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Thailand's mid-century greenhouse gas emission pathways to achieve the 2 degrees Celsius target

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Abstract

Background: The Paris Agreement aims at minimizing threats of climate change by keeping global temperature rise well below 2 degrees Celsius above the pre-industrial level and to pursue efforts to limit the rise to 1.5 degrees Celsius. The Representative Concentration Pathways (RCPs) are developed to investigate GHG emission pathways. RCP2.6 focuses on limiting the global temperature rise to less than 2 degrees Celsius. This paper assesses the impacts of carbon price and CCS on energy and GHG emissions in Thailand. The no carbon price (T0) and the carbon price pathways are compared. In addition, the net-zero emissions and year are discussed.

Results: The decarbonized energy system with low-carbon power generation and increased electricity usage in the final energy consumption is the main pillar of GHG mitigation. Imposing carbon prices; increasing solar, wind, and biomass electricity generation; energy efficiency improvements in power generation; and energy savings in the industry and the building sectors, will be the key options for clean power generation in the carbon prices (CT) scenarios. Renewable electricity, coal and natural gas, coupled with CCS and bio-energy with CCS (BECCS) will be utilized significantly to curb GHG emissions. The increase of renewable energy and the electrification of end-use plays a key role in reducing GHG emissions. Fuel switching from diesel to biodiesel, energy efficiency improvement and electric pick-ups and trucks will help reducing GHG emissions in the transport sector.

Conclusions: There are three major policy implications to meet Thailand's 2 degrees Celsius target. First, carbon prices will be the mechanism to accelerate the transformation in the energy sector. Wind and solar electricity will be key pillars of clean electricity in 2050. Policy-makers should update the renewable electricity plans to meet Thailand's 2 degrees Celsius target in 2050. Second, coal- and gas-fired plants, and BECCS will become important options in reducing CO_2 emissions. The policy-makers should investigate the application of CCS in the power sector and the storage location. Third, a major transformation in the transport sector is critically needed. Liquid biofuel and electrification in pick-ups, sedans, and trucks will help reduce GHG emissions.

Keywords: GHG mitigation, 2 Degrees Celsius target, AIM/Enduse, Carbon prices, Carbon capture and storage, Shared socio-economic pathways, Thailand

Background

The Paris Agreement aims to reinforce the global response to threats of climate change by holding the global temperature rise well below 2 degrees Celsius above the pre-industrial level and pursuing efforts to limit the rise to 1.5 degrees Celsius [1]. To achieve these targets, parties under the agreement submitted their

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Nationally Determined Contributions (NDCs) by preparing the post-2020 climate action plan [2]. Thailand signed and ratified the Paris Agreement in 2016. In the fifth assessment report (AR5), the Representative Concentration Pathways (RCPs) are used to assess GHG emission pathways and atmospheric concentrations [3]. The RCPs consist of four radiative forcing levels, namely, 8.5 W/m^2 (RCP8.5), 6.0 W/m^2 (RCP6.0), 4.5 W/m^2 (RCP4.5) and 2.6 W/m^2 (RCP2.6). RCP 2.6 focuses on limiting the global temperature rise to below 2 degrees Celsius compared to the pre-industrial level [3]. In the RCP2.6 scenario, energy efficiency improvement, renewable energy and nuclear share expansion, and bio-energy with carbon capture storage (BECCS) play a vital role in reducing global GHG emissions [4]. To cover the possibility for mitigation and the adaptation influence over our environment and society, the scientific community developed a two-dimensional scenario between the RCPs and Shared Socio-economic Pathways (SSPs) [5]. Five SSPs have been developed to elucidate the possible future society through relevant indicators including demographics, human development, economics and lifestyle, policies and institutions, technology, and environmental and natural resources [6]. These scenarios are SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequity), and SSP5 (fossil-fueled development) [7–11]. However, to keep the temperature rise below 2 degrees Celsius, as in the case of RCP2.6 with different SSPs, carbon prices are needed to achieve the target. For Thailand, the RCP scenarios should consider both the feasibility and the social situation.

Carbon pricing is a market-based mechanism. It often refers to a carbon tax or carbon emission trading. The aim of carbon pricing is to put a monetary value on carbon emissions. Economists set a carbon price to reduce the emissions. The carbon price is the most efficient tool to reduce domestic fossil fuel CO_2 emissions [12]. The price is charged to CO_2 contributors. This charge is the amount payable for the right to emit a ton of CO_2 [13]. Carbon tax and carbon emission trading are both optional and complementary [14].

Carbon tax is an environmental tax levied on production or service activities, whereas carbon emission trading sets a CO_2 emission level for buying or selling the right to emission level at a particular price. To mitigate GHG emissions, efficient technologies such as EV, hydrogen and CCS are the main drivers. However, carbon prices are intended to induce the kind of technological progress that can bring down future abatement costs [15].

Many countries have implemented carbon pricing initiatives. In 2019, Mexico and Japan applied the carbon tax at 1–3 US$/ton CO_2, while Sweden and European Union countries (EUs) used 127 US$/ton CO_2. In order to achieve the 2 degrees Celsius target, the carbon price should be 75 US$/ton CO_2 in 2030 [12]. Without consensus to raise the carbon price to the necessary level, other less-effective instruments should complement carbon pricing to reduce domestic fossil fuel CO_2 emissions [12]. The terms carbon price and carbon tax are interchangeably used in this study.

To achieve the 2 degrees Celsius target, this paper assessed the impacts of carbon price and CCS on energy and GHG emissions in Thailand. A comparison of no carbon price (T0) and the carbon price pathways is carried out. In addition, the net-zero emissions years are discussed.

Overview of low-carbon emissions in Asia and Thailand

Collectively, Asian countries emitted 38% of total world GHG emissions in 2005. Due to economic development and lifestyle change, the emissions are expected to increase over time [16]. Mitigation actions are required to curb the emissions by the end of this century. In addition, GHG mitigation policies should be based on a country's domestic conditions [16]. There have been several research studies on Asia's low-carbon pathways [17–20]. Energy efficiency and low-carbon electricity generation, together with behavioral change, can reduce energy consumption and GHG emissions in Vietnam [20]. In 2025, the GHG emissions in Malaysia could be reduced by 40% from increased use of renewable electricity and energy efficiency improvement on the demand side [21]. China can achieve the stringent GHG emissions reduction targets by accelerating the pace of renewable energy in the primary energy mix [18]. In Japan, renewable energy could play a key role in a decarbonized energy system and climate change mitigation [19]. In addition, the expansion of bio-energy with CCS and energy saving in the demand-side sectors can achieve the net-zero emission target by 2050; however, the carbon price should be considered at 2000 US$ per ton of CO_2 [22].

There are some studies related to Thailand's low-carbon society and its impacts on the economy. Renewable energy use can be expanded in the industry and transport sectors [23]. Moreover, CO_2 reduction potential in Thai industry was investigated to achieve low-carbon pathways [24]. The Thai power sector has also been examined for possible low-carbon measures including CCS technology [25]. In the Thai building sector, efficient appliances, insulated houses, and building codes could reduce CO_2 emissions by 35% by 2050 [26]. The national energy efficiency plan (EEP2015) and alternative energy development plan (AEDP2015) are sufficient to meet the emissions reduction by 2030 as stated in the national NDC [27]. Biogas and CCS are key technologies to mitigate

CO_2 emissions in the residential and the industry sectors [27].

Based on several researches, the carbon prices would be fixed during the study period [28–30]. [28] set the constant carbon taxes ranging from 25 to 1000 US$/ton CO_2 during 2020–2050. [29] considered an emission tax regime, where uniform and constant emission taxes ranged from 50 to 500 US$/ton CO_2.

To achieve the Paris Agreement target, an increase in carbon prices should be considered in reducing the GHG mitigation. This study assesses the impacts of carbon price and CCS on energy and GHG emissions in Thailand. No carbon price (T0) and carbon price pathways are applied to the Thai energy system. In addition, the net-zero GHG emissions' date is investigated to be in-line with the Thailand Carbon Neutrality target as announced in COP26.

Methods

This section provides the methodology, including the conceptual framework of the AIM/Enduse model and the assumptions used in analyses. Moreover, the scenario description is elucidated.

Conceptual framework of the AIM/Enduse model

The Asia–Pacific Integrated Assessment model/Enduse (AIM/Enduse) is a bottom-up model that relies on a framework of linear programming based on the General Algebraic Modeling System (GAMS) which is a high-level modeling system for mathematical programming problems [31]. The AIM/Enduse model is a partial equilibrium model which selects the combination of technological frameworks inside an energy and environment system for medium to long-term assessment [31]. It was developed by the National Institute for Environmental Studies (NIES), Kyoto University, the Mizuho Information & Research Institute, and several research institutes in the Asia–Pacific region [19]. The selected technologies are assessed by using a linear optimization framework. The objective function of the model is to minimize the total system cost. In addition, several constraints can be included in the optimization process for satisfying service demand growth, analyzing maximum share of technology diffusion, preparing energy resources, reducing pollutant emission, ensuring equipment stock and so on [31–33]. The AIM/Enduse model is a recursive dynamic model used to solve the problem for multiple years. It can analyze the time-series optimized results under various scenarios, including policy packages in each sector [34, 35]. The model considers the balance between the supply and demand sides. The supply side and demand side interact by using the equation of total service demand and supply balance in the AIM/Enduse model. The total service demand must not exceed the total service output supplied (see the equations in Additional file 1).

The model structure primarily consists of three components including "Energy", "Energy Technology", and "Energy Service" (as shown in Fig. 1) [31]. "Energy

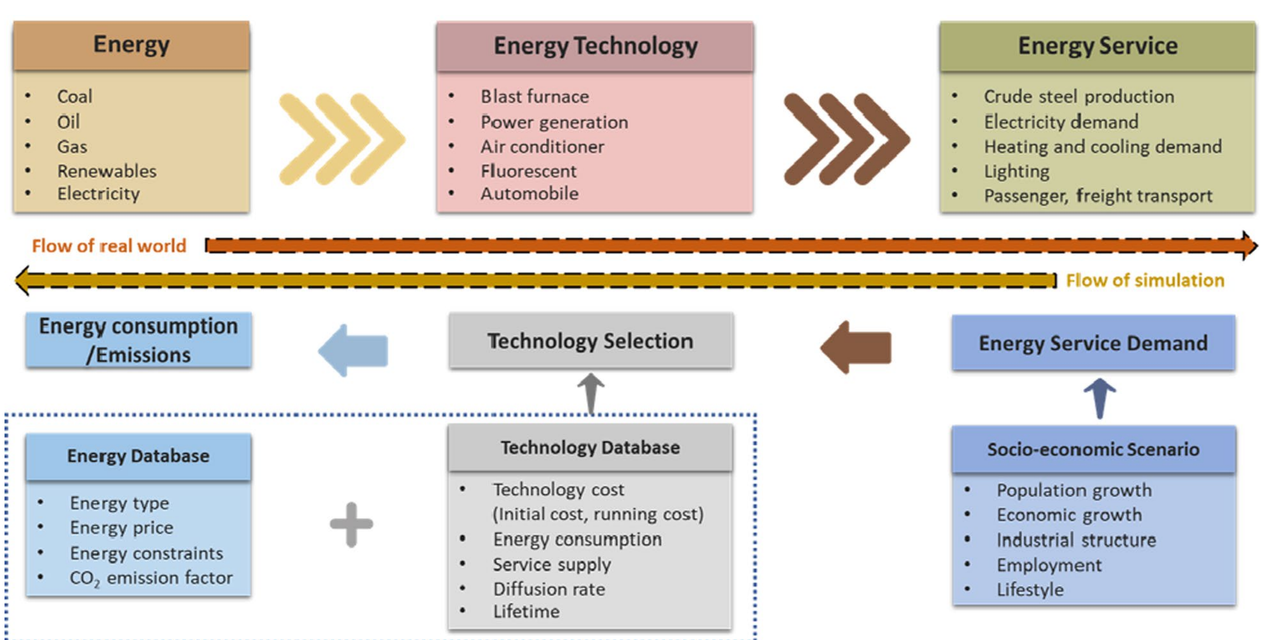

Fig. 1 Structure of AIM/Enduse model

Technology" refers to a device that provides useful "Energy Services" by consuming "Energy". The "Energy" information consists of fuel types and fuel prices as well as designated emission factors to determine the emissions. "Energy Technology" considers the details of the technologies such as capital cost, fixed and variable cost, efficiency or energy consumption per output unit, and lifetime. The energy service demands are determined exogenously from external sources. The AIM/Enduse model calculates energy consumption from the amount of specific energy consumed by each technology and the combination of technologies. Emissions are determined from energy consumption and emission factors of fuel types. In addition, the model can analyze impacts of fuel switching, energy savings, emission mitigation, and fuel diversification.

Thailand's AIM/Enduse model

The structure of the AIM/Enduse model covers both the demand and supply side which can be connected by the concept of internal services and energy sources in the model. The energy service of the power sector in the supply side can be linked to the energy component of devices in the demand sector [26]. The linkage between the supply side or the power sector and the demand side is illustrated in Fig. 2.

The structure of energy supply for power generation particularly relies on fossil fuel, for example, natural gas, coal, and oil. Renewable energy resources in the energy supply include biomass, biogas, hydropower, solar and wind. The conventional generating technologies in the baseline model include the combined cycle and thermal power plants. The cogeneration capacity will be increasing in the future plan [36–38]. The current policies have included promotion of capital-intensive renewable energies for power generation such as solar, wind and biomass; they are integrated into the model along with the continuing development of existing hydro-power projects [37–39]. To promote low-carbon electricity generation, the integrated gasification combine cycle (IGCC) and supercritical power plants are required. Similar to the clean technologies, carbon capture storage (CCS) is the alternative technology to mitigate CO_2 emissions.

Electricity production from various generation technologies should be integrated with other energy sources to provide a sufficient final energy supply for service appliances in the demand-side sectors (see Fig. 2). The demand-side sectors include the residential and commercial building, industrial, and transportation sectors. These sectors have various final energy consumption types such as liquefied petroleum gas (LPG) in the building sector, natural gas and coal in the industrial sector, and gasoline and diesel in the transportation sector. Furthermore, renewable energies such as biomass, charcoal, and agricultural wastes are consumed in the demand-side sector. For example, fuel wood, charcoal and paddy husk are supplied for traditional stoves in Thailand's rural households [36]. In the development of low-carbon Thailand, energy efficiency improvement and renewable energy are the important measures to reduce energy consumption and mitigate emissions. Several types of services are categorized in terms of quantitative demand for various appliances in the sector such as space cooling, lighting, heating, etc.

SSPs of Thailand

Based on the characteristics of an SSP, a number of possible elements have been concluded [40]. The socio-economic information, a combination of social and economic concepts, is the key factor used in evaluation of the SSPs situation in Thailand.

Demographics

Thailand's population increased from 59.46 million in 1995 to 66.19 million in 2017 with an average annual growth rate (AAGR) of 0.49% [41]. The Office of the National Economic and Social Development Council (NESDC) [42] projected the population for Thailand during 2010–2040 to increase at an AAGR of 0.08%. The population will increase until 2028 and then decrease until 2040 [42].

In the SSPs database, Thailand's population has been estimated in various SSP situations including SSP1, SSP2, SSP3, SSP4, and SSP5 [43]. When assessing the population in the SSP situations, the population in SPP1, SSP2, SSP4 and SSP5 will decrease with AAGRs of 0.179% 0.282%, 0.137%, and 0.253%, respectively, during 2010–2040. The population in SSP3 has increased and will continue to increase until 2040. The population pattern in SSP4 is similar to Thailand's population projected by NESDC. However, the decreasing population projected by NESDC occurs more rapidly than the population decrease in the SSP4 situation.

Economic development

The GDP is a driving socio-economic indicator for tracking economic development. Thailand's GDP increased from 237.88 billion US$ in 1990 to 722.27 billion US$ in 2017 with an AAGR of 4.20% per year [44]. In this paper, the GDP projection during 2018–2036 was employed, which is consistent with the GDP used by the Energy Policy and Planning Office (EPPO) [37]. The estimated GDP will increase to 1512.92 billion US$ in 2036. The AAGR during 2017–2036 will be 3.97%. Manufacturing industries have the highest share in the GDP followed by wholesale and retail trades, financial and insurance

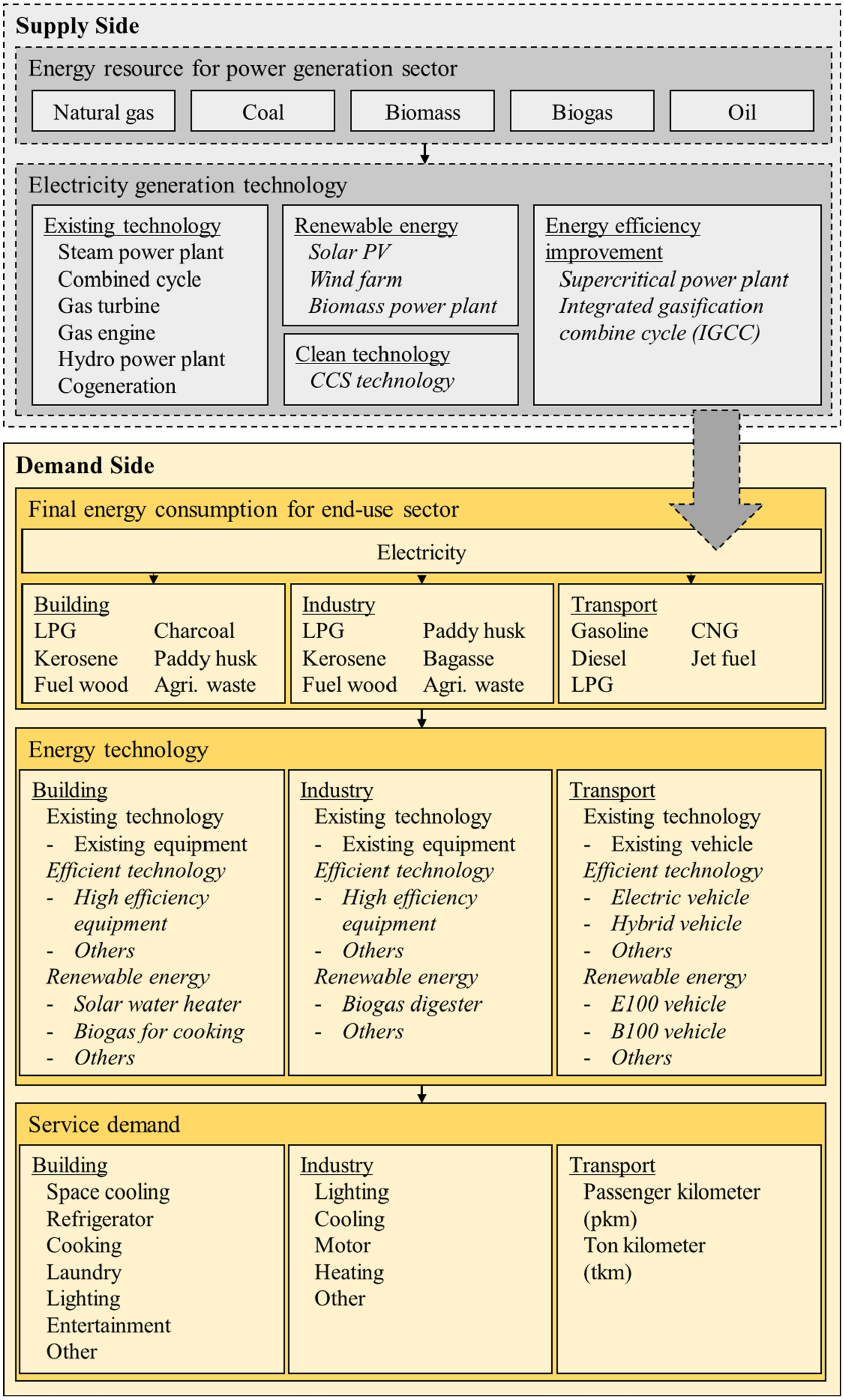

Fig. 2 Structure of Thailand's AIM/Enduse model

activities, and transportation. Half of the Thailand's GDP share is in the Greater Bangkok area followed by the Eastern area, the Northeastern area, and the Southern area. The Western area of Thailand has the smallest share of GDP of 3.00% [44].

The GDP of Thailand has been estimated under various SSP situations including SSP1, SSP2, SSP3, SSP4, and SSP5 [43]. The AAGR of estimated GDP in the SSP situations are 4.91% in SSP1, 4.21% in SSP2, 3.26% in SSP3, 3.91% in SSP4 and 5.61% in SSP5, respectively, during 2015–2040. The GDP estimated by NESDC and the GDP in the SSPs increase at different rates [43, 44].

The proportion of poverty in Thailand is one of the indicators for considering SSP situations. Like many other countries in the East Asia Pacific, Thailand has been successful in reducing poverty over the last few decades. From 2007, the number of poor people in Thailand decreased from 20.0% to 8.6% in 2016, a rate of 9.0% per year [45]. Moreover, Thailand's household poverty diminished from 3.5 million households in 2007 to 1.7 million households in 2016 with an AAGR of 7.7% [45]. Most of the household poverty is located in rural areas where it accounts for 60.3% of total household poverty in Thailand.

Welfare

Education in Thailand is provided mainly by the Thai government through the Ministry of Education from pre-school to senior high school. In 2016, the budget for education in Thailand was about 3.9% of GDP and 20.2% of national budget [46]. However, the education budget in 2016 was higher than the education budget in 2010 by almost 1.34 times [47]. Equal access to education is an important problem and is a result of the income gaps [48]. The issues that lead to discrimination include disability and education level. There are various factors affecting people's opportunities to access education, such as the inequality of income and property, the dissatisfaction with education, gender, age and location [48].

The government of Thailand has established the National Health Security Office (NHSO) for covering and accessing public health with confidence. Everyone who lives in Thailand has been provided health insurance from the government since 2002. The budget for public health was 10.08% of the national budget in 2016 [49]. The public health insurance covers 99.0% of people in Thailand [50].

Technological development

Thailand's research and development (R&D) budget increased from 2005 to 2016 with an AAGR of 19.06% [51]. The R&D budgets were derived from other sources (79.41% of the budget) such as the private sector; only 20.59% of the budget came from the national budget in 2016 [51]. Besides the development of domestic technology, the technological development needs support from developed countries, such as the Joint Crediting Mechanism (JCM) project between Japan and Thailand. The JCM facilitates diffusion of leading low-carbon technologies, products, systems, services, and infrastructure as well as implementation of mitigation actions, and contributes to sustainable development of developing countries. The JCM contributes to the ultimate objective of the UNFCCC by facilitating global actions for GHG emission reduction or removal [52, 53].

The projected socio-economic indicators are population and GDP. The SSP4 is close to the situation of Thailand's current socio-economics. Based on the SSP analysis, Thailand's current socio-economic situation is under the SSP4 narrative or inequality situation. It is implied that Thailand faces a medium socio-economic challenge for mitigation and a high socio-economic challenge for adaptation.

Scenario description

Key scenarios are considered in this study, including a business-as-usual scenario (BAU), carbon prices without CCS scenarios (CT) and carbon prices with CCS scenarios (CT_CCS). The CT and CT_CCS scenarios adopted in this study have been based on the considerations of the effect of carbon prices on energy intensive sectors (especially in the power sector and the industrial sector). Besides the BAU scenario, the CT and CT_CCS scenarios include four carbon prices pathways. The details of the scenarios are given below.

Business-as-usual scenario (BAU)

In this study, the GHG emissions in the BAU scenario follow the emission trend in the updated national GHG emissions inventory [54]. In the BAU scenario, carbon prices and CCS technology are not considered. In the power sector, electricity generation from renewable energy is about 5% of the total electricity generation mix. In the transport sector, the technology mix shows that vehicles using biofuels will be limited to a share of 35% in 2050. Electricity and LPG are the major energy consumption in the residential and commercial sectors, accounting for 50% of energy consumption in those sectors. In the industries, the efficient technologies such as efficient motors and boilers are considered in the end-use services.

The selected technologies in the countermeasure scenarios, including the CT and CT_CCS scenarios, depend on a linear optimization framework where system costs are minimized under constraints. System costs include the initial costs, the operating costs of technologies, energy costs, taxes and subsidies, etc. (see Additional file 1). The reduction of technology cost is also considered in this study; the costs of wind turbines and solar PV in 2050 are assumed to be 40% of the cost in 2005. In this study, the carbon price will accelerate the adoption of low-carbon technologies.

Carbon prices without CCS in the CT scenario

Various studies selected the SSPs for their analysis [22, 55–57]. Oshiro et al. [22] considered the socio-economic conditions by considering the SSP2 scenario for attaining the net-zero emissions pathway by 2050 in Japan. The fossil-fueled development scenario or SSP5 is considered in the Nepal study [55]. Pradhan et al. [55] analyzed the emission reduction target with the carbon price profiles under SSP5 during 2015–2050. Adib et al. [57] assessed the future rainfall pattern considering climate change in Malaysia in the SSP1-2.6, the SSP2-4.5, and the SSP5-8.5 scenarios during 2021–2080.

Out of the five SSPs, the SSP5 is the least environmentally friendly pathway. The scenario relies on the fossil fuel development. The carbon prices profile in SSP5 to achieve the RCP2.6 are high. However, SSP5 is not inline with Thailand's situation. The renewable energy and low-carbon technologies have revealed a tremendous progress in Thailand. Thus, SSP4 is considered to be the pathway for Thailand to achieve the 2 degrees Celsius target [58]. Final energy demand is moderately coupled to economic activity, which results in large disparities in energy consumption because of slow income convergence [59].

In this study, population and GDP are considered from Thailand's government policy/plan for envisaging the service demand in the AIM/Enduse model. The carbon price profiles in SSP4 for achieving RCP2.6 are considered to analyze the effects on Thailand's energy system. The change of future service demands following the socio-economic information of all SSPs is a limitation in this study. Besides, the study time frame is limited to the period 2005–2050 due to the limit of the AIM/Enduse model for the long-term technology selection.

The CT scenarios simulate GHG mitigation by using the carbon prices. The scenarios have been mitigated according to the renewable energy technology, efficiency improvements, advance technologies, and fuel switching during 2020–2050. In the CT scenarios, various carbon prices are considered, including zero (T0) and four different carbon prices pathways under the SSP4 scenario for RCP2.6 [5].

Several studies suggest that the carbon price for achieving specific climate targets will significantly differ across models and scenarios [5, 60–62]. The carbon prices in this study were obtained from the database of SSPs [5, 43]. Four carbon price profiles were obtained from Asia–Pacific Integrated Model/Computable General Equilibrium (AIM/CGE), Global Change Assessment model (GCAM), Integrated Model to Assess the Global Environment (IMAGE), and World Induced Technical Change Hybrid model (WITCH). Hereafter, the CT scenarios are referred to as the AIMC, the GCAM, the IMAGE, and the WITCH scenarios. The carbon prices trajectories are shown in Fig. 3.

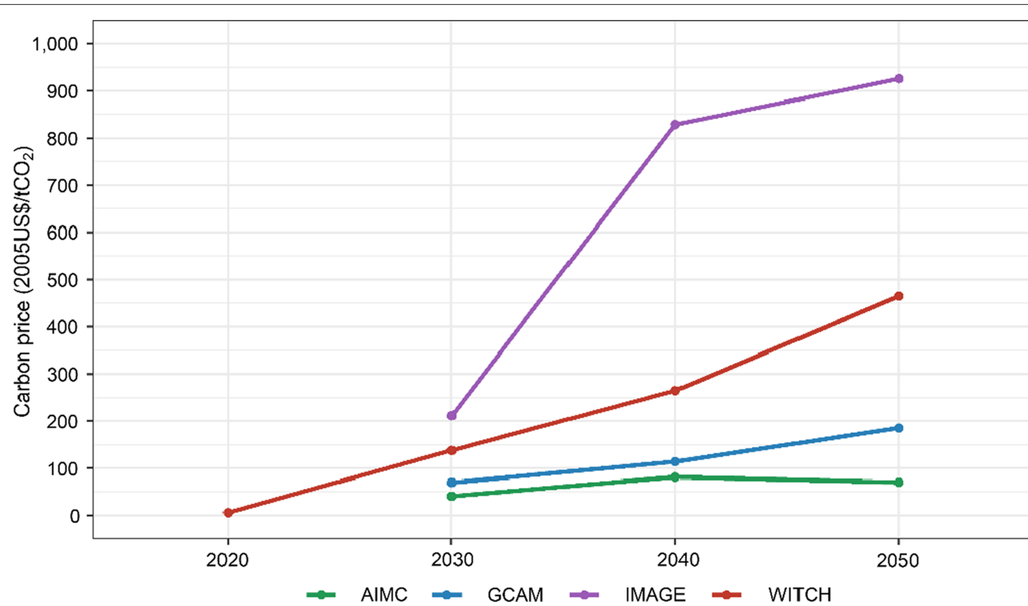

Fig. 3 Carbon prices trajectories considered in the CT and CT_CCS scenarios

Carbon prices with CCS in the CT_CCS scenario

Various literature emphasizes that the deployment of CCS is necessary to achieve the targets [63–67]. The IPCC Fifth Assessment report (AR5) concluded that if bio-energy, CCS, and BECCS are limited, keeping warming to below 2 degrees Celsius cannot be achieved [3]. However, the CCS technologies could be cost-competitive with other low-carbon technologies by 2030 [68]. The CCS technologies consider both fossil fuel and bio-energy based power plants in the CT_CCS scenario with the share setting of CCS technologies ranging from 15 to 30% during 2030–2050. The carbon prices in this scenario are the same as in the CT scenarios. Table 1 summarizes the constructed scenarios for considering Thailand's 2 degrees Celsius target.

Table 1 Thailand's 2 degrees Celsius scenarios

Scenario	Low-carbon technology		Carbon prices in 2050 (2005 US$/ton CO_2)
	RE	CCS	
BAU	*		0
CT			
T0			0
AIMC			70.1
GCAM			185.5
IMAGE			925.4
WITCH			464.8
CT_CCS			
T0_CCS			0
AIMC_CCS			70.1
GCAM_CCS			185.5
IMAGE_CCS			925.4
WITCH_CCS			464.8

*The shares of RE and technology follow the historical patterns from 2005 to 2050

CO_2 removals by sinks

This study considers the CO_2 removal by forestry areas. The calculation of CO_2 sink follows the IPCC guideline. Land use, land use change and forest (LULUCF) in this study were divided into three categories: changes in forest and other wood biomass stocks, forest and grassland conversion, and abandonment of managed land [69, 70]. The Royal Forest Department (RFD) of Thailand announced that total forest areas will be 40% by 2026 [71, 72].

The RFD projected that the economic forest area will increase to 15% of the country's total area in 2026. However, this study assumes that the 15–level will be reached in 2030. The economic forest area is estimated by using the linear interpolation from 2013 to 2030. The economic forest area will be 77,646.9 km^2 in 2030. It was assumed that the area will be constant towards 2050. The estimated areas are assumed to be constant from 2030 onwards due to land limitations. Figure 4 shows the CO_2 removal by sinks in this study. Total annual CO_2 removal by sinks will be 187 MtCO_2 in 2050. The cumulative CO_2 removal by sinks will be 2.7 GtCO_2, during 2010–2030 and 6.4 GtCO_2 during 2010–2050, respectively.

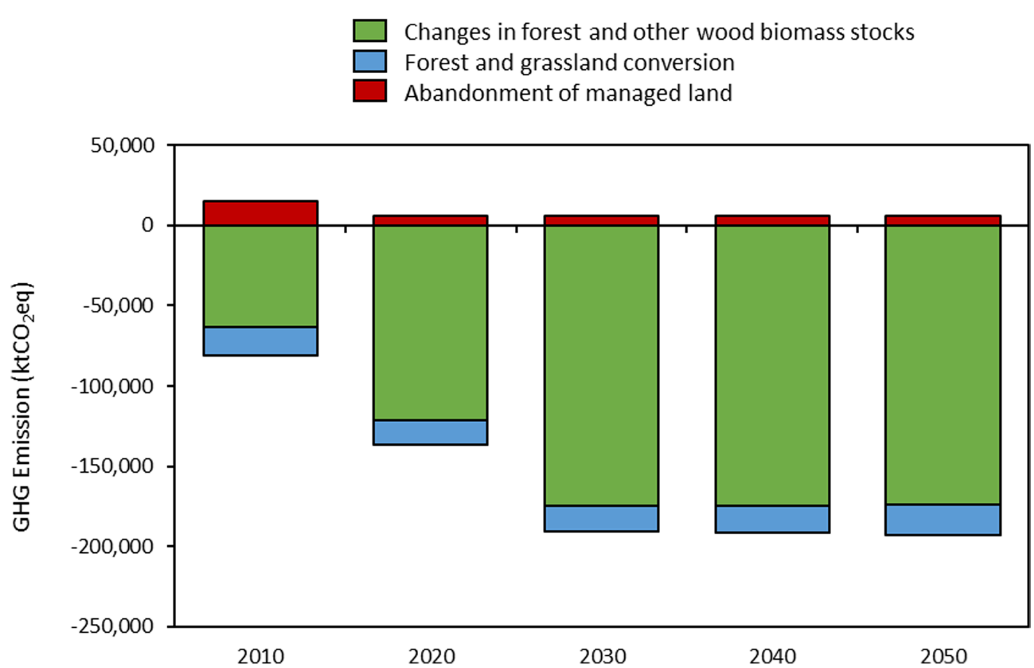

Fig. 4 CO_2 removals by sinks in selected years

Results

GHG emissions

Figure 5 illustrates the GHG emissions trajectory in the energy sector. In the BAU scenario, GHG emissions show a marked increase. The GHG emissions will reach 818.8 $MtCO_2eq$ in 2050, approximately 3.7 times higher than emissions in 2015 (see Fig. 5a). The power sector dominates the GHG emissions in the energy system. In 2050, the power sector will account for 52.9% of total GHG emissions, followed by the industry (27.4%),

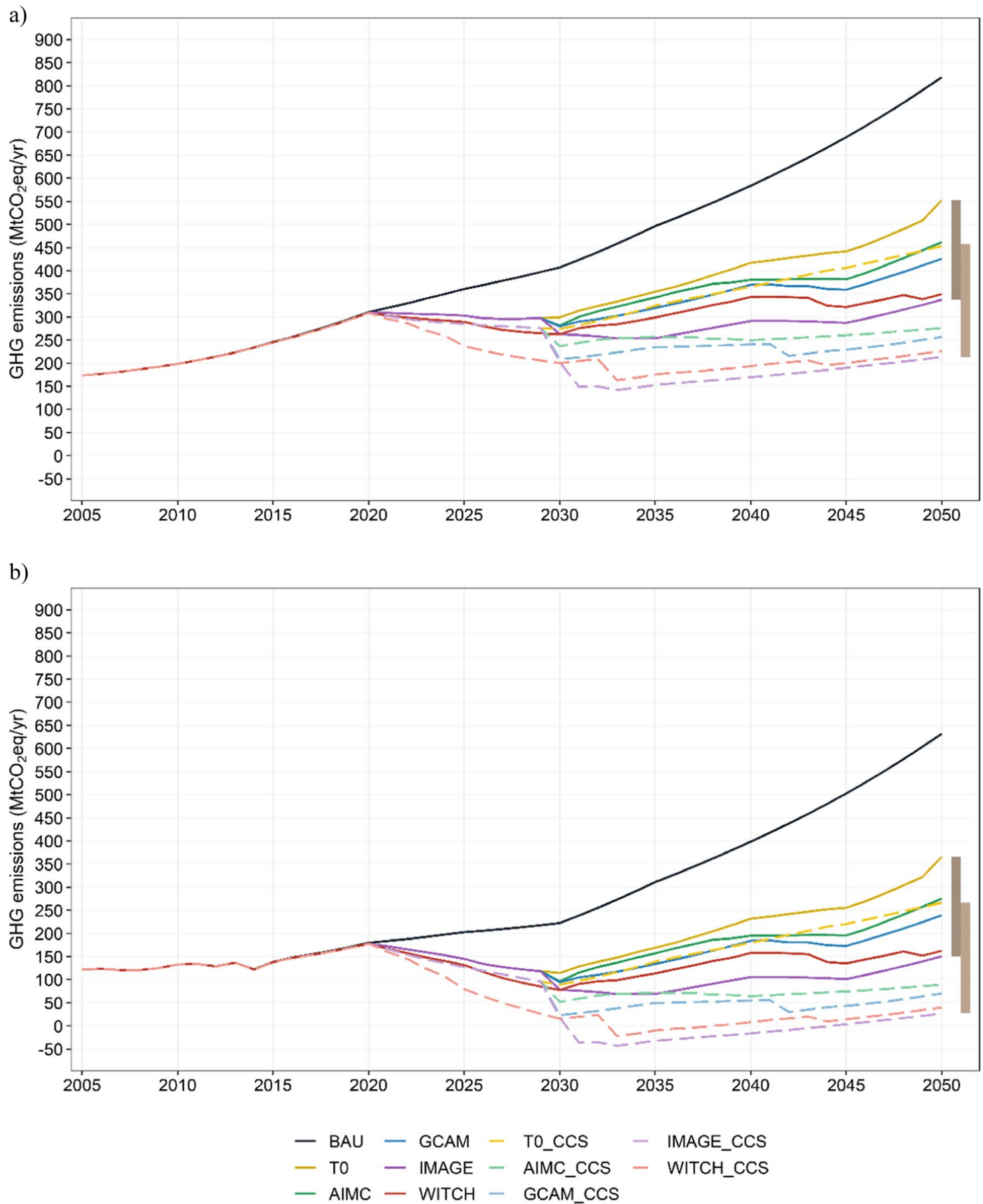

Fig. 5 Thailand GHG emissions pathways **a** excluding removals from LULUCF sector and **b** including removals from LULUCF sector

transport (14.6%), and building (5%) sectors. The GHG emissions in the power sector mainly come from natural gas power plants. In 2050, emissions from natural gas will be 61% of GHG emissions in the power sector followed by coal (35%). In 2050, the fuel combustion in the non-metallic sub-industry will be the main source of GHG emissions in the industry sector. In the transport sector, pick-ups and trucks will be the major GHG emission contributors in 2050. The cumulative GHG emissions during the period 2015–2050 in the BAU scenario will be 17,385.0 $MtCO_2eq$.

The GHG emissions in CT scenarios have been significantly decreased since 2020. In the CT scenarios, the IMAGE scenario will play a significant role in reducing GHG emissions by 58.8% compared to the BAU level in 2050 (see Fig. 5a), while the emissions in the no tax scenario (T0) will be reduced by only 32.5% in 2050. During 2015–2050, the cumulative GHG emissions will be in the range of 10,321.8–12,151.9 $MtCO_2eq$.

The deployment of CCS will significantly reduce CO_2 emissions in CT-CCS scenarios. In 2050, the GHG emissions in the IMAGE_CCS scenario will be reduced by 73.9%, followed by the WITCH_CCS (72.3%), the GCAM_CCS (68.6%) and the AIMC_CCS (66.3%) compared with the BAU scenario (see Fig. 5a). The GHG emissions in the T0_CCS scenario will be reduced by 44.6% compared with the BAU scenario in 2050. The cumulative GHG emissions over the period 2015–2050 will range from 7917.0 to 9628.2 $MtCO_2eq$.

In 2050, the GHG emissions will range from 337.4 to 552.9 in the CT scenario and 213.7–453.4 $MtCO_2eq$ in the CT_CCS scenario (see Fig. 5a). The IMAGE and IMAGE_CCS scenarios show the highest GHG reduction because the high carbon price at 925.4 US$/$tCO_2$ will result in fuel switching to low-carbon fuels and technological shifting to cleaner technologies. In the emission removals by sinks, the forestry sector will reduce the CO_2 emission by 187.0 $MtCO_2$ in 2050 [28]. The net GHG emissions in all scenarios cannot achieve net-zero GHG emission in 2050. The remaining GHG emissions will range from 150.7 to 366.2 $MtCO_2eq$ in the CT scenario and 26.9–266.7 $MtCO_2eq$ in the CT_CCS scenarios in 2050. However, net-zero GHG emissions will be possible to achieve after 2050 in the IMAGE_CCS and the WITCH_CCS scenarios (see Fig. 5b). To meet the net-zero CO_2 emission in 2050, deep decarbonization will be needed. This study suggests that the carbon price should be increased in the period 2030–2050. The carbon price will reach 1500 US$/$tCO_2$ by 2050.

a) Thailand's GHG emission pathways (excluding removals from the LULUCF sector)

b) Thailand's net GHG emission pathways (including removals from the LULUCF sector)

Impacts of carbon prices on the sectoral GHG emissions

Figure 6 shows the sectoral GHG emissions in 2050. The carbon prices in the CT scenarios can reduce GHG emissions in all sectors, but in particular the power and the industry sectors. In the power sector, the GHG emissions will reduce by more than 50% in CT scenarios compared with the BAU level in 2050. In the BAU scenario, coal and natural gas power plants will play key roles in electricity generation. In the power sector, the carbon intensity will increase from 567 g of CO_2 per kilowatt-hour (gCO_2/kWh) in 2015 to 575 gCO_2/kWh in 2050 due to natural gas and coal consumption.

The decarbonized energy system with low-carbon power generation and increased electricity usage in the final energy consumption is the main pillar of GHG mitigation. In 2050, the carbon intensity will be reduced to 340 gCO_2/kWh and 264 gCO_2/kWh in the T0 and the AIMC scenarios. The carbon intensity will be 67% lower in the IMAGE and WITCH scenarios compared to the BAU scenario. It is important to note that the electricity generation from coal power plants will be replaced by natural gas and renewable energy in the IMAGE and WITCH scenarios. Natural gas power plants account for 40% of total electricity generation in 2050. Wind and solar will dominate the generation mix in 2050 in the IMAGE and the WITCH scenarios, with a share of 56% of total electricity generation. In 2050, the solar electricity generation will increase from 0.3 TWh to 161–167 TWh in the IMAGE and the WITCH scenarios, while the electricity generation from wind will increase from 5 TWh in 2020 to 254–257 TWh.

The CCS technology is proposed in the CT_CCS scenarios and found to be cost effective in power generation. Due to the CCS technologies and carbon prices, GHG emissions in the power sector will be relatively low compared with the CT scenarios. Among the CT_CCS scenarios, the AIM_CCS scenario will impose the lowest carbon price (see Fig. 3). The AIM_CCS scenario shows the highest GHG emissions in 2050. These emissions will come mostly from natural gas and municipal solid waste power plants. The power sector will reach the zero CO_2 emissions in the GCAM_CCS, the IMAGE_CCS, and the WITCH_CCS scenarios (see Fig. 6). The share of coal-fired power plants will be 0.5% of generation mix in 2050. Renewable electricity, coal and natural gas coupled with CCS and BECCS will be utilized significantly to curb GHG emissions. The growth of CCS technology in the power sector will be driven by carbon prices. The fossil fuel power plant with CCS will reduce CO_2 emissions by

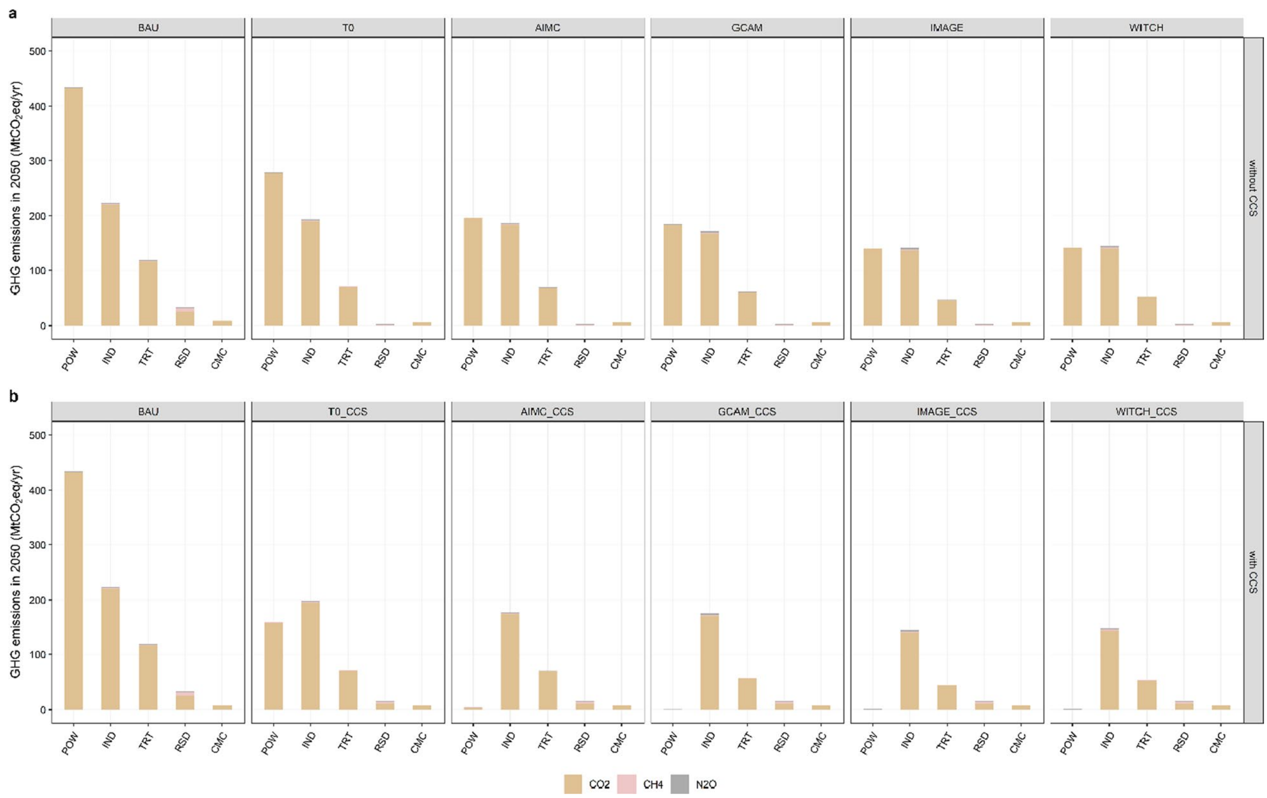

Fig. 6 GHG emissions in **a** the CT and **b** the CT_CCS scenarios in 2050

about 140–143 $MtCO_2$ in 2050. The bio-energy with CCS will provide negative emissions of 33–35 $MtCO_2$ in 2050.

The industry sector will become the largest energy related GHG emission contributor in 2050 in the WITCH, IMAGE, and CT_CCS scenarios. The GHG emissions will be reduced by 13–37% and 12–35% in the CT and the CT_CCS scenarios, respectively, compared with the BAU scenario in 2050. The non-metallic, food and beverage and chemical industries will contribute about 76% of the GHG emissions in industries in 2050. Coal used in the heating process will be the main source of GHG emissions, followed by oil. The energy efficiency improvement and fuel switching will reduce the GHG emissions from coal combustion by 14–36% and 12–34% in the CT and the CT_CCS scenarios. Due to the stringent carbon prices in the CT_CCS scenarios, CCS technology will be deployed in the non-metallic, the paper and pulp, and the chemical sub-industries from 2025 onwards.

In 2050, the GHG emissions in the transport sector will be reduced from 119 $MtCO_2eq$ in the BAU scenario to 47.3–71.2 $MtCO_2eq$ in the CT scenario and 44.0–71.3 $MtCO_2eq$ in the CT_CCS scenario. Pick-ups and trucks will dominate the GHG emissions in freight transport in all scenarios. The GHG emissions from these vehicles will account for 57–65% of total GHG emissions in the transport sector in 2050 in the CT and the CT_CCS scenarios. In 2050, fuel switching from diesel to biodiesel, energy efficiency improvement and electric pick-ups and trucks will help reduce GHG emissions in the range of 37–55% in the CT scenario and 37–60% in the CT_CCS scenario compared with the BAU scenario. The GHG emissions in the IMAGE and the IMAGE_CCS scenarios will be largely mitigated by 55% and 60%, respectively, compared with the BAU level in 2050. In 2050, sedans and vans will reduce the GHG emissions by approximately 92% in the IMAGE and the IMAGE_CCS scenarios compared with the GHG emission from sedans in the BAU scenario. The vehicles will switch from gasoline to biofuels. In 2050, electric two- and three-wheelers will reduce GHG emissions by around 50% in the CT and the CT_CCS scenarios compared with the GHG emissions from these vehicles in the BAU scenario.

The building sector includes residential buildings, offices, hospitals, hotels and other commercial buildings. Its direct GHG emissions will increase from 6.4 $MtCO_2eq$ in 2005 to 42.4 $MtCO_2eq$ in 2050 in the BAU scenario. The building sector will contribute around 5% of total GHG emissions in the energy sector in 2050. Such GHG emissions are dominated by LPG used in cooking applications in residences and heating systems in hospitals and hotels in the CT and the CT_CCS scenarios. In 2050, hospitals and hotels will account for 85% and 70% of total GHG emissions of the commercial buildings in the CT and the CT_CCS scenarios. There will be a shift from LPG to biogas, traditional biomass (charcoal, paddy husk, and fuel wood) and electric cooking stoves. Therefore, the residential sector will reach zero CO_2 emissions by 2040. In 2050, offices and condominiums will be fully electrified in the CT scenarios. The indirect GHG emissions will be dominated by the heating purpose in the residential sector in the BAU scenario. Indirect GHG emissions will hinge on energy efficiency improvement in appliances in the end-use sectors, renewable electricity and the deployment of CCS technology. The emissions in the AIMC_CCS, the GCAM_CCS, the IMAGE_CCS, and the WITCH_CCS scenarios will reach zero CO_2 emissions in 2050.

Energy supply and final energy consumptions

Energy supply in the power sector

Thailand's energy supply will increase to 83.4 Mtoe in 2030 and 171.9 Mtoe in 2050 in the BAU scenario. The electricity generation will be dominated by natural gas power plants which will account for 65.4% of the total energy supply in 2050. Coal will be about 20.3% of the energy supply in 2050. The biomass and non-biomass renewable energy will provide 7.3% and 1.3% of the energy supply in 2050, respectively. Figure 7 illustrates the energy supply in 2030 and 2050.

The energy supply will be reduced by 37.7%, 40.2%, 40.7%, 39.5% and 39.2% in the T0, the AIMC, the GCAM, the IMAGE and the WITCH scenarios, respectively, when compared to the BAU scenario in 2050. Coal consumption will continue only in the T0, the AIMC and the GCAM scenarios. There will be a substantial shift from coal-fired power plants to natural gas-fired power plants, biomass, wind and solar in the IMAGE and the WITCH scenario in 2050 (see Fig. 7). Coal consumption will continue in the CT_CCS scenarios. In 2050, the T0_CCS, the AIMC_CCS, the GCAM_CCS, the IMAGE_CCS and the WITCH_CCS scenarios will reduce the energy supply by 50.6%, 46.6%, 45.5%, 44.3% and 45.5% when compared to the BAU scenario, respectively. The T0_CCS will require the lowest energy supply among the CT_CCS scenarios. The CCS technology will be deployed in the AIMC_CCS, the GCAM_CCS, the IMAGE_CCS and the WITCH_CCS scenarios.

The electricity generation will increase from 117.5 TWh in 2005 to 749.9 TWh in 2050 in the BAU scenario. Natural gas-fired power plants will be the main source of electricity generation in the BAU scenario, and account for 71.2% of total electricity generation in 2050. Renewable electricity will be a promising option for decarbonization in the CT scenarios. The generation from renewable energy will increase from 35% in 2030 to 60% in 2050 (see Table 2). In the T0 and the T0_CCS scenarios, solar, wind and MSW will be the main energy sources of electricity generation. Electricity generation from solar, wind and MSW in the T0 and the T0_CCS scenarios account for 35.8% and 37.3% in 2050, respectively. By increasing carbon prices, the generation from MSW will be phased out. Solar and wind generation will be 400 TWh by 2050. In the CT_CCS scenarios, renewable electricity will account for 57.9–58.8% in 2050. Coal- and gas-fired power plants with CCS will contribute about 200 TWh by 2050. The BECCS will also play an important role in reducing GHG emissions in the CT_CCS scenarios (see Table 2). In CT_CCS scenarios, the electricity generation will be more expensive compared to the CT scenarios. Thus, the electricity demand in the demand-side sector will shift to other fuels at lower cost.

Final energy consumption in the demand-side sector

In 2030, final energy consumption (FEC) in the BAU scenario will increase to 122.6 Mtoe and 248.0 Mtoe in 2050. In 2050, electricity will account for 27.9% of FEC, followed by biomass (24.5%) and oil (22.4%). Figure 8 shows the final energy consumption in all scenarios in 2030 and 2050.

The shares of fuel types in the CT and the CT_CCS scenarios will change due to the carbon prices. Electricity generation from solar and wind will increase in the CT scenario (see Fig. 8). The FEC will be reduced in the range of 18.0–18.7 Mtoe in the CT scenarios in 2030. The share of electricity will be 28.9–29.3% of FEC. The share of oil consumption will be reduced by 11.0–11.7% compared with the BAU scenarios in 2030. The FEC will be reduced by 17.4–20.7% in 2050. The share of electricity consumption will account for 33.4–34.8% in the CT scenario in 2050. The share of oil consumption will be reduced by 14.0–16.4% compared with the BAU scenarios in 2050 (see Fig. 8).

In the CT_CCS scenario, the FEC will be reduced in the range of 16.8–17.4 Mtoe in 2030. The share of electricity consumption will be 26.3% in 2030. The oil consumption will be reduced by 10.0–10.5% when compared with the BAU scenarios in 2030. The FEC will be reduced by 15.6–18.4% in 2050. Electricity will dominate in FEC in the CT_CCS scenario, and account for 26.3–28.3% in 2050. The proportion of oil consumption will be reduced by 11.8–14.2% compared with the BAU scenarios in 2050 (see Fig. 8). The deployment of CCS technologies will play an important role in reducing CO_2 emissions.

Figure 9 shows energy consumption by the demand-side sector in the CT and the CT_CCS scenarios in 2050.

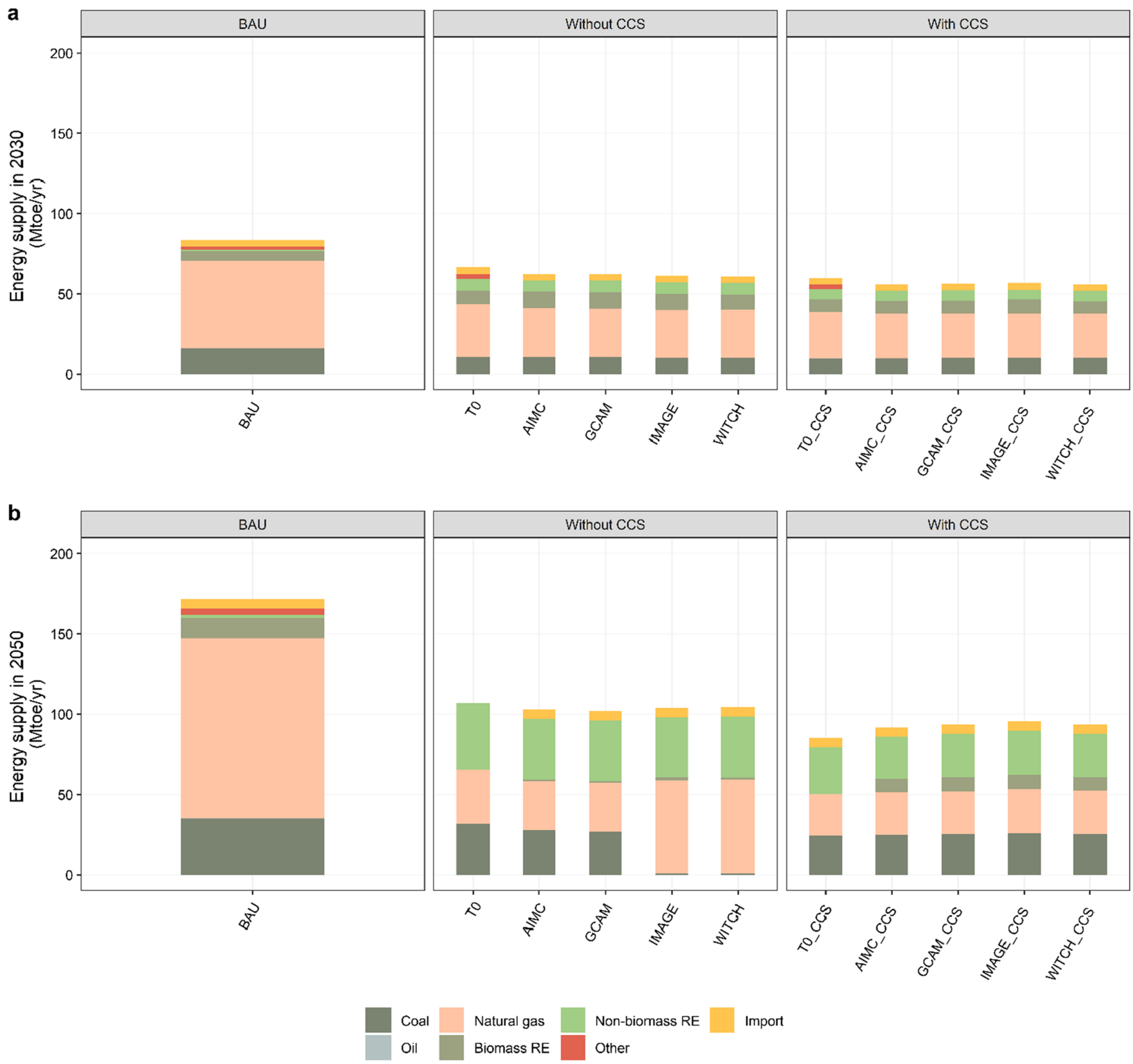

Fig. 7 Energy supply in the power sector in **a** 2030 and **b** 2050

In the industrial sector, the FEC will be reduced by 10.5–16.1 Mtoe in the CT scenario and 9.2–14.1 Mtoe in the CT_CCS scenario when compared to the BAU scenario in 2050. GHG emissions will be largely mitigated in the IMAGE and the IMAGE_CCS scenarios. There will be a shift from fossil fuels to biomass and energy efficiency improvements in the CT and the CT_CCS scenarios. Biomass will play a critical role in emission reduction in the food and beverage, non-metallic and chemical industries. In 2050, biomass consumption will be 33.2–38.2 Mtoe in the CT and the CT_CCS scenarios (see Fig. 9). The electricity consumption will be reduced by 10% due to efficiency improvements in electric motors and cooling systems in 2050. In the transport sector, energy consumption will be reduced by 11.0–13.6 Mtoe in the CT scenarios and 11.7–13.9 Mtoe in the CT_CCS scenarios when compared to the BAU scenario. By imposing carbon prices, oils will be shifted to liquid biofuel and electricity. Road transport will play a key role in the decarbonized transport sector. In 2050, the share of oil consumption will be reduced from 68% in the BAU scenario to 7% in the CT and the CT_CCS scenarios. In 2050, liquid biofuels will be the main source of clean energy, and account for 70.2% in FEC in the CT and

Table 2 Electricity generation mix in 2050

Category	BAU	Without CCS (CT scenarios)					With CCS (CT_CCS scenarios)				
		T0	AIMC	GCAM	IMAGE	WITCH	T0_CCS	AIMC_CCS	GCAM_CCS	IMAGE_CCS	WITCH_CCS
Total electricity generation (TWh)	749.9	814.6	742.1	741.9	741.7	751.0	583.8	582.8	596.6	609.7	597.3
Renewable electricity											
Share in total generation	7.2%	60.0%	60.0%	60.0%	60.0%	60.0%	57.9%	58.5%	58.8%	58.7%	58.7%
Share of solar and wind in total generation	1.1%	35.8%	54.1%	56.5%	55.9%	56.4%	37.3%	47.7%	49.0%	49.2%	49.1%
Carbon capture and storage (CCS) generation (TWh)											
Coal- and gas-fired plants with CCS	0.0	0.0	0.0	0.0	0.0	0.0	68.4	214.7	220.4	225.2	221.8
Bio-energy with CCS (BECCS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.2	34.0	34.8	34.0
Electricity generation from fossil fuel power plants (without CCS)											
Coal-fired plant	20.8%	17.7%	17.7%	17.7%	0.4%	0.4%	12.2%	0.5%	0.5%	0.5%	0.5%
Natural gas-fired plants	71.4%	22.3%	22.3%	22.3%	39.5%	39.5%	18.1%	4.2%	3.8%	3.9%	3.7%

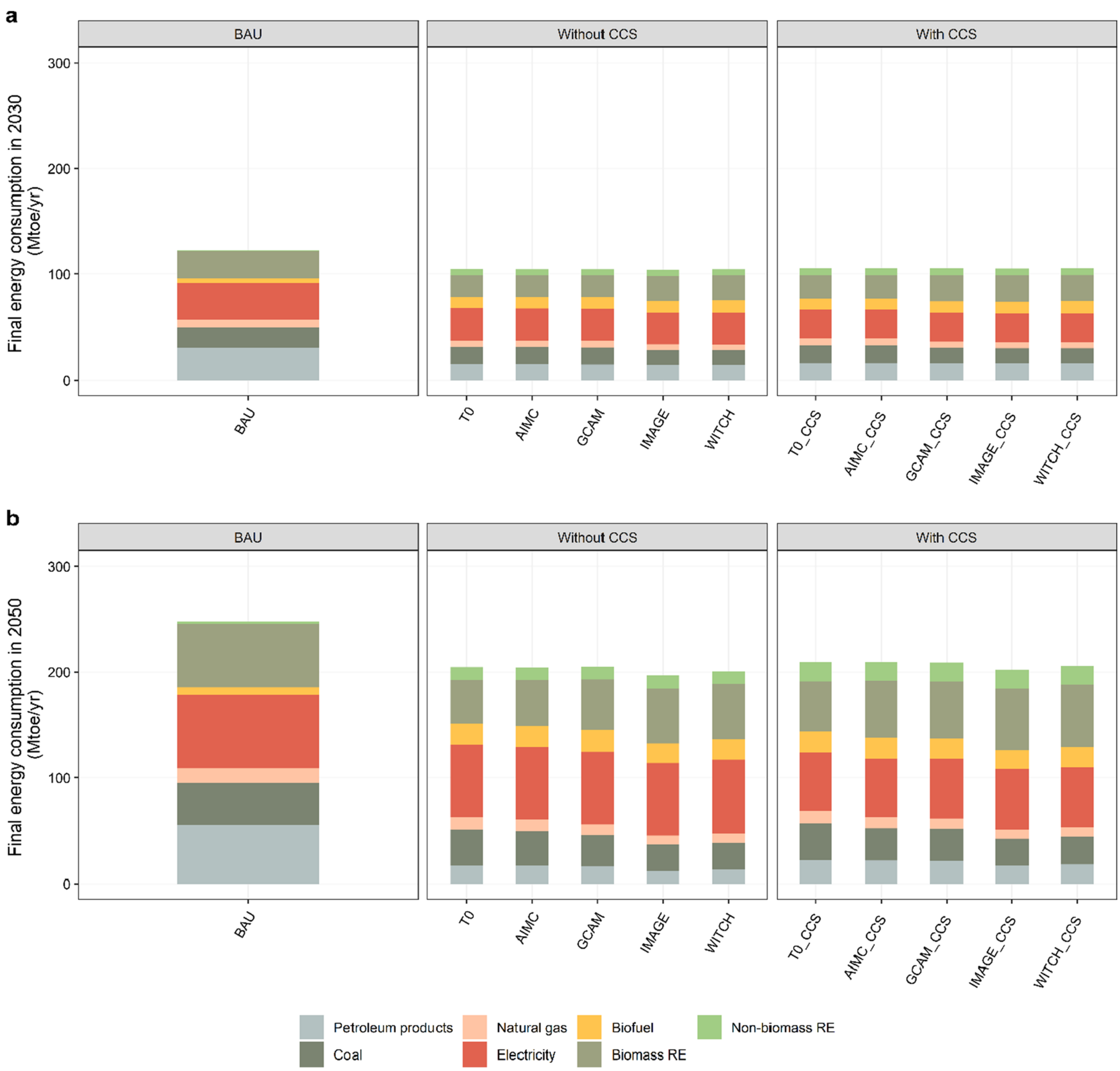

Fig. 8 Final energy consumption in various scenarios in 2030 and 2050

CT_CCS scenarios. Liquid biofuels will be mainly consumed by pick-ups and sedans, accounting for more than 70% of total liquid biofuel consumption. Electrification will play an important role in reducing GHG emissions when the carbon prices increase. In 2050, the electricity consumption in pick-ups and sedans will be 65.8% and 67.7% of electricity consumption in the transport sector in the IMAGE and the IMAGE_CCS scenarios, respectively. In 2050, the share of electric trucks will be 20.4% and 20.8% of electricity consumption in the transport sector in the IMAGE and the IMAGE_CCS scenarios, respectively. The electrification for long-haul trucks will rely on large-scale batteries rather than those currently used. The electricity consumption in electric trains will account for 8.0% and 6.6% in the IMAGE and the IMAGE_CCS scenarios, respectively, in 2050.

The energy consumption in the residential sector will be reduced by 12.6–12.8 Mtoe in the CT scenarios and 9.1–9.2 Mtoe in the CT_CCS scenarios in 2050. The share of renewable energy in TFC will be 44.4% in the CT scenarios and 66.5% in the CT_CCS scenarios. In 2050, there will be a substantial shift from LPG cooking stoves

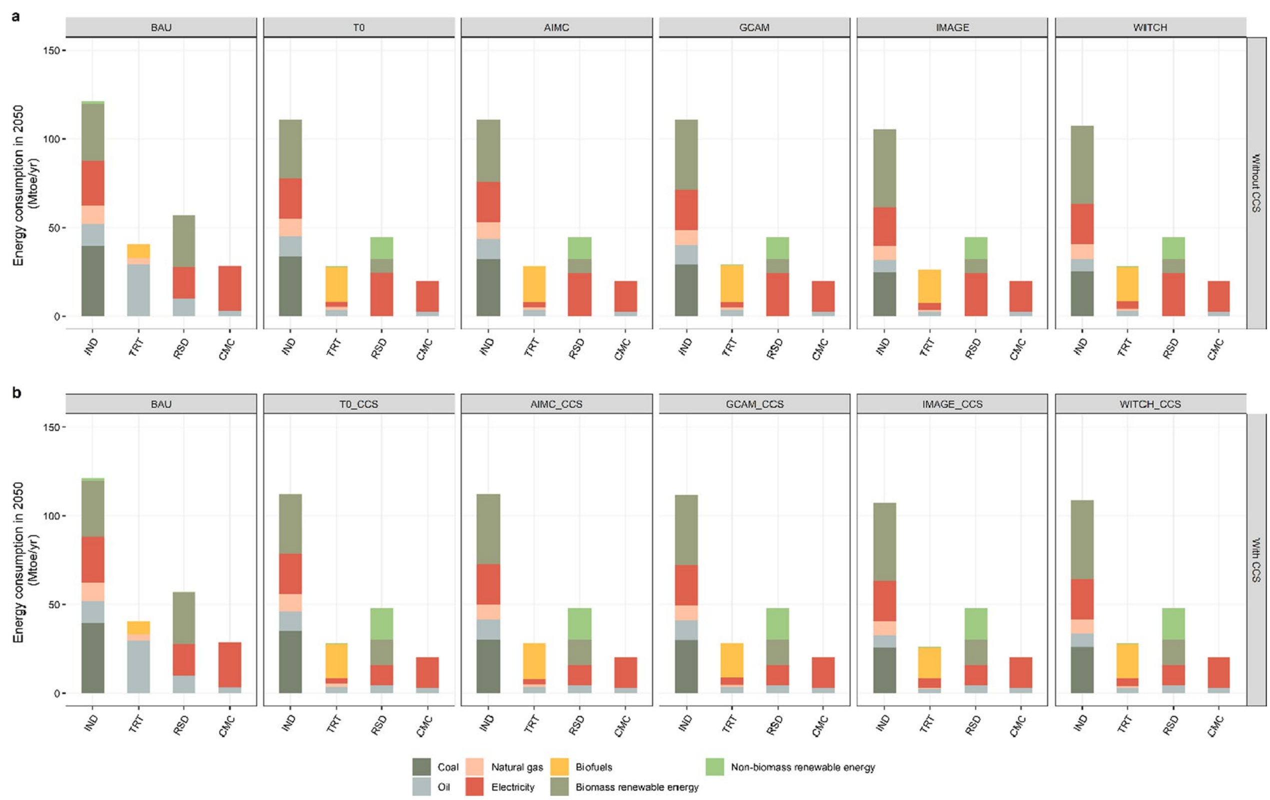

Fig. 9 Energy consumption in **a** the CT and **b** the CT_CCS scenarios in 2050

to electric and bio-energy cooking stoves in the CT and the CT_CCS scenarios with bio-energy accounting for 88% and 85%, respectively. In commercial buildings, the energy consumption will be reduced by 8.4–8.8 Mtoe in 2050. The electricity consumption will be 87.7% and 84.7% of total energy consumption in the commercial sector in the CT and the CT_CCS scenarios in 2050 (see Fig. 9).

Discussion

The study reveals that the carbon prices mechanism and the CCS technologies will be central pillars to achieve the net-zero emission and the 2 degrees Celsius target by 2050. Imposing carbon prices, increasing use of solar, wind, and biomass electricity; improving energy efficiency in power generation; and saving energy in the industry and the building sectors, will be the key options of clean power generation in the CT scenario. By imposing carbon prices, the deployment of CCS technology and renewable electricity will rapidly decarbonize the emissions in the power sector. The increase of renewable energy and the electrification of end-use play key roles in reducing GHG emissions. Passenger road transport will be a key element of GHG mitigation. The GHG reduction will be primarily reflected by the stringent use of liquid biofuel, energy efficiency improvement and the shift to electric vehicles. Biodiesel plays a key role in reducing the GHG emissions in the transport sector. In Thailand, biodiesel is derived from palm, soybean, sunflower oil and other oils as a diesel fuel substitute [73, 74]. It is bio-degradable and nontoxic when burned as a fuel [75].

The deployment of CCS technology in the power sector will affect total system costs and the electricity price in the CT_CCS scenarios. These scenarios will continue using LPG for cooking purposes. The biogas and the traditional biomass will play a vital role in the heating of cooking devices.

Results show that a substantial shift from coal-fired power plants to natural gas-fired power plants occurs in the IMAGE and WITCH scenarios in 2050 (see Fig. 7). In contrast to the Japanese case, the energy supply from fossil fuels such as coal, oil, and gas will be reduced and replaced with renewable energies such as biomass, solar and wind [22]. Japan's energy supply sector desires an extreme transformation similar to Thailand. The implementation of CCS and BECCS technologies is necessary for the stringent level of mitigation targets in Japan, China, India and Thailand [18, 22]. The clean power generation will affect the demand-side sector.

Japan's long-term goal will require the building sector to reduce its direct emissions to nearly zero by 2050 [22]. In this study, there will be a shift from LPG to biogas, traditional biomass and electric cooking stoves in the residential sector. Commercial buildings will be fully electrified in 2050. In Malaysia, a low-carbon lifestyle including energy efficient appliances and energy saving practices is an effective action in reducing the GHG emission in the near term. It will contribute 21% of emission reduction in 2025 [21].

Oshiro et al. [22] reveal that the share of low-carbon carriers needed in the transport sector will increase to nearly 70% by 2050. In this study, the GHG emissions in the transport sector will reduce by 60%, respectively, compared with the BAU emission level in 2050. The GHG reduction will be primarily from the stringent use of liquid biofuel, energy efficiency improvement and the shift to electric vehicles. Similarly, the diffusion of low-carbon vehicles in the integrated green transport action, is one of the top three actions in Malaysia's low-carbon society [21]. This study agrees that the absence of mitigation actions beyond the NDC target by 2030 and the limitation of low-carbon technologies will exacerbate the challenge to meet net-zero emission by 2050 [22].

To meet the net-zero CO_2 emission by 2050, the power sector must adopt CCS and bio-energy with CCS. The fuel mix in the industries and buildings sectors will be only clean electricity and renewable energy. However, the transport sector will face difficulty in mitigating CO_2 emissions; in particular, for domestic aviation, water transport, and road freight transport.

In the SSP database, the world carbon prices are similar to the carbon prices of the Asia region in SSP4 for RCP2.6 scenarios [43]. From the results of IMAGE model, the carbon price of the Asia region is only higher than the world carbon price in 2030. However, the carbon prices after 2030 are the same as in the rest of the world [43]. Out of the SSP scenarios, the GCAM is mainly represented by the SSP4 scenario. The GHG emissions in the Asia region will decrease from 18,561 $MtCO_2eq$ in 2010 to 8564 $MtCO_2eq$ in SSP4 to achieve RCP2.6 [10], a 1.9% reduction per year. In this study, the GHG emissions will increase 0.3–1.8% annually in CT scenarios and decrease 1.0–3.0% annually in CT_CCS scenarios.

When compared with the GHG emission in Asia region under SSP4 for RCP2.6, the share of Thailand GHG emissions is 0.72% in 2010. The share of Thailand GHG emissions will increase to 1.76–3.21% in 2050 under CT scenarios. However, the share of Thailand GHG emissions will be 0.47–2.04% in 2050 when implementing the CCS with carbon price.

Conclusion

This study focuses on Thailand GHG reduction to meet the 2 degrees Celsius target. The SSP4 was found to be the most likely pathway given the current Thailand socio-economic situation. To achieve the 2 degrees Celsius target, carbon prices are imposed by taking appropriate carbon prices in the RCP2.6. There are four carbon price pathways coupled with Thailand's long-term GHG mitigation scenarios. The carbon sequestration by the forest sector is considered. There are three major policy implications to meet Thailand's 2 degrees Celsius target. First, carbon prices will be the mechanism to accelerate the transformation in the energy sector. The CT and the CT_CCS scenarios show that wind and solar electricity (around 60% of electricity generation) will be a key pillar of clean electricity in 2050. These scenarios imply that policy makers should update the renewable electricity plans to meet Thailand's 2 degrees Celsius target in 2050. Second, stringent carbon prices will reduce the electricity generation from gas-fired power plants in the CT and the CT_CCS scenarios in 2050. In Thailand's 2 degrees Celsius target, coal-fired, gas-fired, and bio-energy with CCS will become important options in reducing CO_2 emissions. In 2050, power generation with CCS technology will range from 247.9 to 260 TWh in the CT_CCS scenarios. Results imply that policy makers should investigate the application of CCS in the power sector and the storage location. Third, a major transformation in the transport sector is critically needed. Results also indicate that liquid biofuel and electrification in pick-ups, sedans, and trucks will help reduce GHG emissions. The ultra-fast charging stations need to be installed along the dense transport routes. This study suggests that the carbon price will reach 1500 US$2005/$tCO_2$ by 2050 if Thailand needs to accelerate its GHG mitigation ambition to meet the zero GHG emission in the energy sector by 2050. The power sector and the industries will be key contributors in reducing GHG emissions.

Abbreviations

AAGR: Average annual growth rate; AEDP2015: Alternative energy development plan; AIM/CGE: Asia–Pacific Integrated Model/Computable General Equilibrium; AIM/Enduse: Asia–Pacific Integrated Assessment model/Enduse; AR5: IPCC Fifth assessment report; BAU: Business-as-usual scenario; BECCS: Bio-energy with carbon capture storage; CCS: Carbon capture storage; CT: Carbon prices without CCS scenarios; CT_CCS: Carbon prices with CCS scenarios; EEP2015: National energy efficiency plan; EPPO: Energy Policy and Planning Office; FEC: Final energy consumption; GAMS: General algebraic modeling system; GCAM: Global change assessment model; IGCC: Integrated gasification combine cycle; IMAGE: Integrated model to assess the global environment; JCM: Joint crediting mechanism; LPG: Liquefied petroleum gas; LUCF: Land use change and forest; NDCs: Nationally determined contributions; NESDC: Office of the National Economic and Social Development Council; NHSO: National Health Security Office; NIES: National Institute for Environmental; RCPs: Representative concentration pathways; RFD: Royal forest department; SSPs: Shared socio-economic pathways; WITCH: World induced technical change hybrid model.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-022-00349-1.

Additional file 1: The equations of AIM/Enduse model. The equations include objective function, energy consumption constraints, emission estimation constraints, stock balance and cost estimation.

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Author contributions

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

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Availability of data and materials

This study relied on the socio-economic 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 is provided in the references.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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