/images/POLICY/PDF/PDP2018.pdf
[25] Heaps C.G. 2023. LEAP: The Low Emissions Analysis Platform. *Stockholm Environment Institute*. Somerville, MA, USA. Available: https://leap.sei.org
[26] SEI. 2023. NEMO: Next Energy Modeling system for Optimization. *Stockholm Environment Institute*. Somerville, MA, USA. Available: https://www.sei.org/tools/nemo-the-next-energy-modeling-system-for-optimization/
[27] Emodi N. V., Emodi C. C., Murthy G. P., and Emodi A. S. A., 2017. Energy policy for low carbon development in Nigeria: A LEAP model application. *Renewable and Sustainable Energy Reviews* 68: 247–261.
[28] Lorm R. and Limmeechokchai B., 2024. Thailand net zero emissions 2050 : Analyses of decarbonized energy system beyond the NDC. *International Energy Journal* 24(2): 95–108.
[29] World Bank. 2024. WDI: World Development Indicators. *World Bank* [Online serial] Retrieved June 15, 2024 from the World Wide Web: https://databank.worldbank.org/source/world-development-indicators
[30] United Nations. 2024. World Population Prospects 2022. *Department of Eeconomic and Social Affairs, Population Division, United Nations* [Online serial] Retrieved January 01, 2024, from the World Wide Web: https://population.un.org/wpp/
[31] NSO. 2024. Thailand Statistical Yearbook 2003-2019. *National Statistical Office of Thailand* [Online serial] Retrieved December 20, 2023 from the World Wide Web: https://www.nso.go.th/nsoweb/nso/ebook?set_lang=en
[32] IIASA. 2024. Share Socioeconomic Pathways Database-Version 2.0. *International Institute for Applied Systems Analysis* [Online serial] Retrieved December 20, 2024, from the World Wide Web: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10%0A
[33] MoT., 2020. *Transport Statistics 2018*. Available: https://datagov.mot.go.th/dataset/7c3d8945-fcb5-4f74-a69f-e757dd981bc1/resource/01dd8c9c-ae61-403e-bab8-74c220212003/download/transport-statistics-2018-complete.pdf
[34] [34] ACE., 2022. *The 7th ASEAN energy outlook 2020-2050*. Jakarta, Indonesia. Available: https://asean.org/book/the-7th-asean-energy-outlook-2020-2050/
[35] 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.
[36] NREL. 2024. Annual Technology Baseline 2023. *National Renewable Energy Laboratory, U.S. Department of Energy* [Online serial] Retrieved January 01, 2024, from the World Wide Web: https://atb.nrel.gov/electricity/2023/technologies
[37] IEA., 2024. *World energy outlook 2024*. Available: https://www.iea.org/reports/world-energy-outlook-2024
[38] EGAT., 2013. *Power Purchase Agreement of Nam Ngiep 1 Project between EGAT and Laos*. Available: https://policy.asiapacificenergy.org/sites/default/files/Power Purchase Agreement of Nam Ngiep 1 Project between EGAT and Laos.pdf
[39] Kim B. J., Hyun M. K., and Yoo S. H., 2024. Economic effects of the hydrogen fuel cell sector in South Korea: An input-output analysis. *International Journal of Hydrogen Energy* 68(May): 955–969.
[40] Ananwattanaporn S., Patcharoen T., Bunjongjit S., and Ngaopitakkul A., 2021. Retrofitted existing residential building design in energy and economic aspect according to Thailand building energy code. *Applied Sciences* 11(4): 1–19.
[41] GIZ., 2019. *ASEAN Fuel Economy Roadmap for the Transport Sector 2018-2025: with Focus on Light-Duty Vehicles*. Available: https://asean.org/wp-content/uploads/2021/11/ASEAN-Fuel-Economy-Roadmap-FINAL.pdf

[42] IRS. 2025. Yearly average exchange rates for converting foreign currencies into U.S. dollars. *IRS* [Online serial] Retrieved February -05, 2025, from the World Wide Web: https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates

[43] Apergis N., Payne J.E., and Rayos-Velazquez M., 2020. Carbon dioxide emissions intensity convergence: Evidence from central American countries. *Frontier in Energy Research* 7: 1–7.