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The impact of different GHG reduction scenarios on the economy and social welfare of Thailand using a computable general equilibrium (CGE) model

Salony Rajbhandari[1], Bundit Limmeechokchai[1*] and Toshihiko Masui[2]

Abstract

Background: The Nationally Determined Contribution (NDC) of Thailand intends to reduce greenhouse gas (GHG) emissions by 20 to 25% from the projected business as usual level by 2030 with the deployment of renewable energy technologies and energy efficiency improvement measures in both the supply and demand sectors. However, in order to contribute towards meeting the long-term goal of the Paris Agreement to stay well below 2 °C, ambitious mitigation efforts beyond 2030 are needed. As such, it is necessary to assess the effects of imposing more stringent long-term GHG reduction targets in Thailand beyond the NDC commitment.

Methods: This paper analyses the macroeconomic effects of limiting the GHG emissions by using a computable general equilibrium (CGE) model on Thailand's economy during 2010 to 2050. Besides the business as usual (BAU) scenario, this study assesses the macroeconomic effects of ten low to medium GHG mitigation scenarios under varying GHG reduction targets of 20 to 50%. In addition, this study also assesses three different peak emission scenarios, each targeting a GHG reduction of up to 90% by 2050, to analyze the feasibility of zero GHG emissions in Thailand to pursue efforts to hold the global temperature rise to 1.5 °C above pre-industrial levels, as considered in the Paris Agreement.

Results: According to the BAU scenario, the GHG emissions from the electricity, industry, and transport sectors would remain the most prominent throughout the planning period. The modeling results indicate that the medium to peak emission reduction scenarios could result in a serious GDP loss compared to the BAU scenario, and therefore, the attainment of such mitigation targets could be very challenging for Thailand. Results suggest that the development and deployment of energy-efficient and renewable energy-based technologies would play a significant role not only in minimizing the GHG emissions but also for overcoming the macroeconomic loss and lowering the price of GHG emissions.

Conclusions: The results reveal that without a transformative change in the economic structure and energy system of Thailand, the country would have to face enormous cost in reducing its GHG emissions.

Keywords: Computable general equilibrium, GHG emission reduction, Paris Agreement, Thailand

* Correspondence: bundit@siit.tu.ac.th
[1]School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani 12120, Thailand
Full list of author information is available at the end of the article

Background

Climate change is an issue of global concern. The adverse consequences of climate change, such as rising sea levels, increasing temperatures, changing precipitation patterns, and risks of intense droughts and heat waves, are posing threats to both the environment and people globally. The process of rapid urbanization, industrialization and economic development has contributed to unsustainable use of natural resources, increase in harmful pollutants, degradation of land, and other environmental issues [1]. However, according to the Intergovernmental Panel on Climate Change (IPCC), the adverse impacts of climate change would vary among different countries; some regions may be less affected or even be benefitted while others may suffer from significant losses [2]. The climate change-induced temperature rises can cause significantly increased net damage costs over time and have serious impacts on a country's economy. In order to avoid the large economic losses from climate change, it is necessary for an upper middle-income country like Thailand to shift towards a low-carbon economy.

In an international effort to tackle climate change, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement during the 21st Conference of the Parties (COP21) on 12 December 2015. The agreement, a legally binding framework, brings all the nations together to combat climate change by maintaining a global temperature rise of less than 2 °C above pre-industrial levels by the end of this century and pursuing efforts to limit the temperature increase even further to 1.5 °C [3]. In support of these goals, Thailand signed the Paris Agreement on 22 April 2016 and ratified the agreement on 21 September 2016 [4].

Few researches on greenhouse gas (GHG) mitigation policy instruments have been conducted to date considering very stringent mitigation targets. The Paris Agreement triggered an urgent need for research among countries on climate policy and mitigation targets in order to be consistent with the 1.5 °C emission pathways [5]. This prompted all the Parties to come up with strong mitigation measures through Nationally Determined Contributions (NDCs), indicating the country's emission reduction commitments, measures to attain the objectives, and reporting its progress. As stated in the Paris Agreement, as well as in various other assessments conducted at this stage, the current NDCs are not in line with the 2 °C or 1.5 °C climate goal and require an update to more ambitious emission reduction efforts in order to hold the increase in the global average temperature to the desired level by the end of this century [3, 6, 7]. The Paris Agreement mentions that all Parties are required to submit a new NDC in 5-year cycles with more ambitious goals than the previous NDC. Thailand submitted its NDC on 1 October 2015 stating a goal to reduce the nation-wide GHG emissions by 20% when compared to the business as usual projections by 2030. Furthermore, the NDC of Thailand also stated that the level of GHG emission reductions could go up to 25% by 2030 subject to enhanced access to the technological development and transfer, financial resources, and capacity building supports [8–10].

Several international studies focusing on NDCs and their economic impact have been assessed in the form of either scientific papers, journals, or reports [7, 11–19]. Some of these assessments have proposed alternative scenarios to attain either the 2 °C or the 1.5 °C goals, as the future emissions level targeted by the NDCs results in a temperature rise larger than 2 °C. Some of these studies focused on the deployment of cleaner technology options or the role of renewable energy on either the demand side or the supply side or both, and their associated economic impacts in achieving the GHG mitigation targets given in the NDCs. Few of these assessments have focused on lowering the carbon mitigation cost of achieving NDC targets in 2030 [11]. A study conducted to estimate the global and regional abatement costs of NDCs found that the abatement costs of achieving 2030 emission levels consistent with 2 °C pathways would be at least three times higher than the NDC and for the 1.5 °C pathways five to six times higher [20]. According to a study in Indonesia, the emission reduction target of its NDC can be achieved at an economic cost of less than 1% of the gross domestic product (GDP), thus requiring mitigation actions that would not harm the economic development [14]. In most cases, lowering the cost of GHG emission reductions requires transformative changes in the economic structure and energy systems, such as the case of Korea [12]. A study in India showed that the emissions during the period of 2016–2030 would still be 25 billion tonnes of carbon dioxide (CO_2) equivalent, higher than compatible with the 2 °C stabilization target even after the full implementation of the NDC target [13].

Fujimori et al. (2017) stated that the medium- and long-term emissions reduction need would be drastically large if the emissions in 2030 were as indicated in the NDCs, thus requiring large negative emissions in the latter half of the century to meet the 2 °C goal. Fujimori et al. (2017) suggested that in order to achieve the 2 °C climate goal, the review and revision of policies in the current NDCs to consider additional reduction targets is a necessity. A medium chance of avoiding 1.5 °C temperature increase is to reach net zero carbon emissions globally by 2050 and to reach negative emissions during the period of 2050–2100, about 10–20 years earlier than that in the 2 °C scenarios [21]. Some studies suggested that the long-term climate goal can be achievable if the countries come up with concrete emissions reduction targets in their NDCs to be met after 2030 [7, 22]. However, there is no particular trend among various countries that can be considered as a benchmark for the implementation of carbon reduction targets of the Paris Agreement and NDC goals. The achievement of such targets varies according to the different trends of economic growth, patterns of energy consumption, and varying shares of renewable energy [23]. A study conducted by Gu and Wang [24] emphasizes the need to increment the energy-saving research and development investment rates of the major carbon emitting countries to keep the global warming below 2 °C or 1.5 °C by 2100. The study found that the major carbon emitting countries will not be able to achieve their NDC targets by continuing their current pattern of research and development. While low-carbon technology transfer will help to abate carbon emissions, it will not help in achieving the 2 °C target [24].

There are several studies focusing on the GHG mitigation targets and other low-carbon scenarios in the case of Thailand [25–30]. These studies mainly aim at determination of energy-efficient technological options, benefits of renewable energy development, benefits of emission reduction policy in terms of energy security and local pollutant reduction, and other policies for maintaining a low-carbon economy; however, they do not consider the impacts of such policies from the macroeconomic perspective. Some studies have even considered the economic and environmental implications of GHG mitigation policies in Thailand using the computable general equilibrium models [31, 32]. Timilsina (2009) assessed the economic and environmental consequences of a carbon tax scheme in Thailand under the clean development mechanism [31]. Thepkhun et al. (2013) analyzed the effects of GHG mitigation measures under emission trading scheme and carbon capture and storage (CCS) technology under Thailand's Nationally Appropriate Mitigation Action (NAMA) using the computable general equilibrium models for a period from 2005 to 2050 [32].

In addition, a few studies focusing on NDCs have been conducted for Thailand [33, 34]. The studies conducted by Limmeechokchai et al. (2017) and Chunark et al. (2017) showed that the GHG mitigation targets of Thailand's NDC are achievable by 2030 under the implementation of the Thai Power Development Plan 2015 [33, 34]. Though these studies present the economic impacts of the GHG emission reduction targets of Thailand's NDC along with the role of renewable energy, they do not capture the detailed structural changes in output such reduction targets would cause in the economy. Also, neither of these studies analyzed the economic impacts of the long-term GHG mitigation targets beyond the NDC commitment.

The concern of this study is related to the economic development and the potential impacts of GHG mitigation targets. The impact of long-term GHG emission reduction targets on the economic development policies and social welfare is an important concern as such stringent targets would have greater consequences in the developing countries. As the long-term climate goal demands an immediate reduction after 2030, it becomes necessary to consider the impacts that GHG emission reduction targets will have on the economic development of the developing countries [35]. Even though Thailand has already ratified its NDC commitments to the UNFCCC, there exists a significant emission gap which needs to be overcome to attain the 2/1.5 °C climate goal. This shows an urgent need to study the impacts of imposing more stringent GHG mitigation targets beyond the NDC commitments. Therefore, this study aims at assessing the macroeconomic impacts of different low, medium, and high levels of GHG emission reduction targets on the Thai economy using the dynamic computable general equilibrium (CGE) model. This study not only considers the macroeconomic analysis of the GHG emission reduction targets intended by Thailand's NDC 2030 but also considers the reduction targets beyond 2030 that would aim at reducing the GHG emissions to net zero by 2060 to comply with the global GHG stabilization target of the Paris Agreement.

The rest of the paper is organized as follows. Section 1.1 provides brief information on the NDC of Thailand. Sections 2.1, 2.2, and 2.3 present the methodology, data, and scenario descriptions, respectively. Results and discussions are presented in sections 3 and 4, respectively, while the last section summarizes the main findings of this study.

NDC of Thailand

Total GHG emissions in Thailand increased from 226 million tonnes CO_2 equivalent ($MtCO_2eq$) in 2000 to 319 $MtCO_2eq$ in 2013. During the same period, the equivalent GHG emissions removal from the land use, land use change, and forestry (LULUCF) sector increased from 12 to 86 $MtCO_2eq$ [10]. The NDC of Thailand estimates that the total GHG emissions will increase from 273 $MtCO_2eq$ in 2005 to 555 $MtCO_2eq$ by 2030 under the business as usual (BAU) scenario (named as "BAU-NDC" hereafter). However, the NDC does not consider the GHG emissions and removal potentials from the LULUCF sector. As mentioned in the "Background" section, Thailand intends to reduce its GHG emissions by 20 to 25% from the projected BAU-NDC level by 2030 [8]. Therefore, the total GHG emissions in 2030 are estimated to be approximately 440 $MtCO_2eq$

and 416 $MtCO_2eq$ under 20% (named as "NDC20%" hereafter) and 25% (named as "NDC25%" hereafter) GHG emission reduction scenarios, respectively (see Fig. 1).

To meet the reduction targets set by NDC, Thailand has developed a "Nationally Determined Contribution Roadmap on Mitigation 2021-2030 (Thailand's NDC Roadmap)" based on the relevant national plans already approved or in the pipeline for approval by the Cabinet. Thailand's NDC was formulated based on the following national plans: National Economic and Social Development Plans, Climate Change Master Plan (2015–2050), Power Development Plan (2015–2036), Thailand Smart Grid Development Master Plan (2015–2036), Energy Efficiency Plan (2015–2036), Alternative Energy Development Plan (2015–2036), Environmentally Sustainable Transport System Plan (2013–2031), National Industrial Development Master Plan (2012–2031), and Waste Management Roadmap [9, 10].

Thailand's NDC roadmap prioritizes important measures to mitigate GHG emissions, which include energy efficiency improvement, promotion of biofuels, and increasing deployment of renewable energy-based technologies in the energy and transport sectors; substitution of clinker in the cement industry and replacement of refrigerant in the industrial processes sector; and solid waste and industrial/municipal wastewater management in the waste sector [9, 10]. According to the roadmap, by deploying the aforementioned mitigation measures Thailand could abate about 115.6 $MtCO_2eq$ of GHG emissions, accounting for a reduction of 20.8% by 2030 as compared to the BAU-NDC level [9]. The roadmap showed a possibility of 20.4% (i.e., 113.0 $MtCO_2eq$) of GHG emission reductions by 2030 from the energy and transport sectors by deploying the energy efficiency improvement and renewable energy development measures as compared to the BAU-NDC level. Furthermore, the roadmap highlighted the possibility of 0.1% (i.e., 0.3 $MtCO_2eq$) and 0.3% (i.e., 2.0 $MtCO_2eq$) of GHG emission reductions from BAU-NDC level in 2030, respectively, from the industrial processes and waste sector [9].

Methods

The CGE model

A multi-sector, recursive dynamic CGE model has been constructed considering the input-output data of 2010 to analyze the aspects of GHG mitigation targets on the Thai economy during 2010–2050. The CGE model considered in this study is jointly developed by the National Institute for Environmental Studies, Japan and Sirindhorn International Institute of Technology, Thammasat University, Thailand. The CGE model uses the Mathematical Programming System for General Equilibrium Analysis (MPSGE) as the modeling language embedded within the Generalized Algebraic Modeling System (GAMS) interface [36]. As the strength of the CGE models are to evaluate economy-related policies [37], this type of modeling tool has been widely adopted to assess the economic and environmental impacts of various energy and climate policies at the global [38], national [39], and sub-national levels [11, 40–42].

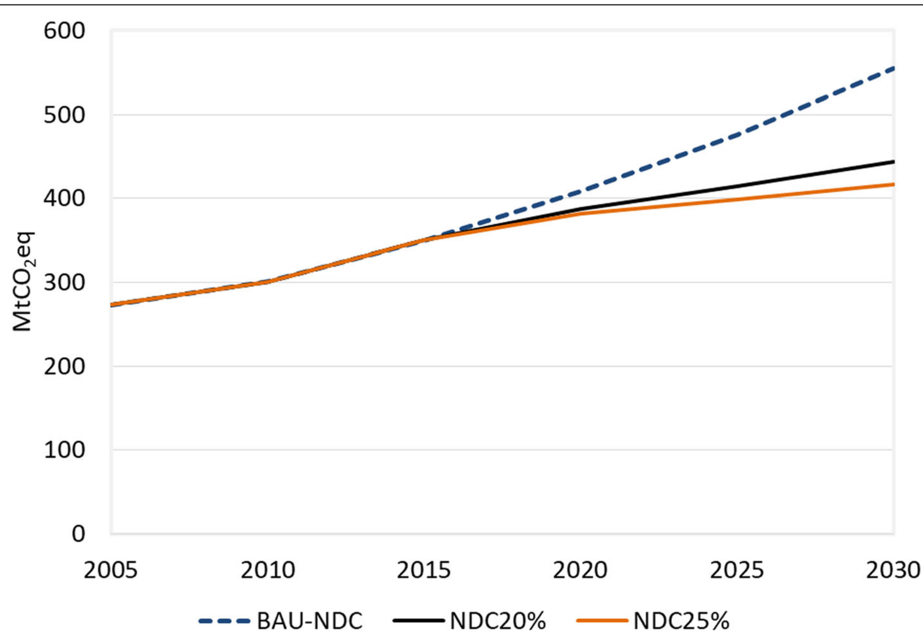

Fig. 1 Nationally Determined Contribution targets for Thailand

The mathematical description of the CGE model considered in this study is similar to that in [11]. The model includes the following blocks: production, government and household income and expenditure blocks, and a foreign trade block considering both the domestic and international transactions. The following section provides the brief description of each of these blocks.

Production

The production block provides the production activity wherein each sector maximizes profit subject to the availability of production technology. As the production processes exhibit a constant returns-to-scale [43], the activities of each production sector in this study are represented by the nested constant elasticity of substitution (CES) function (see Fig. 2). Each sector comprises two types of production functions, one for the existing stock and the other for new investment. The activity output at the first level of the nested structure is determined by a fixed coefficient aggregation and is considered to be a Leontief function of the value added-energy composite, non-energy intermediate composite, and composite of process-related GHG emissions. Using the Leontief function at the first level of the production function has been the standard procedure in CGE models, basically to prevent unrealistic substitution among inputs [44, 45]. The value added and energy composite at the second level of the production structure is a CES aggregation of capital-energy and labor inputs. The composite of non-energy intermediate inputs are modeled in Leontief form. At the third level, the capital-energy composite is a CES function of capital and energy composite. The energy composite is a CES aggregation of different non-fossil and fossil fuels at the fourth level.

Household consumption

Households and government are the final consumers of goods. The household endows the primary factors of production (i.e., labor and capital) and receives income from the rental of these primary factors and fixed factors (i.e., land and natural resources) and lump sum governmental transfers (i.e., revenue from the carbon tax).

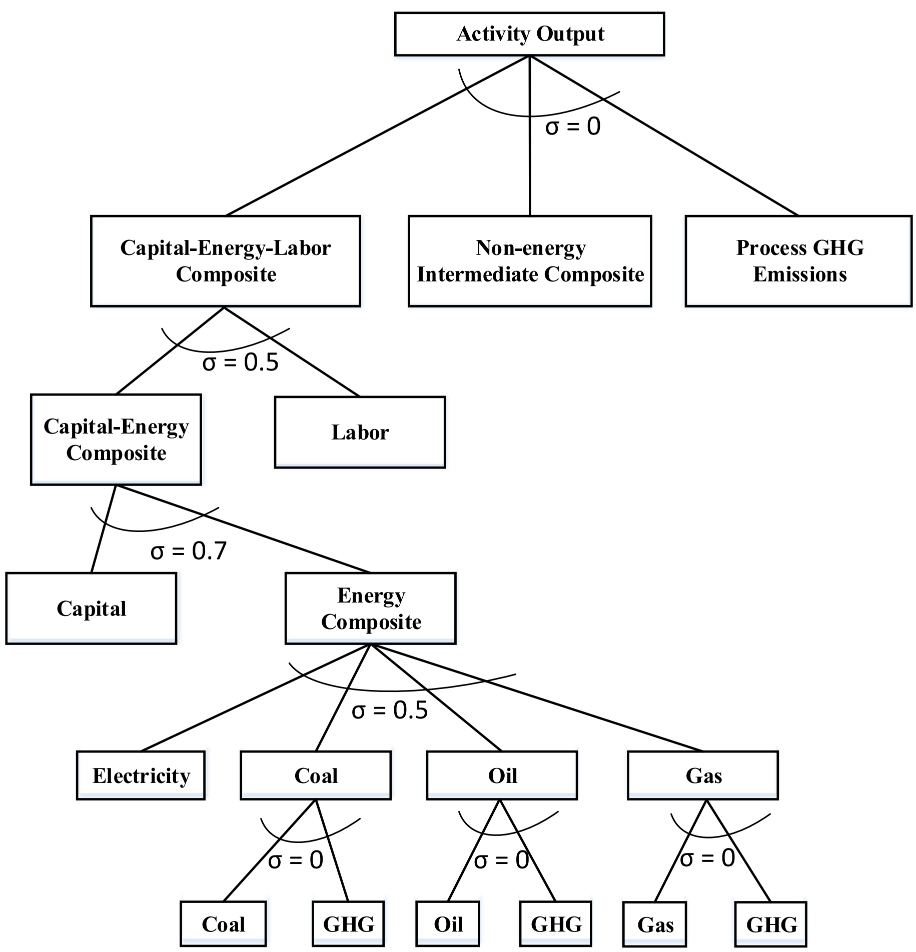

Fig. 2 Nested structure of production sector

Households then use this income either for final consumption, investment, or saving [11]. The study considers a three-step hierarchical process to represent the household that maximizes utility by consuming different levels of energy and non-energy goods, subject to the constraints of budget and commodity prices (see Fig. 3). The nested structure for household consumption for energy goods composite is represented by the CES function while that for the non-energy goods composite is represented by the Cobb-Douglas function.

Government

The government is subject to collect taxes, which includes direct taxes on household income, indirect taxes on gross domestic output, import tariffs on imports, and other taxes such as carbon tax. The revenue earned from carbon tax is assumed to be recycled to the households as a lump sum transfer. Government expenditure includes government consumption, revenue transfers to public services, and export rebates. Investment forms a vital part of the final demand of both the household and government. Total investment in the model is characterized by both the circulating capital investment and fixed capital formation.

Domestic and international transactions

Figure 4 depicts that the goods that are supplied to the domestic market can either be domestically produced or imported. At the same time, producers can sell their goods in an international market. Following Armington's assumption, this study considers the imported and domestically produced goods to be imperfect substitutes [46]. Therefore, the total domestically supplied goods are modeled as a CES function of domestic and imported demand for goods. As for the case of exports, this study uses a constant elasticity of transformation (CET) function to allocate total production of goods between exports and domestic demand for goods (see Fig. 4). As the model is assumed to be an open economy model, both the imports and exports of goods are determined endogenously by the prices of domestic goods and services relative to the international prices [43]. The model considers both the domestic and international currencies price variables to adjust the exports and imports prices.

Market closure

Three principles of closure are considered in the CGE model: a government budget balance, an investment-saving balance, and a foreign trade balance. To balance the government budget, the government consumption is considered to be an exogenous variable in the model while the government saving is considered to be endogenous. The investment in this model is assumed to be an exogenous variable. The exchange rate is determined endogenously to balance the foreign trade module.

Input data

The developed CGE model uses Thailand's 2010 input-output (I/O) table obtained from the Office of the National Economic and Social Development Board (NESDB) to calibrate the model [47]. The I/O table is disaggregated into 32 production sectors of which six are energy sectors (see Table 1). Besides the I/O table, the model requires other parameters such as energy balance, population, GDP, prices (both energy and

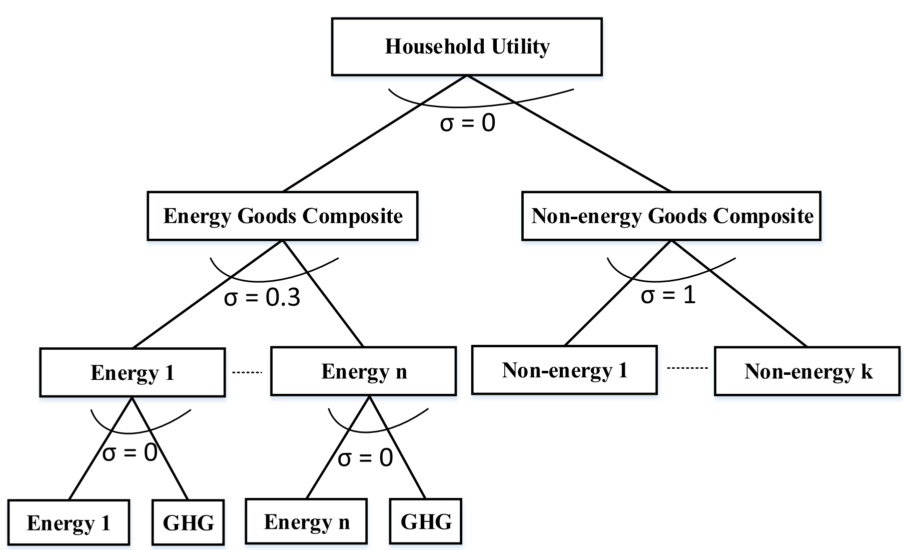

Fig. 3 Nested structure of household sector

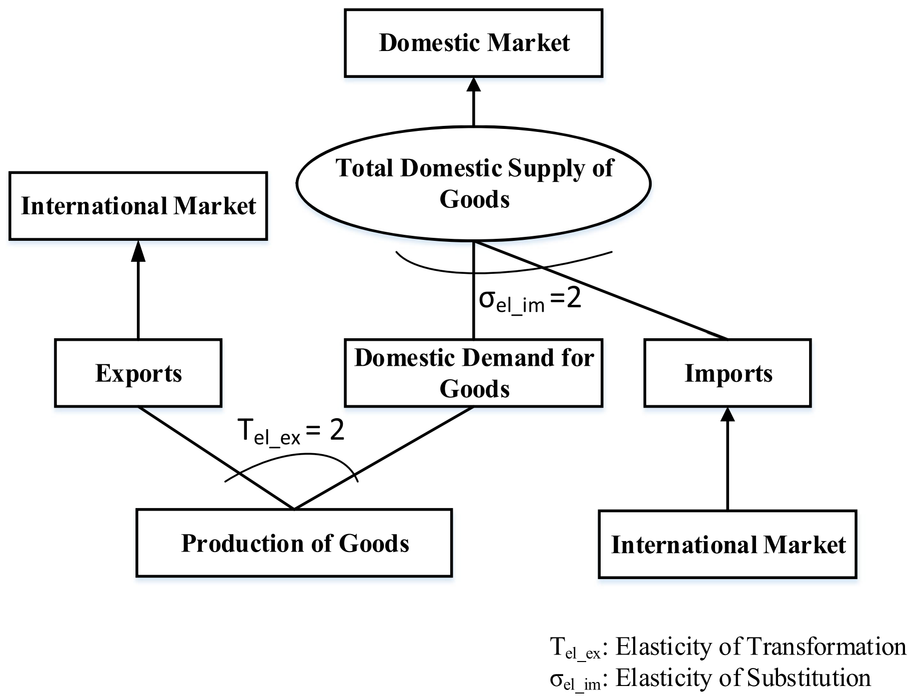

Fig. 4 Structure of foreign trade module

technology), and emission factors, which are exogenously input into the model. Both the export and the import prices are exogenously provided to the model. The CGE model adopts the "law of one price" for energy prices among different sectors. Generally, some inconsistencies are found in the energy consumption data across sectors between the I/O and energy balance tables. As such the I/O table in this CGE model is reconciled with the energy information given in the energy balance table.

Population projections up to 2040 are taken from the national statistics of Thailand and are based on an assumption of declining fertility rates [48]. Based on such assumptions, the population in this study is estimated to grow at the compound annual growth rate (CAGR) of 0.03% during 2010 to 2040. The population growth during 2040 to 2050 is assumed to follow the similar declining trend (see Table 2). The GDP projection is based on the estimated long-term average GDP growth rate of 3.78% during 2018 to 2050 [49, 50]. This

Table 1 Sectoral classification in the CGE model

Non-energy sectors				Energy sectors	
Agriculture and forestry	1. Crops	Industries	14. Metal and non-metal ore	1.	Coal and lignite
	2. Livestock		15. Food, beverages, and tobacco products	2.	Crude oil
	3. Forestry		16. Textile	3.	Petroleum products
	4. Fishery		17. Paper and printing	4.	Gas
Transport	5. Railways		18. Chemical industries	5.	Electricity
	6. Road transport		19. Rubber and plastic products	6.	Biomass
	7. Water transport		20. Non-metallic products		
	8. Air transport		21. Basic metal		
	9. Other transport services		22. Fabricated metal products		
Services	10. Water supply system		23. Machinery		
	11. Communication		24. Construction		
	12. Trade		25. Other manufacturing products		
	13. Other services	Others	26. Other sectors		

Source: Authors

Table 2 Projection of population

Year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (thousands)	63,878	65,729	66,667	67,046	66,847	66,015	64,514	62,775	61,081

Source: [48] and study estimates

study considers the real GDP at a constant benchmark price of 2010.

In addition to the carbon dioxide (CO_2) emissions, methane (CH_4) and nitrous oxide (N_2O) are treated as GHG emissions in the model. The GHG emission coefficients are calculated using the I/O data and the estimated CO_2, CH_4, and N_2O emissions in 2010. The sectoral fuel consumption information obtained from the energy balance [51] and associated emission factors (taken from [52]) are used to estimate CO_2, CH_4 and N_2O emissions by fuel type for the base year 2010. In order to avoid double counting, the GHG emissions from energy use and material use of fossil fuels are treated independently in this study. The elasticities of substitution and transformation considered in the CGE model are based on several international studies [11, 45, 53–55].

Description of scenarios

This study has formulated 14 scenarios: a BAU and 13 GHG emission reduction target (ERT) scenarios. Among the 13 scenarios, five represent constant GHG emission reduction scenarios while the remaining eight scenarios represent the GHG emission reductions with increasing levels of low, medium, and high reduction targets during 2030 to 2050 (see Fig. 5). The BAU scenario in this study is an NDC extended scenario that considers the same GHG emission path as mentioned in the BAU-NDC scenario in Thailand's NDC 2030, but extended till 2050. That is, following the NDC, the GHG emissions under the BAU scenario are estimated to increase from 555 $MtCO_2eq$ in 2030 to 1031 $MtCO_2eq$ in 2050, increasing at an average growth rate of 3.1%.

The five GHG emission reduction scenarios, namely ERT20, ERT25, ERT30, ERT40, and ERT50, consider constant GHG emission reduction targets of 20%, 25%, 30%, 40%, and 50%, respectively, during 2030 to 2050 as that compared to the BAU scenario. In order to analyze the macroeconomic impacts of persisting the same level of reductions as committed by Thailand's NDC beyond 2030, the ERT20 and ERT25 scenarios are designed to consider constant reductions of 20% and 25%, respectively, until 2050. The ERT30, ERT40, and ERT50 scenarios are constructed as alternative options to achieve the medium GHG mitigation targets and analyze the implications of such strict targets on Thailand's economy. Among the remaining eight GHG reduction scenarios, five scenarios, namely ERT20–30, ERT20–40, ERT20–50, ERT25–40, and ERT25–50, have been formulated

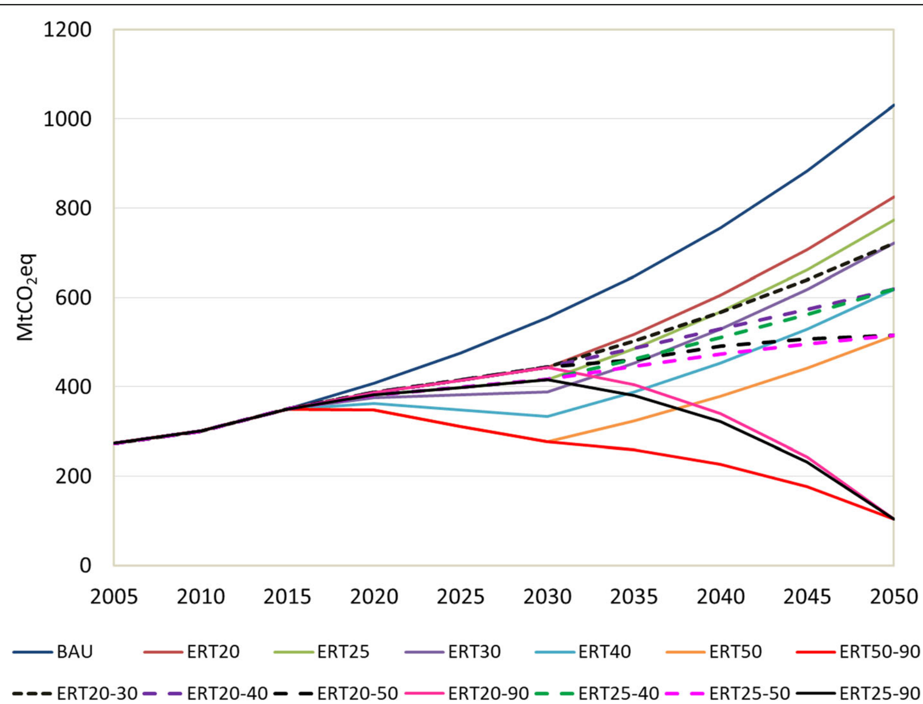

Fig. 5 GHG emission trajectories in all scenarios

considering increasing levels of low to medium GHG emission reduction targets of 20 to 30%, 20 to 40%, 20 to 50%, 25 to 40%, and 25 to 50%, respectively, during 2030 to 2050 as that compared to the BAU scenario.

Furthermore, this study has formulated three peak emission scenarios with higher GHG emission reduction targets, namely ERT20–90, ERT25–90, and ERT50–90, which assume the total GHG emissions to reach zero by 2060, to align with the global climate target of holding the increase in the average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C. The goals of limiting the temperature rise expressed in the Paris Agreement require more ambitious pathways for the energy system than the current announced policies and targets. To meet such ambitious pathways, more stringent GHG emission reduction targets are required. According to the International Energy Agency (IEA), the global emissions can be reduced to net zero by 2060 to meet the global climate goals of holding the increase in the average temperature below 2 °C through technological improvements and deployment of already available or in the innovation pipeline technologies pushed towards their maximum practicable limits. Bioenergy with CCS (BECCS) is expected to emerge as a prominent technology option to support the goal of attaining net zero emissions around 2060 from the energy sector, thus increasing a chance of going beyond the 2 °C temperature goal [56]. As such, in order to explore the economic impacts of such strong mitigation targets in the economy, this study assesses the ERT20–90, ERT25–90 and ERT50–90 scenarios of reducing the GHG emissions from 20 to 90%, 25 to 90%, and 50 to 90%, respectively, during 2030 to 2050 when compared to the BAU scenario, thus leading to zero emissions by 2060 (see Fig. 5). Besides this, sensitivity analyses are also performed thereby adjusting the energy productivity in order to improve the overall energy efficiency up to 40% as compared to the BAU with other things remaining the same, thus analyzing the implications of technological changes on the economic structure, energy systems, and GHG prices for the peak emission scenarios.

All 14 scenarios are based on the common assumptions in terms of population, GDP, and productivities of labor, capital, energy, and non-energy inputs. As mentioned earlier in the "Methods" section, the CGE model categorizes capital into existing stock and new investment. The model updates the capital stock using investment (fixed capital formation), depreciation, and economic growth. In all the scenarios, the total depreciation rate for the existing capital is assumed to be 5% while that for the household's energy equipment is assumed to be 10%. It is assumed that the installed capital is immobile and cannot be transferred to other sectors, whereas new investments can be made in any sector. The model assumes a linear relationship between the capital stock and the capital endowment (income). Labor is considered to be fully mobile across the sectors within the country.

As the model is formulated based on the input-output data, the study assumes fixed technological coefficients, no constraints on resources, and efficient employment of all local resources. The model considers various key technologies for electricity generation based on both renewable (solar, wind, hydro, and biomass) and non-renewable (coal, oil, and natural gas) energy sources in the base year 2010. However, the future composition of the energy mix for electricity generation does not change over time. Also, the model does not include nuclear power in the analysis. The model considers two different technology options for each sector: existing and efficient technologies with energy productivities of 10% and 20%, respectively, in all the scenarios. In addition to this, the model considers an advanced technology in the ambitious reduction target of ERT50–90 scenario in which the factor of energy productivity is assumed to be increased by 20% as that compared to the existing technology in BAU.

Results

The effects of the GHG emission reduction targets on GDP, government and household consumptions, sectoral output, sectoral GHG emissions, GHG prices, capital requirement, and foreign trade are discussed in this section.

Impacts on GDP

The GDP is one of the important primary macroeconomic indicators to measure the status of a country's economy. The GDP of Thailand is estimated to rise from US$ 335 billion in 2010 to US$ 1576 billion in 2050 under the BAU scenario, increasing at a CAGR of 3.95% (see Fig. 6). The result shows that the GDP would attain a slightly higher growth rate of 0.2% than the expected long-term average GDP growth rate of 3.78% in the BAU scenario if the economy continues to follow the current pattern of consumption. The modeling results show that the imposition of GHG reduction targets would cause a decline in the GDP as compared to the BAU (see Fig. 6), thus forcing the GDP to rise at a lower CAGR, varying from 3.83 to 3.62% in ERT20 to ERT50, 3.79 to 3.63% in ERT20–30 to ERT25–50, and 3.86 to 3.69% in ERT20–90 to ERT50–90 scenarios, respectively, during 2010 to 2050.

This study found that with increasing GHG emission reduction targets, the GDP reduction compared to the BAU substantially increases throughout the period of 2030 to 2050 under all the GHG emission reduction scenarios (see Fig. 7). As compared to the BAU, the

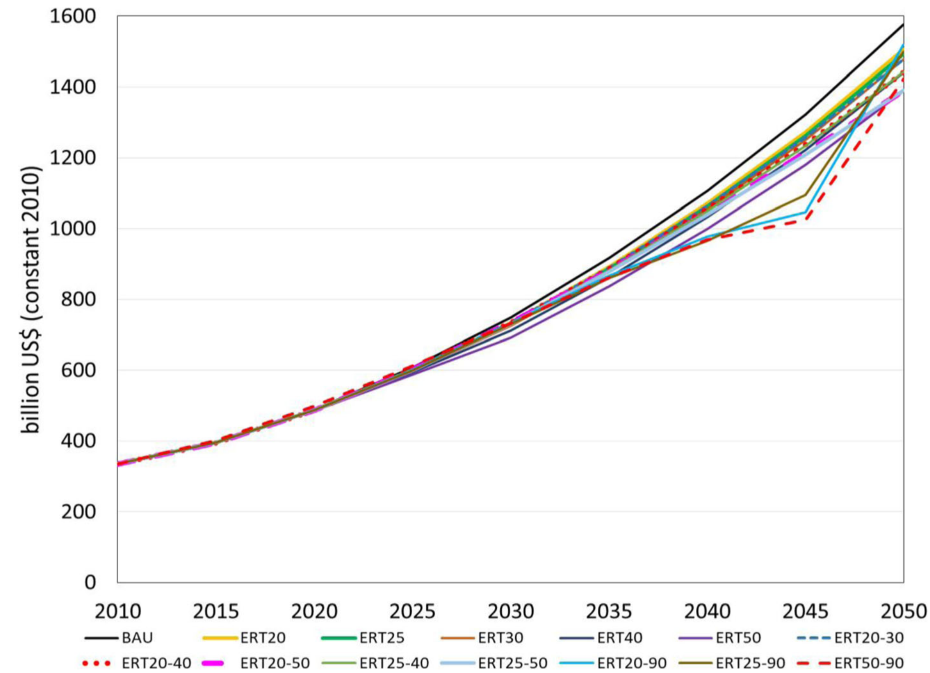

Fig. 6 GDP during 2010 to 2050 under BAU and GHG emission reduction scenarios

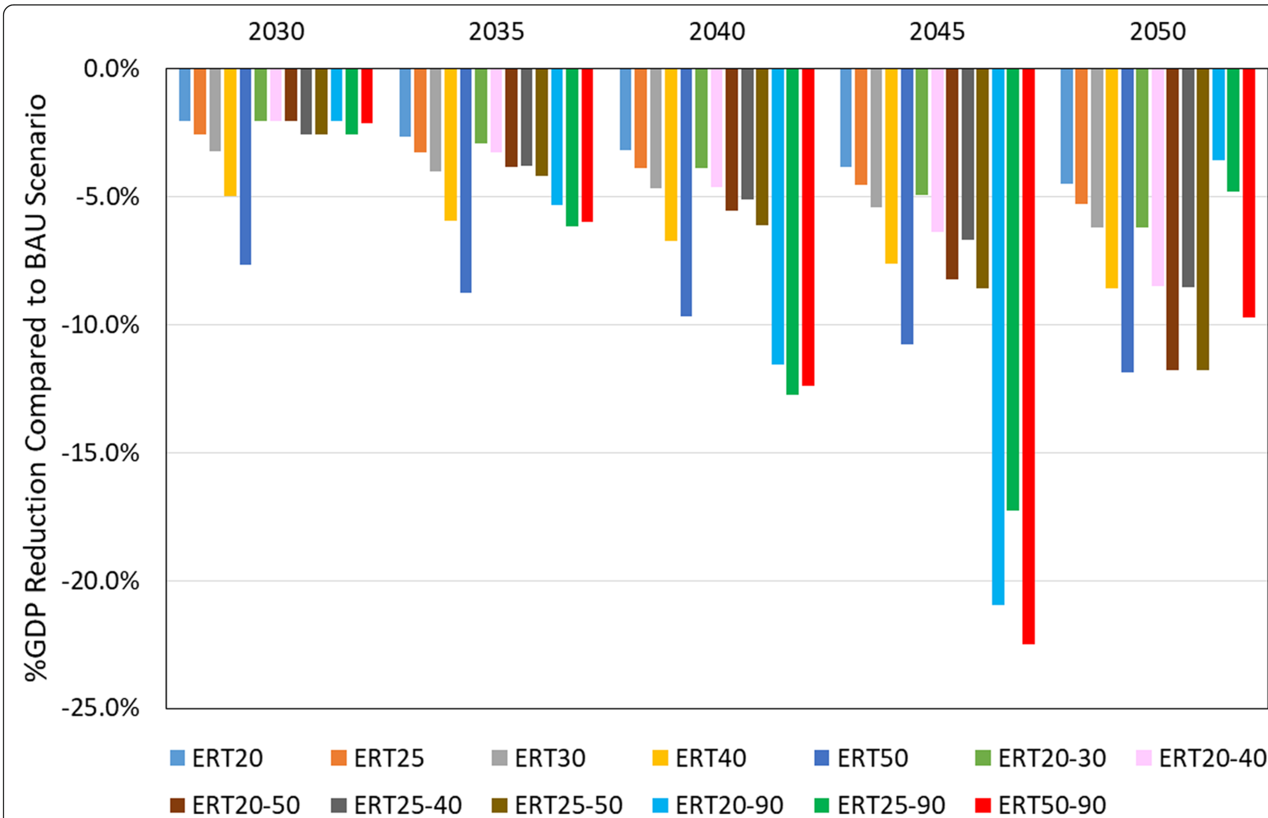

Fig. 7 GDP reduction compared to BAU under GHG emission reduction scenarios

GDP reduction varies from 2.0 to 7.7% in 2030 and from 4.5 to 11.9% in 2050 under the ERT20 to ERT50 scenarios, respectively. GDP reductions ranging from 2.0 to 2.6% in 2030 and 6.2 to 11.8% in 2050 are observed in the low to medium reduction scenarios of ERT20–30 to ERT25–50, respectively, as compared to the BAU. If Thailand aims to follow more ambitious GHG emission reduction targets as specified by the ERT20–90 to ERT50–90 scenarios, then the economy will face a major decline in GDP around 2040 to 2050 in comparison to the BAU, with the most severe reductions occurring in 2045. The GDP loss could go as high as 21.0 to 22.5% in 2045 under the ERT20–90 to ERT50–90 scenarios, respectively, as compared to BAU (see Fig. 7).

As the GHG emission reduction targets encourage the use of more efficient and low-carbon technologies requiring higher investments, they lead to the distortions in the future GDP. The results of the sensitivity analysis show that the expansion of alternative energy industries and energy efficient technologies would help to change the input-output relations and counteract some of the GDP losses. The sensitivity analysis shows that the GDP loss could be lowered up to 2.2 to 7.0% by 2050 under the ERT20–90 to ERT50–90 scenarios, respectively, by improving the overall efficiency of technologies by 40% as compared to BAU.

Impacts on household and government consumption

Government and household final consumption expenditure forms the major component in total GDP. Together, they constituted a share of about 67.2% and 57.9% in total GDP in 2010 and 2050, respectively, under the BAU scenario. The GHG emission reduction targets cause a significant increment in the government consumption and a drastic decline in the household consumption, more specifically in the cases of ambitious reduction scenarios. The government consumption would increase significantly from US$ 53 billion in 2010 to US$ 251 billion in 2050 under the BAU. The household consumption is estimated to increase from US$ 172 billion in 2010 to US$ 662 billion in 2050 under the BAU, increasing at a CAGR of 3.4%. With the increasing emission reduction targets, the cumulative government consumption during 2010 to 2050 would increase by 24.9 to 99.0% under the ERT20 to ERT25–90 scenarios, respectively, as that compared to the BAU. However, improving the energy efficiency by 20% would cause the cumulative government consumption to increase by 92.5% during 2010 to 2050 under the ERT50–90 scenario as compared to the BAU, thus showing a lower increase in comparison to the ERT20–90 and ERT25–90 scenarios.

However, compared to BAU, it would cause a drastic decline in the cumulative household consumption by 16.6% in ERT20 to 56.4% in ERT50–90 scenarios, respectively, during 2010 to 2050. The increasing reductions in the household consumption with rising levels of GHG emission reduction relates to the increasing welfare loss when compared to the BAU scenario. As such, the welfare loss would tend to increase from 12.0 to 48.5%, respectively, under the GHG emission reduction scenarios of ERT20 to ERT50–90 as compared to the BAU scenario. This shows that the economy will face severe damage if the emission reduction targets specified by the NDC and beyond are imposed without considering the technological improvements.

Performing a sensitivity analysis showed that the consideration of 40% improvement in energy efficiency could lower the cumulative government consumption by 12.4 to 16.6% and increase the cumulative household consumption by 24.4% each in ERT20–90 to ERT25–90 scenarios, respectively, in comparison to the same scenarios without considering such efficiency improvement measures. Similarly, the inclusion of 40% improvement in energy efficiency could lower the cumulative government consumption by 1.6% and increase the cumulative household consumption by 12.8% in the ERT50–90 scenario as compared to the same reduction scenario with only 20% energy efficiency improvement. The study thus found that increasing the deployment of energy-efficient technologies could help in improving the household consumption thereby lowering the welfare losses up to 39.6% under the ERT50–90 as compared to the BAU scenario.

Government plays an important role when the economy is in recession and should increase spending in order to stimulate economic activities. The modeling result shows that the increasing emission reduction targets tend to increase government spending on welfare benefits, education, research and training, industries, petroleum, electricity sector, transport, infrastructure investments, etc. The results show that the increase in the total governmental consumption would vary from 32.7% in ERT20 to as high as 200.5% in ERT50–90 scenarios as that compared to the BAU scenario.

The service sector that comprises banking and insurance, real estate, business, and public services including public administration, education, research, sanitary, hospitals, restaurants, and hotels, would have the largest share in the total government and household consumption both in the BAU and the alternative scenarios (see Fig. 8). The service sector would face an increasing share ranging from 42.5 to 83.7% in 2050 in the total government and household consumption, respectively, under the BAU to ERT50–90 scenarios (see Fig. 8). With the varying shares of 28.3% in BAU to 7.7% in ERT50–90 scenario, the industry sector would have the second largest share in total government and household consumption by 2050. The shares of the petroleum and

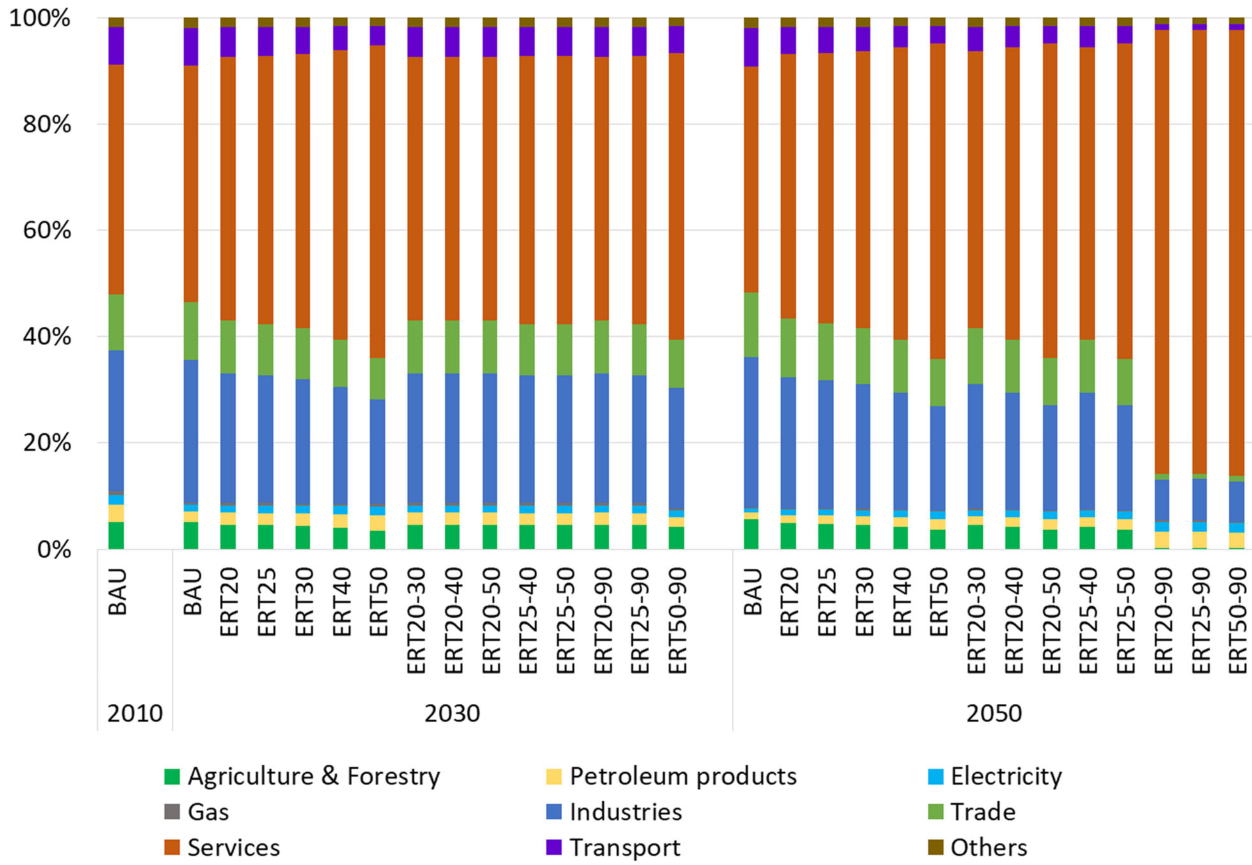

Fig. 8 Sectoral shares in total consumption under the BAU and ERT scenarios

electricity industries in the total consumption would increase from 1.2 to 2.8% and 0.8 to 1.8%, respectively, by 2050 under the BAU to ERT50–90 scenarios.

Impacts on sectoral output

Figure 9 illustrates the impacts of GHG emission reduction targets on the sectoral output in 2030 and 2050 in comparison to the BAU scenario. The total value of the sectoral output is estimated to increase from US$ 836 billion in 2010 to US$ 4139 billion in 2050 under the BAU scenario. The total output is estimated to reduce by 5.4 to 12.8% in 2030 and by 9.5 to 18.0% in 2050 under the ERT20 to ERT50 scenarios, respectively, as compared to the BAU. The total output reductions under the ERT20–30 to ERT25–50 scenarios would vary from 5.4 to 6.3% in 2030 and from 11.8 to 17.9% in 2030, respectively. The study shows that the total sectoral output would increase by 3.2% in ERT20–90 and by 1.1% in ERT25–90 in 2050 in the absence of technological development. The consideration of an energy efficiency improvement of 20% causes the total output to reduce by 12.6% in 2050 under the ERT50–90 scenario. However, the sensitivity analysis showed that by further improving the energy efficiency to 40%, the total sectoral output reductions would vary by 8.8 to 13.4% under ERT20–90 to ERT50–90 scenarios, respectively, as compared to the BAU.

The study showed that the GHG emission reduction targets tend to increase the production from agriculture and forestry, construction, and services sectors. The study found that the production from the agriculture and forestry sector (i.e., biomass production) would have to increase significantly, i.e., by 8.5 to 5.5 times, as compared to the BAU in order to attain the stringent targets of ERT20–90 to ERT50–90, respectively, in 2050. This shows that the increasing levels of GHG mitigation promotes higher production from the forestry sector, highlighting the need of increasing use of biomass-based technologies to meet the zero emissions target in 2060. However, with 40% energy efficiency improvement, the production from the forestry sector would increase by only 3.0 to 3.1 times, respectively, under the ERT20–90 to ERT50–90 scenarios. The service and the construction sectors would experience an increase of about 66.2 to 51.5% and 1.9 to 1.1% in their output, respectively, in 2050 in the ERT20–90 to ERT50–90 scenarios compared to the BAU.

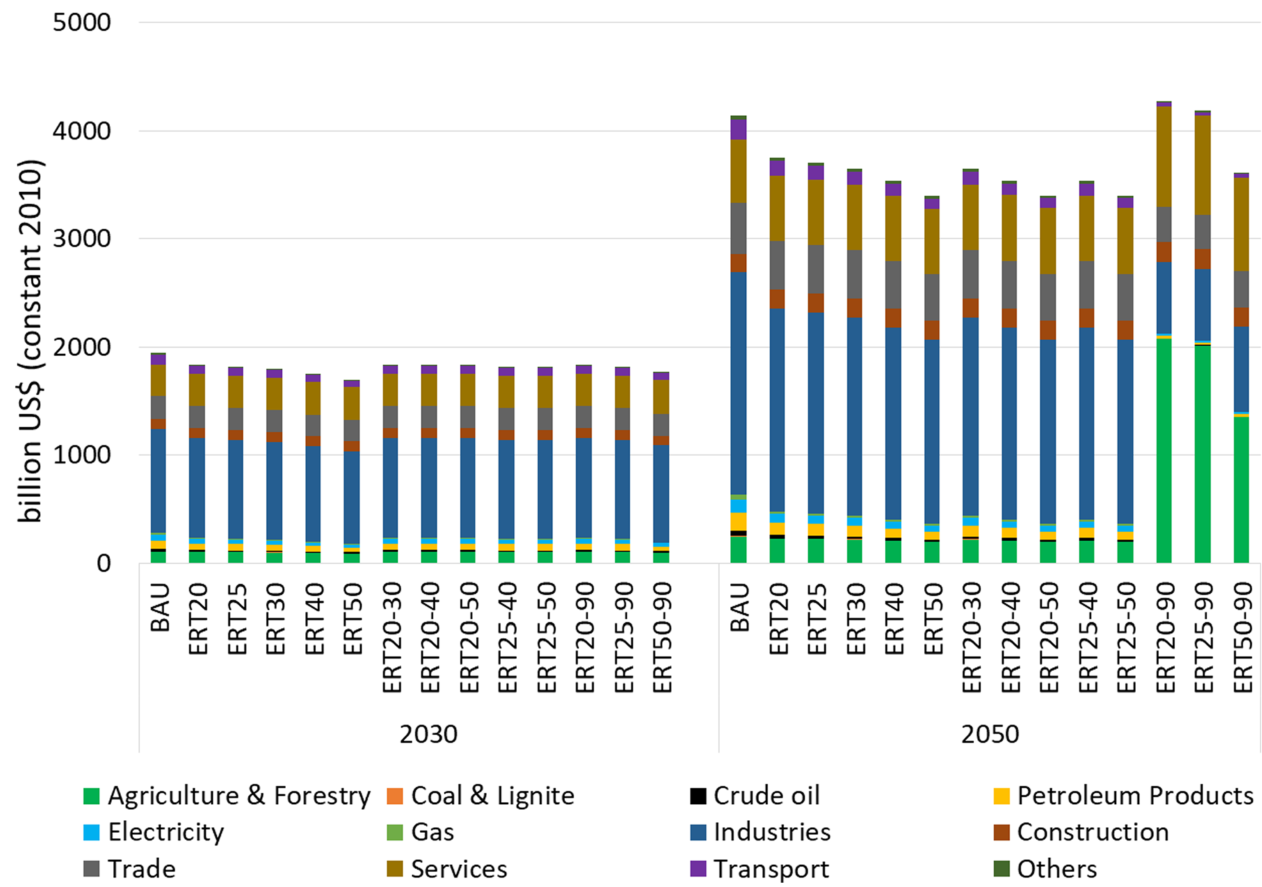

Fig. 9 Sectoral output in all scenarios in 2030 and 2050

The increase in the GHG emission reduction targets tends to mostly impact the fossil fuel industries, thereby promoting higher use of renewable energies from 2030 to 2050. Basically, the coal and lignite mining industries would suffer a heavy output cut by 73.5 to 99.2% in 2050 under the ERT20 to ERT50–90 scenarios, respectively, compared to the BAU. The petroleum refineries and gas industries would have to reduce their productions by 33.9 to 86.0% and 45.0 to 91.4% in 2050 under ERT20 to ERT50–90, respectively, as compared to the BAU.

The simulation results identified that the electricity sector would have to reduce its output by 32.2% in ERT20 to 85.9% in ERT50–90 by 2050 in order to fulfill the overall GHG emission reduction target, if and only if there are no other policy strategies imposed besides giving a maximum GHG emission budget. Results suggest that in the absence of any other policy measures, the country would have to rely heavily on imported electricity to meet its demand in order to attain the desired level of emission reductions. The sensitivity analysis showed that with a 40% improvement in energy efficiency, the production from the electricity sector could be reduced by 81.4% in ERT50–90 by 2050 (i.e., a lower reduction as compared to ERT50–90 with 20% efficiency improvement).

Being carbon-intensive sectors, the transport and industry sectors output would be affected significantly by the GHG mitigation targets. The GHG emission reduction target would result in decreasing output of the transport sector from 28.5 to 78.9% in 2050 in the ERT20 to ERT50–90 scenarios, respectively. The industrial output would be reduced from 8.6 to 61.4% in 2050 in the ERT20 to ERT50–90 scenarios, respectively, compared to the BAU.

Impacts on GHG emissions and GHG intensity

The total GHG emissions are forecasted to increase from 555 $MtCO_2eq$ in 2030 to 1266 $MtCO_2eq$ in 2050 under the BAU scenario. The total GHG emissions would vary from 361 $MtCO_2eq$ to 226 $MtCO_2eq$ in 2030 and from 671 $MtCO_2eq$ to 84 $MtCO_2eq$ in 2050 in the ERT20 to ERT50–90 scenarios, respectively. The GHG emissions from the electricity sector would reduce by 54.0 to 95.3% in 2050 under the ERT20 to ERT50–90 scenarios, respectively. The GHG emissions from the industry sector will be reduced by 49.2 to 96.7% and those from the transport sector will be reduced by 38.0 to 90.5% in 2050 under the ERT20 to ERT50–90 scenarios, respectively. The sensitivity analysis performed in this study suggests that such large GHG emission reductions would only be possible if efficient technologies and technologies based on renewable energies are deployed in all the economic sectors. For example, the use of clean and energy-efficient technologies such as electric, biofuel, and hybrid vehicles in the transport sector and CCS technologies (including bioenergy) in the industry and electricity generation sectors would help to curb large amounts of GHG emissions in the country [9, 10, 30].

The electricity sector had the major share of 35.4% in the total GHG emissions in 2010 under the BAU scenario, followed by industries (including construction sector, 26.3%), transport (13.8%), gas pipeline (9.1%), petroleum refineries (7.0%), services (including the wholesale and retail trade, 4.3%), agriculture and forestry (2.1%), crude oil (1.8%), others (0.3%), and coal and lignite mining (0.1%) sectors (see Fig. 10). With a share of 36.5% and 39.4%, the electricity sector would still be the major GHG emitter in 2030 and 2050, respectively, under the BAU scenario. The industry sector would attain a share of 32.4% in 2030 and 31.5% in 2050, while the share of the transport sector would remain almost the same at 13.9% in 2030 and 13.3% in 2050 under the BAU scenario. Imposition of GHG mitigation targets would reduce the shares in the total GHG emissions from the electricity and industry sectors to 28.1% and 15.5%, respectively, in 2050 under the ERT50–90 scenario. Conversely, the shares of the transport and service sectors would increase to 19.0% and 8.9%, respectively, in 2050 in the ERT50–90 scenario.

The GHG emission intensity, measured in terms of emission per unit GDP, is a commonly used indicator to assess the linkage between the GHG emissions and economic growth across countries and across different scenarios within the same country. Figure 11 illustrates the decrement in the GHG emission intensity across various reduction scenarios as compared to the BAU. The GHG emission intensity would vary from 0.75 to 0.80 kgCO_2eq/US$ during 2030 to 2050 under the BAU scenario. The Thai economy would achieve reductions in GHG emission intensity from 34% in 2030 to 45% in 2050 by considering the 20% GHG emission reduction commitments of Thailand's NDC (i.e., ERT20). The

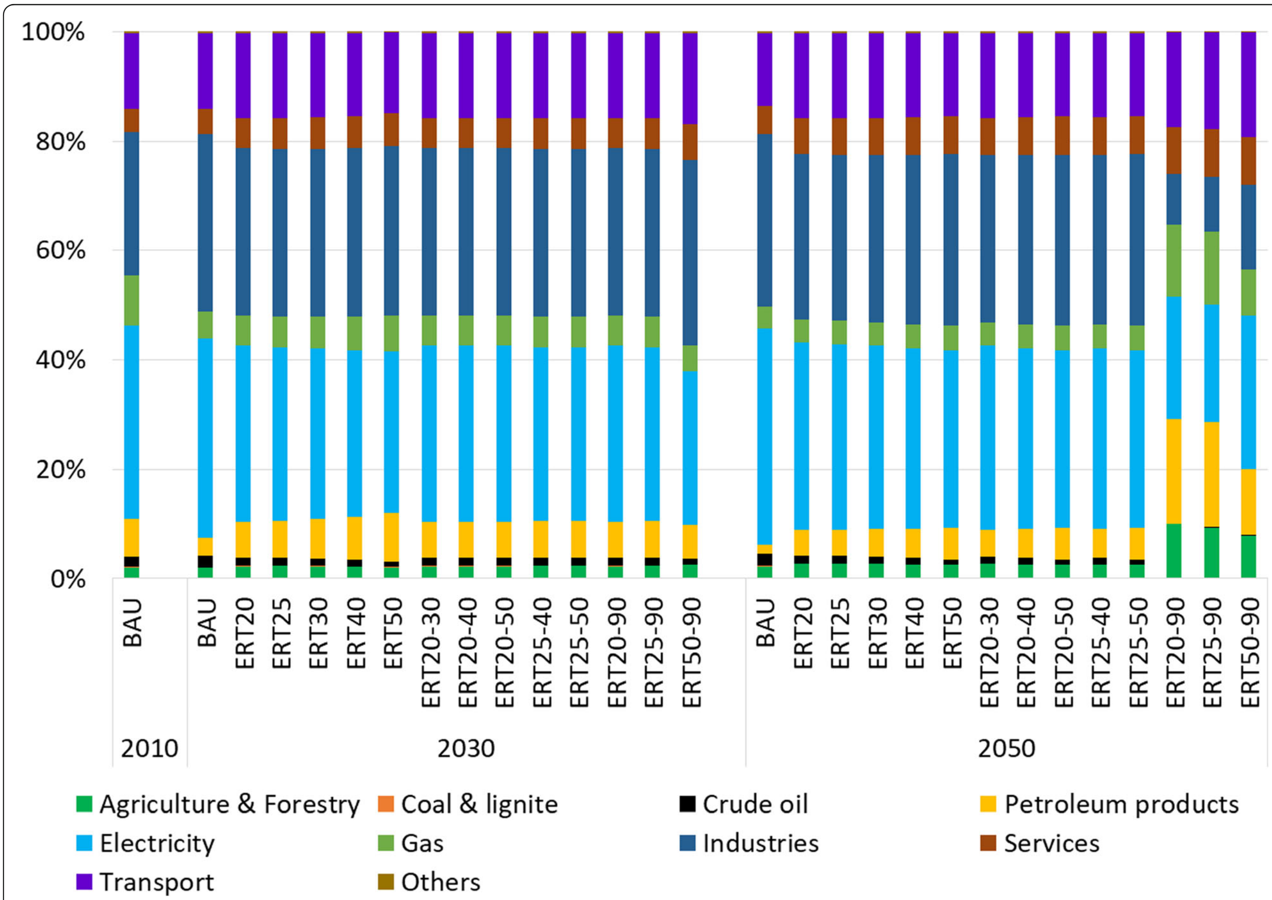

Fig. 10 Variations in sectoral share in total GHG emissions in all scenarios

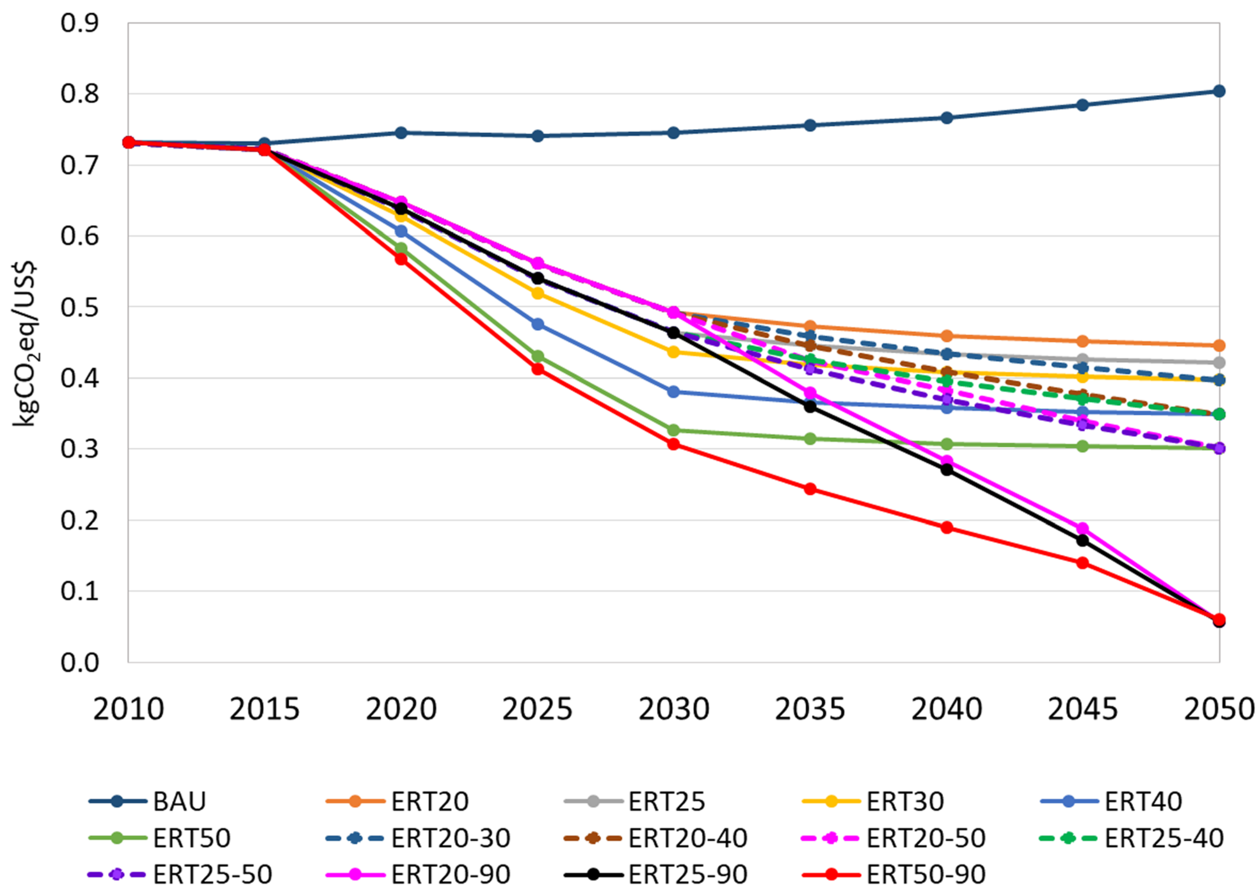

Fig. 11 GHG emission intensity in all scenarios

reduction can increase up to 38% in 2030 to 48% in 2050 if the Thai economy attains the 25% GHG emission reduction commitment of the NDC (i.e., ERT25). The GHG emission intensity would be reduced by 41 to 56% in 2030 and by 51 to 62% in 2050 under the ERT30 to ERT50 scenarios, respectively, as compared to the BAU scenario. In the ERT50–90 scenario, the GHG emission intensity would see a large reduction ranging from 59 to 93% during 2030 to 2050 compared to the BAU scenario.

Variations in GHG price

The GHG prices would increase with the level of various GHG emission reduction targets (see Table 3). It is noted that the GHG prices would decline after 2030 in all the constant emission reduction scenarios. This is mainly because of the GHG emission reduction trajectories assumed in this study have a sharp declining trend from 2020 onwards until 2030 and then a constant reduction of 20 to 50% during 2030 to 2050 in the ERT20 to ERT50 scenarios, respectively, compared to the BAU scenario (see Fig. 5). The GHG price would vary from US$ 38.6 per tCO_2eq to US$ 91.0 per tCO_2eq in 2050 in the low to medium reduction scenarios of ERT20–30 to

Table 3 Implications of GHG emission reduction targets on GHG price (US$/$tCO_2eq$)

Scenario	2020	2025	2030	2035	2040	2045	2050
ERT20	15.9	30.1	42.8	39.3	34.3	30.0	26.2
ERT25	18.0	36.8	54.6	49.2	42.3	36.6	31.8
ERT30	20.5	44.8	69.5	61.5	52.3	44.9	38.6
ERT40	26.5	66.2	112.8	97.1	80.9	68.3	58.0
ERT50	34.5	99.0	188.8	158.7	130.0	108.3	90.9
ERT20–30	15.9	30.1	42.8	44.0	42.3	40.5	38.6
ERT20–40	15.9	30.1	42.8	49.2	52.3	55.2	58.1
ERT20–50	15.9	30.1	42.8	58.8	64.9	76.4	91.0
ERT25–40	18.0	36.8	54.6	58.2	58.2	58.2	58.1
ERT25–50	18.0	36.8	54.6	65.1	72.4	80.8	91.0
ERT20–90	15.9	30.1	42.8	86.5	169.2	584.4	33,805.3
ERT25–90	18.0	36.8	54.6	103.0	194.5	887.7	33,805.3
ERT50–90	21.8	69.6	134.1	196.8	306.3	683.6	15,741.6

ERT25–50, respectively. The study showed that in the absence of technological progress, reaching more ambitious emission reduction targets depicted by the ERT20–90 and ERT25–90 scenarios would yield a prohibitively high economic cost of US$ 33,805.3 per tCO_2eq in 2050.

The GHG prices show that going beyond the 2 °C temperature goal represented by ERT50–90 scenario still requires an extremely high GHG price of US$ 15,741.6 per tCO_2eq in 2050 even if the technological progress of 20% energy efficiency improvement is taken into account. A higher GHG price leads to a larger reduction in the household consumption of goods and services as well as demands for a switch to cleaner energy resources and technologies. The study found that in order to lower the GHG prices, the economy needs to increase the deployment of more energy-efficient technologies. Performing a sensitivity analysis, the study found that by increasing the overall energy efficiency of technologies by 40% as compared to the BAU in all the economic sectors, the GHG price could be lowered up to US$/$tCO_2eq$ 10,558.4 to US$/$tCO_2eq$ 7400.4 in 2050 under the ERT20–90 to ERT50–90 scenarios, respectively. This shows the need of encouraging investments in the low-carbon technology options for lowering the GHG prices and limiting the macroeconomic loss.

Impacts on capital requirement

The increasing GHG emission reduction targets will not much alter the total amount of capital requirement during 2030 to 2050; however, such mitigation targets will change the sectoral composition of the total capital requirement. The industry sector had the highest share (i.e., 27.8%) in the total capital requirement in 2010 in the BAU scenario, followed by the wholesale and retail trade (26.5%), services (20.6%), agriculture and forestry (12.0%), transport (4.0%), electricity (2.6%), crude oil (2.1%), construction (1.9%), petroleum refineries (1.1%), gas industry (0.8%), coal and lignite mining (0.1%), and other (0.5%) sectors (see Fig. 12). Among the industrial sub-sectors, the capital requirement in the machinery industry (basically including industrial machinery, electrical

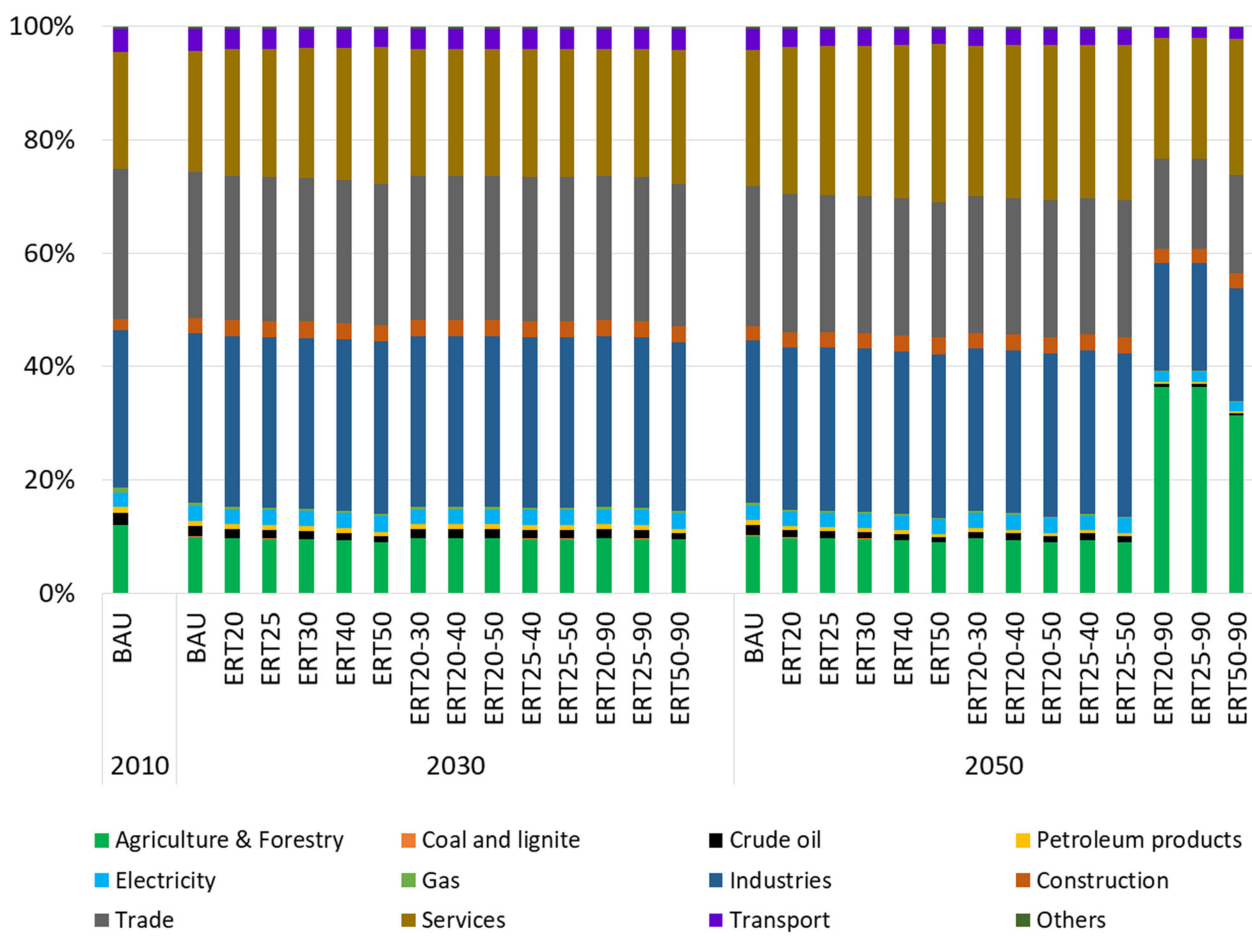

Fig. 12 Variations in capital requirement in BAU and ERT scenarios

machinery and apparatus, motor vehicle and repairing and other transport equipment) had the largest share (35%) in 2010 in the BAU scenario. Besides the machinery sector, the food, beverage, and tobacco industries had the second largest capital demand with a share of about 18% in 2010.

Except for the agricultural and forestry sector, the GHG emission reduction targets will cause a decrement in shares of most of the sectors in the total capital requirements in the ERT20 to ERT50–90 scenarios. The industrial sector, whose share in the total capital requirement would decline from 29.8% in 2030 to 19.8% in 2050 in the ERT50–90 scenario, will be most affected. The agriculture and forestry sector will have the highest share of 31.3% in the total capital requirement in 2050 in the ERT50–90 scenario. The capital requirement of the agriculture and forestry sector will be increased by 210% in 2050 in the ERT50–90 scenario in comparison to the BAU. This shows that to achieve zero emissions by 2060 requires heavy investments in the forestry sector which acts as a potential carbon sink to absorb GHG emissions. This emphasizes the need of investment required for the deployment of biomass-based CCS technologies to curve out the GHG emissions towards meeting the net zero goal in 2060.

Effects on foreign trade

In the absence of the GHG emission reduction targets, the economy would cause both the exports and imports to increase from US$ 224 to US$ 1213 billion and US$ 202 to US$ 1009 billion, respectively, during 2010 to 2050 under the BAU scenario. The substantial production growth in the construction, coal and lignite, electricity, industries, trade and service sectors are the major cause behind the rising exports and imports in the BAU. As the GHG emission reduction targets cause gross output to decline and hence the total demand for goods and services, both the exports and imports would decrease in the ERT20 to ERT25–50 scenarios as compared to the BAU (see Table 4).

The ambitious reduction targets of ERT20–90 to ERT50–90 would result in a decreasing demand of both the exports and imports in 2030. However, the limitation of technological progress would cause a substantial increase in both the exports and imports in 2050 under the ERT20–90 and ERT25–90 scenarios. With a 20% improvement in energy efficiency, both the exports and imports would show a lower positive increment under the ERT50–90 scenario. However, the increase in the demand of both the exports and imports can be lowered up to 5.6 to 1.1% and 6.7 to 1.4%, respectively, under ERT20–90 to ERT50–90 as compared to BAU with a 40% improvement in efficiency.

Discussion

This paper was drawn with the aim to analyze the macroeconomic impacts of various low to high GHG emission reduction targets. In order to contribute towards the long-term goal of pertaining the temperature well below 2 °C of the Paris agreement, the study analyzed the macroeconomic effects of imposing more stringent GHG reduction targets beyond 2030 besides the emission reduction targets of 20 to 25% that are indicated by the Thai NDCs. Studies suggest that the soonest possible attainment of the global peak in GHG emissions is necessary to achieve the long-term temperature goal in order to reduce the intensity of mitigation efforts that would be required due to a delayed peak [35]. This analysis showed that by imposing the GHG reduction targets of ERT20–90 and ERT25–90 during 2030 to 2050, there is a possibility for Thailand to attain an emissions peak in 2030 that would be compatible with the stringent target of maintaining the temperature at or below 2 °C. In order to obtain 50% of GHG reductions by 2030 as that compared to the BAU, the possibility of achieving emissions peak for Thailand could even be earlier in 2020 under the higher reduction targets of ERT50–90. However, Thailand should put more effort in mitigation actions to achieve peak emissions by 2030.

Lowering the activity level of the energy-intensive industries, improving end-use energy efficiency, switching fuel, deploying CCS technologies in the power and industrial sectors, and expanding renewable energy-based technologies are identified to be important mitigation measures for Thailand in attaining such an emissions peak. The sensitivity analysis undertaken as a part of this study shows that

Table 4 Variations in export and import relative to BAU scenario

Scenarios	Export (%)		Import (%)	
	2030	2050	2030	2050
ERT20	−4.6	−8.1	−5.5	−9.8
ERT25	−5.4	−9.0	−6.4	−10.8
ERT30	−6.1	−9.9	−7.4	−11.9
ERT40	−7.8	−11.8	−9.4	−14.2
ERT50	−9.6	−13.9	−11.5	−16.7
ERT20–30	−4.6	−9.9	−5.5	−11.9
ERT20–40	−4.6	−11.8	−5.5	−14.2
ERT20–50	−4.6	−13.8	−5.5	−16.6
ERT25–40	−5.4	−11.8	−6.4	−14.2
ERT25–50	−5.4	−13.9	−6.4	−16.7
ERT20–90	−4.6	39.5	−5.5	47.5
ERT25–90	−5.4	36.2	−6.4	43.5
ERT50–90	−7.6	9.7	−9.1	11.7

the expanding alternative energy technologies and shifting towards more energy-efficient technologies would bring about positive impacts in terms of lowering government consumption, welfare losses, sectoral output, and sectoral GHG emissions. The study showed that such technological changes not only accelerates abatement but would also help to counteract the GDP losses and even lower the price of GHG emissions.

This study however has several limitations. The simulation results are based on the input-output data of 2010 with 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 may be a potential option to abate GHG emissions, is not considered in this analysis. The simulation results are based on the fact of attaining the imposed level of GHG emission reduction targets in the presence of limited technological progress. In the absence of any other policy strategy besides providing a maximum GHG emission constraint, the model shows that the output reduction is the only option to reduce emissions, thereby increasing the economic costs of reaching more ambitious emission reduction targets. The analysis showed that the attainment of peak GHG emission scenarios depicted by ERT20–90, ERT25–90, and ERT50–90 would yield an excessively high GHG price in the absence of technological progress. With the technological improvement of 40% as compared to BAU, the GHG price could be lowered by 69% in ERT20–90 to 53% in ERT50–90, respectively, as compared to the same reduction scenarios without considering technological improvements. Such phenomenon of GHG price reductions have even been explained by [11].

Due to the assumptions of constant input-output coefficients, the model has limitations for shifting towards less emission intensive inputs with GHG reduction targets. As such, the ambitious GHG mitigation targets call for a substantially high level of productions from the agriculture and forestry sectors to meet the demand. However, expansion of productions from the agriculture and forestry sectors not only demands a larger area of landmass but also requires technological development to efficiently use bioenergy resources. The results also highlight that the implementation of large-scale afforestation would be necessary for carbon sequestration. However, this study does not provide limits on the availability of land, energy, and water resources. And incorporation of such limitations would definitely change the magnitude of production from the agriculture and forestry sectors to yield more realistic results. But still, this provides an insight that the agriculture and forestry sector could play a significant role in fostering GHG mitigation opportunities for Thailand. The NDCs of Thailand do not comprehensively include agriculture and forestry in their mitigation targets. As such, government should revise and formulate ambitious renewable energy goals by incorporating agriculture and forestry mitigation targets and measures in the NDC to meet higher emission reductions goal [57].

Results show the requirement of heavy output reductions from the electricity generation sector with the imposition of GHG reduction targets under the technology-constrained scenarios. The study also showed that the output reductions could be lowered by considering technological advancements. The electricity generation sector in Thailand is dominated by natural gas with a share of 65.1%, followed by coal/lignite (25.0%), renewable (9.9%), and others (0.1%) [58]. In order to reduce dependence on a single country (Myanmar) for its natural gas imports, the country has set ambitious targets to diversify its electricity generation mainly based on coal and renewables [50]. As such, adoption of CCS technologies in both the fossil fuel-fired and biomass-based power plants, along with the increment in other forms of renewable energy-based power generations would provide significant potential to lower GHG emissions from the electricity industry. However, uncertainties and challenges still remain in the wide adoption of CCS technology in both the electricity and manufacturing industries, and in power quality instability of using significant amount of renewable energy-based electricity generation [30].

The cost of mitigation and macroeconomic loss could be lowered by maintaining a clear communication between the government and the private sector which would help in rapid penetration of renewable energy and energy-efficient technologies, thereby stimulating private sector investments [33]. The abilities to implement GHG mitigation measures could be enhanced through international support in the form of finance, technology transfer, capacity building, and raising awareness and adaptation related to climate change.

Conclusions

The simulation analysis using a dynamic recursive CGE model indicated that Thailand should increase its share of energy-efficient technologies and renewable energy options more extensively to achieve a 90% reduction in GHG emissions by 2050. This study found that in the absence of transformative structural and technological changes, more stringent GHG emission reduction targets would impose more challenges to the energy and economic systems of the country and would lead to greater GDP and welfare losses compared to the BAU scenario. In particular, such targets would cause a decline in the final consumption of households causing subsequent effects in the economic development of the country. The absence of any policy strategy besides imposing a maximum GHG emissions goal would cause a decline in the production output, especially from the carbon intensive industries such as coal and lignite mining, petroleum refineries, gas industries, electricity, transport, and industry sectors.

Being carbon intensive, the GHG emission reduction targets would cause a deep decline in the emission shares of the electricity and industry sectors. Despite the economic loss, the Thai economy would experience an improved GHG emission intensity in the GHG emission reduction scenarios as compared to the BAU. However, an appropriate energy policy plan with the effective deployment of renewable energy (such as biofuels, biomass, solar, wind), CCS-based technologies, and energy-efficient options could lessen the challenges of macroeconomic loss and even help to overcome the GHG price distortions. As Thailand is heading towards diversifying the power sector with the development of more coal-fired-based power plants, it becomes important to consider technologies like CCS to minimize the impacts of severe GHG emission reduction targets on the economy. The study showed that the BECCS and afforestation could act as the major mitigation measures for attaining negative GHG emissions to achieve the global climate goal.

As the development and deployment of renewable energy and energy-efficient technologies could play an important role in minimizing both the total GHG emissions as well as the macroeconomic loss of the country, extensive research and development should be prioritized for the possible increment in the energy efficiency and reliability of such technologies in both the demand as well as the supply sides. Overall, this study indicated that the attainment of the most stringent GHG mitigation target would be very challenging for Thailand without transformative changes in its economic structure and energy systems. In this sense, it is essential for Thailand to formulate strong visions and plans for a low-carbon society that uses resources and technologies more efficiently, thus fostering sustainable development.

Abbreviations
BAU: Business as usual; BECCS: Bioenergy with carbon capture and storage; CAGR: Compound annual growth rate; CCS: Carbon capture and storage; CES: Constant elasticity of substitution; CET: Constant elasticity of transformation; CGE: Computable General Equilibrium; CH_4: Methane; CO_2: Carbon dioxide; ERT: Emission reduction targets; GDP: Gross domestic product; GHG: Greenhouse gas; I/O: Input-output; N_2O: Nitrous oxide; NDCs: Nationally Determined Contributions

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Availability of data and materials
This study relied on the socioeconomic and energy data provided by the Thai governmental sources and various other national/international literatures. All data used in this study are publicly available online. The information on the sources of data are provided in the references.

Authors' contributions
SR conceived the study, collected the data, conducted the model run, analyzed the results, and wrote the manuscript. BL supervised this study, contributed to the critical reading of the manuscript, and provided input for the final version. TM contributed in model formulation, concept, and design. All authors read and approved the final manuscript.

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
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Author details
[1]School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani 12120, Thailand. [2]Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan.

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