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ORIGINAL ARTICLE

Macroeconomic impacts and co-benefits of deep-decarbonization in Thailand

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Abstract

The updated Nationally Determined Contributions (NDC) in 2022 of Thailand includes an aggressive GHG emission reduction target of 40% in 2030 from its baseline emissions. However, the macroeconomic impacts and co-benefits associated with reducing GHG emissions are not addressed. This study analyzes the macroeconomic implications and co-benefits of GHG emission reduction in Thailand to achieve the NDC and net zero emission (NZE) targets by 2050 using the AIM/Hub-Thailand model. This paper provides co-benefits for Thailand on ambitious long-term GHG emission reduction targets. Considering the co-benefit analysis in the policy documents will provide holistic insights on the positive impacts of GHG mitigation. Results show that Thailand would have to bear a GDP loss of 7.7% in 2050 compared to the BAU level if the net zero emissions need to be achieved. Fuel switching from fossil fuel to electricity in the demand side and improvement of technologies in the power sector also reduces air pollutant emissions. The increasing dependence on domestic energy supply in the NZE scenario will make the country less vulnerable to the fluctuating prices in the international energy market. In terms of trade-offs, the land use for sustainable biomass in both the NDC and NZE scenarios will be larger than in the BAU scenario. Results show better land use for biomass production and higher yields in agricultural production. Moreover, the achievement of NZE pathway will require effective usage of land area and better use of energy resources, thereby making the country more energy secure.

Keywords AIM/Hub model · Net zero emissions · Macroeconomic impacts · Co-benefits of GHG mitigation · Thailand

1 Introduction

Climate change is one of the most serious and challenging global problems. It has far-reaching effects on human societies, and ecosystems, including rising sea levels, changes in weather patterns, more frequent and severe natural disasters, and changes in agricultural productivity. The main cause of climate change is anthropogenic GHG emissions from burning of fossil fuels, deforestation, industrial processes and changes in land use. The scientific community has issued a clear warning about the urgent need to act in reducing the worst effects of climate change (IPCC, 2014). The consequences of climate change are being seen all over the world. Addressing climate change requires urgent action from individuals, governments and businesses. To reduce impacts of climate change, reducing the GHG emissions on a significant scale is required with the ultimate goal of achieving net-zero carbon emissions. The process of gradual elimination of carbon-emitting fuels and shifting to

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cleaner alternatives is phrased as "deep decarbonization". This involves transforming energy systems, industries, transportation, and other sectors to minimize GHG emissions, particularly carbon dioxide (CO_2), which is a major contributor to climate change (Holmes et al. 2021; Sovacool et al. 2017).

Anthropogenic emissions that cause the global surface temperature to increase need to be reduced by using comprehensive climate change mitigation policies. The implementation of emissions reduction policies will reshape the macroeconomic variables. Identifying the macroeconomic impacts of such policies are the focus of the policy makers. The GHG mitigation analysis often ignores the co-benefits of achieving the GHG mitigation targets. Air-pollutants are co-emitted during the combustion of fossil fuels and biomass for energy use. Air-pollutants are one of the leading causes of respiratory diseases and premature deaths. In Thailand, it is estimated that long-term exposure to fine particles or PM2.5 was attributable to 29,000 premature deaths in 2021 (Farrow et al. 2022). Reducing GHG emissions concurrently reduces the emissions of air pollutants. Along with GHG mitigation, prevention of negative impacts on air and human health brings co-benefits to the GHG mitigation actions. Likewise, improved energy security of the country is one of the co-benefits of GHG mitigation that has received little attention (Deng et al. 2017). Achieving carbon neutrality and net zero emission goals will require a dramatic shift in the energy mix. The energy sector is responsible for Thailand's largest GHG emissions. The GHG emissions in the energy sector accounted for 67.14% of total emission in 2000, which increased to 69.96% in 2019 (MNRE,2022b). GHG emissions in the energy sector mainly come from fuel combustion in electricity generation, transport, manufacturing industries and construction, and other sectors. Thailand has implemented energy and climate change related plans and policies in reducing GHG emissions in the energy sector. To achieve net zero emission targets, the energy sector will play a key role in mitigating GHG emissions after 2025. Key mitigation actions are increasing of renewable energy share, enhancing energy efficiency improvement, promotion of electric vehicles, and implementation of the advanced technologies, etc. (MNRE, 2022a). Adoption of energy efficiency measures and use of low carbon domestic renewable energy will reduce the dependency on imported fossil-fuel, thereby increasing energy security (Matsumoto 2015). In the NDC and LT-LEDS documents of Thailand, the co-benefits of GHG mitigation measures have not been considered. Analyzing co-benefits motivates mitigation (Schwanitz et al. 2015) and can promote policies that will better mitigate climate change and improve overall welfare (West et al. 2011).

Several studies have been conducted to investigate the macroeconomic effects of GHG mitigation. The economic impacts of an international carbon market following China's INDC target were investigated by Qi and Weng (2016). In addition, Mittal et al. (2016) suggested that the role of renewable energy can reduce the economic loss, and the introduction of carbon capture and storage (CCS) can be another significant technology to control GHG emission levels. In achieving Vietnam's INDCs target, the gross domestic product (GDP) loss and welfare loss caused by renewable energy were assessed and it was determined that renewable energy in the electricity generation sector could reduce mitigation costs (Tran et al. 2016). Thepkhun et al. (2013) assessed Thailand's Nationally Appropriate Mitigation Action (NAMA) in the energy sector under an emission trading scheme (ETS). They suggested that the ETS will play a vital role in reducing GHG emissions through energy efficiency improvements and the implementation of renewable energy together with CCS technologies. Dai et al. (2016) examined the economic impacts of large-scale installation of renewable energy and its co-benefits in China and suggested that the renewable energy resources, and the availability and reformation of grid connectivity, should be verified. Moreover, the installed capacity of renewable energy will boost the renewable energy manufacturing industries (Dai et al. 2016). Shakya et al. (2023) analyzed environmental, energy security and equity benefits of net-zero emissions in Nepal. Air pollutants can be reduced in Nepal with more measures in a net zero emission scenario. The study also found that there is a significant improvement in energy security indicators and energy equity.

In the case of Thailand, Rajbhandari et al. (2019) analyzed the macroeconomic effects by setting various GHG emission reduction target using a computable general equilibrium (CGE) model on Thailand's economy, and the GDP loss in achieving GHG reduction is estimated to be up to 11.8% by 2050. To minimize such impacts, energy efficiency development and renewable energy are suggested to be key options in lowering the economic loss and the GHG prices. Rajbhandari et al. (2019) emphasized that Thailand will face enormous costs in reducing GHG emissions if transformative changes in the economic structure and energy system are overlooked. Chunark et al. (2017) assessed the GHG mitigation potential using renewable energy in Thailand's INDCs and the economic impacts from GHG emission reduction and found that the GDP loss ranges from 0.2% in the case of a 20% reduction target to 3.1% in the case of a 40% reduction target in 2030. Limmeechokchai et al. (2023) used a macroeconomic model to assess the economy-wide effects of various GHG emission reduction scenarios, including net zero emissions in 2050, during the period 2010–2050. To understand the impacts of the emissions reduction target of Thailand's NDC in the transport sector, Boonpanya and Masui (2021) evaluated the impacts on socio-economic status and GHG emissions by developing GHG mitigation scenarios in freight transport in line with Thailand's NDC target, and the results showed that new mitigation options in freight transport could lower GDP loss by 1.04% and consumption loss by 0.9%. These studies reveal that energy efficiency improvements and the greater use of renewable energy are keys in reducing economic losses and GHG emissions. However, the co-benefits of net zero emissions in Thailand have not been analyzed in any of the existing literature. Therefore, this study aims to analyze co-benefits of NDC and net zero emissions targets in addition to the macroeconomic implications in Thailand using the top-down computable general equilibrium (CGE), AIM/Hub-Thailand model. The analysis provides useful insights not only for Thailand but also for other emerging economies on how to achieve ambitious GHG reduction targets in 2050 to align with the 1.5 °C target of the Paris Agreement.

This paper is divided into four sections. Section 1 is the introduction. Section 2 presents the research mechanism used in the study along with the description of the model and data inputs. Section 3 presents the results of the study which includes decarbonization in the energy system, macroeconomic implications and co-benefits, and Section 4 concludes the findings of the study.

1.1 Research mechanism

To study the effects of emissions reduction in Thailand's economic behavior, an economy wide model named AIM/Hub-Thailand is formulated. AIM/Hub-Thailand is model standing for the interrelationship between different sectors in the economy (Fujimori et al. 2021a; Limmeechokchai et al. 2023). The CGE model includes (1) firms that maximize profits by minimizing costs; (2) households that maximize their welfare/utility by purchasing commodities according to prices; (3) markets that balance prices until supply and demand are equal; and (4) governments that collect taxes and spend their revenue on consumption and transfer to households. The AIM/Hub-Thailand model is based on a one-year step by step recursive dynamic general equilibrium model. The AIM/Hub model has been used for analyzing various energy and climate related policies. It is an efficient tool for assessing economic and energy policies related to GHG mitigation analysis at global, regional and national levels (Fujimori et al. 2016; Fujimori, Masui, et al., 2017; Fujimori et al. 2017b; Limmeechokchai et al. 2017; Oshiro et al. 2017; Shukla et al. 2017).

The model simplifies the real-world events through the representation of the relevant key players. The model analyzes the effects of the market equilibrium through the impacts of economic policies. When all markets in the economy are in equilibrium, the economy attains a state of general equilibrium. In this paper, the AIM/Hub-Thailand model examines forty-one industrial classifications as shown in Fig. 1 (Chunark et al. 2017; Limmeechokchai et al. 2023). The model evaluation period ranges from 2010 to 2050. The input data, including GDP, population, and fuel cost are supplied exogenously to the model. The model endogenously estimates the energy mix and emissions.

The production sectors are considered to maximize their profits under the multi-nested constant elasticity of substitution (CES) functions and relative prices of inputs (Korkmaz

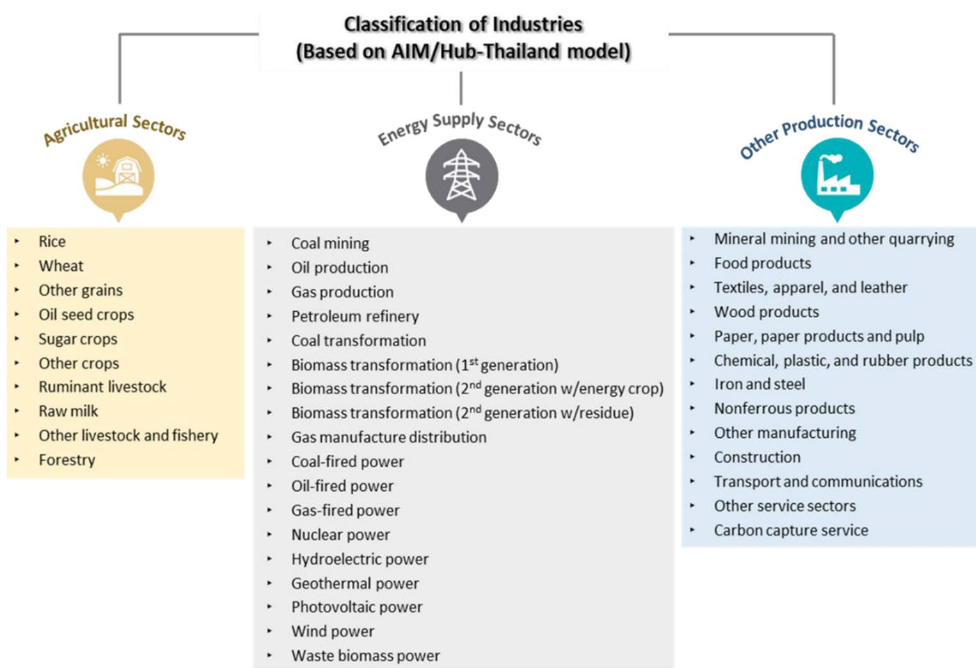


Fig. 1 Industrial classification in the AIM/Hub-Thailand model

et al. 2020). Household expenditures per commodity are represented by a linear expenditure system (LES) function. Domestic and foreign direct investments are the sources for savings. The savings are expressed externally as a percentage of the change in GDP compared to the base year. The formation of fixed capital is characterized by a constant coefficient of total investment in the model. The international trade in this study follows Armington (1969) which assumes domestic and imported goods as imperfect substitutes. The domestic supply of goods is a CES function of the domestic and imported goods. The constant elasticity of transformation (CET) function is used for allocating the produced goods into exports and domestic demand for goods. This study considered both the energy and non-energy sectors. The methodological details and parameter settings considered in this study are based on Fujimori et al. (2021); Fujimori, Masui, et al. (2017).

Though this study covers the interaction between entire goods and production factors in an economy, the technological details are not expressed as much as in the bottom-up energy system models. The distribution of technological shares, such as conventional fossil fuel-fired, solar, wind, etc., is dependent on the electricity demand. This allocation is guided by the power generation prices associated with each technology, and a logit function is employed for this purpose. The determination of power generation prices for each technology is based on their respective production functions. To ensure an energy balance, the logit functional form was employed, as the constant elasticity of substitution function did not guarantee it. The parameters incorporated in the logit function involve certain assumptions and strongly require further studies for improvement.

The autonomous energy efficiency improvement (AEEI) in energy consumption and logit share parameters, which are crucial for determining the share of power generation by various technologies, were calibrated in that period, and subsequently applied to guide future scenarios. This study attempted to align scenarios with existing national policies by fully incorporating relevant measures. The emission constraints for 2030 were considered based on the Thailand's NDC. The major national-level energy and climate mitigation policies were considered, either integrating them as model constraints or utilizing them as reference benchmarks. The power development plan formulated by the Ministry of Environment served as a foundational constraint to construct the AIM/Hub-Thailand model (Fujimori et al. 2021).

1.1.1 Input data

A Social Accounting Matrix (SAM) is employed to calibrate the AIM/Hub-Thailand model. The consistency checks between the original SAM in the model and the energy statistics are maintained to evaluate both the flow of energy as well as the GHG emissions. The Global Trade Analysis Project (GTAP) is used as the basis for the SAM development (Avetisyan et al. 2011; Dimaranan 2006). The SAM of Thailand for the year 2005 is provided in the supplementary material. The global warming potentials (GWP) of methane (CH_4) and nitrous oxide (N_2O) are taken to be 28 and 265, respectively, based on the IPCC's Fifth Assessment Report (IPCC, 2014).

Figure 2 presents the socio-economic parameters considered in this study. The population projections up to 2040 considered in this study are based on the national statistics of Thailand titled "Population projections for Thailand 2010–2040" (NESDC, 2019). The population forecast shows that the country is moving towards a full-fledged ageing society population. The population is estimated to reach its peak in 2025 with approximately seventy-two million persons and then gradually decline thereafter at an average rate of -0.3% per annum during 2025–2050 (see Fig. 2(a)). The estimated future population is found to be in line with the national study (NESDC, 2019). Based on the estimations of the Ministry of Energy, the study assumes the GDP to grow at an average growth rate of 3.78% during 2018–2050 (EPPO, 2015, 2019, 2020) (see Fig. 2(b)). Constant price estimates of GDP are used in this study, which are calculated by expressing values in terms of USD in 2005 price. Based on these assumptions, the per capita GDP of Thailand is assumed to undergo a four-fold increase during 2010 to 2050 (see Fig. 2(c)).

1.1.2 Description of scenarios

In this paper, three scenarios are formulated. There are business-as-usual (BAU), NDC, and net zero emission (NZE). The BAU scenario, also known as a reference case, considers the continuity of current pattern of energy consumption and policies intervention during 2010–2050. The availability of technologies is considered regardless of climate policy interventions. In the BAU scenario, the emissions constraint is not considered. GHG emissions in this study consist of CO_2, CH_4 and N_2O from both energy and non-energy sectors.

On the other hand, the NDC and NZE scenarios consider the involvement of climate policies in Thailand. To increase the ambition level of national mitigation policies, Thailand's updated NDC 2022 aims at reducing the GHG emissions by 30% compared with the BAU scenarios in 2030. The GHG mitigation level could increase up to 40%, depending on international support, such as access to technology development and transfer, financial resources and increased capacity building (UNFCCC, 2022). Thailand's government

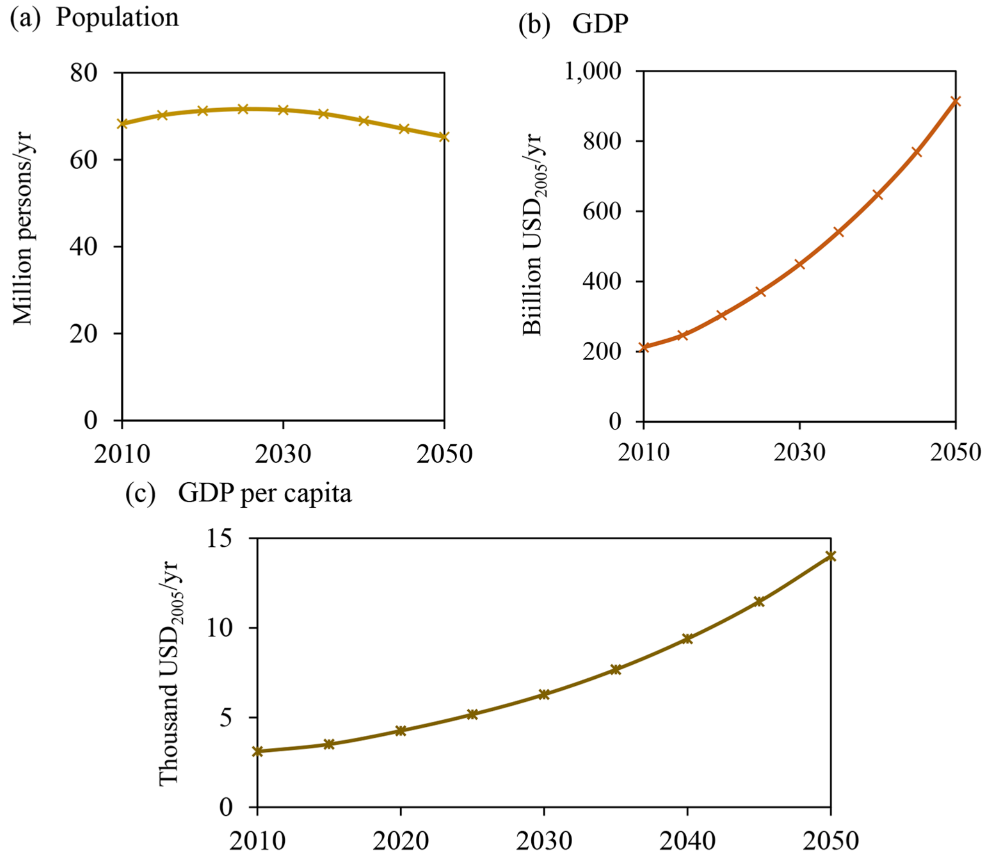


Fig. 2 Socio-economic trends in the BAU scenario (**a**) Population, (**b**) GDP and (**c**) GDP per capita

has integrated updated NDC 2022 target into the National strategy by creating the NDC sectoral action plan. The plan specifies measures to mitigate emissions and sectoral targets in energy, transport, industry, waste and agriculture sectors. The relevant measures to reduce emissions include development of energy efficiency and renewable energy technologies; enhancement of electrification of transport; deployment of carbon capture and storage (CCS), carbon capture utilization and storage (CCUS) and bioenergy with carbon capture and storage (BECCS), promotion of waste-to-energy technologies; improvement of waste management technology and system; and technologies, innovations and capacity building to support the practices for sustainable climate smart agriculture (UNFCCC, 2022).

Thailand, a country that relies on fossil fuel for its primary energy supply, is facing unprecedented challenges in meeting the net zero emission targets. The country announced its intention of achieving carbon neutrality by 2050 and net zero GHG emissions by 2065 at the COP26 and has submitted the updated LT-LEDS to UNFCCC in 2022(MNRE, 2022a). However, the NZE scenario in this study is designed for the net zero GHG emissions by 2050, even earlier than the target in the LT-LEDS of Thailand. Renewable energy development and energy efficiency improvement are key components of Thailand's GHG mitigation strategies to move the country's energy system toward a decarbonization pathway and reach the NZE scenario. In addition, CCS and CCUS and green hydrogen technologies are identified as potential negative emission technologies to support decarbonization efforts in the energy sector. The mitigation measures in the demand side sector are needed such as efficient appliances, electric vehicles, and the use of renewable energy. The emission pathways in the NDC and NZE scenarios are considered as input to the AIM/Hub-Thailand model.

1.2 Results and discussion

1.2.1 GHG emissions

GHG emissions in the BAU scenario are expected to rise from 479.7 $MtCO_2eq$ in 2010 to 653.2 $MtCO_2eq$ in 2050, at an annual growth rate of 0.77%. Figure 3 (a) shows the GHG emissions by sector in the BAU scenario. Most of the GHG emissions are contributed by the energy sector whose share is estimated to increase from 70.4% in 2010 to 79.8% in 2050. During 2010–2050, the industrial process and product use sector, and the waste sector would maintain their shares at 4.7-5.5% and 3.7–3.9%, respectively. The proportion of GHG emissions in the AFOLU sector declines from 21.0% in 2010 to 11.0% in 2050.

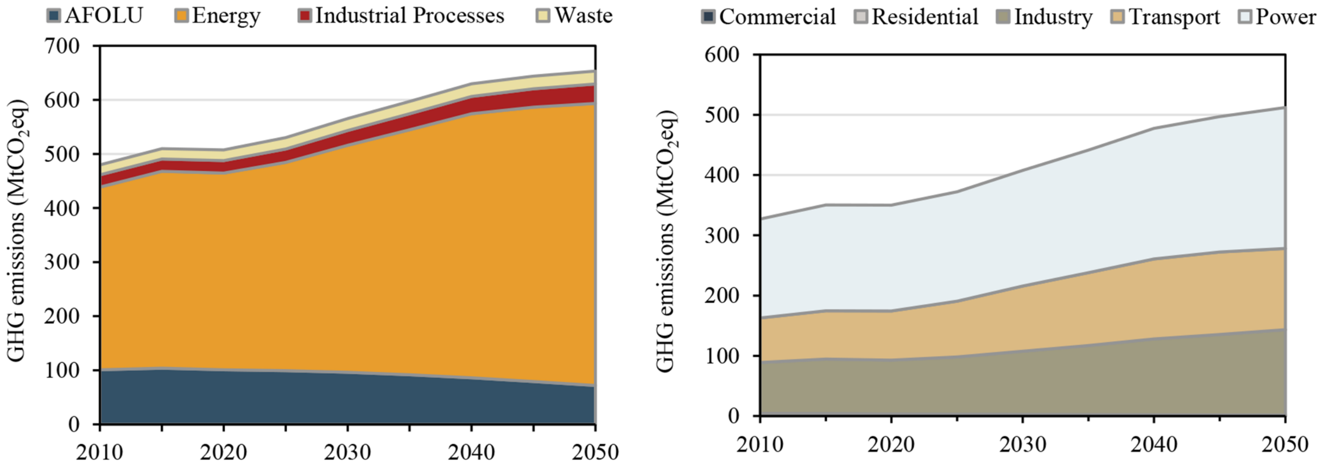
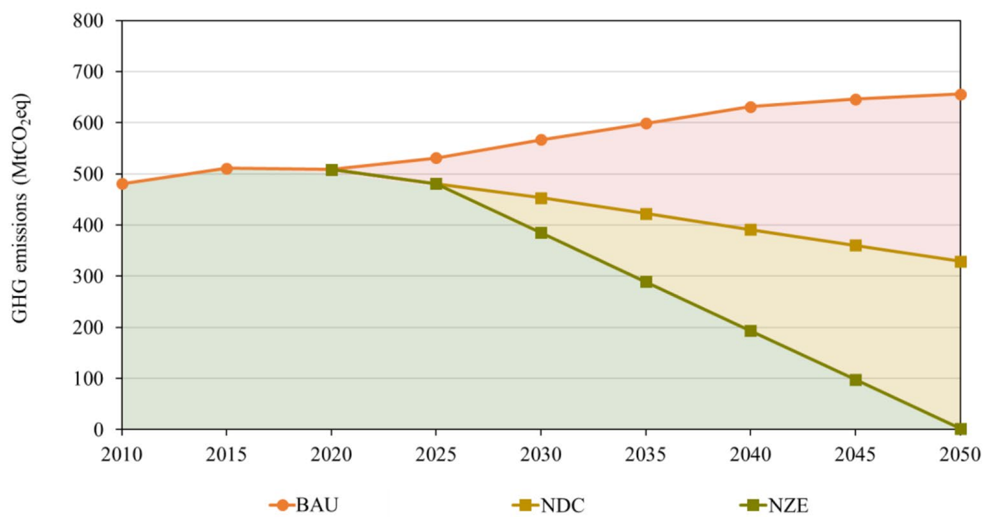


Fig. 3 (**a**) Thailand's GHG emissions by sectors (**b**) Energy-related GHG emissions in the BAU scenario

Fig. 4 Thailand's GHG emission pathways in the BAU, NDC and NZE scenarios



The energy supply sector dominates the total energy related GHG emissions of Thailand. GHG emissions from power generation account for half of total GHG emissions in the energy sector in 2010, while the industry and transport sectors combined account for 48% of GHG emissions in the energy sector in 2010. By 2050, the industry and transport sectors would jointly make up more than half of emissions in the energy sector, while the power sector's share would drop to less than half. The commercial and residential sectors together make up less than 1.5%. Figure 3 (b) shows GHG emissions from the energy sector in the BAU scenario during 2010–2050.

The trend of GHG emissions in Thailand during 2015–2020 did not change much. The GHG emissions were 510.8 $MtCO_2eq$ in 2015 and decreased slightly to 508.5 $MtCO_2eq$ in 2020 (see Fig. 4). However, the GHG emissions in the BAU scenario, as a base case, are expected to increase. (UNFCCC, 2021).

Compared to the BAU level, the GHG emissions in 2030 would be lowered by 20.0% in the NDC scenario, while in 2050 it would be lowered by 49.8%. In the NZE scenario, net GHG emissions are assumed to be zero by 2050; GHG emissions are estimated to reduce sharply after 2025 to meet the net zero GHG emission targets in 2050. GHG emissions in 2030 are estimated to be lowered by 32.1% from BAU level in the NZE scenario. Full deployment of fossil fuel with CCS, BECCS, and non-biomass based renewable energy technologies in the power and the industrial sectors would play a vital role in reducing the GHG emissions in the NZE scenario (see Fig. 4).

It should be noted that the revised NDC of Thailand has a target to increase the GHG mitigation level to 30-40% in 2030, depending on the international support such as financing, technology development and transfer, and capacity building. These supports can also be in the form of foreign direct investment (FDI) in mitigation measures or technologies such as solar power plants or mass rapid transports.

Studying the role of FDI in the mitigation will provide useful insights to the policy makers regarding its effect on the economy of the country. However, the role of such support hasn't been recognized in this study. Such analysis was carried out by Shakya Raj (2014) for the case of Nepal to study the effect of FDI by introducing foreign owned capital to cover exogenously specified shares of the additional investment required in the transport and electricity sectors.

1.2.2 Macroeconomic impacts

Analyzing the technological and macroeconomic implications of imposing varying GHG emission reduction targets by 2050 is particularly important for Thailand's decarbonization pathways. There have been a limited number of studies on the macroeconomic impacts of GHG mitigation pathways of Thailand that are consistent with a 2 °C–1.5 °C temperature limit, and existing literature typically focuses specifically on the energy system characteristics of either 2 °C and/or 1.5 °C scenarios (Chaichaloempreecha et al. 2022; Rajbhandari and Limmeechokchai 2021). However, few existing studies have analyzed the economic impacts of reaching 100% GHG emission reduction targets by 2050, the role of CCS technologies in GHG mitigation, and the rate of carbon sequestration by CCS technologies (Limmeechokchai et al. 2023). Figure 5 (a) presents the average GDP losses sustained from 2030 to 2050 in achieving NDC and net zero GHG emissions targets. GDP loss is the difference between the GDP in the BAU scenario and the GDP in the GHG mitigation scenarios. The GDP loss in the NZE scenario (2.2% compared to the BAU scenario) will be higher than the GDP loss in the NDC scenario (1.3% compared to the BAU scenario) in 2030. In 2040, GDP loss compared to the BAU level will be 2.3% in the NDC scenario and 8.1% in the NZE scenario. In the NDC scenario, the GDP will decrease around 2.3–2.4% during 2040–2050. In the NZE scenario, the highest GDP loss will occur in 2045 at around 8.4% compared to the BAU scenario. However, the GDP in the NZE scenario will be lowered by 7.7% in 2050 compared to the BAU scenario.

Households maximize energy use by selecting a combination of commodity bundles subject to the income constraint and commodity price. This study shows that achieving GHG emissions reduction affects household consumption. Household consumption loss is estimated to be 1.3% in the NDC scenario and 2.2% in the NZE scenario compared to the BAU level in 2030. In 2040, household consumption loss is estimated to be higher in the NZE scenarios (8.4% compared to the BAU scenario) than in the NDC scenarios (2.4% compared to the BAU scenario). The household consumption loss is estimated to be 2.9% in the NDC scenario and 9.6% in the NZE scenario compared to the BAU level in 2050. Figure 5 (b) shows the household consumption loss in the NDC and NZE scenario during 2030–2050.

There would be slight changes in the imports and exports in the three scenarios. In the BAU, the exports and imports (in percentage of GDP) decreased during 2020 to 2050. The imports and exports in 2050 in the BAU would be 63.4% and 61.7% of the GDP, compared to 78.5% and 77.6% respectively in 2020. The net import (in percentage of GDP)

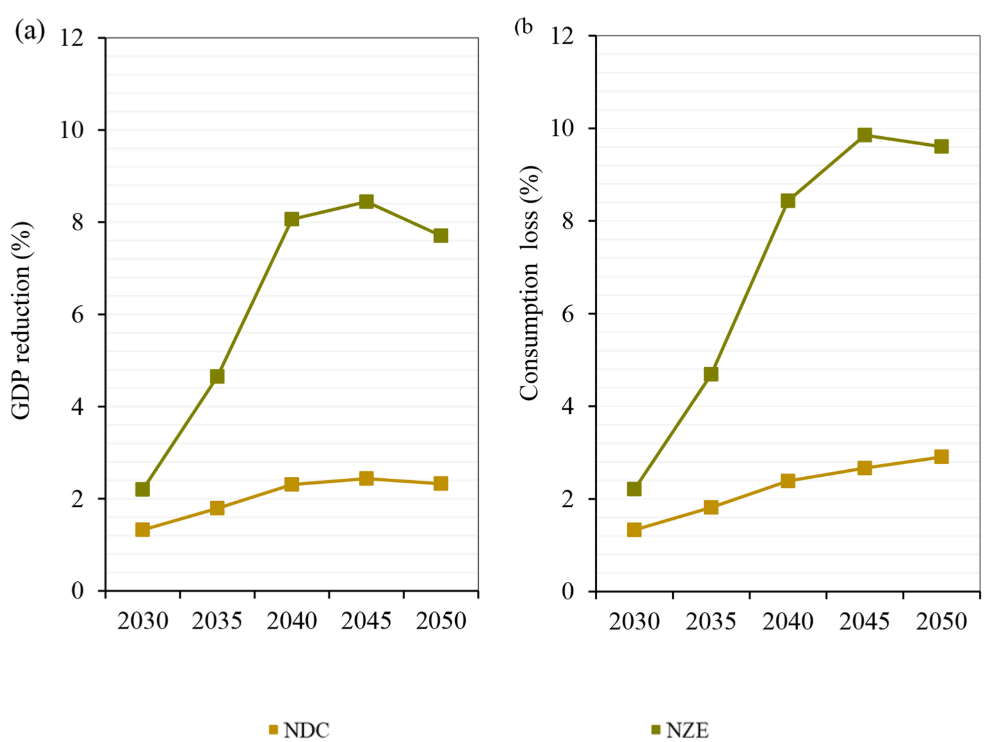


Fig. 5 (**a**) Reduction in GDP and (**b**) household consumption loss during 2030–2050

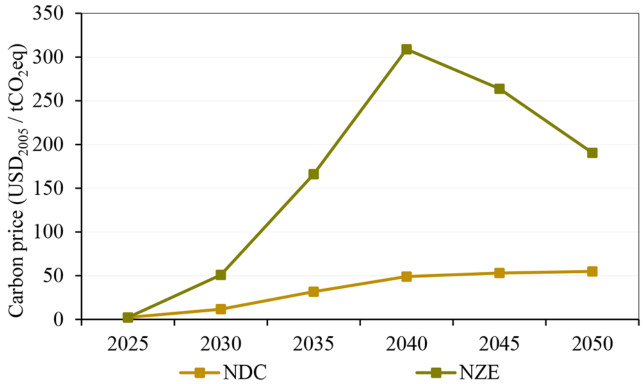


Fig. 6 Carbon prices in NDC and NZE scenarios

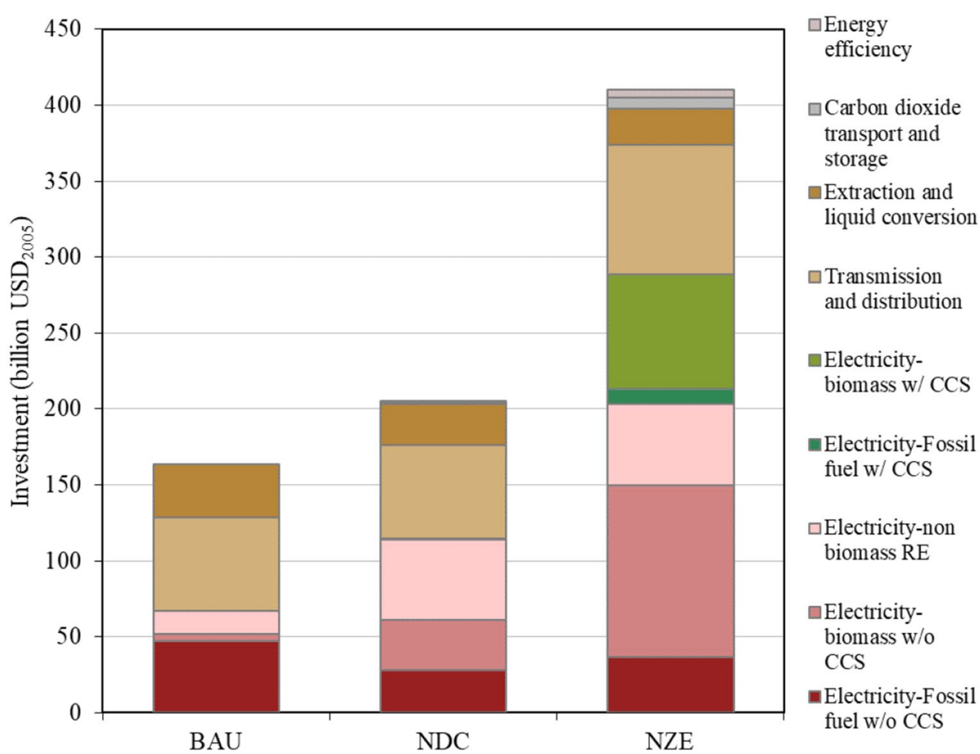
in the BAU would increase from 0.9% in 2020 to 1.8% in 2050. The net import would be lower in NDC and NZE scenarios in 2050 compared to the BAU level. The net imports in NDC and NZE scenarios in 2050 would be 1.3% and 0.06% respectively.

Carbon pricing is an effective policy tool for controlling GHG emissions by driving the economy towards improved energy efficiency and low carbon technologies. This study estimates the carbon price trajectories needed to achieve various levels of GHG emission reductions. Figure 6 reveals the carbon prices in both the NDC and NZE scenarios between 2025 and 2050. In the NDC scenario, the carbon price is estimated to increase from 2.2 USD/tCO_2eq in 2025 to 54.9 USD/tCO_2eq in 2050. Due to high GHG reduction targets, the carbon price in NZE scenarios increases at a faster pace compared to the NDC scenarios. However, the carbon price in the NZE scenario peaks at 308.9 USD/tCO_2eq in 2040 and then reduces to 190.5 USD/tCO_2eq in 2050. Similar findings are observed in the study by Limmeechokchai et al. (2023). The consideration of the power development plans given in the PDP2018 Revision 1 plan, coupled with efficient and advanced technological options, has helped reduce the carbon prices in this study (EPPO, 2020). Increasing the GHG mitigation level results in higher adoption of fossil fuel and biomass-based power plants equipped with CCS technologies beyond 2035 in the NZE scenario. In addition, increased deployment of biomass-based electricity generation without CCS is also observed beyond 2040 in the NZE scenario. This causes the carbon price to decline during 2040 to 2050 in the NZE scenario.

1.2.3 Investment for decarbonization

Figure 7 illustrates the investment needed during 2010–2050 in decarbonizing the energy system of Thailand under the BAU, NDC and NZE scenarios. Results show the need for higher cumulative investment in the NZE scenario than in the NDC scenario during 2010–2050. When compared to the BAU scenario, the undiscounted cumulative investment requirements during 2010–2050 are 205.4 billion USD (constant 2005 price) in the NDC scenarios and 410.1 billion USD in the NZE scenarios, i.e., a cumulative increase of 26% and 151% in the NDC and NZE scenarios, respectively.

Fig. 7 Undiscounted cumulative investments during 2010–2050 in the NDC and NZE scenarios



To comply with the NDCs 2020 pledge, the PDP2018 Revision 1 plan considered in this study focuses on generation of electricity based on renewable energy and natural gas power plants (EPPO, 2020). The power plants without CCS and electricity generation based on non-biomass renewable energy will account for about 50% of total investment in 2030. Investment in the energy supply sector would increase dramatically in any Thailand decarbonization scenarios. This is due to the high investment in CCS technologies and renewable energy. The additional investment needed in the energy sector between 2010 and 2050 is estimated to be 205.4 billion USD in the NDC scenario and 246.8 billion USD in the NZE scenario compared to the BAU scenario. The investment in renewable energy during 2010–2050 will increase 3.5 times in both the NDC and NZE scenarios. In the NZE scenario, the investment in the CCS technologies (both fossil fuel and biomass) for electricity generation is estimated to be 85.3 billion USD or 21% of total investment during 2010–2050.

The investments of the energy supply side include not only the cost of power plants, but also the costs of transmission and distribution systems, extraction of energy, and liquid conversions. It is noted that the extraction of energy refers to the mining of solid fuels such as coal and drilling of gaseous or liquid fuels, such as natural gas and crude oil, while the liquid conversions refer to the refineries. Upscaling the electricity generation from renewable energy and electrification in the demand side requires an additional investment in the transmission and distribution system. When compared with the BAU scenario, the investments in the transmission and distribution system decrease to 29.9% and 20.8% of the total investment in the NDC and NZE scenarios during 2010–2050. The investment in energy efficiency measures is less than others in the energy supply side.

The energy efficiency investments are 1.7 and 5.1 billion USD in the NDC and NZE scenarios in 2030, respectively. Most of the energy efficiency investments are in the industry and the building sectors. The investment share of extraction and liquid conversion in the total cumulative investment is observed to decline with the increasing level of GHG reduction in both the NDC and NZE scenarios. Its share is found to fall from 21.3% in the BAU scenario to 13.2% in the NDC scenario and 5.8% in the NZE scenario. Carbon-free energy carriers are supposed to take over fossil investments by 2050. However, the investment share of the extraction of fuel and liquid conversion will not be reduced to zero due to its demand in the industrial sector.

1.2.4 Co-benefits of net zero emissions

Thailand's NDC does not include the impacts of co-benefits (UNFCCC, 2022). In addition, the climate policy document of Thailand does not address co-benefits of achieving GHG emission reduction and underestimates the positive impacts. Incorporation of co-benefits in the assessment of the emission pathways will significantly improve the outcomes.

1.2.5 Air-pollutants reduction

Air pollution is one of the causes of respiratory diseases. In 2016, the World Bank disclosed that fifty thousand Thai people died from illnesses caused by air pollution. At the same time, the impact of air pollution on the country's health budget accounted for 6% of Thailand's annual GDP (TDRI, 2021). Actions to reduce GHG emissions result in lower air pollution. Thailand's air pollutants are estimated to be lower in 2050 than the 2010 level in the BAU scenario. The emissions of black carbon (BC) are found to reduce from 0.11 Mt BC in 2015 to 0.07 Mt BC in 2050. The carbon monoxide (CO) emission is estimated to drop from 13.21 Mt CO in 2015 to 11.22 Mt CO in 2050. The nitrogen oxide (NO_x) emission is estimated to decrease from 1.38 Mt NO_x in 2015 to 1.18 Mt NO_x in 2050. The air pollutant mitigation in the demand sectors is due to switching to electricity from biomass, coal, oil, and natural gas. In addition, low carbon technologies as well as energy shifting to renewable sources in the power sector will help reduce the ambient local air pollutants further. In the NDC scenario, the BC, CO and NO_x emissions are estimated to be lower by 12.4%, 12.8% and 18.6%, respectively, compared to the BAU scenario in 2050. If net zero GHG emission is achieved, the BC emission will be reduced by 20% compared to the BAU level in 2050. Although there is a significant drop in BC emissions in the demand side sector, there is not much reduction in supply side due to high biomass-based generation. High reliance on biomass in the power sector will make air pollution reduction less significant in the NZE scenario. Similarly, CO and NO_x emissions are estimated to be reduced by 17% and 41%, respectively, in 2050. Reducing air pollutants is expected to have an additional benefit of avoiding adverse health outcomes and loss of crop yield as well as reducing the impact of climate change and the melting of glaciers in the mountainous countries (Shakya et al. 2023). However, most emission sources will be far from human settlements in the NZE scenario compared to the BAU scenario, as cleaner fuels will be used in the demand side and local pollutant emissions are primarily driven by the supply side. Figure 8 presents air-pollutants in the BAU, NDC and NZE scenarios.

1.2.6 Improved energy security

Reaching the net zero emissions target will provide positive effects on Thailand's energy system in terms of energy

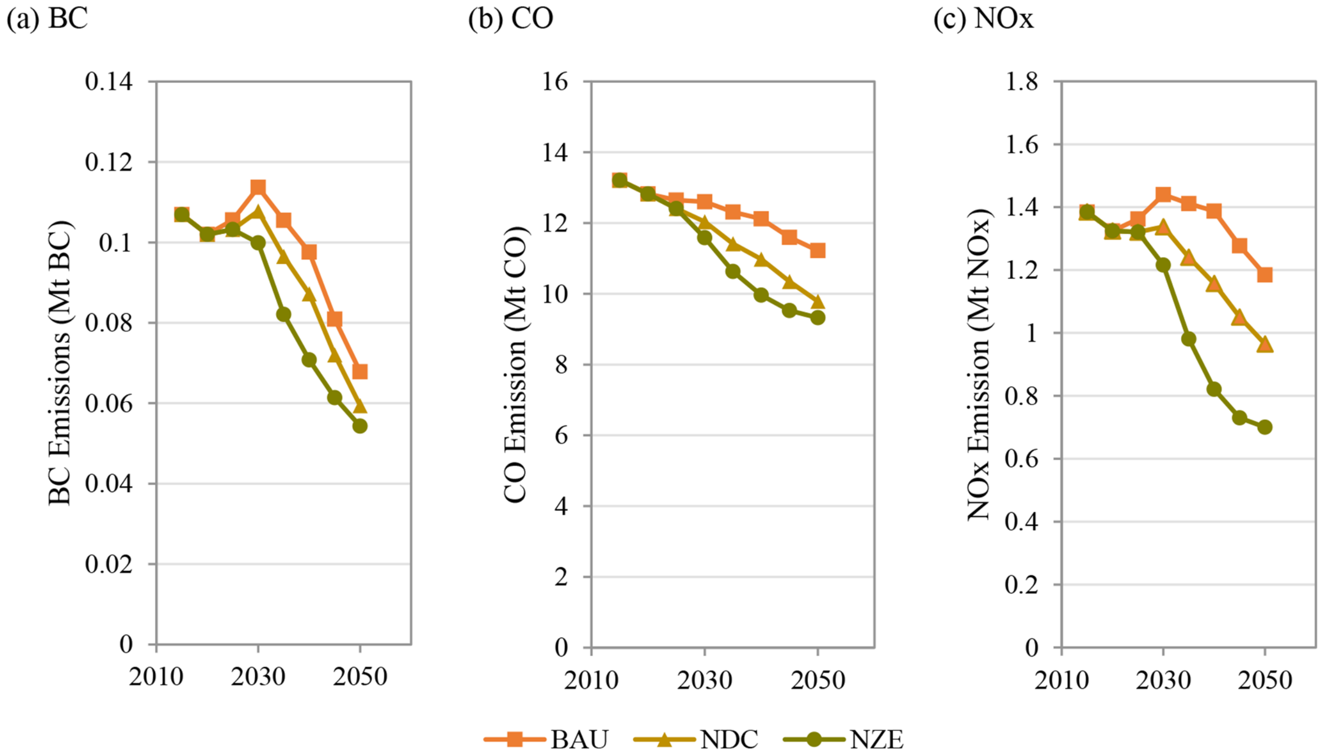


Fig. 8 Air-pollutants (**a**) black carbon (**b**) carbon monoxide (**c**) nitrogen oxide in BAU, NDC and NZE scenarios

security. Currently, the energy system in Thailand relies heavily on oil and natural gas. The country has become increasingly dependent on fossil fuel imports to maintain its growing fuel demand. The net energy import dependency (NEID) is the ratio of all net imported energy (net primary energy import and net electricity import) to the total primary energy supply in the country. It is often expressed in percentage terms. NEID in Thailand was 69.8% in 2020. NEID will increase to 77.6% in 2050 in the BAU scenario. In the NDC and NZE scenarios, NEID will reduce to 73.4% and 71.5%, respectively, in 2050. The use of domestic biomass and non-biomass renewable resources will be optimized in both NDC and NZE scenarios. However, the energy system still relies on imported biomass in the NDC and NZE scenarios. If biomass could be produced domestically, NEID would be further reduced to 66% in the NDC scenario and 48% in the NZE scenario by 2050. Effective management and allocation of land use should be considered. The dependence on domestic energy supply could help the country to be less vulnerable to the fluctuation of imported energy prices, thereby making the energy supply more secure. Figure 9 shows Thailand's NEID in the BAU, NDC and NZE scenarios (both including and excluding biomass).

1.2.7 Trade-offs in the land use

The land use for sustainable biomass in both the NDC and NZE scenarios is found to be larger than in the BAU scenario. The results show better land use for biomass production and higher yields in agricultural production because there is a trade-off between land use for non-energy crops, energy crops and forests. The cropland area will decrease in both the NDC and NZE scenarios, while the forest area will increase. The carbon sequestration of the forest sector plays a significant role in offsetting the emissions from fossil fuel combustion to achieve net zero GHG emissions. Several studies of Thailand show that the land use sector provides the potential to increase the forest area and remove carbon through afforestation, reforestation, forest conservation and forest management for sustainable production, etc. (MNRE, 2021; Pradhan et al. 2019). Figure 10 presents changes in cropland and forest areas in the BAU, NDC and NZE scenarios.

1.2.8 Role of carbon sequestration by carbon capture and storage

The CCS technology plays a critical role in achieving net zero emission in the power sector. This technology reduces GHG emissions in the industrial process as well. Figure 11(a) – 11(c) present carbon sequestrations by CCS

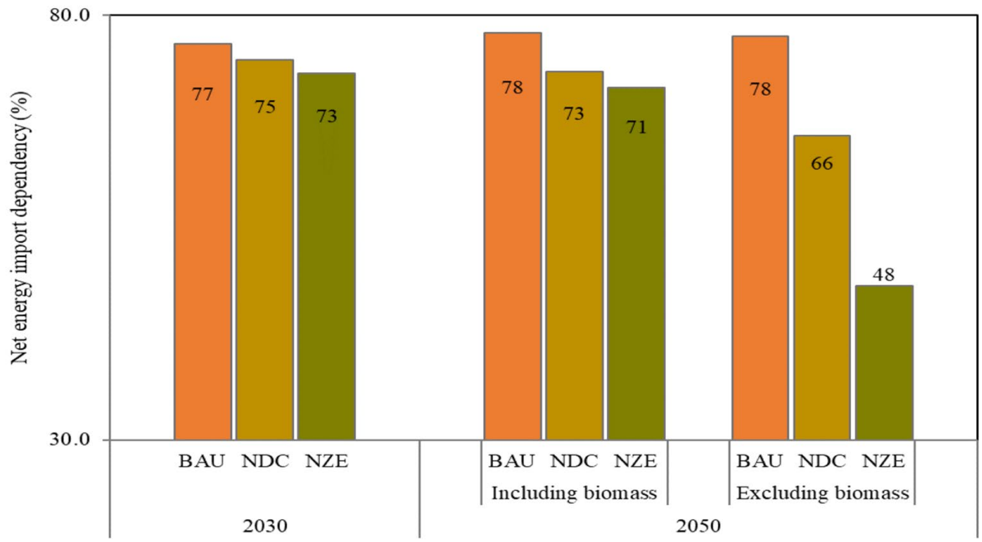


Fig. 9 Net energy import dependency (NEID) in BAU, NDC and NZE scenarios

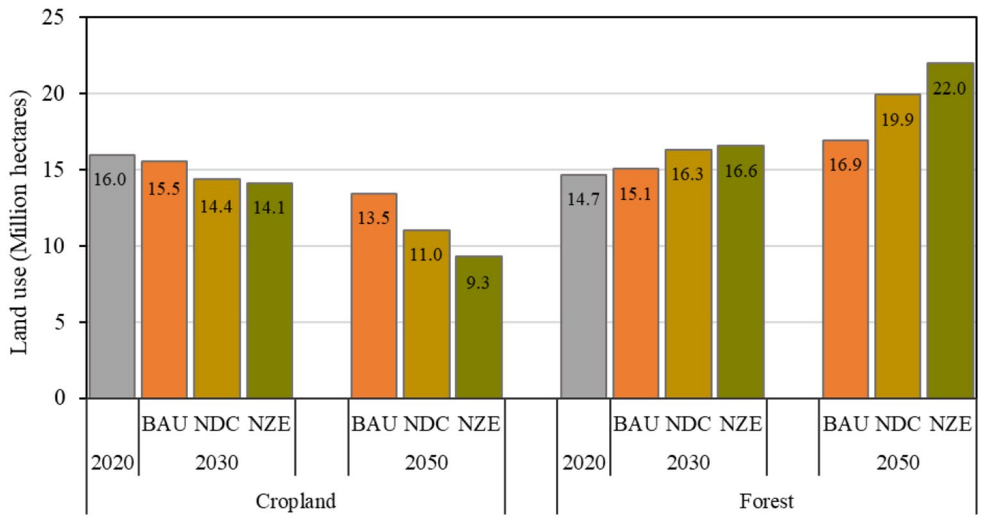


Fig. 10 Changes in cropland and forestland areas in the BAU, NDC and NZE scenarios

technologies for fossil fuel, biomass, and industrial processes. Total sequestration by CCS is shown in Fig. 11 (d). In the NDC scenario, the CCS technology in fossil fuel technologies would increase between 2035 and 2050; however, after 2045 BECCS would be deployed. To achieve net zero GHG emissions, carbon sequestration by CCS technology from fossil fuel and biomass would rapidly increase after 2030 and 2035, respectively. The shift from coal to gas for electricity generation and deployment of CCS in coal- and gas-fired power plants have the highest decarbonization potential on the fossil fuel side (Lau 2023). In the NZE scenario, carbon sequestration from fossil fuel by CCS would be 129.2 $MtCO_2$ by 2050 (see Fig. 11(a). In the same year, carbon sequestration from BECCS would be 151.6 $MtCO_2$ (see Fig. 11(b) and carbon sequestration in the industrial processes by CCS would be 6.0 $MtCO_2$ in 2050 (see Fig. 11(c). Thus, the total carbon sequestration by CCS technology would increase after 2035 in the NDC scenario and after 2030 in the NZE scenario. However, there would be a rapid increase in carbon sequestration after 2040 in the NZE scenario (see Fig. 11(d). There are proposed CCS projects in ASEAN countries involving Singapore, Indonesia, Malaysia, Thailand, and Vietnam (Lau 2023).

The share of carbon sequestration by CCS in the total mitigation will remain between 5% and 6% during 2035–2050 in the NDC scenario. However, in the NZE scenario, the role of CCS to achieve net zero emissions will be significant. The share of CCS and BECCS in total GHG mitigation in NZE would increase from 3% in 2030 to 44% by 2050 (see Fig. 12). The cumulative GHG sequestration from CCS technologies in the NDC scenario up to 2050 would be 200 $MtCO_2$. In the NZE scenario, the cumulative sequestration would be 2.2 $GtCO_2$. Studies have reported that geological storage sites for carbon dioxide storage in Thailand through CCS technologies is 10.3 $GtCO_2$(ADB, 2013; Kimura et al. 2021; Pradhan et al. 2022). This study finds that carbon sequestration up to 2050 would be feasible if the geological storages sites are found feasible. However, an increase in

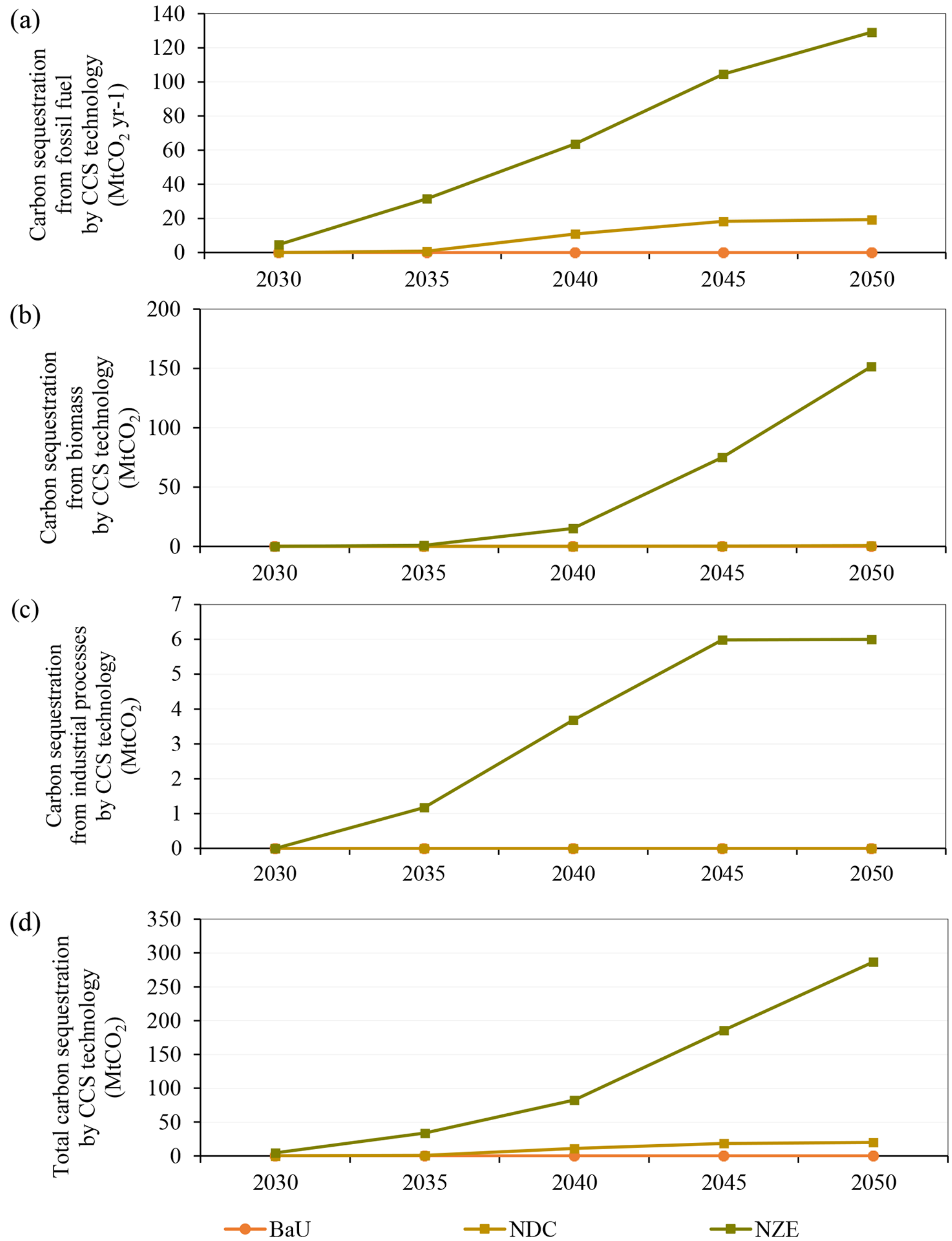
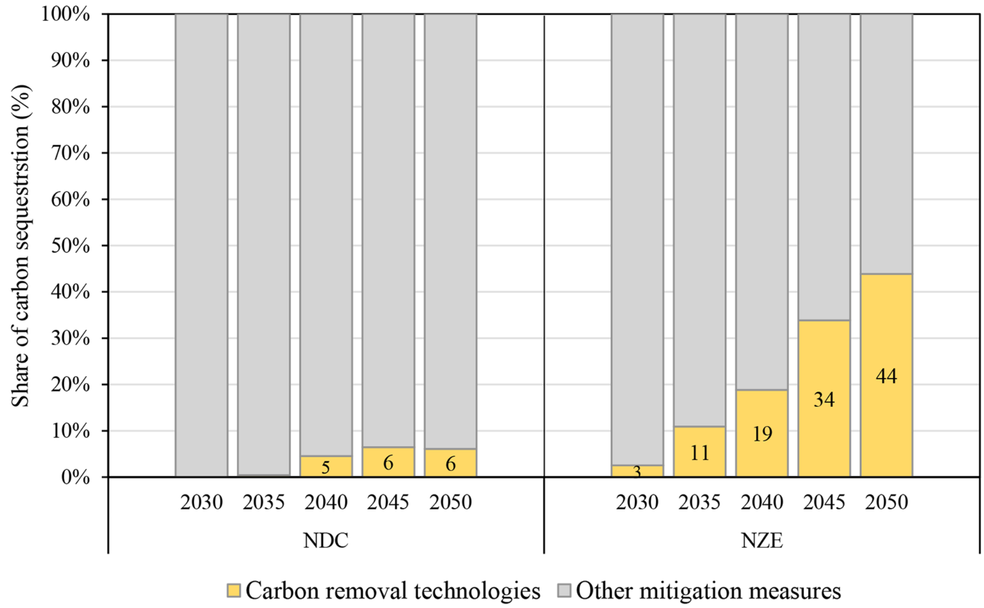


Fig. 11 Carbon sequestration by the CCS technology by (**a**) fossil fuel, (**b**) biomass technologies, (**c**) industrial process and (**d**) total carbon sequestration

the carbon sequestration post-2050 to maintain carbon neutrality by the end of the century can be a concern in terms of CO_2 storage, if the country remains highly dependent on CCS technologies.

The AIM/Hub model of Thailand, however, have some limitations. The CGE models are data intensive, and availability of data is crucial for accurately modeling the interaction between different sectors in an economy. The parameters used in the CGE modeling are often not available for developing countries and are borrowed from existing literatures, which can introduce biases in the outputs of the model. As discussed earlier in the model description, the model employed in this study lacks detailed representation of energy and technology flow unlike in the bottom-up energy system models. Integrating macroeconomic model and bottom-up model can make the modeling approach more robust and will be useful to provide policy insights regarding the effect of various energy and climate policies on the energy system as well as the economy. CGE models provide valuable insights, however, their limitations must be recognized, and caution must be taken while interpreting the results. Alternatively, integrated modeling approach and techniques should be examined as changes in population, income, or technology cost might alter crop production, energy demand, and water withdrawals, changes in demand for energy affect energy, water, and land (JGCRI, 2018).

Fig. 12 Share of carbon sequestration in the NDC and NZE scenarios



The integrated assessment models can study the interaction between various sectors such as energy, economy, crop production, air quality, water and forest, etc. Integrated assessment models provide climate science researchers with information about humans and the earth's system. Furthermore, the linkage between Southeast Asia and Asia using the existing and advanced modeling approaches can also be an area of further research.

1.3 Conclusion

This study analyzes the macroeconomic implications and co-benefits of GHG emission reduction in Thailand to achieve the NDC and net zero emission targets in 2030 and 2050, respectively, using the top-down computable general equilibrium, AIM/Hub-Thailand model. The analysis provides useful insights for Thailand on how to achieve ambitious GHG reduction targets in 2050 to align with the 1.5 °C target of the Paris Agreement.

To achieve net zero GHG emission, the decarbonization of the electricity generation sector is possible by increasing the use of renewable energy and through the implementation of CCS technologies. The BECCS with its net carbon sequestration features plays a significant role in offsetting CO_2 emissions. In addition, the BECCS technology increases the requirement of biomass resources, which helps curb GHG emissions. The energy supply sector is expected to reach the highest capabilities to reduce GHG emission to net zero by using the BECCS and renewable energy technologies in 2050. The natural gas and coal-based power plants with CCS technologies are expected to replace the conventional gas and coal-based power plants from 2030, thereby reducing GHG emissions in the NZE scenario. Biomass plays a significant role in the decarbonization of the energy sector. Efforts are being made to enhance natural carbon sinks to mitigate climate change. The Thai government has set an ambitious target to expand its forest area to 40% from the present level of 31.6%, out of which 15% is targeted to be production or economic forest and the remaining 25% is expected to be protected forests (MNRE, 2018). The shift from agricultural land to forest land is expected to occur in both NDC and NZE scenarios. Increasing energy efficiency of technologies is an effective measure to reduce GHG emissions from the demand side. In the transport sector, higher use of biofuels and increasing electrification reduce GHG emissions in both NDC and NZE scenarios. The implementation of CCS technology is examined in the non-metallic industries, especially in the cement industry, to achieve the NZE scenario. Increased usage of electricity along with the enhanced energy efficiency improvement measures will increase the mitigation in the building sector. To achieve net zero GHG emissions, this study shows that Thailand would heavily rely on bioenergy and the public acceptance of CCS technologies. Since CCS is a modern technology with limited commercial usage worldwide, there are uncertainties about viability and available storage capacity in Thailand. Besides the significant installation costs, the social acceptance of CCS technology also poses a serious challenge. The higher dependence on biomass in achieving the stringent GHG reduction targets raises questions related to the domestic supply potential of biomass. Research on these issues is still inadequate and needs to be addressed before concluding that bioenergy and CCS are solutions for future climate change mitigation targets. Thus, policy makers need to analyze the issues from various perspectives before formulating the long-term climate policies and action plans.

Reducing GHG emissions will cause losses to the economy in both the NDC and NZE scenarios. In the NDC scenario, the GDP of Thailand is estimated to decline by 2.3–2.4% from the BAU level during 2040–2050. To achieve net zero targets, the highest GDP loss compared to the BAU scenario is found to be 8.4% in 2045. However, the GDP loss in the NZE scenario is estimated to be reduced to 7.7% compared to the BAU scenario in 2050. The household consumption loss is estimated to increase to 2.9% in the NDC scenario and 9.6% in the NZE scenario compared to the BAU level in 2050. Finally, this study presents a carbon price profile which is an important instrument to achieve the GHG emissions reduction target of the NDC and NZE scenarios. Results found that the highest carbon price occurs in 2040 in the NZE scenario. The imposition of early stringent emissions reduction reduces the GHG emissions in the NZE scenario.

The strategies, plans and policies of Thailand focus only on the GHG emission reduction. The co-benefits in terms of avoided impacts and trade-offs are not investigated in the policy documents. Health benefits from lowering local air pollutants due to decarbonization actions will increase the social willingness to undertake deep decarbonization policies. This study found that major air pollutants would be lowered by 17–41% from the BAU level in the net zero emission scenario. Local air pollutants will be reduced by switching to electricity from biomass and fossil fuels in the demand sectors, while at the same time promoting more renewable energy in the power sector. Air pollutant emissions can have a transboundary effect; thus deep-decarbonization actions in Thailand may have additional benefits such as avoiding adverse health outcomes and loss of crop yield both in Thailand and neighboring countries, as well as mitigating global climate change. Achieving the net zero emissions target could provide positive impacts on Thailand's energy system. The NEID is found to be lower in the NDC and NZE scenarios. Relying on domestic energy sources could help the country become less vulnerable to the world energy market and help to make Thailand's energy supply and energy prices more secure. The sustainable land use for biomass in both the NDC and NZE scenarios will be larger than in the BAU scenario. Better land use for biomass production and higher yields in agricultural production are needed to domestically produce the bioenergy required in the NZE scenario. Thus, it is recommended that policy makers consider the co-benefits of GHG emissions reduction while assessing issues or activities related to low carbon development. Moreover, the net zero emission pathway will require effective usage of land area and domestic energy resources, thereby making the country more energy secure. Therefore, achieving net zero emission should be analyzed in an integrated and holistic approach to incorporate all benefits related to it. This study estimates the emissions level of air-pollutants in different scenarios. However, this study does not estimate the impacts of air quality on health due to model limitations.

From the analysis, this study identifies key policy recommendations to decision-makers and related stakeholders. The decarbonization in the electricity generation sector can be achieved through increasing the use of renewable energy and through the implementation of CCS and BECCS technologies. Research on CCS and BECCS needs to address such appropriat locations for storing such captured CO_2 and storage potential. The national captured and transport CO_2 cost is needed; therefore, investors can allocate their budgets and meet the breakeven point. Increasing use of renewable energy, especially solar and wind electricity are needed to be carefully observed. Various future solutions can achieve climate change mitigation targets in Thailand such as hydrogen technology, direct air capture and others. GHG mitigation brings additional benefits, including improved health, enhanced resource utilization and reduced resource use. Considering the co-benefits of GHG emissions reduction while assessing issues or activities related to low carbon development is necessary. Including co-benefits analysis in the climate policy documents such as NDC and LT-LEDS will make a strong incentive for the policy through reductions of emissions. These climate policies could therefore help countries to achieve the SDG agenda through reducing the health and environmental impacts of air pollution and improving the wellbeing of the population.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Declaration of competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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