



Research article

Thailand's long-term GHG emission reduction in 2050: the achievement of renewable energy and energy efficiency beyond the NDC



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ABSTRACT

The sources of greenhouse gas (GHG) emissions in Thailand come from the energy sector, including power generation, transport, industries, buildings, and households. In 2016, the energy sector contributed 77 percent of total GHG emissions. Thailand's energy policies are the essential instrument to deal with GHG emission reduction under the United Nations Framework Convention on Climate Change (UNFCCC). The renewable energy (RE) plans aim at increasing the share of RE in final energy consumption while the energy efficiency (EE) plans aim at improving energy efficiency as well as reducing fossil-fuel consumption. GHG emission mitigation will result in several co-benefits such as increasing energy security and decreasing local air pollutants. Therefore, this study analyzes potentials of GHG emission reduction during 2015–2050 from utilization of renewable energy and increasing energy efficiency using the Long-range Energy Alternative Planning system (LEAP) model. Results include potentials of domestic RE and EE measures to achieve Thailand's nationally determined contribution (NDC). Moreover, it was found that to meet Thailand's first NDC of 20 percent GHG emission reduction target in 2030, targets in the RE plan and the EE plan must be achieved by at least 50 percent and 75 percent, respectively, or targets in the RE plan and the EE plan must be achieved by at least 75 percent and 50 percent. In addition, the extended NDC scenario in 2050 is analyzed in the long-term perspective of Thailand showing 30.4 percent reduction when compared to the BAU. The policy implication includes promotion of energy efficiency, acceleration of the deployment of renewable energy and advanced technologies such as CCS, completion of transmission network for renewable electricity, zoning of biomass sources, and public awareness in climate changes.

1. Introduction

Climate change occurs due to increasing emissions of greenhouse gases (GHGs) into the atmosphere. The main sources of emissions come from human activities such as combustion of coal, oil and natural gas, deforestation, agriculture and livestock, and industrial processes. In 2014, global GHG emission was 48.9 Gt-CO₂eq whereas the energy sector was the largest emission source [1]. The global GHG emission in the energy sector was 35.8 Gt-CO₂eq, and accounted for 73.2 percent of global GHG emission [2].

Fuel combustion was a major source of GHG emissions released from the energy sector, emitting CO₂ of about 32.3 Gt-CO₂, or about 96.1 percent of global CO₂ emissions [3]. In 2016, Asia was the largest GHG emission region and emitted 17.4 Gt-CO₂ which is two times higher than the United States (7.1 Gt-CO₂) and three times higher than Europe (5.1 Gt-CO₂). China emitted 9.10 Gt-CO₂ and accounted for half of the emissions in Asia. In 1997, the first commitment of the developed

countries on GHG emission reduction was agreed upon at the Third Conference of the Parties (COP3), known as the Kyoto Protocol, under the UNFCCC in Kyoto, Japan. Three international cooperation mechanisms, namely Emissions Trading (ET), Joint Implementation (JI), and Clean Development Mechanism (CDM), played an important role under the Kyoto Protocol to help the parties achieve their emission targets in the cost-effective way. The Kyoto Protocol included two commitment periods: the first (2008–2012) and the second (2013–2020) [4]. In the first commitment period, the European community and Annex-I parties to the UNFCCC had committed to reduce GHG emissions against the 1990 level. In the first commitment period, only Australia, Iceland and Norway could reduce GHG emissions. Due to the failure in meeting the mitigation targets of the Kyoto protocol, UNFCCC encouraged all Parties to approve their amendments to reduce GHG emission goals during the second commitment period at COP18 in Doha [5]. The Annex-I parties to the UNFCCC committed to reduce GHG emissions by at least 18 percent below the 1990 level in the period of 2013–2020, and the non-Annex I

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parties to the UNFCCC agreed to establish the Nationally Appropriate Mitigation Actions (NAMAs) with their voluntary mitigation programs or policies and support by the developed countries on technology, financing, and capacity building [6]. At COP21 in 2015, the Paris Agreement built upon the Convention and for the first time brought all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects. The key objectives of the Paris agreement are to keep the global temperature increase well below 2° above the pre-industrial level within this century and to pursue efforts to limit the temperature increase even further to 1.5° [7]. Both developed and developing countries have been required to put forward their mitigation efforts through the Nationally Determined Contributions (NDCs) and to report their emissions as well as implementation efforts throughout the submission period. As of December 2019, 183 countries have submitted their NDCs to the UNFCCC [8]. To enhance the ambition over time, the Paris Agreement provides that successive NDCs will represent a progression compared to the previous NDCs and reflect its highest possible ambition. At the COP24 in Katowice, Poland, the Paris Rulebook was provided. All Parties are requested to submit the next round of NDCs (second NDCs or updated NDCs) by 2020 and every five years thereafter [9]. It is expected that in 2030 the emission gap between the full implementation of conditional NDCs and the least-cost emission pathway consistent with the 2-degree stabilization will be in the range of 9–15 Gt-CO₂eq [10].

This paper is organized in seven sections. Section 1 is the introduction. Section 2 describes Thailand's energy situation, energy plans and climate change master plan. Section 3 describes the GHG mitigation actions in Thailand under UNFCCC. Section 4 presents the methodology. Section 5 describes the business-as-usual and alternative mitigation scenarios. Results of analyses are presented in section 6. Co-benefits of GHG mitigation and policy recommendations are presented in section 7.

2. Energy policy and climate policy in Thailand

2.1. Energy situation in Thailand

During 2000–2017, total final energy consumption in the economic sectors, including the transport, the industrial, the building, the household and the agriculture sectors increased by 95.6 percent [11]. In the same period, energy consumption in the transport and industrial sectors accounted for three-quarters of total energy consumption in Thailand. The shares of petroleum products and electricity in the transport and industrial sectors were 48.5 percent and 21.0 percent, respectively. In the power sector, two-thirds of the electricity was generated from natural gas [12]. In 2015, the total electricity capacity supplied to the national grid was 38.7 GW, comprising 15.5 GW from firmed power plants of EGAT, 14.8 GW from independent power plants (IPPs), 5.1 GW from small-scale power plants (SPPs), and 3.3 GW from electricity imports [13].

2.2. Thailand's renewable energy, energy efficiency, power development and the climate change master plans

The Ministry of Energy updated the renewable energy plan (AEDP2015) and the energy efficiency plan (EEP2015) in 2015. These plans have been developed in compliance with energy security, economy, and ecosystem. The EEP2015 plan aims at energy efficiency improvement while the AEDP2015 plan aims at promotion and utilization of domestic renewable energy resources. The power development plan (PDP) in 2015, or PDP2015, was taken into consideration both domestic renewable energy potential and energy savings, and set a target of renewable electricity at 30 percent in 2036. The climate change master plan of Thailand aims at Thailand being a low carbon society in 2050.

2.2.1. Thailand's Alternative Energy Development plan (AEDP)

The long-term Alternative Energy Development Plan 2015–2036 (AEDP2015) shows that renewable electricity will be expanded by

following domestic potential and technological development. The AEDP2015 plan has the objective to increase the share of renewable energy in the final energy consumption up to 30 percent within 2036 [14]. Thailand's AEDP2015 plan has been implemented in three measures: (i) electricity generation, (ii) heat generation, and (iii) biofuel production. Details of these three measures are as follows:

- 1) *Renewable electricity generation.* The AEDP2015 plan sets the target of RE electricity up to 20 percent in 2036. The renewable power capacity target in the AEDP2015 will be 19.6 GW. This target is consistent with RE electricity generation in the PDP2015. The PDP2015 has the target of a RE electricity share of 15–20 percent within 2036 [15]. There are six types of RE sources in the AEDP2015 plan, including municipal solid waste (MSW), small hydro, biomass, biogas, wind, and solar. However, small hydro, biomass and solar will have large shares of 17, 28 and 30 percent, respectively, of total RE electricity generation in 2036.
- 2) *Renewable energy for heat generation.* In Thailand, heating services in households, buildings and industries mainly comes from LPG and natural gas. The AEDP2015 plan sets the target to substitute 37 percent of heat demand from renewable energy in 2036. The domestic RE sources include waste, biomass, biogas, fast growing trees, solar, and others. Heat generated from biomass and biogas is expected to be 80 percent of total heat generation from RE in 2036. Three solar technologies, i.e., solar water heater, solar dryer and solar cooling, have been promoted to generate heat in the residential, commercial and industrial sectors.
- 3) *Biofuels in the transport sector.* The AEDP2015 plan sets the target of biofuel production at 25 percent in 2036. Biofuels in Thailand include bio-oils for biodiesel production and ethanol for gasohol production. By 2036, biofuels will be shared by bio-oils (50 percent), ethanol (24 percent), compressed bio-methane gas (23 percent) and others (3 percent).

2.2.2. Thailand's energy efficiency plan (EEP)

The energy efficiency plan in 2015 (EEP2015) is revised from the first Thailand energy efficiency plan in 2011 [16]. Compared to the energy intensity level in 2010, the target of the EEP2015 needs to be reduced by 30 percent of 2036. The measures in the EEP2015 plan are implemented in four economic sectors, namely the transport, the industrial, the building, and the residential sectors. The EEP2015 plan provides three strategies to achieve its objectives: (i) compulsory program, (ii) voluntary program, and (iii) complementary program [17]. In 2036, the electricity saving target in the EEP2015 plan will be 89,672 GWh. The total energy savings in the EEP2015 plan will be 51,700 kilo-tonne of oil equivalent (ktoe). These savings are of electricity (7,641 ktoe) and thermal energy (44,059 ktoe). The transport sector will be the largest energy saving sector (58 percent), followed by the industrial sector (28 percent), the building sector (9 percent), and the residential sector (4 percent).

2.2.3. Thailand's Power Development Plan (PDP)

Thailand's Power Development Plan 2015, called PDP2015 [15], set a target of renewables in electricity generation of 21.6 GW in 2036 (12.6 GW from domestic sources and 9.5 GW import from neighboring countries). The PDP2015 states that by the end of 2036, total capacity installation will be about 70.3 GW, comprising total installed capacity (as of December 2014) of 37.6 GW and total new capacity of 57.5 GW. The total added capacity of 57.4 GW can be detailed as power generated from renewable energy (21.6 GW), from cogeneration (4.1 GW), from combined cycle power plants (17.5 GW) and coal/lignite-thermal power plants (12.1 GW), and others (2.1 GW). The total added capacity of thermal power plants during 2015–2036 comprises power purchase from neighboring countries of 1.5 GW, gas turbine power plant of 1.3 GW, thermal power plants from domestic coal and lignite of 7.4 GW, and nuclear power plants of 2.0 GW Table 1 summarizes Thailand's integrated energy plans.

Table 1. Summary of Thailand's integrated energy plans.

Energy plan	Objectives	Targets and assumptions
PDP2015	To increase efficiency and reduce electricity demand together with reducing environmental impact.	Energy savings in the EEP are included 15 percent reserve margin of reliability. Diversity of fuels.
EEP2015	To decrease energy intensity of 30% by 2036 compared to 2010.	Reduce energy intensity in the transport sector by 58%, industrial sector by 29%, building and household sectors by 12%, and other sectors by 1%
AEDP2015	To increase renewable energy share to 30% by 2036.	Increase renewable electricity and thermal utilization Increase utilization of biofuels in the transport sector

The updated PDP plan is called the PDP2018. The fuel mix in the PDP2018 relies on fossil fuels, mainly natural gas (53.0 percent) and coal (12.0 percent) [18]. Although the target of RE capacity in the PDP2018 will increase to 40.0 percent of the total power generation capacity in 2036, imported electricity will be 11.0 percent of total power generation which is higher than the target in the PDP2015 (see Figure 1).

The dependence on imported electricity implies that the PDP2018 may not comply with the sustainable development goals. Currently, the government is revising the PDP2018. Therefore, this study employed renewable electricity targets in the Alternative Energy Development Plan (AEDP2015) and the Energy Efficiency Plan (EEP2015) because both plans are consistent with the PDP2015. In addition, Thailand's first NDC to UNFCCC was analyzed by using the AEDP2015, the EEP2015 and the PDP2015 plans.

2.2.4. Thailand's climate change master plan

Thailand's Climate Change Master Plan (2015–2050) [19] is designed to help Thailand achieve sustainable development, low carbon growth, and climate change resilience by 2050, by the following missions: (i) building climate resilience by integrating policies and measures in all sectors, (ii) creating mechanisms to reduce GHG emissions, leading to sustainable low carbon growth, (iii) building readiness of master plan implementation by enhancing potential and awareness of stakeholders, and (iv) developing a database, knowledge, and technology to support climate change adaptation and mitigation.

3. Thailand's ambition in GHG mitigation actions under UNFCCC

Thailand is confronting the impacts of climate change [20]. Increasing sea levels have impacted the coastal areas and mangrove forest areas, resulting in a reduction in the breeding of aquatic animals [21]. Thailand has joined international cooperation mechanisms such as the CDM projects, which have been supported by developed countries. The registered CDM projects include 66 projects that received issuance of

CERs in 2019, corresponding to certified GHG emission reduction of 14, 165,794 t CO₂eq [22].

Strong actions against climate impacts have been performed under the Thailand's NAMA since the second commitment of Kyoto Protocol. In 2014, Thailand proposed its NAMAs roadmap in the energy and transport sectors to reduce emissions to between 7 to 20 percent below its business as usual (BAU) level in 2020 [23]. With NAMA tracking information at the end of 2015, Thailand reported achievement of a 16 percent reduction of GHG emissions over its BAU level [24].

Furthermore, in order to keep the global temperature increase well below 2° within this century, Thailand submitted its NDC with the stated goal to reduce GHG emissions by 20 percent when compared with its business-as-usual (BAU) level in 2030 in the energy, industrial processes and product uses (IPPU), and waste sectors. The GHG emissions can further be reduced by 25 percent in 2030 with the condition that financial support and advanced technical knowledge are transferred [25].

In 2013, GHG emissions in the energy sector contributed about 74 percent of the overall emissions in Thailand [24]. During 2000–2013, GHG emissions in the energy sector increased about 4 percent. Because most emissions came from the energy sector, energy policies will be the essential instrument in achieving the emission reduction target. Therefore, this study will analyze the potential of energy savings and renewable energy utilization in helping to reach the GHG emission reduction target in the energy sector under Thailand's first NDC target in 2030 and the extended NDC in 2050.

4. Methodology

In this study, the Long-range Energy Alternative Planning system, or LEAP model, is employed to assess the achievement of the GHG mitigation target of Thailand in the period of 2015–2050. The target years are 2030 for the NDC and 2050 for the extended NDC.

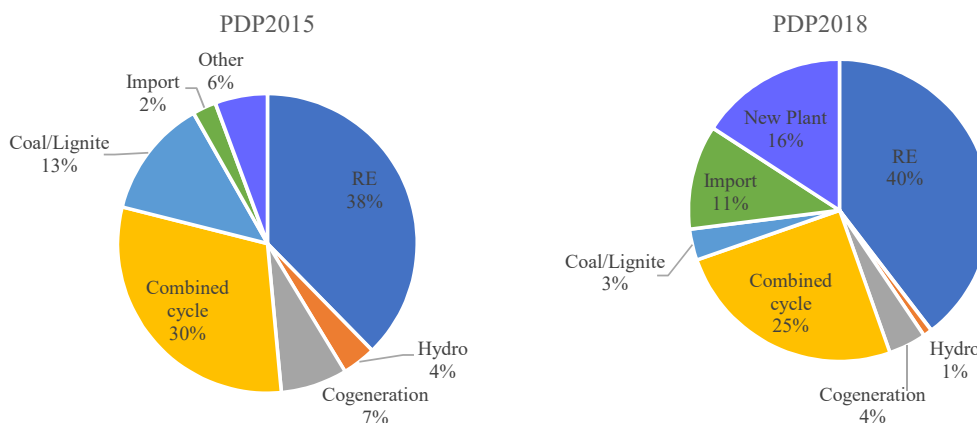


Figure 1. Comparison of capacity mix by technology in the PDP2015 and PDP2018.

4.1. LEAP modeling framework

The LEAP model was developed by the Stockholm Environment Institute (SEI) [26]. The LEAP model can be used as a tool to analyze various scenarios for energy policy and GHG mitigation assessments. For example, Nojedehei, Heidari [27] employed LEAP to analyze power production from landfill gas and its environmental impacts in Tehran in 2035. Uhorakeye and Möller [28] assessed electricity demand towards 2050 in Rwanda using LEAP where power generation was deficient. Kumar and Madlener [29] employed LEAP to assess the environmental impacts of renewable electricity generation in India. In the demand side, LEAP was applied to estimate energy demand in the industrial, the transport, the commercial and the household sectors and to analyze the long-term energy policy, environmental impacts and GHG mitigation potential in many countries, i.e. Canada [30], China [31], Columbia [32, 33], Nigeria [34], South Korea [35], Thailand [36], etc.

Generally, the LEAP framework can be applied to estimate GHG emissions, which are related to the amount of energy consumption, in both supply and demand sides. The LEAP structure for Thailand is illustrated in Figure 2. The transformation module includes electricity generation, oil refining, mining production, and others. The information of electricity generation technology, i.e., installed capacity, efficiency, dispatching rule, merit order, historical production, reserved margin, load factor, energy loss, etc., are put into this module. The selection of power generation technology under the given constraints is based on the concept of merit order. The demand module includes the economic sectors: the residential, the building, the industry, the transport sectors,

and others. The activity data involves the socio-economic variables, i.e., GDP, population, number of households, etc. The quantity of energy consumption can be calculated in terms of activity data and energy intensity as shown in Eq. (1).

$$Energy\ consumption = Activity\ data \times Energy\ intensity \tag{1}$$

In addition, emission factors (EF) are required by specific types of energy resource or fuel in order to analyze the environmental impacts using Eq. (2). In this study, emission factors used to analyze GHG emissions are based on default values of the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines [37].

$$GHGEmissions = Energyconsumption \times EF \tag{2}$$

4.2. Input data and assumptions

This study considered five economic sectors: the power, the transport, the industry, the buildings and the household sectors. The power generation is analyzed in the transformation module and all energy demands are analyzed in the demand module.

4.2.1. Transformation module

4.2.1.1. Model of Thailand's power generation. The power generation in Thailand is constructed under the transformation module. Historical production, installed capacity, plant efficiency, dispatching rule, merit order, load factor, reserved margin, lifetime and energy requirement are

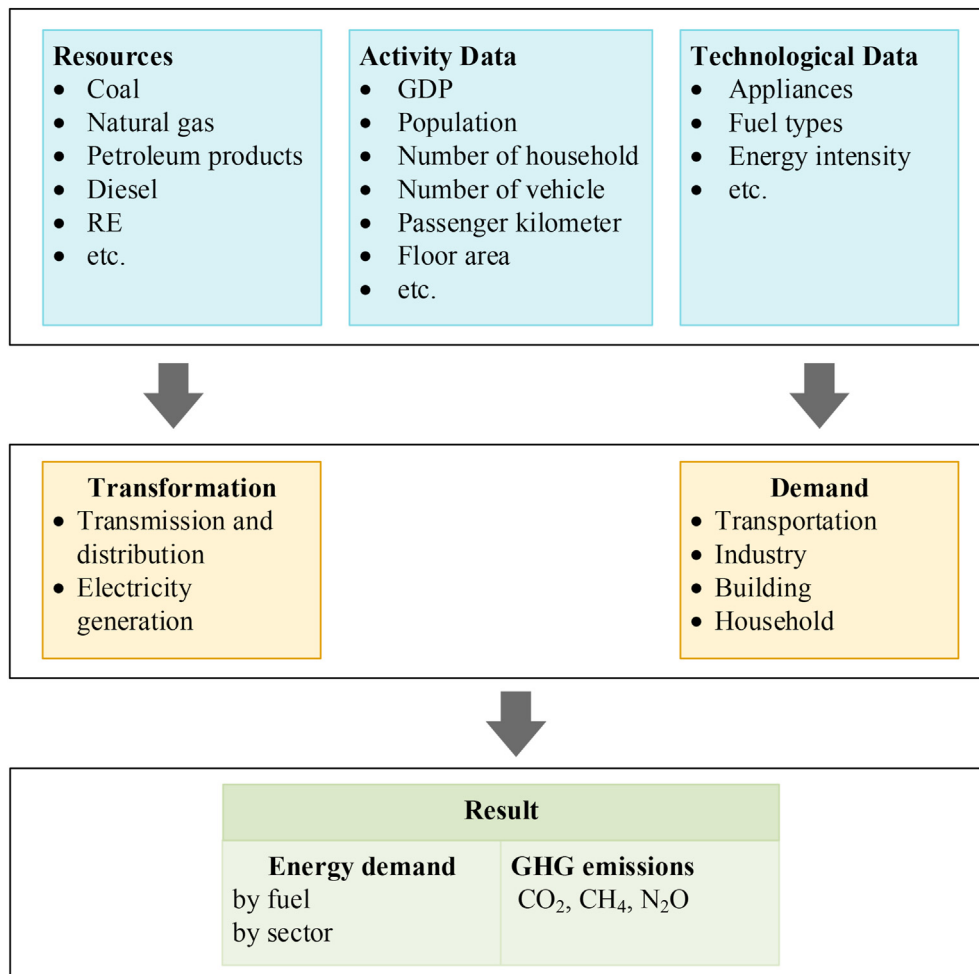


Figure 2. Schematic diagram of Thailand's LEAP model in this study.

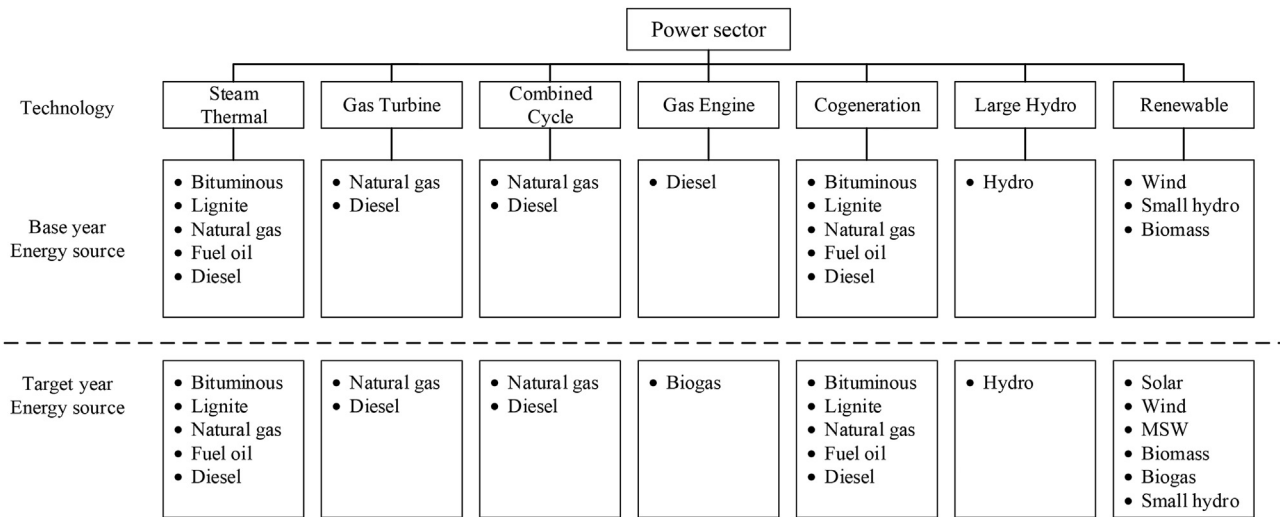


Figure 3. Structure of Thailand's electricity generation in the LEAP model.

the key parameters of the LEAP model. In this study, the base year is 2010. There are seven types of power plants in Thailand, including steam thermal, gas turbine, combined cycle, cogeneration, gas engine, hydro (large hydro) and renewable electricity (see Figure 3). The data of power production are obtained from the annual reports [38].

4.2.2. Demand module

The demand module in this study consists of the transport, the industrial, the building and the household sectors.

4.2.2.1. Model of Thailand's transport sector. In this study, the transport sector is divided into three main modes: road & rail, water, and air transports. Each mode of transport is categorized into two types: passenger and freight transports (see Figure 4). There are nineteen vehicle types classified in the road transport in Thailand [39]. However, in this study, they are grouped into nine vehicle types, seven vehicle types for

the road passenger transport and two vehicle types for the road freight transport. The seven vehicle types in the road passenger transport include sedans, vans, tuk-tuks, taxis, motorcycles, buses and others, and the two vehicle types in the road freight transport include pick-ups and trucks. There are five fuels, i.e., gasoline, diesel, LPG, CNG and electricity consumed in the road passenger and freight transport. In this study, biofuels produced from gasoline blended with ethanol by 10%, 20%, and 85% volume are called E10, E20, and E85, respectively. Biodiesel is produced from diesel blended with 5% methanol and called biodiesel B5.

In the rail transport, passenger trains consume both diesel and electricity while freight trains consume only diesel. For water transport, only freight ships are considered in the passenger transport. Diesel is a major fuel used in freight ships. In the air transport, jet fuel is consumed in both passenger and freight air transports.

In the transport sector, passenger-kilometers (pkm) represents passenger transport and ton-kilometer (tkm) represents freight transport.

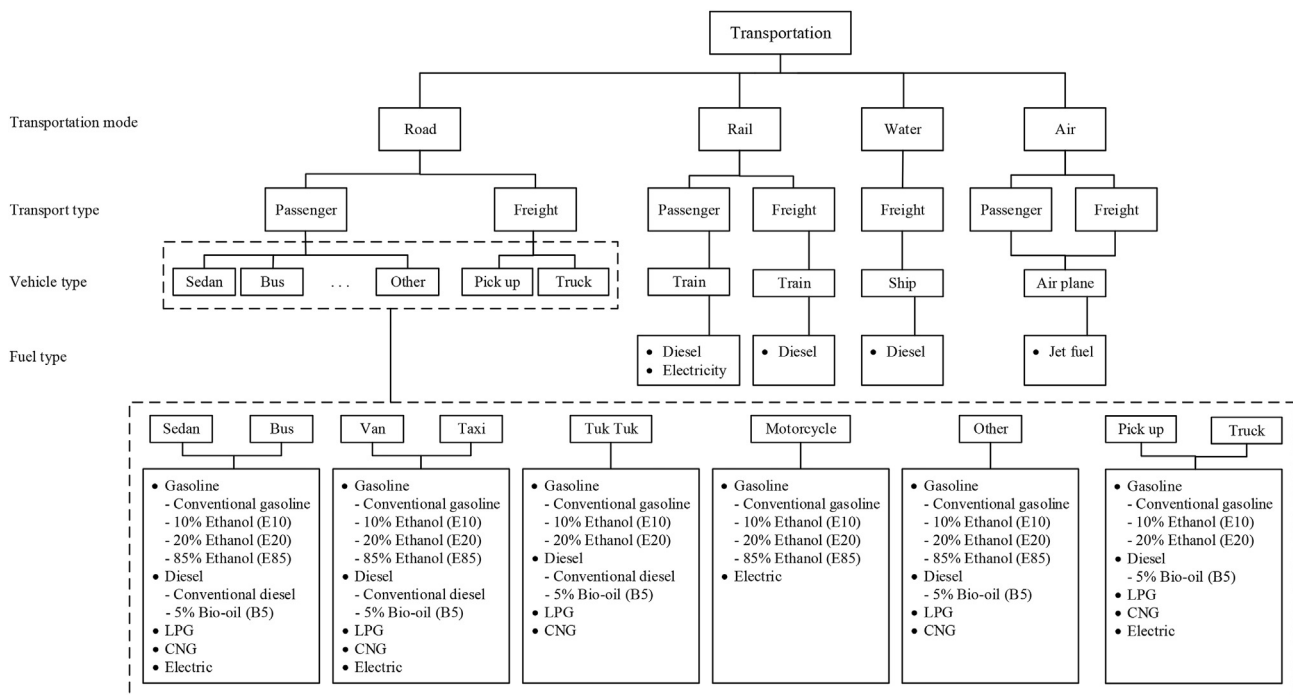


Figure 4. Structure of Thailand's transport sector in the LEAP model.

The travel volume demand in the function of the average number of passenger or weight of goods and travelled distance in each vehicle can be determined by Eq. (3). In this study, the travel volume demand was employed from selected publications [40]. Historical information of number of vehicles used to determine the total travel volume demand is collected and published by the Department of Land transport (DLT).

$$\text{Travel Volume Demand} = \text{Average No. of passenger or weight of goods} \times \text{Travelled Distance} \quad (3)$$

To estimate the energy demand in the proposed scenarios in the period of 2010–2050, estimation of travel volume demand is required. The steps to estimate the energy demand are illustrated in Figure 5. The GDP increased from 5,098 million USD in 1990 to 13,137 million USD in 2014 [41]. Population increased from 56.30 million persons in 1990 to 68.87 million persons in 2014 [42]. The estimation of energy demand in the transport sector can be obtained by multiplication of travel volume demand and fuel requirement in the transport.

4.2.2.2. Model of Thailand's industrial sector. The industries are classified based on the annual report of “Thailand energy situation”. There are nine sub-industries: food and beverage, textile, wood and furniture, paper and pulp, chemical, non-metallic, basic metal, fabricated metal and others as shown in Figure 6. Electricity is consumed through four electric devices, i.e., cooling, lighting, motor and others. Non-electricity, comprising coals, oil, natural gas and renewable energy, is consumed for producing heat. Each energy service consists of existing and efficient equipment.

Based on the bottom-up model, energy consumed at the end-use devices plays a major role in the assessment of energy demand in industries. However, only aggregated information of energy demand by sub-industry is reported and presented by Department of Alternative

Energy Development and Efficiency (DEDE). Steps in the projection of energy demand are shown in Figure 7.

The information on statistical energy consumption categorized by fuel type and industry is collected from the annual report of Thailand energy situation. The statistical GDP data are published annually by the Office of the National Economic and Social Development Board (NESDB), Thailand. GDP growth rate was forecasted at an average of 3.94 percent per year, which is the same figure used to estimate the future electricity demand in the PDP2015 [15]. The population statistics were published by NESDB. The World Bank estimated the average growth rates of coal, oil and natural gas prices during 2016–2025 at 3.81, 9.33 and 4.83 percent per year, respectively [43, 44, 45]. During 2026–2050, this study estimates average growth rates of coal, oil and natural gas prices at 2.34, 3.48 and 2.57 percent per year, respectively. Statistical and estimated renewable energy prices of wood, paddy husk and biomass are obtained from the Energy Policy and Planning Office (EPPO).

4.2.2.3. Model of Thailand's building sector. Buildings in Thailand are classified into eight types, including condominiums, offices, hotels, hospitals, department stores, schools, hypermarkets and miscellaneous. Electric devices in buildings include cooling, lighting, appliances, heating and others. Non-electricity in buildings, mainly LPG, is used to produce heat only. The electric heating devices are used only in condominiums as shown in Figure 8. Steps of the projection of energy demand in buildings are shown in Figure 9.

4.2.2.4. Model of Thailand's household sector. Households are divided into three main areas: Greater Bangkok, municipal, and rural areas. Households in the Greater Bangkok area consumed around 14 percent of total energy consumption in the household sector.

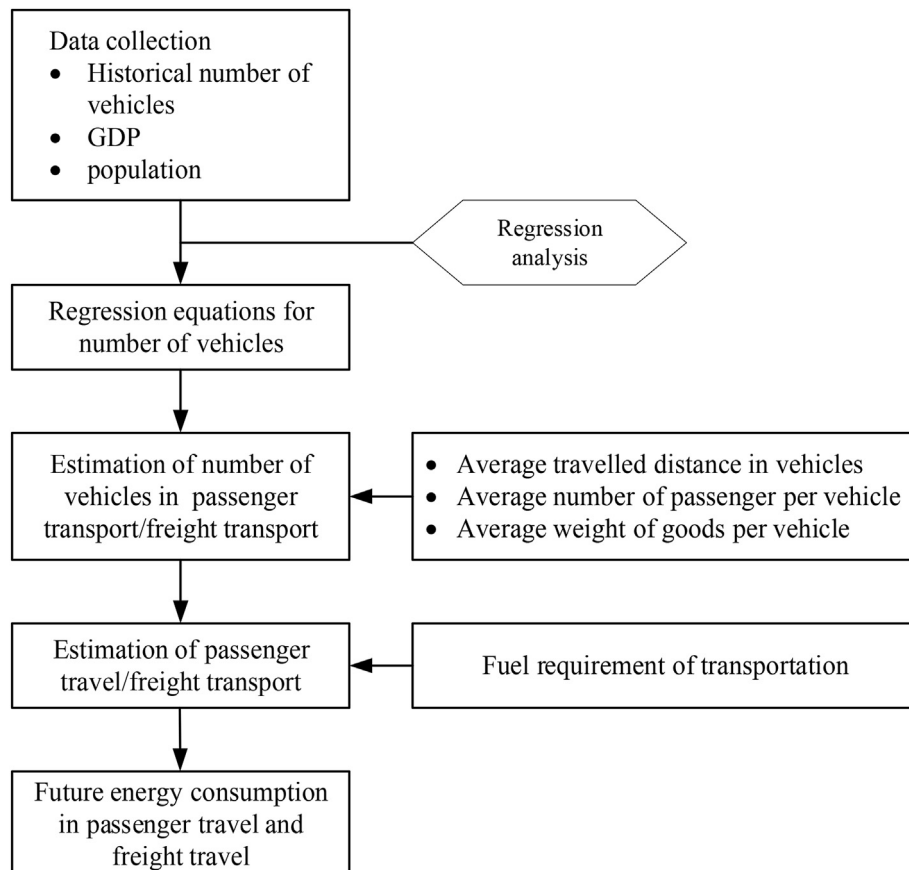


Figure 5. Steps of projection of energy demand in Thailand's passenger and freight transport.

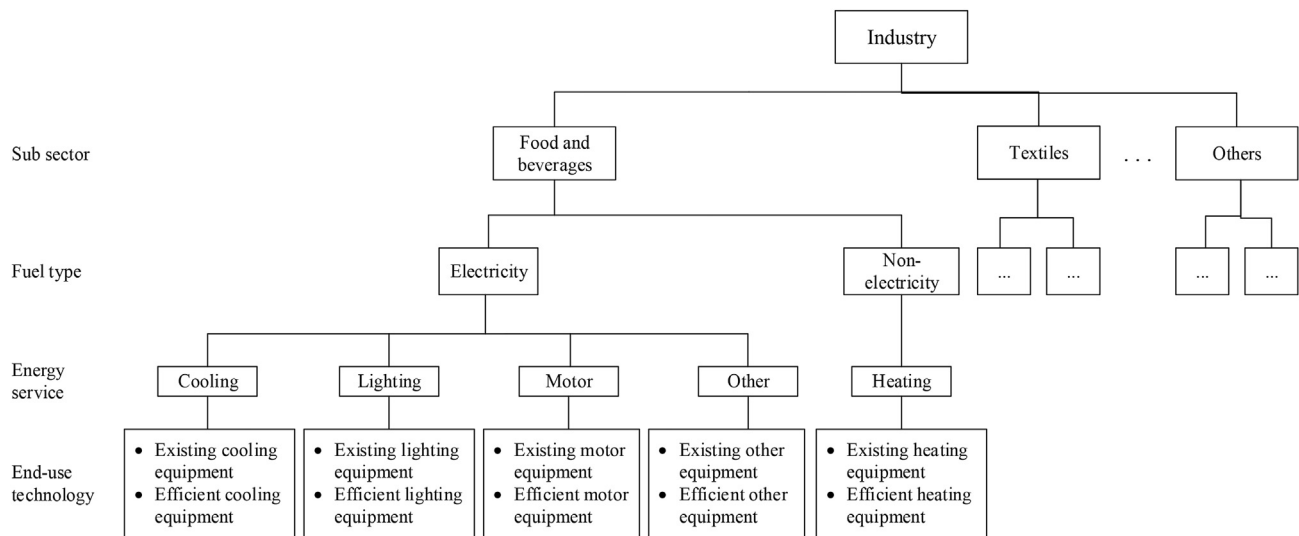


Figure 6. Structure of Thailand's industries in the LEAP model.

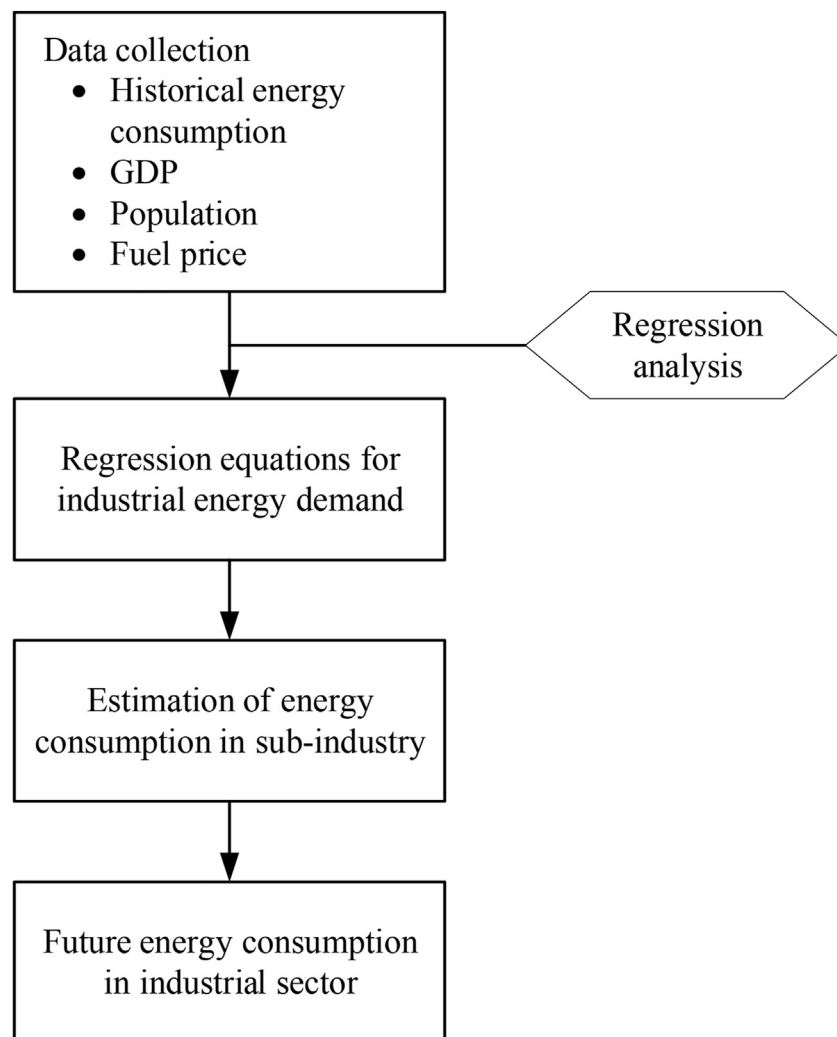


Figure 7. Steps of projection of energy demand in Thailand's industrial sector.

Electricity is used for heating, cooling, entertainment and other services. Lighting and cooking devices consume both electricity and non-electricity. There are four types of lighting devices i.e., compact

fluorescent, incandescent, fluorescent, and LED lighting. Kerosene lamps for lighting service were phased out in 2012. The end-use devices in the household sector are presented in Figure 10.

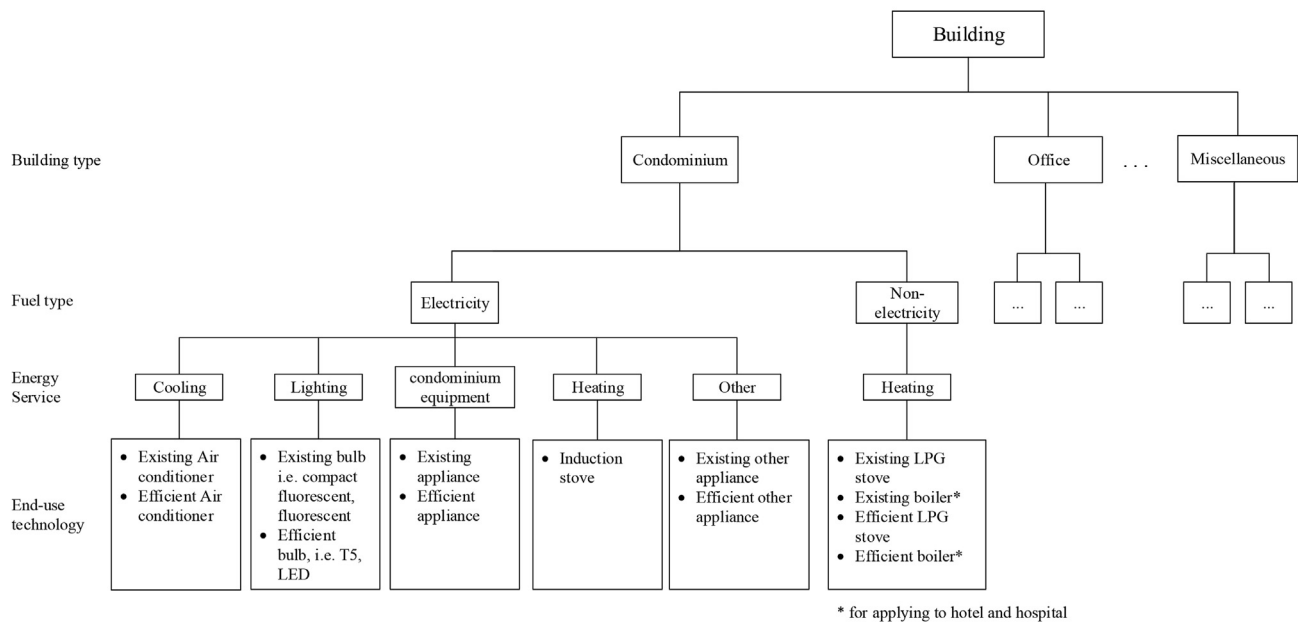


Figure 8. Structure of Thailand's building sector in the demand module of LEAP.

The number of households was obtained from the Department of Provincial Administration (DOPA). The number of households increased from 21.7 million in 2010 to 24.1 million in 2014. In this study, the growth rate of number of households is estimated to increase at 1.8 percent per year. Energy intensity in households can be determined by multiplication of number of appliances per household, usage hours of appliances and energy requirements of appliances as shown in Eq. (4).

$$Energy\ intensity = NO.\ of\ appliance \times usage\ hour \times Energy\ requirement\ of\ appliance \quad (4)$$

The number of appliances is reported annually by the National Statistical Office [46]. The usage hours and energy requirements in appliances are obtained from the Energy Policy and Planning Office (EPPO) [47]. The steps to estimate the future energy demand in households are presented in Figure 11.

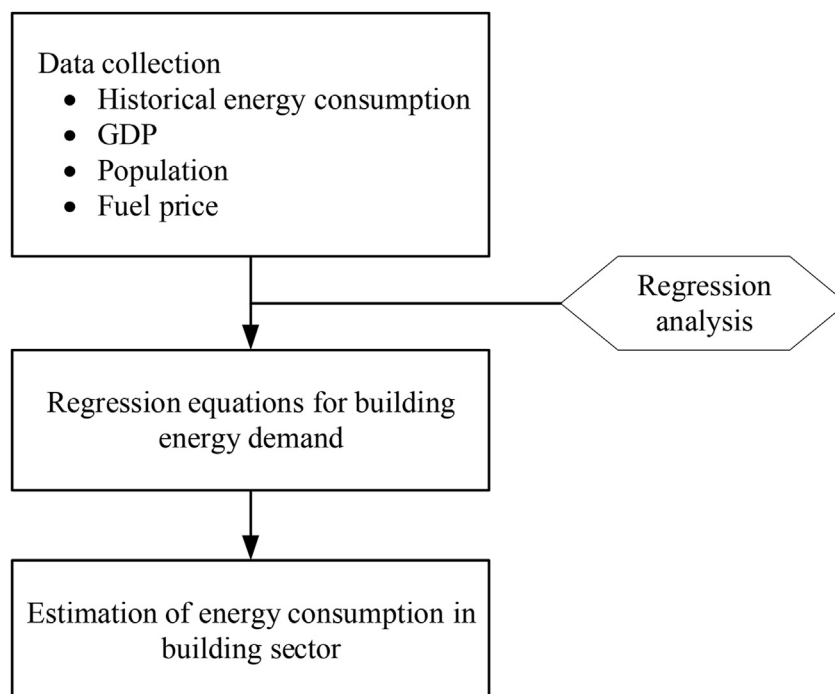


Figure 9. Steps of projection of energy demand in Thailand's building sector.

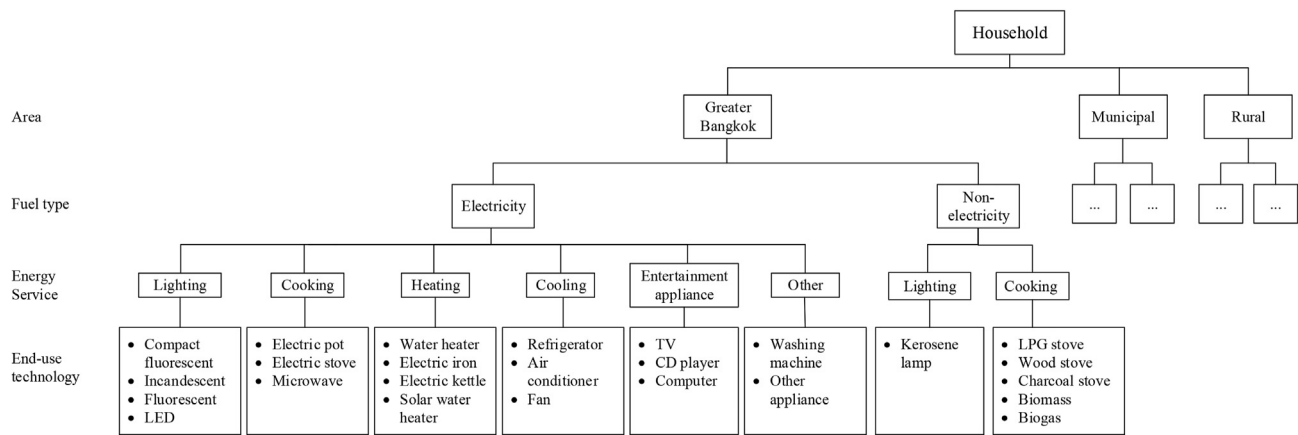


Figure 10. Structure of Thailand's households in the demand module of LEAP.

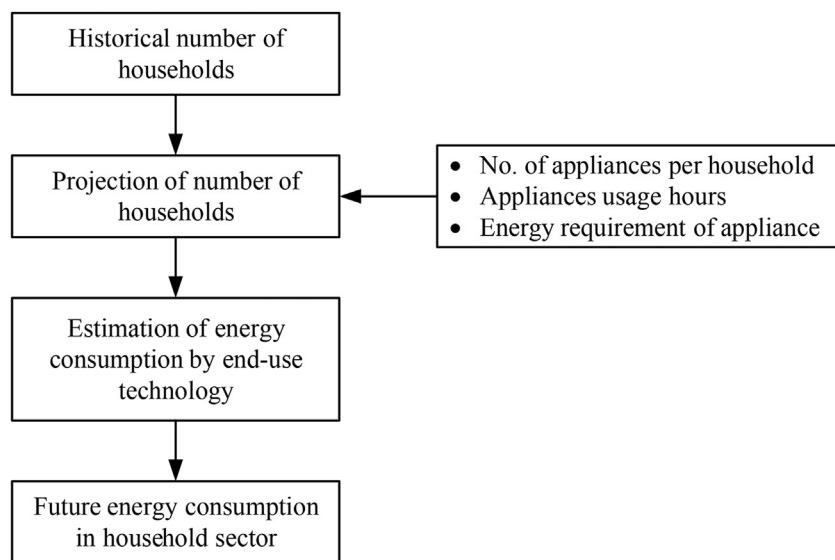


Figure 11. Steps of projection of energy demand in Thailand's households.

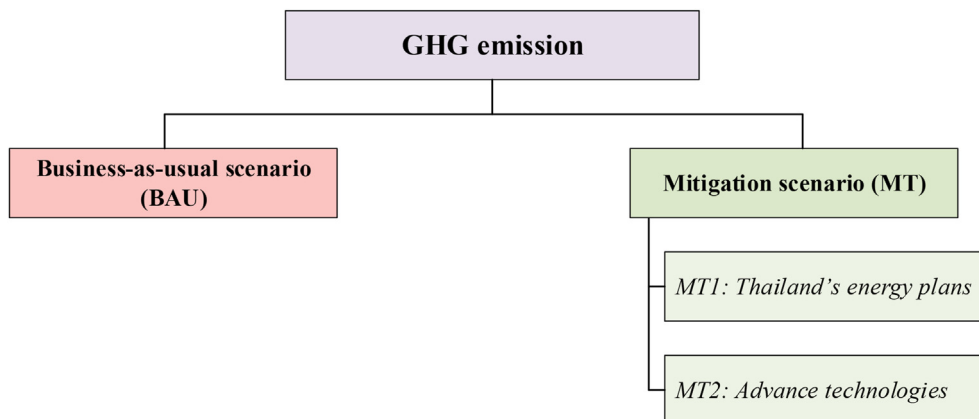


Figure 12. GHG mitigation scenarios in the study.

4.3. Scenario descriptions

The energy sector is divided into five sub-sectors, including the power sector, the transport sector, the industrial sector, the building sector, and

the household sector. Three scenarios, namely the Business-as-usual (BAU) scenario, the Mitigation 1 scenario (MT1) and the Mitigation 2 scenario (MT2), are used in assessment of GHG emission reduction during 2010–2050 (see Figure 12).

4.3.1. Business-as-usual (BAU) scenario

The BAU scenario is the base case without any policy consideration. The energy consumption patterns of all sectors are projected to 2050. In the BAU, energy consumption and GHG emissions were calibrated to match the conditions in the PDP2015, AEDP2015 and EEP2015 plans as well as the Thailand's NDC.

4.3.2. GHG mitigation scenarios

The mitigation scenarios are designed to assess GHG mitigation potential in Thailand. There are two proposed mitigation scenarios, the MT1 and the MT2 scenarios. Both scenarios are divided into two studied periods. The first period follows the time frame of 2015–2036 used in the AEDP2015 and EEP2015 plans. The second period is extended beyond 2036, which covers the time frame of 2037–2050.

4.3.2.1. MT1 scenario. In the period of 2015–2036, GHGs emission reductions under the AEDP2015 plan and the EEP2015 plan were assessed. There are no additional policies on GHG mitigation during 2037–2050. Therefore, GHG emission will be continued at the same share settings as in the period of 2015–2036. Details of the sectoral measures in the MT1 scenario are described below.

1. Power sector: In the MT1 scenario, six renewable energy technologies for power generation, i.e., MSW, small hydro, biomass, biogas, wind and solar will be promoted under the AEDP2015. The target of RE electricity will be 20 percent of total electricity generation in 2036. It is expected that the installed RE capacity will increase from 0.2 GW in 2010 to 16.8 GW in 2036 and 33.7 GW in 2050.

2. Transport sector: Biofuel is the key measure to be implemented in the transport sector under the AEDP2015 plan. In the EEP2015 plan, two main measures, i.e., energy efficiency improvement and development of double track and public railways will be implemented. Therefore, these measures are considered as GHG mitigation measures in the passenger transport sector during 2010–2036. Details of measures in the transport sector are as follows:

- i) **Implementation of biofuels.** The conventional gasoline will be replaced by gasohol, including E10, E20 and E85. The share of gasohol will be 20.0 percent of the total energy used in the transport sector in 2036. The conventional diesel will be replaced by biodiesel. The share of biodiesel will be 20.0 percent of the total energy used in the transport sector in 2036.
- ii) **Implementation of energy efficiency improvement in the transport sector.** Fuel economy of the vehicles will be improved drastically. Thus, it is expected that new vehicles will be more energy efficient than the conventional ones. The fuel requirement in sedans using gasoline and gasohol will be decreased by 50.0 percent in 2036. Likewise, fuel requirements in sedans using diesel and biodiesel will be decreased by 40.0 percent in 2036. The fuel requirement in vans using gasoline and gasohol will be decreased by 60.0 percent in 2036. Likewise, fuel requirements in vans using diesel and biodiesel will be decreased by 90.0 percent in 2036. The fuel requirement in pick-ups using gasoline and gasohol will be decreased by 35 percent in 2036, while fuel requirements in pick-ups using diesel and biodiesel will be decreased by 50 percent in 2036.
- iii) **Development of double track and public railways.** Under the current large investment in rail transport in Thailand, it is expected that the transport sector will have a significant modal shift from roads to rails. The share of the rail transport in 2036 will be increased by 15.0 percent from the BAU.

3. Industrial sector: In the AEDP2015 plan, the key measure in industries is the deployment of renewable energy. In the EEP2015 plan, five main measures comprising LED lighting, energy labeling, EERs, designated factories and monetary incentives will be implemented. Thus,

six measures in the industrial sector are considered to estimate GHG emissions during 2010–2036 (see Table S1 in supplementary table).

5. Building sector: Under the AEDP2015 plan, the key measure in the building sector is solar applications in cooling systems and water heating. Six measures in buildings comprising LED lighting, energy labeling, EERs, designated building, building energy code and monetary incentives will be implemented. Thus, total seven measures are assessed for GHG emission reduction in the building sector during 2010–2036. (see Table S2 in supplementary table).

6. Household sector: Under the AEDP2015 plan, there is only one measure on solar water heating applications in households. In the EEP2015 plan, three main measures comprising LED lighting, energy labeling and EERs will be implemented. Therefore, a total of four measures are analyzed to estimate the GHG emissions in households during 2010–2036. (see Table S3 in supplementary table).

4.3.2.2. MT2 scenario. In the MT2 scenario, GHG mitigation during 2010–2036 is the same as in the MT1 scenario. However, there are additional policies such as new and advanced technologies that are applied to the demand side during 2037–2050. New technologies refer to technologies that had not been considered before 2037. Advanced technologies refer to the technologies that have higher energy efficiencies than the conventional ones.

1. Power sector: GHG mitigation potential in the period of 2015–2036 is consistent with the MT1 scenario. But in the period of 2037–2050, the new and advanced technologies will be deployed, including geothermal and tidal energy, and hydrogen fuel cells. Geothermal is expected to be a future renewable energy resource in Thailand. The temperature of hot water is not so high and is classified as a low temperature source (the temperature is lower than 140 °C) [48]. However, future development of energy technology research could resolve this problem. Tidal energy presents a technological revolution with tremendous potential of power generation. The difference in water levels must be at least 5 m to produce electricity due to the limitations of the present technology [49]. Thus, tidal energy could be an additional opportunity in electricity generation technology in the future. Hydrogen fuel cell technology is an alternative solution for reducing GHG emissions [50]. Fuel cells are an important technology for converting hydrogen to power and heat through the electrochemical reaction of hydrogen with oxygen [51]. Carbon capture storage (CCS) [52] is another advanced technology that will be proposed to reduce GHG emissions. In this study, only CCS applied in coal and natural gas power plants is considered.

2. Transport sector: Details of measures during 2015–2036 are the same as in the MT1 scenario which follows the AEDP2015 plan. In the period of 2037–2050, the alternative energy, including E100, B10 and fuel cell, will be substituted for the conventional ones. E100 is pure ethanol. Many countries have produced and used ethanol as an alternative fuel in the internal combustion engine vehicles [53]. B10 is a biofuel produced from diesel blended with 10 percent of bio-oil by volume. Thailand has plenty of palm oil, especially in its southern part. Therefore, it has high potential to increase the proportion of bio-oil in diesel as an alternative fuel. The share of E100 and B10 in sedans will be increased by 0.1 and 4.9 percent in 2050, respectively (see Table S4 in supplementary table). The share of B5 will be increased by 37.9 percent in 2050 when compared to the BAU. In this study, the share of fuel cells in buses will be increased by 17.6 percent in 2050.

3. Industrial sector: In the MT2 scenario, the advanced technology will replace conventional electric devices in cooling and heating services and CCS technology will be deployed starting from 2037. The CCS technology in industries will be deployed only in the fossil-based heating service. The CCS technology in industry has been identified as the large-scale mitigation option available to deliver additional CO₂ emissions reduction that would be necessary to meet the global climate goal in 2050 [54]. In the MT2 scenario, it is expected that the share of advanced technologies in cooling and heating services will be increased by 25.7

percent in 2050. The CCS technology will be deployed in non-metallic, chemical, and paper and pulp sub-industries because these sub-industries are the main industrial fossil-fuel consumers. Thus, the share of CCS technologies in industries will be increased by 30.0 percent in 2050 when compared to the BAU.

4. Building sector: The advanced technologies in buildings will be deployed in cooling and heating services during 2037–2050. In the MT2 scenario, it is expected that the share of advanced technology in cooling services will be increased by 43.5 percent in 2050. However, the share of conventional and energy efficient devices will be decreased by 6.5 and 50.0 percent, respectively. For heating services, it is expected that the share of advanced technologies replacing the existing fossil-based technology will be increased by 42.5 percent in 2050 (see Table S5 in supplementary table).

5. Household sector: In the period of 2037–2050, GHGs mitigation potential in households will include the advanced technologies and biogas for cooking. The advanced technologies will be promoted in the cooling and heating services. Biogas for cooking is a type of biofuel which is naturally produced from decomposition of organic waste, including food scraps, animal waste and agricultural waste. Therefore, there is significant potential to use biogas as a substitute for LPG in cooking stoves. In the MT2 scenario, in Greater Bangkok and municipal area the conventional LPG stoves in 2050 will be replaced by efficient LPG stoves (50.0 percent) and advanced technologies (15.0 percent). In the rural area, biogas for cooking replacing conventional LPG stoves will be increased by 15 percent in 2050. Advanced technology refrigerators and air conditioners replacing conventional refrigerators and air conditioners will be increased by 15 percent in 2050. (see Table S6 in supplementary table).

4.3.2.3. Extended NDC scenario 2050. In this study, Thailand's first NDC target of 20 percent GHG emission reduction in 2030 is extended to 2050 using the same assumptions of share settings of the renewable energy technologies and energy efficiency of end-use devices in the power, the transport, the industrial, and the building sectors.

5. Results and discussion

5.1. GHG emission reduction

In the energy sector, GHG emissions in the BAU scenario were about 217,842.5 GgCO_{2eq} in 2010 and will increase 517,203.1 Gg CO_{2eq} in 2036 and 817,631.0 Gg CO_{2eq} in 2050, an average annual growth rate (AAGR) of 6.7 percent. The GHG emissions in the MT1 and MT2 scenarios will increase to 233,325.0 Gg CO_{2eq} in 2036 and GHG emissions will be 54.9 percent lower than the BAU. The GHG emission reduction of 54.9 percent in 2036 comes from measures in the EEP2015 plan (31.2%) and the AEDP2015 plan (23.7%). Thus, in terms of GHG emission reduction, energy saving measures are more cost effective than alternative energy technologies. In the period of 2037–2050, GHG emissions in the MT2 scenario will be lower than the MT1 scenario because of the deployment of advanced technologies and CCS. In 2050, GHG emissions in the MT2 scenario will be reduced by 107,549.8 Gg CO_{2eq} when compared to the MT1 and 553,277.0 Gg CO_{2eq} when compared to the BAU (see Figure 13).

Thus, promotion of higher energy efficient devices and acceleration of the deployment of cleaner technologies will result in lower GHG emissions. Specific results found in all sectors are as discussed in the following sections.

5.1.1. Power sector

In Figure 14, GHG emissions in the BAU scenario will increase from 87,777.5 GgCO_{2eq} in 2010 to 215,783.0 GgCO_{2eq} in 2036 and 348,703.6 GgCO_{2eq} in 2050. The deployment of renewable energy technologies for

electricity generation in the MT1 and MT2 scenarios will result in GHG emissions of 122,386 GgCO_{2eq} in 2036.

In the MT1 scenario, GHG emissions will be reduced by 144,099.7 GgCO_{2eq} in 2050 or 41.3 percent when compared to the BAU, while in the MT2 scenario GHG emissions will be reduced by 194,658.6 GgCO_{2eq} or 46.7 percent when compared to the BAU because of the deployment of advanced technologies in power generation, including geothermal, tidal and hydrogen fuel cell, and the CCS technology.

5.1.2. Transport sector

In the BAU scenario, GHG emissions in the transport sector in 2010 were about 57,301.2 Gg CO_{2eq} and will increase to 102,575.5 Gg CO_{2eq} in 2036 and 148,189 Gg CO_{2eq} in 2050, an AAGR of 3.9 percent. The measures implemented in the MT1 and MT2 scenarios follow the AEDP2015 and the EEP2015 plans during 2015–2036. The GHG emissions in the transport sector in the MT1 and MT2 scenarios will increase to 52,157.1 Gg CO_{2eq} in 2036 and GHG emission reduction will be 49.2 percent lower than the BAU. The reduction comes from improved fuel economy of vehicles (23.2%), the double track and public railway (16.6%), and promotion of alternative energy (9.4%).

In the period of 2037–2050, beyond the AEDP2015 and EEP2015 plans, GHG emissions in the MT2 scenario will be lower than the MT1 scenario due to deployment of gasohol E100 and biodiesel B10 in sedans and deployment of fuel cells in buses. GHG emissions in the MT2 scenario will be reduced by 77,026.6 Gg CO_{2eq} in 2050 when compared to the BAU (see Figure 15).

5.1.3. Industrial sector

In the BAU scenario, GHG emissions in industries in 2010 were 80,555.9 GgCO_{2eq} and will be increased by 222,520.3 GgCO_{2eq} in 2036 and 354,087.5 GgCO_{2eq} in 2050, an AAGR of 8.6 percent. The GHG emission in the MT1 and MT2 scenarios will be 123,784.5 GgCO_{2eq} in 2036 and GHG emission reduction account for 40.5 percent when compared to the BAU. The reduction comes from the monetary incentive (20.8 percent), designated factory (11.2 percent), and the deployment of renewable energy (8.5 percent).

In the period of 2037–2050, GHG emissions in the MT2 scenario will be lower than the MT1 scenario because of the implementation of advanced technology and deployment of CCS technology. GHG emission in the MT2 scenario will be reduced by 36,600.5 Gg CO_{2eq} when compared to the MT1 scenario and 199,085.6 Gg CO_{2eq} in 2050 when compared to the BAU (see Figure 16).

5.1.4. Building sector

In the BAU scenario, GHG emissions in the building sector were 29,971.1 GgCO_{2eq} in 2010 and will be increased by 72,977.8 GgCO_{2eq} in 2036 and 116,971.5 GgCO_{2eq} in 2050, an AAGR of 7.1 percent. GHG emissions in the building sector will increase to 36,915.8 GgCO_{2eq} in 2036 and GHG emission reduction will be 44.6 percent when compared to the BAU. The reduction comes from energy efficiency labelling (17.1%), building energy code (13.2%), designated building (6.7%), monetary incentives (5.1%), LED lighting (4.8%), EERS (2.1%), and deployment of renewable energy (0.4%). During 2037–2050, the GHG emissions in the MT2 scenario will be lower than the MT1 scenario due to deployment of the advanced technologies. GHG emissions in the MT2 scenario will be reduced by 62,989.4 Gg CO_{2eq} in 2050 when compared to the BAU (see Figure 17).

5.1.5. Household sector

In the BAU scenario, GHG emissions in the household sector were 23,248.7 GgCO_{2eq} in 2010 and will increase to 58,077.5 GgCO_{2eq} in 2036 and 102,577.5 GgCO_{2eq} in 2050, an AAGR of 7.6 percent. The GHG emissions in the MT1 and MT2 scenarios will increase to 52,813.2 GgCO_{2eq} in 2036 and GHG emission reduction will be 9.1 percent when compared to the BAU. The reduction comes from energy efficiency

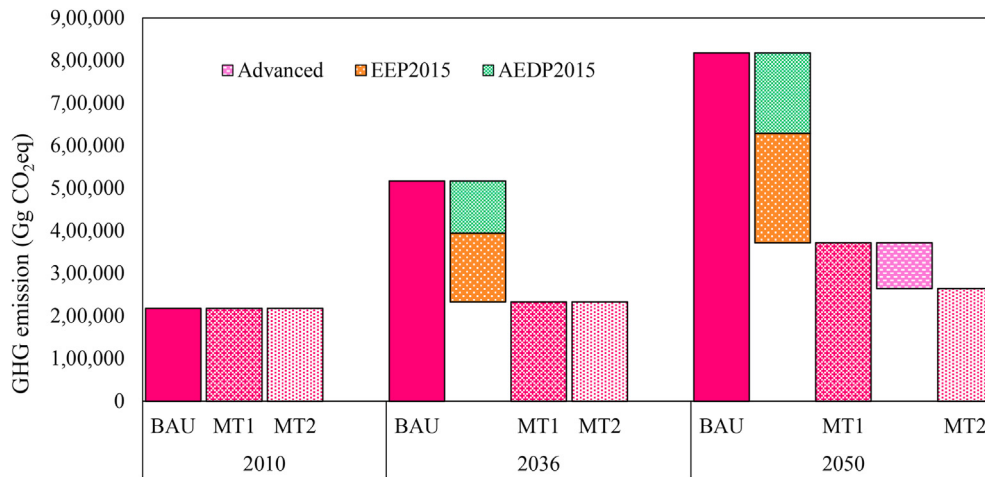


Figure 13. GHG emission reduction in the MT1 and MT2 scenarios in selected years.

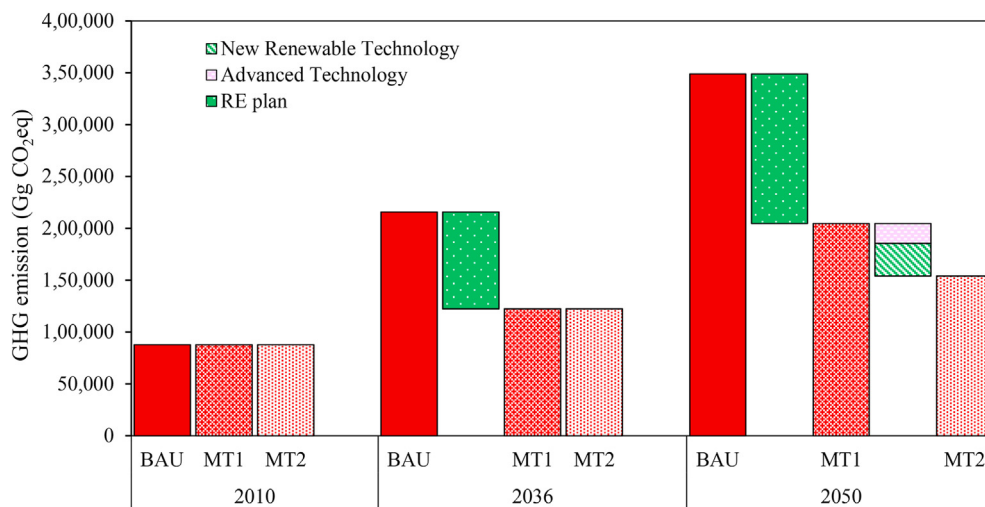


Figure 14. GHG emissions and reduction in the power sector in 2036 and 2050.

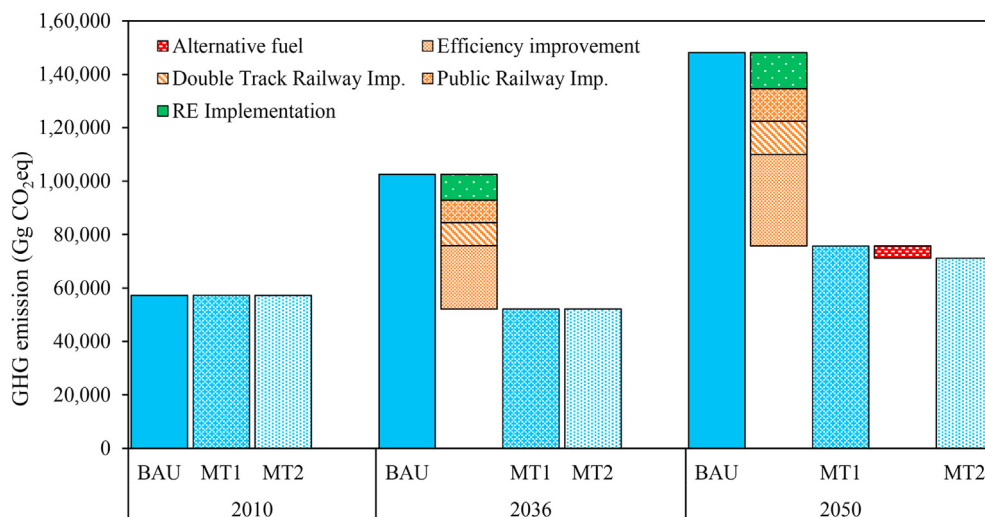


Figure 15. GHG emissions in the MT1 and MT2 scenarios in the transport sector.

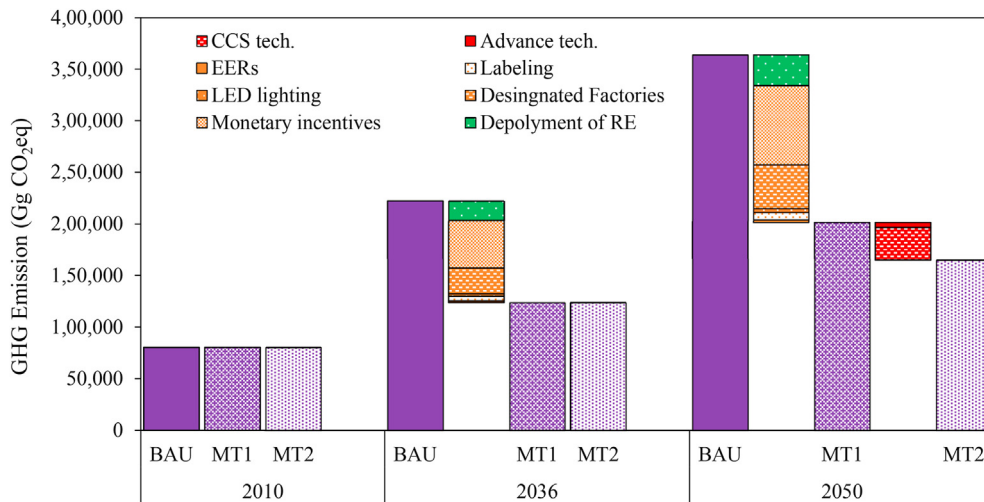


Figure 16. GHG emissions in the industrial sector in the MT2 scenario.

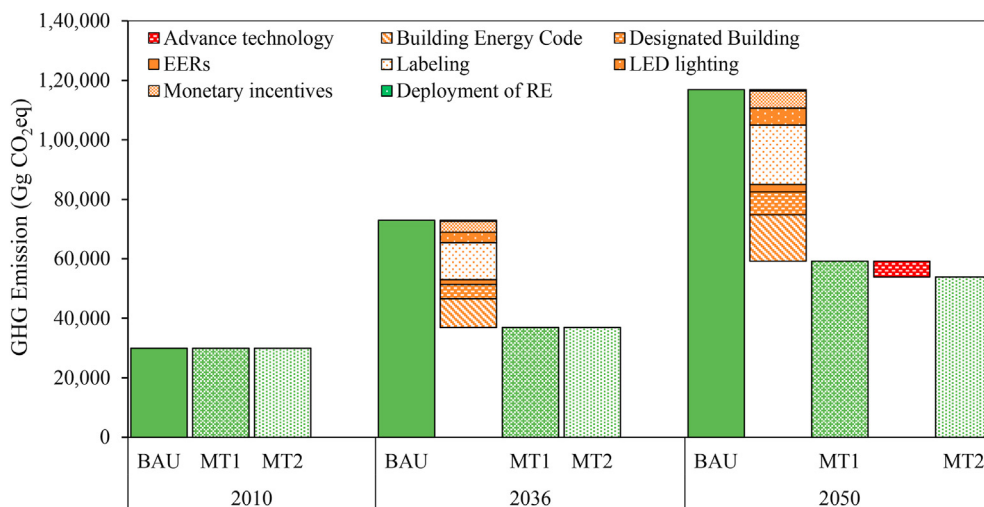


Figure 17. GHG emissions in the building sector in the MT2 scenario.

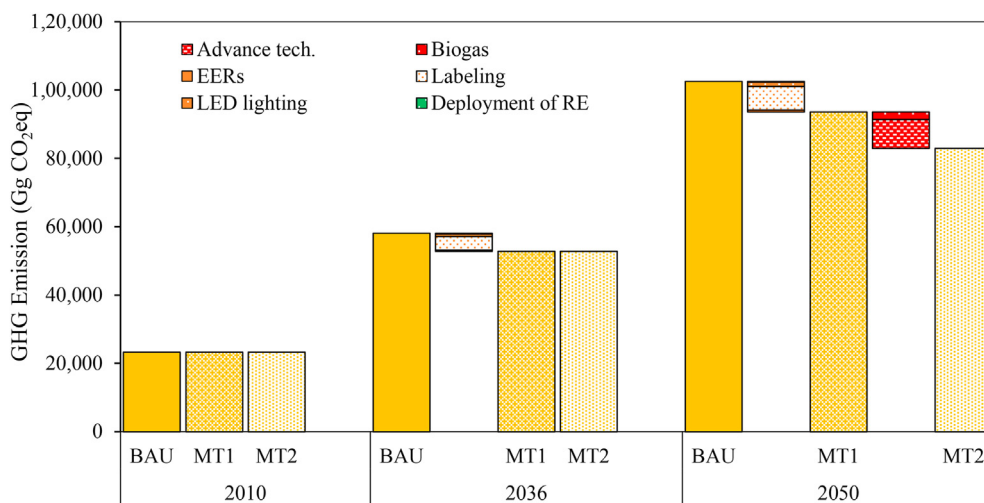


Figure 18. GHG emissions in the household sector in the MT2 scenario.

labelling (6.9%), deployment of LED lighting (1.4%), EERS (0.6%), and deployment of renewable energy (0.2%).

In the period of 2037–2050, the GHG emissions in the MT2 scenario will be lower than the MT1 scenario because of the deployment of advanced technology in electric cooling devices and deployment of biogas for cooking in households. GHG emissions in 2050 in the MT2 scenario will be reduced by 19,616.8 Gg CO_{2eq} when compared to the BAU (see Figure 18).

In terms of GHG emissions per capita, GHG emissions per capita in 2050 will be reduced by 54.5 percent in the MT1 scenario and 67.7 percent in the MT2 scenario when compared to the BAU scenario. In Thailand's NDC 2030, GHG emissions per capita in 2030 will be reduced by 30.4 percent when compared to the BAU.

5.2. Implication of GHG mitigation reduction vs Thailand's NDC target in 2030

In the BAU scenario, GHG emissions in 2050 will increase to 817,631 GgCO_{2eq}. In the MT1 and MT2 scenarios, GHG emissions reduction from the measures in the AEDP2015 and EEP2015 plans in 2030 will be 199,931 Gg CO_{2eq} when compared to the BAU. The GHG emission reduction of 199,931 Gg CO_{2eq} in 2030 is compared to the GHG emission in Thailand's NDC. In Thailand's first NDC to the UNFCCC, the nationwide GHG reduction target will be 113,000 Gg CO_{2eq} in 2030 when

compared to the BAU [25]. Thus, if targets in both RE and EE plans are achieved, Thailand's first NDC can be achieved successfully.

Then the GHG emission reductions of the extended NDC target in 2050 are projected. The GHG emissions in Thailand's extended NDC scenario in 2050 are estimated to be 569,099.3 GgCO_{2eq}. Thus, GHG emission reduction in Thailand's first NDC extension in 2050 will be 248,531.7 GgCO_{2eq} or a 30.3 percent reduction when compared to the BAU 2050 (817,631 GgCO_{2eq}).

Moreover, we assumed targets of the implementation of GHG mitigation measures in the AEDP2015 and EEP2015 plans can be achieved by 25, 50, and 75 percent in 2030 in both MT1 and MT2 scenarios. Then, GHG emission reductions were estimated. Figure 19 illustrates GHG emissions in 2030. The 25 percent achievement of both plans in 2030 will result in GHG emission reduction of 49,983.8 GgCO_{2eq}. The 50 percent achievement of both plans in 2030 will result in GHG emission reduction of 99,965.5 GgCO_{2eq}. Finally, the 75 percent achievement of both plans in 2030 will result in GHG emission reduction of 149,948.3 GgCO_{2eq} (see Figure 19).

Only the case of 75 percent achievement of the RE and EE plans will help Thailand to meet the GHG reduction target in Thailand's first NDC in 2030 (113,000 Gg CO_{2eq}). However, both AEDP2015 plan and EEP2015 plan have different promising GHG emission reductions. The full implementation of AEDP2015 will result in GHG emission reduction of 94,012.1 Gg CO_{2eq} in 2030 while the full implementation of EEP2015

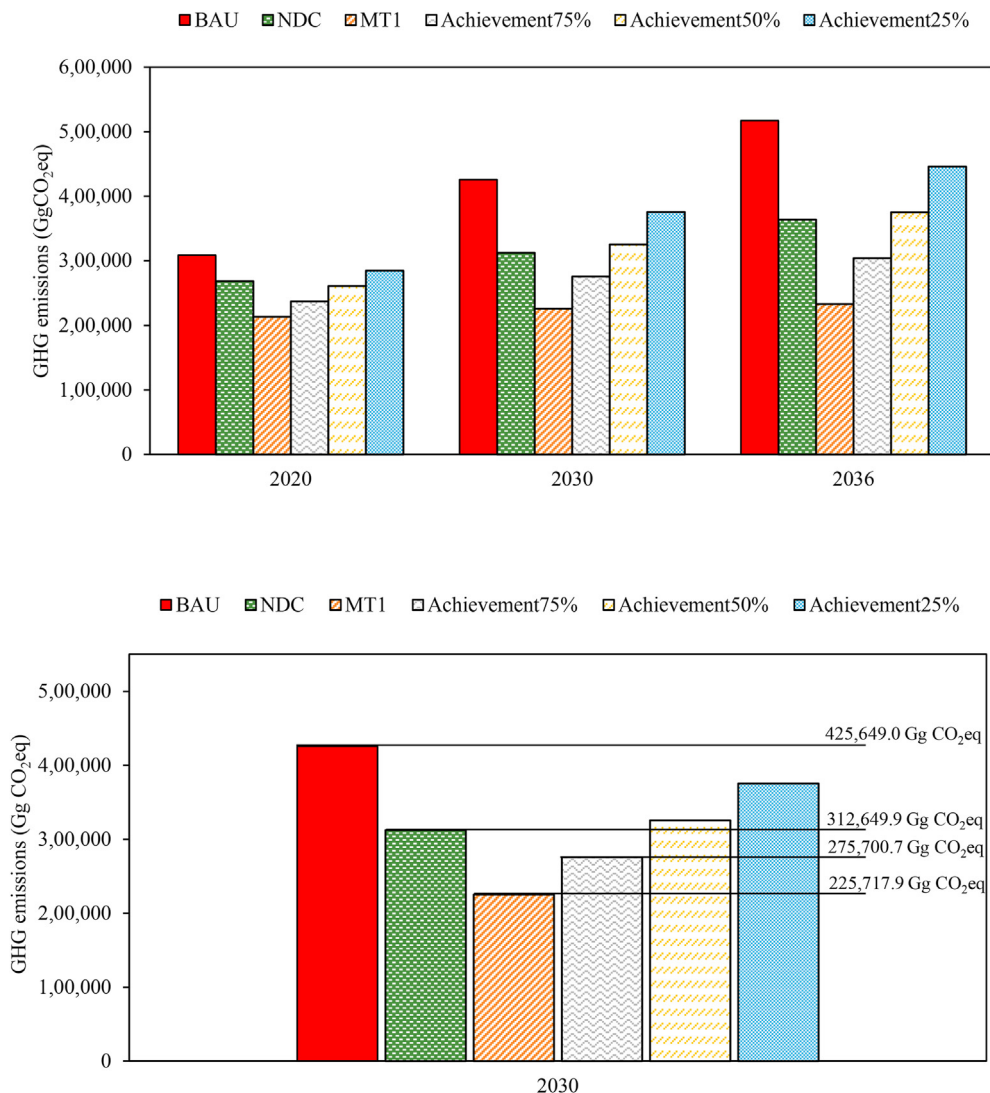


Figure 19. GHG emissions in Thailand's NDC 2030 and different levels of achievement targets.

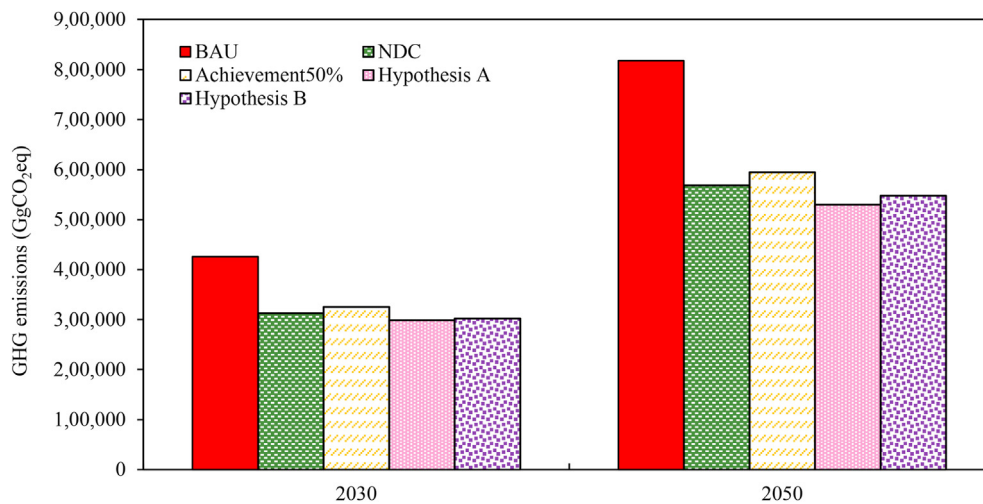


Figure 20. Comparison of the GHG emissions in the AEDP2015 and the EEP2015 plans vs NDC.

will result in GHG emission reduction of 105,919.0 Gg CO₂eq in 2030. Results reveal that measures in the energy efficiency plan will help reduce GHG emissions slightly more than the measures in the renewable energy plan.

Thus, the consideration of GHG emission reduction in the AEDP2015 plan and the EEP2015 plan is grouped into two hypotheses.

Hypothesis A. It is assumed that Thailand can achieve the AEDP2015 target by 50% and the EEP2015 target by 75% in 2030.

Hypothesis B. It is assumed that Thailand can achieve the AEDP2015 target by 75% and the EEP2015 target by 50% in 2030.

Figure 20 shows GHG emissions in the BAU and in Hypotheses A and B compared to the NDC target in 2030. In HypothesisA, GHG emission reduction in 2030 will be 126,445.3 Gg CO₂eq and 287,254.0 Gg CO₂eq in 2050. In HypothesisB, GHG emissions in 2030 will be 302,180.4 Gg CO₂eq and 547,726.0 Gg CO₂eq in 2050 corresponding to emission reductions of 123,468.6 Gg CO₂eq in 2030 and 269,905.0 Gg CO₂eq in 2050.

In conclusion, Thailand can achieve the GHG emission reduction target in its first NDC in 2030 (GHG emission target of 113,000 Gg CO₂eq) by using either the proportion of measures in HypothesisA (GHG emission reduction of 126,445.3 Gg CO₂eq) or HypothesisB (GHG emission reduction of 123,468.6 Gg CO₂eq.) It means that in 2030 the AEDP2015 target and the EEP2015 target must be achieved by at least 50% and 75%, respectively, or vice versa (see Figure 20).

5.3. Co-benefits of GHG emission reduction

The co-benefits are the indirect benefits apart from the main objectives. This study considers three indicators of co-benefits, including GHG intensity, energy intensity and diversification of primary energy demand (DoPED) [55]. The GHG intensity is described as GHG emissions against GDP. It relates to decoupling of the economy in connection with GHG emissions. Results of co-benefit analysis under the AEDP2015 and the EEP2015 plans are presented in Table 2. In 2050, the GHG intensity will be decreased by 16.5 percent when compared to 2010. Moreover, GHG intensities in the MT1 and the MT2 scenarios in 2050 will be reduced by 54.5 percent and 67.7 percent, respectively, when compared to the BAU. In addition, GHG intensity in Thailand's NDC 2030 will be decreased by 33.0 percent. In terms of diversification of primary energy demand, the DoPED in the MT1 scenario will be improved by 4.9 percent in 2030 and 8.1 percent in 2050. In the MT2 scenario, the DoPED in 2050 will be improved by 10.1 percent. Therefore, measures of GHG emission reduction in the AEDP2015 and EEP2015 plans will contribute co-benefits to the society resulting in sustainable development.

In this study, local air pollutants are presented in terms of NO_x, CO, MNVOC and PM_{2.5} (see Table 3). The largest source of local air pollutants is the transport sector. NO_x and CO are the major local air pollutants from diesel combustion in vehicles. Combustion of coal and lignite in the power sector and combustion of fuels in vehicles will be the major source of PM_{2.5}. The measures implemented in the AEDP2015 and the EEP2015 plans will help reduce NO_x, CO, MNVOC and PM_{2.5} (see Table 3). In

Table 2. Co-benefits under the AEDP2015 and the EEP2015 plans.

	EI (toe/1000 USD)	GHG intensity (kg CO ₂ eq/USD)	DoPED
Base year 2010	0.419	0.94	78.18
BAU 2030	0.388	0.86	81.51
BAU 2050	0.386	0.78	79.67
MT1 scenario			
MT1 2030	0.333	0.46	85.55
MT1 2050	0.342	0.36	86.15
Change of MT1 2030 compared to BAU 2030	-14.08%	-46.97%	4.95%
Change of MT1 2050 compared to BAU 2050	-11.44%	-54.51%	8.14%
MT2 scenario			
MT2 2030	0.333	0.46	85.55
MT2 2050	0.345	0.25	87.75
Change of MT2 2030 compared to BAU 2030	-14.08%	-46.97%	4.95%
Change of MT2 2050 compared to BAU 2050	-10.72%	-67.67%	10.14%

Table 3. Air pollutants in the MT1 and the MT2 scenarios in selected years.

Air pollutants	thousand tonne			
	2010	2020	2030	2050
BAU scenario				
NO _x	958.1	1,257.5	1,691.7	3,088.7
CO	2,443.9	2,994.8	3,568.6	5,958.8
NMVOG	459.3	563.5	673.3	1,125.3
PM _{2.5}	34.1	70.5	106.3	188.4
MT1 scenario				
NO _x	958.2	1,011.7	1,092.1	1,685.2
CO	2,443.9	2,304.7	2,171.0	2,894.3
NMVOG	459.3	432.5	409.2	545.6
PM _{2.5}	34.1	43.2	62.5	107.5
MT2 scenario				
NO _x	958.2	1,011.7	1,092.1	1,542.7
CO	2,443.9	2,304.7	2,171.0	2,501.8
NMVOG	459.3	432.5	409.2	471.6
PM _{2.5}	34.1	43.2	62.5	57.1

2050, the deployment of advanced technologies in the MT2 scenario will help in reducing larger local air pollutants by 12.6 percent when compared to the MT1 and 55.9 percent when compared to the BAU scenario.

6. Conclusions

In this study, the GHG emission reduction potentials in the energy sector were assessed under measures in the AEDP2015 and the EEP2015 plans. The GHG emissions in the transformation process and the demand side were assessed by using the LEAP model. In the BAU scenario, the GHG emissions will increase from 217,842.5 Gg CO₂eq in 2010 to 817,631.0 Gg CO₂eq in 2050. In 2050, GHG emissions in the MT1 scenario will be reduced by 54.5 percent when compared to the BAU. In the MT2 scenario, GHG emissions in 2050 will be reduced by 67.7 percent when compared to the BAU if advanced technologies such as higher energy efficient devices and CCS are deployed. The GHG emission reductions in the MT1 and MT2 scenarios will be 46.9 percent in 2030 compared to the BAU. The GHG emission reduction target in Thailand's first NDC was pledged at 20 percent of the BAU. Therefore, partial achievement of both AEDP2015 and EEP2015 plans was assessed against the NDC target in 2030. It was found that Thailand will be able to achieve its NDC target of 20 percent in 2030 if the target in the AEDP2015 plan and the EEP2015 plan can be achieved by at least 50% and 75%, respectively, or vice versa.

7. Policy implications

In this study, the implementation of the AEDP2015 and the EEP2015 plans would be the effective actions to fulfill the achievement of GHG emission reduction target in Thailand's first NDC in 2030. Advanced technologies such as CCS will be able to reduce substantial GHG emissions in 2050. The policy makers should accelerate the deployment of renewable energy and advanced technologies and promote higher energy efficient devices. The implementation of renewable electricity will result in lower energy intensity, higher energy security and better diversification of primary energy demand. Moreover, policy makers should be aware of the risks in the implementation of the renewable energy and energy efficiency plans. Finally, the barriers and limitations of the external factors that can influence the success of GHG emission reduction are concluded as follows:

- *Volatility of crude oil prices* will affect the retail prices of gasoline and diesel in the transport sector.
- *Preparedness of electric transmission lines to support renewable electricity technology* needs to be enhanced and completed [52, 56, 57]. In the past decade, renewable electricity generation has faced the limitation on transmission lines in the areas of renewable energy sources. If the smart grid is fully developed, it will help promoting renewable electricity.
- *The prices of biomass* will increase when the demand for biomass increases due to limited resources [58, 59]. It will affect the economics of renewable energy.
- *Siting of renewable energy resources* such as solar farms, wind farms and biomass power has impacts on land use. Thus, area zoning for appropriate and available energy resources will alleviate the problem.
- *Advanced technologies* need to be imported. The cost of imported advanced technologies will affect the investment and decision making.
- *Lack of knowledge in GHG emission reduction.* GHG mitigation actions will be successful when people in the country understand the consequence and impacts of GHG emissions and the climate change adaptation.

Declarations

Author contribution statement

Pemika Misila: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Pornphimol Winyuchakrit: Conceived and designed the experiments.

Bundit Limmeechokchai: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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