Analysis of CO_2 Emission Pathways of Thailand to Achieve Carbon Neutrality 2050 Using AIM Model

Salony RAJBHANDARI, Achiraya CHAICHALOEMPREECHA,
Bijay B. PRADHAN and Bundit LIMMEECHOKCHAI*

Sirindhorn International Institute of Technology, Thammasat University
99 Moo 18, Km. 41 on Paholyothin Highway, Khlong Luang, Pathum Thani 12120, Thailand
**E-mail: bundit@siit.tu.ac.th, bundit.lim@gmail.com*

Abstract

The trend of rising greenhouse gas (GHG) emissions in Thailand is a matter of concern, demanding ambitious mitigation efforts beyond 2030 and even before then to contribute towards meeting the long-term goal of the Paris Agreement of staying within a 1.5°C temperature rise. Carbon dioxide (CO_2) emissions form the major part of the total GHG emissions in Thailand. This study aims to explore the energy, environmental and macroeconomic impacts of limiting CO_2 emissions during 2010–2050 for the underlying target of achieving carbon neutrality by 2050. This study has developed a recursive dynamic Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) model for Thailand which is soft-linked with the AIM/Enduse model. In addition to a business-as-usual (BAU) scenario, the study has formulated two different CO_2-mitigation scenarios, each indicating a carbon-neutrality pathway towards 2050. Results indicate that Thailand should put more effort into mitigation actions to achieve carbon neutrality by 2050. Expansion of renewable-energy-based technologies, improvement of end-use energy efficiency, fuel-switching and deployment of carbon capture and storage (CCS) technologies in both the power and industrial sectors are identified as important mitigation measures for Thailand in curbing CO_2 emissions by 2050. The results show that the introduction of such mitigation measures would provide CO_2 emission reductions, but at the expense of economic losses. The price of CO_2 mitigation was found to vary from 220 to 332 US dollars per ton of CO_2 (tCO_2) in 2050 under the two carbon-neutrality scenarios.

Key words: AIM/CGE, AIM/Enduse, energy efficiency, net zero emissions, renewable energy, Thailand

1. Introduction

The trend of increasing global anthropogenic greenhouse (GHG) emissions and subsequent negative impacts of climate change have spurred both developed and developing countries to formulate and implement plans and actions aimed at putting them on a path toward low-carbon development. Developing countries are more vulnerable to the impacts of climate change. Although developing countries are not obliged to reduce GHG emissions in absolute terms at present, studies have shown that their participation is a must for any substantial reduction of GHG emissions that would stabilize long-term GHG concentrations by the end of this century.

Energy security and rising GHG emissions are the two major problems that Thailand has been facing in terms of energy use. In 2020, Thailand's updated nationally determined contribution (NDC) put forward stringent targets to reduce GHG emissions from the energy sector, bringing its GHG emissions down by 20%–25% by 2030. This is to be accomplished mainly by promoting renewable energy resources and energy efficiency improvements (ONEP, 2020a). However, Thailand's updated NDC relies on a GHG emission reduction from its reference level that would allow its 2030 GHG emissions to reach more than 1.5 times its 2005 emissions. Despite such mitigation targets, the trend of continuously rising GHG emissions in Thailand is a matter of concern and will require ambitious mitigation efforts beyond 2030 or even before then to contribute towards meeting the long-term goal of the Paris Agreement of staying within a 2°C temperature rise. There is also a need for Thailand to review its pledges regularly and set realistic and attainable longer-term mitigation goals.

As carbon dioxide (CO_2) emissions form a significant portion in Thailand's total GHG emissions, this study aims at exploring the energy, environmental and macroeconomic impacts of limiting CO_2 emissions during 2010–2050 in Thailand. It also aims at achieving carbon neutrality by 2050 to contribute towards meeting the long-term goal of the Paris Agreement of staying within a 1.5°C temperature rise. In doing so, a recursive dynamic Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) model has been developed which is soft-linked with Thailand's long-term energy system AIM/Enduse model.

2. Methodology

2.1 The AIM/CGE Model

This study has considered a multi-sector, recursive dynamic AIM/CGE model to analyze the carbon neutrality of Thailand by 2050. The AIM/CGE model is solved in one-year steps toward 2050 using the Mathematical Programming System for General Equilibrium Analysis (MPSGE) as the modelling language embedded within the General Algebraic Modelling System (GAMS) (Rutherford, 1999). The AIM/CGE model is composed of a set of simultaneous equations with no objective functions and uses mixed complementary problems for solution. The designed equations portray the behavior of various activities and sectors within an economy. The behavior of different sectors is captured using fixed coefficients while those of production and consumption activities are captured using non-linear, first-order optimality conditions. The formulated equations include a set of constraints that need to be satisfied by the system and are known as the macroeconomic balance and balance of payment (Fujimori et al., 2012). The mathematical description of the AIM/CGE model considered in this study is based on Dai and Masui (2017) and Fujimori et al. (2012).

The AIM/CGE model consists of a production block, government and household income and expenditure blocks, plus a foreign trade (market) block in which both domestic and international transactions are considered (Fig. 1). The sectoral activity is represented by a nested constant elasticity of substitution (CES) production function, in which inputs are classified into energy commodities, labor, capital, materials and non-energy intermediate inputs. More information on the AIM/CGE model of Thailand can be found in Rajbhandari et al. (2019).

As energy supply and demand are technologically represented in better detail in an energy system model than that in an economic model, a soft linkage has been established between the bottom-up AIM/Enduse model and the top-down AIM/CGE model by using the sector specific GHG emission and techno-specific data generated by the energy system model as an input to the AIM/CGE model. To assess the economic and environmental impact of energy use in Thailand's economy, a techno-specific data linkage was established in terms of technology efficiency improvements, technology penetration rates and variations in energy share in each scenario.

2.2 Structure of the Thailand AIM/CGE Model

The Thailand AIM/CGE model was developed by using the 2010 input-output (I/O) table obtained from the Office of the National Economic and Social Development Council (NESDC) to calibrate the model (NESDC, 2016). The I/O table considered in this study is disaggregated into 31 production sectors of which five are energy sectors (Table 1).

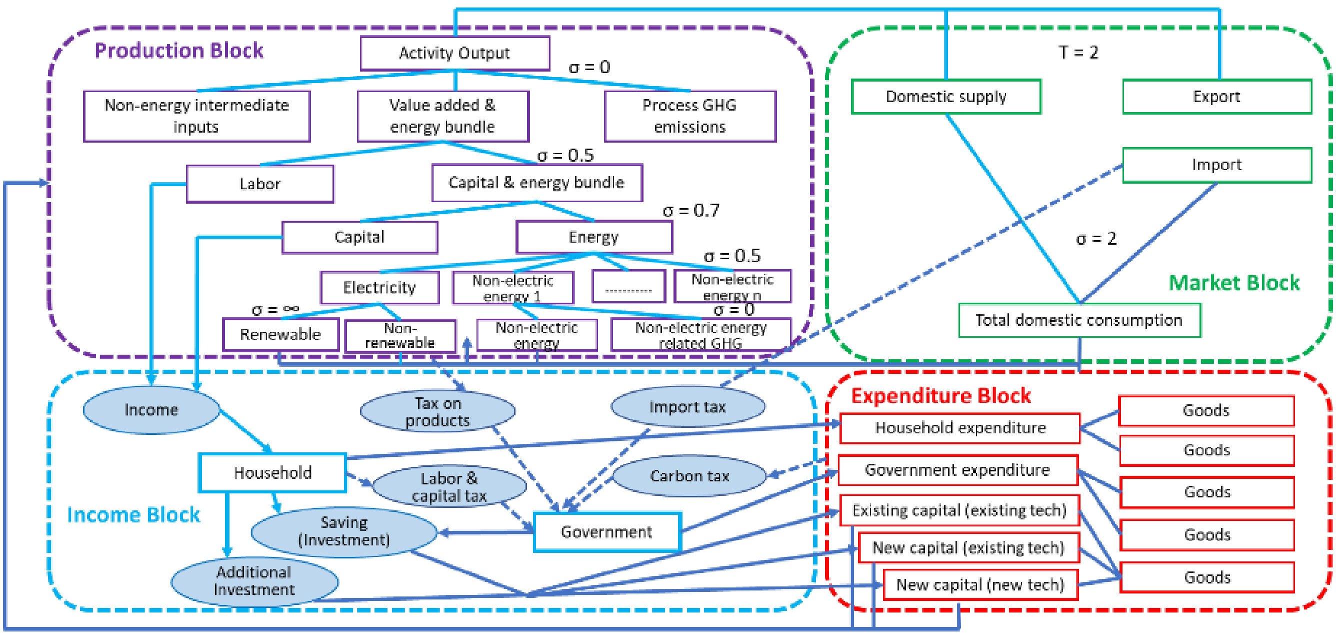

Fig. 1 AIM/CGE Model structure for Thailand.

Table 1 Sectoral classification in the Thailand-CGE model.

Non-energy sectors	
Agriculture & forestry	Crops, livestock, forestry, fisheries
Transport	Railways, road transport, water transport, air transport, Other transport services
Service	Water supply system, communication, trade, Other services
Industries	Metal and non-metal ore, non-metallic products, basic metal, fabricated metal products, machinery, Food, beverages & tobacco products; textiles; paper & printing; chemicals; rubber & plastic products, Construction, Other manufacturing products
Others	Other sectors
Energy sectors	
Coal & lignite, crude oil, petroleum products, gas, electricity (including renewable & non-renewable)	

2.3 The AIM/Enduse Model

The AIM/Enduse model is a technology-rich, bottom-up recursive dynamic energy system model, the objective function of which is to minimize the total system cost subject to numerous constraints. It is a partial equilibrium model that can simulate calculations for numerous years under several case studies, including policy countermeasures for near- and long-term mitigation actions to examine the effect of energy saving and GHG emission abatement (NIES, 2021). Thailand's AIM/Enduse model includes a detailed technology selection framework based on a linear optimization structure.

3. Description of Scenarios

In addition to a business-as-usual (BAU) scenario, this study has formulated two different carbon-neutrality scenarios. The following section describes the formulated scenarios in detail.

3.1 BAU Scenario

The BAU scenario in this study considers the continuation of the existing pattern of energy supply and use considering full availability of technologies without taking into account any climate policy intervention.

3.2 Carbon-neutrality Scenarios

Two carbon-neutrality scenarios, namely SSP1-NZC2050 and SSP4-NZC2050, for net zero CO_2 emissions in 2050 (NZC2050) were formulated for Thailand considering the global CO_2 emission trajectories obtained from six different integrated assessment models (IAMs) under two different Shared Socioeconomic Pathways (SSPs), namely SSP1 and SSP4 for the representative concentration pathway (RCP) to reach 1.9 watts per square meter (W/m^2), called RCP1.9 in each

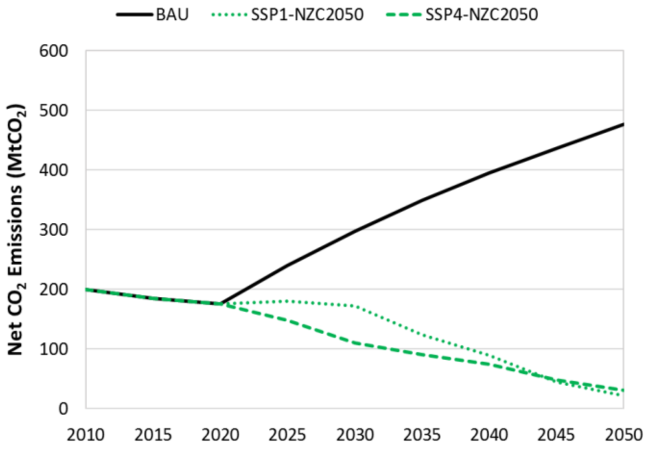

Fig. 2 Net CO_2 emission trajectories of different scenarios.

case. SSP1 is also known as the sustainability scenario and the SSP4 is termed the inequality scenario, which is close to the current socioeconomic situation in Thailand. Both carbon-neutrality scenarios assume aggressive efforts to reduce CO_2 emissions in line with the global temperature stabilization target of limiting the temperature rise to 1.5°C.

The country specific CO_2 emission allowances for Thailand aligned with the 1.5°C stabilization target were computed using an equal per capita burden-sharing scheme based on a convergence approach, considering the global CO_2 emission trajectory with 2050 as the convergence year. The contraction and convergence regime considered in this study is based on the principle that "every adult on the planet has an equal right to emit GHGs" (Bows & Anderson, 2008). The global CO_2-emission trajectory for the SSP1 and SSP4 scenarios for RCP1.9 are taken from the SSP Database (SSP Database, 2018). The average value of the total CO_2 emissions obtained from the six different integrated assessment models for each scenario, SSP1 and SSP4, for RCP1.9 were used for representing the CO_2 emission allowances allocated to Thailand to attain the carbon neutrality target by 2050 in this study.

The total net CO_2 emissions including those of land-use, land-use change and forestry (LULUCF) in the BAU scenario are estimated to increase from 200 $MtCO_2$ to 477 $MtCO_2$ during 2010–2050 (Fig. 2). The historical net CO_2 emissions during 2010–2016 were taken from the Thailand Third Biennial Update Report (ONEP, 2020b). The energy-sector-related CO_2 emissions generated from fossil fuel combustion in the power, agriculture, commercial, residential, industrial and transport sectors during 2020–2050 were obtained from the Thailand's AIM/Enduse modelling analysis. The future estimations of CO_2 emissions from the industrial processes and product use (IPPU), waste, agriculture (non-energy related emissions from liming and urea fertilization), and LULUCF sectors were estimated based on the "Mid-century, Long-term Low Greenhouse Gas Emission Development Strategy" study of Thailand (ONEP, 2021).

CO_2 removal by the LULUCF sector is estimated to increase from 62 $MtCO_2$ in 2010 to 100 $MtCO_2$ in 2050, growing at a compound annual growth rate (CAGR) of 1.2% (ONEP, 2020b, 2021).

By 2050, the average net CO_2 emissions are estimated to reach 22 $MtCO_2$ and 31 $MtCO_2$ respectively in the SSP1-NZC2050 and SSP4-NZ2050 scenarios. The SSP1-NZC2050 scenario indicates a need for the peak emissions to occur in 2025 whereas the SSP4-NZC2050 scenario shows a need for peak emissions in 2020 to achieve carbon neutrality by 2050 and attain the 1.5°C climate goal. As the CO_2 emission allowances for Thailand are computed using the global CO_2 emission trajectories for the SSP1 and SSP2 scenarios, the differences in the emission pathways of SSP1-NZC2050 and SSP4-NZ2050 scenarios result mainly from the variations in global CO_2 emission pathways obtained from different IAMs.

4. Input Data and Assumptions

4.1 Socioeconomic Data

Population projections up to 2040 are taken from the national statistics of Thailand, which assume declining fertility rates (NESDC, 2019). Assuming this trend continues, the population is estimated to decline at a CAGR of −0.5% during 2040 to 2050. The GDP projections considered in this study are based on the estimated long-term average GDP growth rates of "Power Development Plan 2018 (PDP2018)" and "Energy Efficiency Plan 2018 (EEP2018)" (MOE, 2020a, 2020b). The projected GDP is estimated to rise at an average growth rate of 3.37% during 2010–2050. It should be noted that the GDP growth rates are provided as a benchmark for the model. However, the model itself calculates the GDP based on the I/O table, elasticities and productivities of labor, capital, non-energy inputs and energy. This study considers the real GDP with the price of 2010 as a constant benchmark.

4.2 Assumptions

All the formulated scenarios consider common assumptions in terms of the socioeconomic data and productivities of capital, labor, energy and non-energy inputs. Capital is classified into existing stock and new investment in the CGE model. Investment (fixed capital formation), depreciation and economic growth form the basis for updating the capital stock in the model. A 5% depreciation rate per year for existing capital and a 10% rate per year for households' energy equipment are assumed in this study. The installed capital is assumed to be immobilized, meaning that it cannot be transferred to other sectors, whereas new investments can be made in any sector. Capital stock and capital endowment (income) are assumed to maintain a linear relationship. Full mobility of labor is assumed across sectors within Thailand.

The CGE model in this study assumes fixed technological coefficients, no constraint on resources, and efficient employment of all local resources. The model considers both renewable (solar, wind, hydro and biomass) and non-renewable (coal, oil and natural gas) options for electricity generation. However, following the Thai government plan, the model excludes consideration of the nuclear power option. Two different sets of technology options, namely, existing technology with an energy productivity of 10% and efficient technologies with varying energy productivities of 20%–30% are considered for each sector in the BAU scenario, while improvement in energy productivities in the net zero CO_2 emission scenarios is considered to be 20%–70%. The energy productivities in the latter scenarios are estimated based on the cost-effectiveness of technology selection in the energy sector under both of the carbon- neutrality scenarios obtained from the technology-rich AIM/Enduse model of Thailand. The economy-wide energy productivity is measured as the ratio of GDP per unit of primary energy consumed (A2EP, 2022).

5. Results and Discussion

The energy, environmental and economy-wide implications of achieving the carbon-neutrality targets by 2050 are discussed in this section.

5.1 Energy-related CO_2 Emissions in the Carbon-neutrality Scenarios

The attainment of carbon neutrality by 2050 will require substantial changes in Thailand's energy system compared to the BAU scenario. Based on the present scenario of socioeconomic conditions, the total final energy consumption (FEC) of Thailand would undergo more than a two-fold increase during 2010–2050 in the BAU scenario (Fig 3(a)). Petroleum products would account for 47% of FEC in 2050 in the BAU scenario. Electricity and biomass would play vital roles in cutting down CO_2 emissions in both the SSP1-NZC2050 and SSP4-NZC2050 scenarios.

The rising usage of electricity on the demand side would directly affect the electricity generation mix on the supply side. In the BAU scenario, natural-gas-fired combined-cycle power plants continuously dominate electricity generation, accounting for more than a 44% share of total electricity generation during 2030 to 2050. Coal, natural gas and oil-fired thermal power plants would occupy a 30% share of electricity generation in 2050 in the BAU scenario. Renewable energy-based electricity generation from solar and wind would account for 5%, while those from biomass power plants would account for 4% of total electricity generation in 2050 in the BAU scenario (Fig 3(b)). To achieve the carbon-neutrality target, the share of renewable energy-based generation from solar and wind would increase to 66% in the NZC2050 scenarios. Both combined-cycle and thermal power plants equipped with carbon capture and storage (CCS) technologies would emerge as promising options in the NZC2050 scenarios. Biomass power plants equipped with CCS (BECCS) would account for 4%–5% of total electricity generation in 2050 in the NZC2050 scenarios.

Achievement of the carbon-neutrality target will require significant reduction of CO_2 emissions from the energy sector by 2050 (Fig 3(c)). Decarbonization of the energy sector is the primary mainstay for reducing CO_2 emissions, especially from the power, industry and building sectors. CO_2 emissions from the power sector need to be reduced to zero by 2050 to attain the NZC2050 scenarios. Improvements in energy efficiency, increased penetration of renewable energy resources, and deployment of CCS (including both fossil-fuel-based CCS and BECCS) would have a positive effect on CO_2 emission reduction by 2050. The transport sector would emerge as the largest CO_2 emitter in the NZC2050 scenarios. Reducing CO_2 emissions from the transport sector will be a formidable task requiring major shifts from gasoline and diesel vehicles to biofuel, electric and fuel cell vehicles. In addition, a significant modal shift from private to public transport would need to be achieved. The CO_2 emission reductions in the manufacturing industries would mainly be achieved by deploying efficient fossil- fuel-based combustion technologies, particularly in thermal applications. In the NZC2050 scenarios, carbon capture, usage and storage (CCUS) technologies would be deployed from 2035 onwards in the non-metallic, paper & pulp and chemical industries. Due to increased electrification in the NZC2050 scenarios, the CO_2 emissions would be zero in commercial buildings. The achievement of carbon neutrality by 2050 would require use of behavioral change techniques in clean cooking, requiring a shift from LPG to biogas, biomass and electric cookstoves in the residential sector.

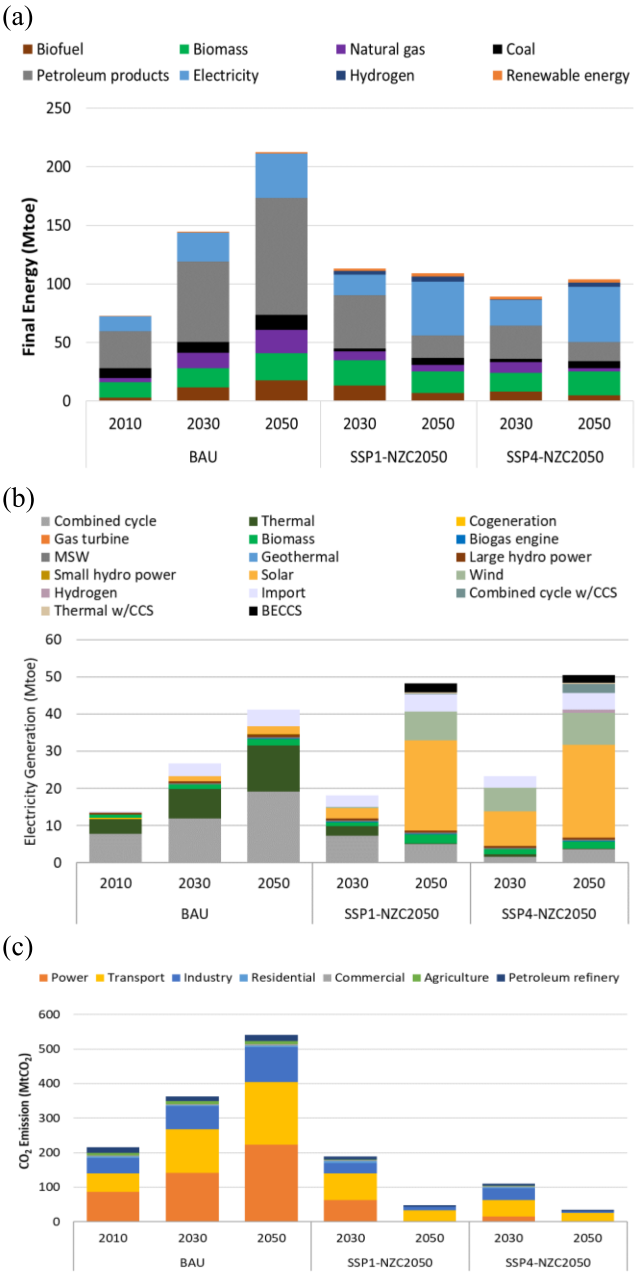

Fig. 3 Energy and emissions: (a) final energy (b) power generation (c) CO_2 emissions by sector.

5.2 Effects on Macroeconomic and Welfare Indicators

5.2.1 Impacts on GDP

The GDP of Thailand would undergo a four-fold increase during the period of 2010–2050, i.e., from US$335 billion in 2010 to US$1,358 billion in 2050 under the BAU scenario, increasing at a CAGR of 3.6% (Fig. 4). The shares of consumption demand in the household and government sectors and the total investment demand as the percentage of GDP would change during the study period. Consumption demand would account for a major share of Thailand's national GDP, with its value as a percentage of the GDP remaining at over 64.0% during 2010–2050 in the BAU scenario. The share of investment demand in the GDP would lie between 62.9% to 59.6% during 2010 to 2050 in the BAU scenario. The net trade balance, measured as the total value of exported goods and services minus the total value of imported products, remains positive throughout the study period in the BAU scenario. This means that Thailand would continue to be

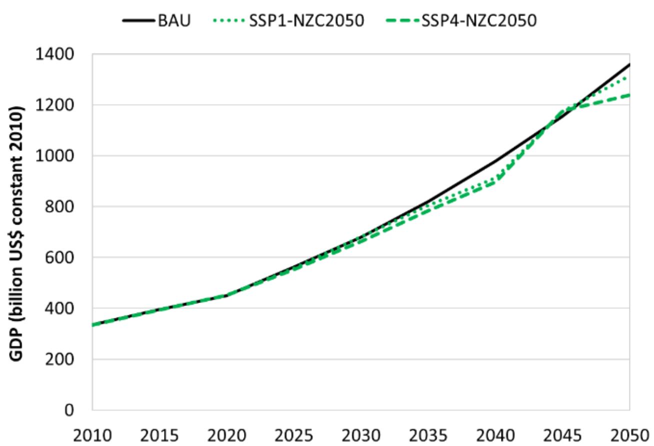

Fig. 4 GDP in all scenarios during 2010–2050.

an export-oriented economy to the same degree throughout the study period under the BAU scenario. However, the net trade deficit taken as a percentage of the GDP would gradually decline during the study period, i.e., from 6.6% in 2010 to 2.7% in 2050 under the BAU scenario.

Thailand AIM/CGE modeling results show that the imposition of various carbon-neutrality scenarios would cause a decline in the GDP. In cumulative terms, the GDP loss would vary from 0.6% to 2.0% between the two carbon-neutrality scenarios. The cumulative GDP loss would be higher in the SSP4-NZC2050 scenario. This study found that forcing CO_2 emissions to decline on the pathway to attain the goals of the Paris Agreement would lead to distortion of the GDP in either of the carbon-neutrality scenarios. When seen in 2050, the GDP loss would vary from 3.2%–8.8%, respectively, in the SSP1-NZC2050 and SSP4-NZC2050 scenarios. Attainment of the carbon-neutrality goal towards 2050 would encourage the use of efficient mitigation measures including carbon removal technologies. Together with stronger mitigation measures, such steeper CO_2 emission reductions would cause output reductions from carbon-intensive industries, mainly the coal & lignite, gas and petroleum industries, thereby leading to GDP distortions. Comparatively, the output reductions in 2050 are much larger in the SSP4-NZC2050 scenario (about 12%) and require lower government consumption expenditures for purchases of goods and services. This results in a higher GDP loss in SSP4-NZC2050 compared to SSP1-NZC2050.

5.2.2 Impacts on Household and Government Consumption

Government consumption would increase by more than five-fold during 2010 to 2050, i.e., from US$53 billion in 2010 to US$292 billion in 2050 in the BAU scenario. Household consumption would undergo an increase of almost four-fold during the same period in the BAU scenario, i.e., from US$172 billion in 2010 to US$608 billion in 2050. Compared to the BAU scenario, the carbon-neutrality scenarios would demand a substantial increase in government consumption in cumulative terms ranging from 24.5% to 26.3% in both NZC2050 scenarios. The increase is more significant in the SSP1-NZC2050 scenario than in the SSP4-NZC2050 scenario. This is mainly due to a higher increase in the government consumption expenditure for goods and services in the agriculture & forestry, electricity, industries, construction, trade, services and transport sectors in the SPP1- NZC2050 scenario. Meanwhile, the CO_2 mitigation pathways following the carbon-neutrality scenarios would cause a severe decline in cumulative household consumption. In cumulative terms, the decline would be in the range of 10.0% in the SSP1-NZC2050 scenario to 12.8% in the SSP4-NZC2050 scenario. The results show that the CO_2 emission reduction targets would cause a decline in production output, especially from carbon-intensive industries, thus leading to a decline in the household consumption of goods and services in the carbon-neutrality scenarios. The government takes essential responsibility during economic downturns and increases spending to boost economic activities. Government spending on welfare activities is higher during 2030 to 2050 in both carbon-neutrality scenarios, i.e., in the period when the CO_2 emission pathways undergo steeper reductions. Thailand's AIM/CGE modeling results show a need for increased government spending on welfare benefits, mainly in the forestry, electricity, construction, machineries, transport and service sectors to achieve carbon neutrality by 2050. The service sector including, banking & insurance, real estate, business and public services (such as public administration, education, research & training, sanitary, hospitals, restaurants and hotels) would comprise the largest share of total government and household consumption in both the BAU and carbon- neutrality scenarios. The share of the service sector in total consumption would increase from 43.2% in 2010 to 45.9% in 2050 in the BAU scenario. By 2050, the share of the service sector would be much larger in the NZC2050 scenarios, ranging from 48.9% to 52.7%. The service sector would play a critical role in Thailand's economic development and would account for a larger share in the NZE2050 scenarios. The results indicate that the country's economy is expected to shift from an agrarian economy to a more service-oriented economy in the long run. This could be a reasonable trend for an emerging and booming economy like Thailand with a rich tourism sector progressing towards industrialization and commercialization.

5.2.3 Welfare Losses

Welfare losses are an important indicator of decreased economic and social well-being as a result of the imposition of policy shocks. The drastic decline in household consumption would lead to a sharp increase in welfare losses in the carbon-neutrality scenarios (Table 2). Welfare losses increase in the range of 9.5% to 10.9% among the considered carbon-neutrality scenarios during 2010–2050. In both NZC2050 scenarios, the welfare losses tend to be higher during the period of 2030–2050. This is because of the sharp decline in GHG emissions during this period which would cause household consumption to drop by 13.5% in SSP1-NZC2050 to 16.2% in SSP4-NZC2050. The country's economy would

Table 2 Welfare losses compared to the BAU scenario.

Scenarios	% loss in cumulative terms		
	2010–2050	2020–2030	2030–2050
SSP1-NZC2050	9.5	3.7	12.9
SSP4-NZC2050	10.9	7.7	14.0

face severe damage from increasing welfare losses if the CO_2 mitigation goals specified by the Paris Agreement's 1.5°C targets as considered in this study are imposed with limited technological improvements.

5.3 Economic Implications of the NZC2050 Scenarios

Carbon prices, or CO_2 mitigation costs, presented in Fig. 5 reflect the stringency of mitigation requirements for Thailand to achieve carbon neutrality by 2050. Based on the CO_2 emission pathways considered in this study, the carbon price increases with the level of mitigation efforts across all scenarios. The price of CO_2 mitigation is in the range of US$32-157/t$CO_2$ in 2030, US$256-310/$CO_2$ in 2040, and US$220-332/t$CO_2$ in 2050 between the two NZC2050 scenarios.

Values for the SSP4-NZC2050 scenario are relatively higher than those of the SSP1-NZC2050 pathway during 2030–2040, but the difference decreases over time, particularly beyond 2040 (Fig. 5). This is because in the SSP1-NZC2050 scenario, there is comparatively less mitigation activity during 2025–2040 and more mitigation towards 2050. The low mitigation target of the CO_2 mitigation pathway towards 2050 depicted by the SSP4-NZC2050 scenario exhibits the lowest values of carbon prices across the two carbon-neutrality scenarios in 2050. The wide range of CO_2 mitigation prices across the scenarios depends on many factors, including CO_2 mitigation targets, availability of technology and characteristics of technologies in terms of investment costs and rate of deployment (Riahi et al., 2017; Rogelj et al., 2015). The pathways that have limited flexibility for substituting fossil fuels with low-carbon technologies such as in the SSP4-NZC2050 scenario in this analysis, provide high estimates of CO_2 prices during 2030–2040. However, towards 2050, the prices of CO_2 mitigation in the SSP1-NZC2050 scenario tend to be the higher between the two scenarios. Though the level of emission reductions does not appear to differ much between the two carbon-neutrality scenarios, the differences in technology selection, variations in government consumption expenditure and reductions in production output and household consumption are responsible for the variation in carbon prices. A higher carbon price implies larger reductions in household consumption of goods and services. Such large reductions in household consumption could be minimized by switching towards cleaner and more efficient energy resources and technologies.

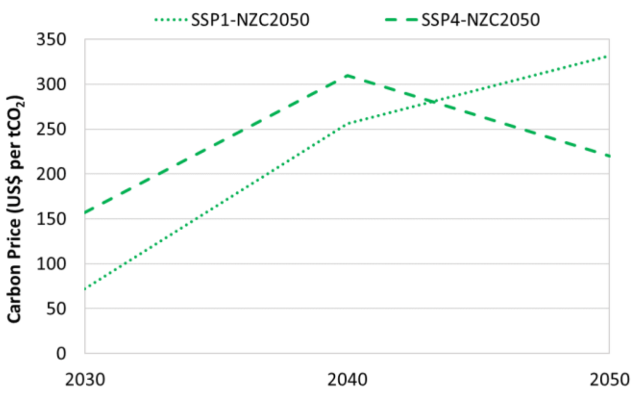

Fig. 5 Variations in carbon prices across various carbon-neutrality scenarios.

The price of CO_2 mitigation is sensitive to the limited availability of technologies and varies according to the non-availability of BECCS technologies (Bauer et al., 2020). The deployment of technologies and mitigation strategies is also sensitive to varying discount rates (Rogelj et al., 2018). The result of this analysis is based on a 10% discount rate for energy equipment and 5% depreciation rate for the existing capital. In addition, socioeconomic conditions and policy assumptions greatly affect the price of CO_2 mitigation. Delayed mitigation policies and measures may even result in a further increase in carbon prices. The increased carbon prices in such cases result mainly from a need for stronger efforts to counterbalance the higher emissions. Finally, studies reveal that there is no unique path for the price of CO_2 mitigation and it varies considerably across studies (Rogelj et al., 2018).

6. Conclusion

This study was designed with the aim of analyzing the energy, environmental and macroeconomic impacts of attaining carbon neutrality in Thailand by 2050. The introduction of low-carbon mitigation measures considered in this analysis provides benefits in terms of CO_2 emission reductions, but the imposition of such strategies would be economically inefficient because of reduced GDP and welfare. To achieve the carbon-neutrality target, the energy sector would need to undergo deep decarbonization. The power sector would need to achieve zero CO_2 emissions by 2050. Renewable energy, CCS and BECCS technologies would play key roles in reducing CO_2 emissions from the power sector. Results suggest that expansion of renewable energy-based technologies, improvement of end-use energy efficiency, fuel switching and deployment of CCS and BECCS technologies in the power and industrial sectors will be important mitigation measures for Thailand in attaining carbon neutrality by 2050.

However, several limitations are involved in this study. The analysis of economic impacts is based on the input-output table of 2010. The study considers national population and GDP from governmental documents, but estimates Thailand's CO_2 emission allowances for attaining carbon neutrality by 2050 using the global CO_2 emission trajectory of the SSP database. Moreover, this analysis is based on underlying assumptions of fixed technological coefficients, constant return of scale, no constraints on resources and efficient employment of all local resources. Nuclear-based power generation, which could be a potential option to abate CO_2 emissions, is not considered in this analysis. Attainment of either of the carbon-neutrality scenarios would necessitate a substantially higher level of production from the agriculture and forestry sectors to meet demand. The expansion of production from the forestry sector, however, would require not only a larger landmass area, but also technological improvements for efficient use of bioenergy resources. In addition, afforestation would need to be implemented on a large scale to sequester carbon emissions. This study, however, does not consider limitations on the availability of land, energy and water resources. Consideration of such limitations would certainly change the magnitude of production activity from the forestry sector and yield more realistic results. Still, this study provides the insight that the forestry sector could play a significant role in fostering CO_2 mitigation opportunities for Thailand. Consideration of an increased removal potential with reforestation could further lower net CO_2 emissions in 2050. This would most probably lead to lower differences in economic losses in the carbon-neutrality scenarios compared to BAU. Finally, high uncertainties and challenges remain to the wide adoption of CCS technologies in both the electricity generation and manufacturing industries.

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References

Australia Alliance for Energy Productivity (A2EP) (2022) What is Energy Productivity? Retrieved from https://www.a2ep.org.au/what-is-energy-productivity (accessed 16 September 2022)

Bauer, N., Rose, S. K., Fujimori, S., van Vuuren, D. P., Weyant, J., Wise, M., et al. (2020) Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, 163(3): 1553–1568. https://doi.org/10.1007/s10584-018-2226-y

Bows, A. and Anderson, K. (2008) Contraction and convergence: an assessment of the CCOptions model. *Climatic Change,* 91(3): 275–290. https://doi.org/10.1007/s10584-008-9468-z

Dai, H. and Masui, T. (2017) Achieving carbon emissions peak in China by 2030: The key options and economic impacts. *In*: Fujimori, S., Kainuma, M. and Masui, T., eds., *Post-2020 Climate Action: Global and Asian Perspectives,* 77–111. Singapore: Springer.

Fujimori, S., Masui, T. and Matsuoka, Y. (2012) AIM/CGE 7.0 Manual. Japan: National Institute for Environmental Studies, and Kyoto University.

Ministry of Energy (MOE) (2020a) Energy Efficiency Plan 2018–2037 (EEP2018). Bangkok: Department of Alternative Energy Development and Efficiency.

MOE (2020b) Thailand Power Development Plan 2561–2580 Revision 1 (PDP2018). Bangkok: Energy Policy and Planning Office (EPPO), Ministry of Energy. Retrieved from http://www.eppo.go.th/images/Infromation_service/public_relations/PDP2018/PDP2018Rev1.pdf. (accessed 16 September 2022)

National Institute for Environmental Studies (NIES) (2021) AIM/Enduse User Manual. Retrieved from https://www.nies.go.jp/media_kit/16.AIM/Enduse/manual.html (accessed 17 September 2021)

Office of Natural Resources and Environmental Policy and Planning (ONEP) (2020a) *Thailand's Updated Nationally Determined Contribution*. Submitted to the United Nations Framework Convention on Climate Change (UNFCCC), Retrieved from https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Thailand%20First/Thailand%20Updated%20NDC.pdf. (accessed 16 September 2022)

Office of the National Economic and Social Development Council (NESDC) (2016) Input-Output Table of Thailand 2010 (16, 26, 58, 180). Office of the National Economic and Social Development Council, Office of the Prime Minister. Retrieved from https://www.nesdc.go.th/nesdb_en/ewt_news.php?nid=4366&filename=national_account (accessed 17 November 2016)

NESDC (2019) Report of the Population Projections for Thailand 2010–2040 (Revision). Bangkok: Office of the National Economic and Social Development Council.

ONEP (2020b) *Thailand Third Biennial Update Report*.

ONEP (2021) Mid-century, Long-term Low Greenhouse Gas Emission Development Strategy of Thailand, Submitted under the Paris Agreement.

Rajbhandari, S., Limmeechokchai, B. and Masui, T. (2019) The impact of different GHG reduction scenarios on the economy and social welfare of Thailand using a computable general equilibrium (CGE) model. *Energy, Sustainability and Society,* 9(1): 19. https://doi.org/10.1186/s13705-019-0200-9

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., et al. (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change,* 42: 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rogelj, J., Reisinger, A., McCollum, D.L., Knutti, R., Riahi, K. and Meinshausen, M. (2015) Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters,* 10(7): 075003. https://doi.org/10.1088/1748-9326/10/7/075003

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018) Mitigation pathways compatible with 1.5°C in the context of sustainable development. *In*: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T., eds., *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 Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 1–82.

Rutherford, T.F. (1999) Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. *Computational Economics,* 14(1): 1–46. https://doi.org/10.1023/A:1008655831209

Shared Socioeconomic Pathways Database (SSP Database) (2018) SSP public database version 2.0. International Institute for Applied Systems Analysis (IIASA). Retrieved from https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10 (accessed 16 September 2022)

Salony RAJBHANDARI

Dr. Rajbhandari is working as a researcher at the Sirindhorn International Institute of Technology, Thammasat University, Thailand. She completed her Doctoral degree in the Engineering and Technology program at the same institute. She holds a Master's degree in Energy from the Asian Institute of Technology, Thailand, with specialization in Energy Economics and Planning, and has a Bachelor's degree in Electrical Engineering from the Institute of Engineering, Tribhuvan University, Nepal. Her major areas of research interests include climate change mitigation, energy economics and environmental policy modeling, energy economics and planning, energy access, and emission inventory. She has expertise in both energy and macroeconomic modeling using the MARKAL, AIM/Enduse and AIM/CGE models.

Achiraya CHAICHALOEMPREECHA

Ms. Chaichaloempreecha is a Ph.D. candidate in the Engineering and Technology program at Sirindhorn International Institute of Technology, Thammasat University, Thailand. She has expertise in energy policies and management and energy modeling, especially in the energy sectors. Her background is as a mechanical engineer. She is currently participating in "The revision and update of Thailand's Long-Term Low Greenhouse Gas Emission Development Strategy (LT-LEDS) and Thailand's National Determined Contribution (NDC)" project. She has published an article on the topic of "Thailand's mid-century greenhouse gas emission pathways to achieve the 2 degrees Celsius target."

Bijay B. PRADHAN

Bijay B. Pradhan works as a postdoctoral researcher at the Sirindhorn International Institute of Technology, Thammasat University, Thailand. He completed his Doctoral degree in the Engineering and Technology program at the same institute. He holds a Master's degree in Energy from the Asian Institute of Technology, Thailand and has a Bachelor's degree in Mechanical Engineering from Kathmandu University, Nepal. His major areas of research interests include climate change, energy modeling, energy economics, energy policies, energy efficiency and renewable energy.

Bundit LIMMEECHOKCHAI

Dr. Limmeechokchai graduated from King Mongkut's Institute of Technology, North Bangkok with First Class Honours in Mechanical Engineering. From there, he gained his Master and Doctoral degrees in Engineering at the Asian Institute of Technology, Thailand. His research expertise includes energy technologies, energy efficiency, energy economics, planning and policy, modeling of energy and environment systems, renewable energy, low-carbon technologies, demand-side management, integrated resource planning, and CO_2 mitigation. Currently he works at the Sirindhorn International Institute of Technology, and heads the Thammasat University Research Unit in Sustainable Energy and Built Environment.

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