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Research Article

Energy demand modeling for low carbon cities in Thailand: A case study of Nakhon Ratchasima province

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Abstract. Nakhon Ratchasima is one of the northeastern cities which has been promoted as one of the low-carbon cities in Thailand. The study aims to evaluate policies and measures on greenhouse gas (GHG) emissions mitigation to meet the target at the provincial level. The Low Emissions Analysis Platform (LEAP) is used as a modeling tool to simulate energy demand for each economic sector. The 2019 data is set as a base year, using top-down and bottom-up approaches depending on the availability of data for the analysis. The model consists of two scenarios: (1) Business-as-usual (BAU) scenario and Low carbon scenario (LCS). Transport and industry sectors are the most energy-consuming and CO_2-emitting sectors in Nakhon Ratchasima Province. In the LCS case, the final energy demand and CO_2 emissions in 2050 will be reduced by about 40% compared to the BAU case. In addition, CO_2 emissions in Nakhon Ratchasima Province will peak around 2038, this is not the case with BAU. The study could predict future energy demand and propose a way forward to reducing GHG emissions at the provincial level.

Keywords: Energy demand modeling, Energy policy, Provincial energy modeling, Climate change, CO_2 emissions, LEAP, Low carbon city

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1. Introduction

Climate change is a most recognized global issue which needs all nations to address it together right away. Based on scientific studies by IPCC (2021), the total human-caused global surface temperature increased from 1850-1900 to 2010-2019 by about 1.07°C. This is approaching the range of 1.5-2.0°C rise which the Paris Agreement aims to limit (UNFCCC 2015). Energy consumption is the biggest source of global anthropogenic GHG emissions, responsible for 76% of worldwide. The energy sector includes transportation, electricity and heat generation, buildings, manufacturing and construction, fugitive emissions, and other fuel combustion (Ge *et al.* 2020). According to UN-Habitat, cities consume about 78% of the world's energy and produce more than 60% of greenhouse gas emissions (United Nations 2022). Moreover, by 2050 more than two-thirds of the world population is projected to live in urban areas (Ritchie and Roser 2018). To achieve national and international goals in reducing GHG emissions, all local communities or cities are really needed to take their own action against climate change.

Nakhon Ratchasima is one of the four cities in Thailand which are selected to set a low-carbon city target (UNDP/GEF and TGO 2020). Nakhon Ratchasima Province is in the northeastern part of Thailand and is the biggest province in terms of area and the second province in terms of population. With the location advantage as an important trade gateway to Indochina countries and in line with the East-West Economic Corridor (EEC), the role of Nakhon Ratchasima Province in the future will be more significant to Thailand's development strategy. This would cause a huge demand for energy in the future. This will be the cause of greenhouse gas (GHG) emissions and local air pollution as well. There are many attempts to tackle this issue, and the target of being a low-carbon city has been set for Nakhon Ratchasima city. Furthermore, Nakhon Ratchasima Province aims to be a smart city focusing on smart mobility as a high-speed rail system has been constructed and a light rail transit (LRT) system has been studied (OTP 2017). According to the aforementioned rationales, Nakhon Ratchasima Province is selected in this study to assess policies and measures for greenhouse gas emissions reductions to meet the target of a low-carbon city.

To evaluate proper GHG emissions reduction measures and policies in Nakhon Ratchasima Province, it is necessary to develop a provincial-level energy demand model. Many studies adopted various energy demand modeling tools to forecast energy demand in the future according to developed scenarios, for example, Chunark *et al.* (2015), Klungboonkrong *et al.* (2017), Fungtammasan *et al.* (2017), Wangjiraniran *et al.* (2017), Emodi *et al.* (2017), Chaichaloempreecha *et al.* (2019), Hooman (2019), Hu *et al.* (2019), Misila *et al.* (2020), Lunsamrong and Tippichai (2022), and Pongthanaisawan *et al.* (2023). In this study, the Low Emissions Analysis Platform (LEAP) is employed to forecast energy demand in each economic sector of Nakhon Ratchasima

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Province up to the year 2050 in two different scenarios, namely, Business as Usual (BAU) and a Low Carbon Scenario (LCS). The results under two scenarios and the associated assumptions used in the model are discussed.

2. Thailand's Efforts against Climate Change

Thailand has reformed its national planning structure by initiating a long-term national strategic plan for 20 years as the National Strategy Act B.E. 2560 in 2017 (NESDC 2017). This national strategic plan will be an umbrella for four traditional 5-year national economic and social development plans. This is to ensure continuous implementation of the national strategic plan. There are other national and master plans such as National Energy Plan and NDC Roadmap which aim to reduce GHG emissions aligning with Thailand's Nationally Determined Contribution (NDC).

2.1 The 20-year national strategic plan

The National Strategy (2018-2037) is the country's first national long-term strategy developed pursuant to the Constitution. It is to ensure that the country achieves its vision of becoming "a developed country with security, prosperity, and sustainability in accordance with the Sufficiency Economy Philosophy" with the ultimate goal being all Thai people's happiness and well-being (NESDC 2017). The Strategy covers six areas which include security, competitiveness enhancement, human capacity development, social equality, eco-friendly growth, as well as rebalancing, and improving public sector management. The Strategy is well-established along with the Sustainable Development Goals (SDGs) of the United Nations and covers all 17 Goals. The Pillar 5 Eco-friendly growth focuses on combating climate change and covers 9 of 17 SDGs (MFA 2018).

2.2 The 5-year national economic and social development plan

The National Strategy is to be translated into action through the five-year National Economic and Social Development Plans, commencing with the 12th Plan (2017-2021, and extended to 2022). Each strategy within the 12th Plan lays out development agendas as well as flagship projects which need to be accomplished to prepare human capital, society, and the economy for future challenges (NESDC 2016). The plan aims to preserve and restore natural resources and environmental quality to support green growth and enhance the quality of life of Thai citizens. One of the 10 Strategies under the plan is for environmentally friendly growth for sustainable development. To do so, several approaches are proposed such as promoting sustainable consumption and production, promoting GHG reduction, and raising adaptive capacity to climate change. Also, indicators such as GHG emissions reduction compared to the baseline scenario for 2030 and the unit cost of GHG emissions reduction were set up to monitor the plan.

Currently, the Office of the National Economic and Social Development Council is developing the 13th Plan (2023-2027) which plans to release in October 2022. One of the 13 Marks under the 13th Plan called 'Circular economy and low-carbon society' aims to add value from a circular economy and efficient use of resources and create a low-carbon and sustainable society. The proportion of renewable energy consumption will increase by no less than 24%, at the end of this plan.

2.3 National energy plan

Thailand had an individual energy plan for the power development plan, renewable energy development plan, and energy efficiency development plan for short and medium-term plans since the 2000s such as the Power Development Plan 2004-2015 (PDP2004), the 3rd Phase of Energy Efficiency Plan 2005-2011, the 15-Year Renewable Energy Development Plan 2008-2022 (EPPO 2004; DEDE 2008). In 2011, the first long-term plan, the Thailand 20-Year Energy Efficiency Development Plan 2011-2030 was developed and the target of 25% energy intensity reduction compared with the 2005 base year was first-time set, in line with the APEC-wide regional goal agreed upon by APEC Leader in 2007 (EPPO 2011). Later, there was an evolution of Thailand's energy plans, all energy development and management plans were integrated into one plan called 'Thailand Integrated Energy Blueprint (TIEB)'. TIEB consisted of five energy plans namely Power Development Plan (PDP), Energy Efficiency Plan (EEP), Alternative Energy Development Plan (AEDP), Gas Plan, and Oil Plan (EPPO 2016; Sutabutr 2016). All plans are in the same 20-year timeframe, 2015-2035.

Currently, the Ministry of Energy is revising a National Energy Plan. The National Energy Policy Council (NEPC) approved the national energy plan framework which has established policy guidelines in the energy sector with the goal of supporting Thailand to be able to move toward clean energy and reduce carbon dioxide emissions to zero (Carbon Neutrality) within 2065-2070 with the following important resolutions (EPPO 2021):

- Increase the proportion of new electricity generation from renewable energy, not less than 50 percent, considering the cost of long-term energy storage systems.
- Change the use of transportation to green electricity with electric vehicle technology (EV) according to a policy called 30@30, i.e., increasing the share of EV productions to 30% by 2030.
- Improve energy efficiency by more than 30% by using modern energy management technologies and innovations.
- Restructure the energy industry to support the trend of energy transition according to the 4D1E guidelines, i.e., reducing carbon dioxide emissions in the energy sector (Decarbonization); the utilization of digital technology to manage energy systems (Digitalization); decentralizing power generation and infrastructure (Decentralization); regulatory improvements to support modern energy policy (Deregulation); changing the form of energy use to electrical energy (Electrification).

It notes that the net-zero carbon emissions target for the period (2065-2070) depends on technological change factors and financial support. The total framework of the National Energy Plan which includes the newly revised PDP, EEP, AEDP, Gas Plan, and Oil Plan is expected to be implemented in 2023.

2.4 Thailand's NDC roadmap and LT-LEDS

Thailand has officially recognized the climate change issue as a national agenda since 2015. This enables relevant agencies with supported budgets to pursue greenhouse gas reduction targets and climate change action (ONEP 2021). The Office of Natural Resources and Environmental Policy and Planning (ONEP), Ministry of Natural Resources and Environment is assigned as the main organization to prepare a roadmap on GHG emissions reduction, which specifies the guidelines and measures in detail together with relevant sector agencies such as Energy Policy and Planning Office (EPPO), Ministry of Energy, the Office of Transport and Traffic Policy and Planning (OTP), Ministry of Transport.

Table 1
Projects related to the reduction of greenhouse gas emissions

Title	Activities/Expected Results
Improving the lighting system for wastewater treatment ponds	Improve the wastewater treatment and roadside fences' lighting system by replacing 234 lamps with LED bulbs.
Low-carbon urban development through sustainable urban development	Together with the Thailand Greenhouse Gas Management Organization (TGO) and the United Nations Development Program (UNDP) organized 4 types of activities: • Energy efficiency of the household sector • Improving the water supply system • Enhance the potential of department stores to reduce energy consumption • Study the economic value lost from traffic congestion in the municipality
Promoting participation according to the zero waste management approach	• Organize activities to promote waste segregation at the source with participation in the community • Campaign for toxic waste separation and follow up on waste separation in communities or other relevant target areas by the year 2019, totaling 17 locations
Waste sorting within the schools	• Organize training workshops on waste separation for environmental protection in at least 5 schools/year • Organize a campaign to raise awareness of sorting, reducing waste and making use of solid waste in schools every year • Follow up and evaluate the sorting operation activities

Sources: Derived from Nakhon Ratchasima City, GEF, TGO, and UNDP (2020)

Thailand has submitted updated nationally determined contributions (NDC) to the UNFCCC, underscoring the country's commitment to reducing greenhouse gas emissions by 20% from BAU levels (as of 2005) by 2030. It added that the target could be increased to 25 percent if it was supported to access technology developments, technology transfer, funding sources, and adequate capacity building. It also emphasized the role of cooperation in international markets as fundamental in contributing to the reduction of greenhouse gas emissions and sustainable development.

In addition, Thailand has submitted its long-term low greenhouse gas emission development strategy (LT-LEDS) to UNFCCC in October 2021, as the basis for further promotion of the NDC. Thailand's LT-LEDS set clear targets and measures to implement to achieve its net-zero GHG emission. Firstly, Thailand aims to reach its peak GHG emissions in 2030 at approximately 370 $MtCO_2eq$. Secondly, Thailand's net greenhouse gas emissions are projected to be approximately 200 $MtCO_2eq$ in 2050, which is consistent with the global 2-degree pathway. The main GHG mitigation measures identified in Thailand's LT-LEDS focus on the energy and transport sectors. Measures identified in the energy sector include energy efficiency improvement, technology switching, and the adoption of renewable energy and carbon capture and storage (CCS). In the transport sector, mitigation measures include modal shifts, energy efficiency improvement, and the promotion of new, efficient, vehicle fleets (MONRE 2021).

Based on the LT-LEDS preparation, Thailand's Prime Minister Prayut Chan-o-cha announced at COP26 that Thailand will accelerate greenhouse gas mitigation targets, joining global communities in keeping the global temperature rise below 1.5 °C to tackle the climate crisis. Thailand aims to reach carbon neutrality by 2050, and net-zero greenhouse gas emissions by or before 2065. With full and equal financial and technological support including capacity building from international cooperation and mechanisms under the framework of the Convention, Thailand will be able to raise our NDC to 40%, bringing Thailand's net greenhouse gas emissions to zero by 2050.

2.5 Nakhon Ratchasima city's related projects and policies

The development plan of Nakhon Ratchasima City Municipality for 2018-2022 aims at natural resource management and reducing greenhouse gas emissions in order to achieve sustainable development (Nakhon Ratchasima City, GEF, TGO, and UNDP, 2020). Table 1 shows the selected projects related to the reduction of greenhouse gas emissions in Nakhon Ratchasima Municipality.

Furthermore, Nakhon Ratchasima Province (2020) sets the purpose of a "Smart City" which aims at energy efficient and environmentally friendly city towards the dimension of sustainable development. The initiative will integrate city planning and infrastructure of smart technology to create a green value chain in the province. There are 7 pillars of the smart city to be implemented during 2019-2028 as follows.

- Smart Mobility focuses on solving traffic problems with intelligent lighting controls and linkages with CCTV cameras. Including the development of public transportation to be convenient and safe. In the long run, it will focus on mass transit systems, and light rail transit systems to accommodate future traffic problems.
- Smart Environment focuses on integrated waste management, covering both the source, midway, and destination, as well as improving the quality of water sources that have deteriorated by controlling and monitoring wastewater discharge into public water sources.
- Smart Living promotes a safe and healthy city with quick and easy access to healthcare facilities. There is an area for exchanging and learning activities together.
- Smart Energy focuses on energy efficiency, reducing unnecessary energy consumption, and promoting the use of renewable energy in the area such as solar energy, wind energy, biogas, etc.
- Smart Economy promotes Nakhon Ratchasima Province to be the center of the economy, a modern investment city, both the agricultural and industrial sectors. There is support for the startup ecosystem to develop the city into a convention center. and the Northeastern Exhibition Center.
- Smart People supports increasing the potential of the education system by providing people with access to learning centers and also pays attention to depression problems that may occur in people.
- Smart Governance focuses on data management and intelligent services. A central database system that

people can easily access and have updated information. This can be used to verify the transparency of government agencies.

3. Methods

In this study, the LEAP model was adopted to forecast the provincial energy demand and greenhouse gas emissions in Nakhon Ratchasima, Thailand between the years 2020 and 2050 to move toward a low-carbon city and meet the target of Thailand's Nationally Determined Contribution (NDC).

3.1 Study area

Nakhon Ratchasima Province locates in the northeastern region of Thailand and has an area of 20,494 square kilometers. There are 77 provinces in Thailand. Nakhon Ratchasima is the 2nd most populous in the country and the first in the northeast region. In 2020, a total of 2,628,602 people were men; 1,291,880 (49.1%) were female; 1,336,722 (50.9%) (DOPA, 2020). In 2019, the average per capita GPP was 121,068 Baht/person/year, with the average per capita income ranked 2nd in the Northeast and 34th in the country. The province's key economic conditions depend on the industrial sector, agriculture, and retail trade (NESDC, 2019). The final energy consumption in Nakhon Ratchasima in 2020, obtained from the Ministry of Energy, was 818.6 ktoe. The industry sector is the most energy-consuming sector with 378.4 ktoe (46.3%), followed by the transport sector (42.0%) and the building sector (7.3%), respectively (MOEN, 2020).

3.2 Data Collection and Modeling Approaches

Data used in the study were collected according to economic sectors namely the household sector, building sector, industry sector, transport sector, and agricultural and other sectors. Data needed in each sector is depending on the modeling approach. The transport sector was modeled by using a bottom-up approach while the building sector, industry sector, and agricultural and other sectors were modeled by using a top-down approach. The household sector was a kind of hybrid approach. Data and type of modeling by sector are shown in Table 2.

As shown in Table 2, modeling approaches for each economic sector are different. The transport sector was the most available data, the bottom-up approach was employed. Modeling for the transport sector was based on the numbers of vehicle registration and sales categorized by vehicle technology and fuel which are available on the website of the Department of Land Transport (DLT 2021). Detailed data on the number of devices/equipment and technology for building, industry, agriculture and other sectors were not available, the top-down approach was employed. Data for the household sector was in between since EPPO (2017) conducted a study to investigate energy consumption by appliances for urban and rural households. However, there is no information on the number of appliances. Modeling techniques for each sector are explained as follows.

3.2.1 Transport sector

As mentioned, the transport sector data is the most available therefore the bottom-up approach is adopted. Also, energy demand and GHG emissions from the transport sector are the most significant and new technologies for vehicles can be introduced widely, therefore the bottom-up approach for the transport sector is most suitable for analysis. Principles regarding the transport sector modeling are as follows.

- *Vehicle ownership*

A vehicle ownership curve is a key concept to estimate the number of vehicles in each country. Specifically, there is a saturation number of vehicles in each country to understand what is a maximized number of vehicles in the country. It is obvious that the number of vehicles in developed countries has been saturated. For example, in the United States, vehicle ownership is about 800-900 vehicles per 1,000 persons and has not increased for many years. In the case of Thailand, in 2020, vehicle ownership is about 200 vehicles per 1,000 persons. However, it doesn't mean that vehicle ownership in Thailand will increase up to 700-800 like in the US or Canada. Each country has different characteristics which can be described by a Gompertz Function (Dargay *et al.* 2007) as follows.

$$V_t = \gamma e^{\propto e^{\beta GDP_t}} \quad (1)$$

where: V_t is vehicle population at time t, γ is the saturation of vehicle ownership, α and β are negative parameters defining the shape, or curvature, of the function.

Vehicle ownership is one of the most important indicators to track a country's economic development which is measured in the number of vehicles per 1,000 persons (Sillaparcharn 2007; Pongthanaisawan and Sorapipatana 2010; Wu et al 2014). Table 3 shows the vehicle ownership and vehicle saturation of the selected APEC economy members between 2013 to 2040.

- *Vehicle stock turnover analysis*

In principle, the number of vehicle sales can be determined by using Equation (2). It is equal to the number of vehicle populations that should be in year t (based on the vehicle ownership model) minus a surviving stock which is the

Table 2
Data and type of modeling by sector

Sector	Type of modeling	Data
Transport	Bottom-up	Vehicle registration by technology and fuel type; vehicle sales by technology and fuel type; vehicle age distribution; fuel economy; vehicle survival rate; vehicle kilometer-traveled; fuel economy, energy efficiency improvement; etc.
Household	Hybrid	Numbers of urban and rural households; energy consumption per household for cooking, lighting, air conditioning, refrigerators, and other purposes; rate of growth in energy consumption; improvement in energy efficiency, and so on.
Industry, Building, Agriculture and others	Top-down	Sectoral value-added, energy consumption by fuel type, energy efficiency improvement, etc.

Table 3
Vehicle ownership and saturation of the selected APEC economy members, 2013-2040

	Vehicle/10000 people				Vehicle saturation
	2013	**2020**	**2030**	**2040**	
Australia	706	731	753	767	780
Canada	646	679	709	737	780
Chile	226	306	382	425	503
China	90	195	271	313	320
Indonesia	84	146	266	385	470
Japan	603	613	623	626	627
Malaysia	427	516	584	608	617
The Philippines	38	45	65	100	410
Russia	321	385	456	511	600
Singapore	163	165	167	168	170
Thailand	198	275	403	492	540
United States	812	820	834	846	870
Viet Nam	18	27	59	124	320

Source: Derived from APERC (2016)

combination of the number of vehicle stocks last year and the number of vehicles retried.

$$Vehicle\ Sales_t = Expected\ Stock_t - (Vehicle\ Stock_{t-1} - Vehicle\ Retirement_{t-1}) \quad (2)$$

Vehicle retirement depends on vehicle profile or vehicle age distribution and survival rate. Vehicle age distribution for each vehicle type was obtained from the statistical data from DLT, while the survival rate is an exponential curve that can be adjusted in order to get the number of vehicles in line with the statistical data. Fig. 1 shows an example of vehicle age distribution and Fig. 2 shows an example of survival curve for passenger cars.

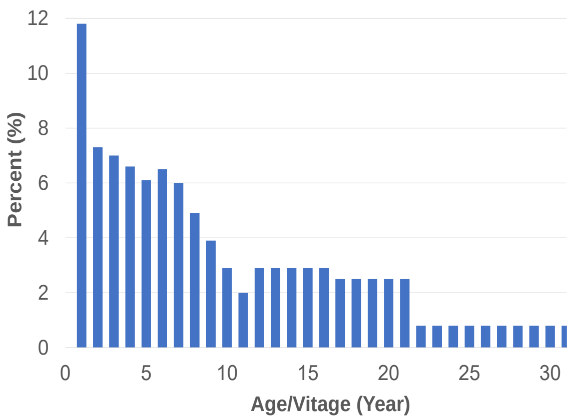

Fig. 1 Example of the vehicle age distribution for passenger cars in 2010

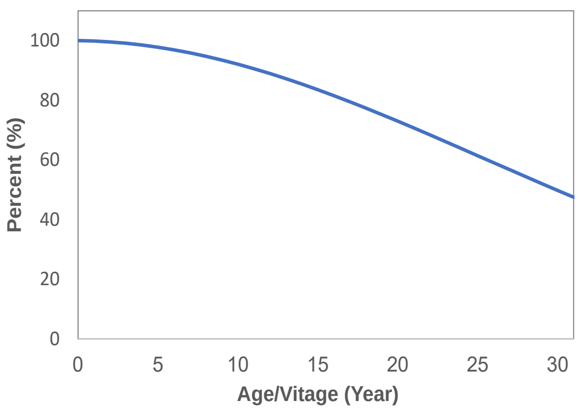

Fig. 2 Example of the survival curve for passenger cars

Table 4
Fuel and technology applicability according to vehicle types

		Gasoline *	Diesel*	LPG/ CNG	Hybrid	PHEV	BEV
Two and three wheels	Motorcycle	●			●		●
	Motorcycle taxi	●					●
	Tuk tuk			●			●
Light duty vehicles	Passenger car	●	●	●	●	●	●
	Pickup		●				●
	Taxi	●	●	●	●		●
Heavy duty vehicles	Bus		●	●	●		●
	Truck		●	●			
	Tractor		●				

Remark: ● indicates that fuel and technology is applicable.
* includes biofuels, i.e., ethanol and biodiesel.

The share of new vehicle technologies will be depending on the consumer's choice which will be affected by policy from the government. However, in this study, the share of vehicle sales technologies will capture a recent policy from the government which aims to promote electric vehicles in Thailand. Specifically, the 30@30 policy aims to increase the share of electric vehicle production up to 30% by 2030. A stock turnover approach is suitable for capturing the changes in new vehicle technologies in the total stock of in-use vehicles. Electric vehicles will take some time to replace the conventional internal combustion engine (ICE) vehicles and deliver an impact to energy consumption and GHG emissions reductions. However, policies from the government could accelerate the penetration of electric vehicles to replace ICE vehicles faster such as incentives for electric vehicle purchasing and scrapping programs for old vehicles.

Fuel and technology of vehicle types considered in the study are shown in Table 4. Fuel economy and vehicle kilometer traveled are two flexible parameters that can be used as calibrating factors for equalizing total energy demand for each fuel type with the base year's consumption.

3.2.2 Household sector

Energy demand of the household sector is calculated according to household characteristics, i.e., urban and rural. There are five energy service demand for households sector including; (1) cooking, (2) lighting, (3) refrigeration, (4) air conditioning, and

Table 5
Energy type applicability according to end use of the household sector

		Electricity	LPG	Charcoal	Wood
Urban	Cooking	●	●	●	
	Lighting	●			
	Refrigeration	●			
	Air condition	●			
	Others	●	●		
Rural	Cooking	●	●	●	●
	Lighting	●			
	Refrigeration	●			
	Air condition	●			
	Others	●	●		●

Remark: ● indicates that energy type is applicable

Table 6
Annual electricity demand per household in the eastern region of Thailand *(Unit: kWh)*

End-use	Urban	Rural	Total
Cooking	199.6	217.6	417.2
Lighting	306.4	303.2	609.6
Refrigeration	400.1	371.3	771.4
Air condition	471.0	239.9	710.9
Others	394.2	350.4	744.6
Total	1,771.3	1,482.4	3,253.7

Remark: Derived from EPPO (2017)

(5) others. Fuel types using in the households sector are electricity, LPG, charcoal and wood as shown in Table 5.

For the households sector, energy demand estimation can be conducted in more detail, energy intensities for end-use demand are categorized by activities mentioned above. This is because the data was derived from the survey study on household energy consumption in Thailand by EPPO (2017). The study divided Thailand into 5 regional areas and Nakhon Ratchasima was allocated in the eastern region together with the other ten provinces. The number of interviewed households was 1,010. The energy intensities for each energy-use activity for urban and rural as shown in Table 6.

3.2.3 Industry, building, agriculture and other sectors

Other sectors including industry, building and agriculture are rarely available data. For these sectors, top-down approach was employed to link between energy consumption by energy type and sectoral value-added which are obtained from NESDC (2019). Applicable energy types for each economic sector are shown in Table 7.

3.3 LEAP and Modeling Scenarios

LEAP (the Low Emissions Analysis Platform) is a widely used software tool for energy policy analysis and climate change mitigation assessment developed by the Stockholm Environment Institute. LEAP is an integrated, scenario-based modeling tool that can be used to track energy consumption, production, and resource extraction in all sectors of an economy (Emodi *et al.* 2017, Heaps 2020). In this study, the energy demand of five economic sectors in Nakhon Ratchasima Province is modeled. Energy production and transformation are not treated in this study. There are 9 types of vehicles from 3 groups, namely motorcycles, light-duty vehicles, and heavy-duty vehicles. There are also categorized according to fuel use as shown in Table 4. The household sector model is divided into 2 sub-sectors: municipal (urban) and non-municipal (rural) areas. The end-use of energy consumption in the household sector is divided into five categories: cooking, lighting, refrigeration, air conditioning, and others, as shown in Table 5. The building sector, industry sector, and agricultural sector are modeled using a top-down approach. The energy demand of the three sectors will grow according to the value-added of each sector, and applicable fuel use is shown in Table 7.

Table 7
Energy type applicability according to economic sectors

	Electricity	Diesel	LPG	Fuel oil	Biomass
Industry	●	●	●	●	●
Building	●	●	●	●	
Agriculture and others	●	●			

Remark: ● indicates that energy type is applicable.

The scenario analysis consists of two cases: (1) Business as Usual (BAU), which is a normal energy consumption forecast; and (2) Low Carbon Scenarios (LCS), which is a prediction of energy demand based on greenhouse gas emissions mitigations to meet the climate goal. There are different assumptions between BAU and LCS in each sector, such as energy efficiency improvement, the shift to modern energy, the share of highly energy-efficient vehicles, etc. Energy efficiency improvement and the share of high energy-efficient vehicles in LCS are higher than in BAU. For example, energy efficiency improvement in BAU is about 1% per year, while it is about 2.5-3% per year in LCS. The detail of the modeling assumptions between BAU and LCS is elaborated in Table 8.

Table 8
Modeling assumptions between BAU and LCS scenarios

Sector	BAU	LCS
Transport	• Vehicle ownership rises according to income • Fuel economy improvement for new vehicles is about 1% per year • Penetration of electric vehicles is moderate	• Vehicle ownership rises slowly due to the modal shift to public transport • Fuel economy improvement for new vehicles is ambitious to meet the climate goal, about 2.7-3.0% per year* • Penetration of electric vehicles is faster to grasp the global trend
Household	• Urbanization increases from 30% to 60% by 2050 • Household growth is about 1% per year • Electric consumption growth is about 3-4% per year	• Urbanization is the same with BAU • Household growth is the same with BAU • Energy efficiency improvement for the electric appliance is about 2-3% per year • Shifting from traditional biomass to LPG and electricity
Industry, Building, Agriculture and others	• Growth of value-added is about 3-5% per year	• Utilization of Solar PV rooftop • Energy efficiency improvement is about 2-3% per year

Remark: *Adopted the target of annual fuel economy improvement rate from GFEI (2013).

4. Results and Discussion

4.1. Final Energy Demand by Economic Sector

The modeling results show that the final energy demand of Nakhon Ratchasima Province in 2050 in the Business-As-Usual (BAU) scenario will be 4,464.4 kilotonnes of oil equivalent (ktoe) higher than the base year (2,018.6 ktoe in 2019) by 2.21 times or increasing with an average annual growth rate (AAGR) of 2.59%. All sectors will require higher energy demand. Final energy demand for the household sector will increase from 308.2 ktoe to 813.2 ktoe, the building sector will increase from 75.5 ktoe to 2,033.2 ktoe, the industry sector will increase from 447.9 ktoe to 1,087.1 ktoe, the transport sector will increase from 1,195.0 ktoe to 2,033.2 ktoe, and the other sector will increase from 40.1 ktoe to 97.4 ktoe. The transportation sector will account for 45.5% of total energy demand in 2050, followed by industry (24.3%), households (18.2%), buildings (9.7%), and other sectors (2.2%) as shown in Table 9. In the case of the Low Carbon Scenario (LCS), the final energy demand of Nakhon Ratchasima Province in 2050 will be 2,659.9 ktoe, higher than the base year by 1.32 times with an AAGR of 0.89%. Fig. 3 shows the final energy demand by economic sector in BAU and LCS scenarios. The final energy demand in LCS still keeps growing until 2050. The household sector requires the most increasing energy demand at the end of the forecasting period, 196.2 ktoe with an AAGR of 1.64%. While the building sector is the fastest growing demand with an AAGR of 3.88%. This is because Nakhon Ratchasima Province aims to be a tourist destination and promotes the service sectors (Nakhon Ratchasima Province 2022). On the other hand, the transport sector is the slowest growing demand for energy due to the trend of energy-efficient improvement of internal combustion engine (ICE) vehicles and the high penetration of electric vehicles pushed by government policies (EPPO 2021). An AAGR of final energy demand for the transport sector in LCS is only 0.33%, lower than the total final

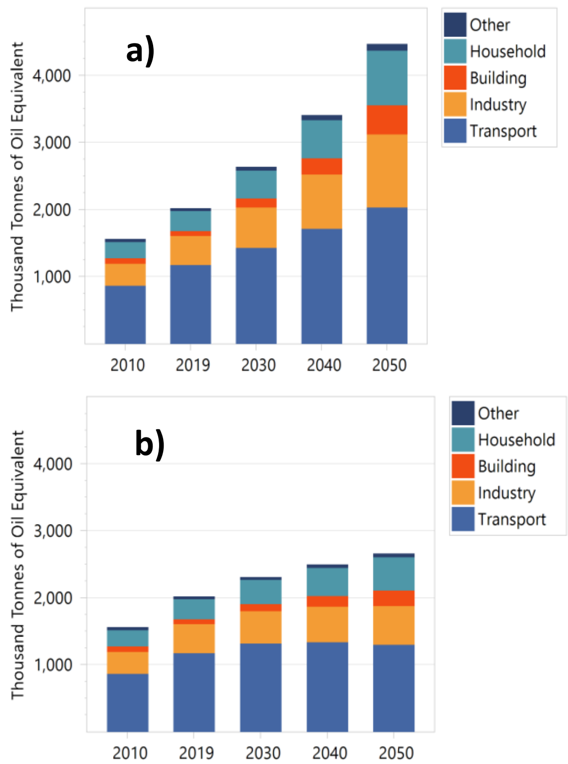

Fig. 3 Final energy demand by economic sector in (a) BAU and (b) LCS scenarios

Table 9
Results of final energy demand by the economic sector

(Unit: ktoe)

	Base year	BAU		LCS	
	2019	2050	AAGR	2050	AAGR
Transport	1,173.6 (58.1)	2,033.2 (45.5)	1.79%	1,298.8 (48.8)	0.33%
Industry	434.8 (21.5)	1,087.1 (24.3)	3.00%	581.1 (21.8)	0.94%
Building	71.2 (3.5)	433.5 (9.7)	6.00%	231.7 (8.7)	3.88%
Household	300.0 (14.9)	813.2 (18.2)	3.27%	496.2 (18.7)	1.64%
Other	39.0 (1.9)	97.4 (2.2)	3.00%	52.1 (2.0)	0.94%
Total	2,018.6 (100)	4,464.4 (100)	2.59%	2,659.9 (100)	0.89%

Remark: AAGR is an average annual growth rate compared to the base year; and numbers in the baskets are percent shares.

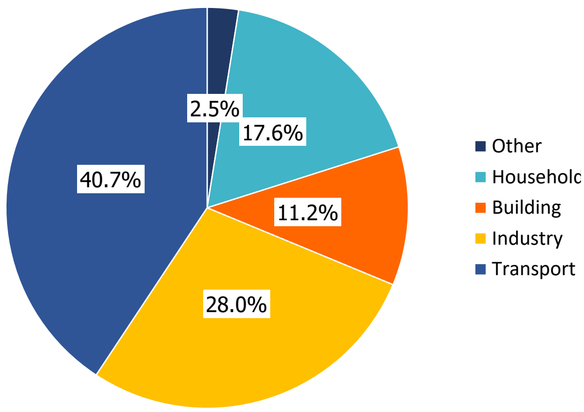

Fig. 4 Contribution of the final energy demand reduction in LCS compared to BAU by economic sector

energy demand. Compared to the BAU case, LCS will require a lower final energy demand in 2050 by 1,804.5 ktoe, or about 40.4% of the demand in the BAU case. The transport sector will share the most energy reduction in LCS compared to BAU with 40.7%, followed by the industry sector with 28.0%, the household sector with 17.6%, the building sector with 11.2%, and the other sector with 2.5% (see Fig. 4).

4.2. Final energy demand by fuel type

The modeling results show that electricity accounts for the greatest share of final energy demand in 2050 in the BAU case, 39.2%, followed by diesel, 31.8%, gasoline, 8.7%, and LPG, 8.2%, respectively. Electricity is also the fastest growing demand with an AAGR of 3.95%, increasing 3.33 times from 526 ktoe in 2019 to 1,751.0 ktoe in 2050. This is because of the electrification in all sectors (see Table 10). In the LCS case, electricity still accounts for the largest share of final energy demand in 2050, at 36.6%, followed by diesel (30.6%), LPG (8.4%), and gasoline (7.9%), respectively (see Fig. 5). All fuel demand in the LCS case is lower than in the BAU case, except for CNG, which will be increased in the LCS case, increasing 51.1% compared to BAU case (see Fig. 6). This is because heavy vehicles, such as buses and trucks, are expected to be replaced by cleaner energy sources such as compressed natural gas (CNG) and electricity. Fig. 7 and 8 show the increasing stock of clean heavy vehicles; electric buses and CNG trucks by 2050 in LCS compared to BAU. Shares of biofuels in fossil fuels for the transport sector between BAU and LCS scenarios are not

Table 10
Results of final energy demand by the fuel type

(Unit: ktoe)

	Base year	BAU		LCS	
	2019	2050	AAGR	2050	AAGR
Electricity	526.6 (26.1)	1,751.0 (39.2)	3.95%	972.8 (36.6)	2.00%
Diesel	779.9 (38.6)	1,418.6 (31.8)	1.95%	814.7 (30.6)	0.14%
B100 (Biodiesel)	55.5 (2.7)	98.7 (2.2)	1.87%	55.9 (2.1)	0.02%
Gasoline	225.4 (11.2)	390.3 (8.7)	1.79%	209.9 (7.9)	-0.23%
Ethanol	42.7 (2.1)	73.1 (1.6)	1.75%	37.6 (1.4)	-0.42%
LPG	160.0 (7.9)	365.8 (8.2)	2.70%	223.2 (8.4)	1.08%
CNG	53.3 (2.6)	82.8 (1.9)	1.43%	125.1 (4.7)	2.79%
Fuel oil	20.5 (1.0)	51.3 (1.1)	3.00%	27.1 (1.0)	0.94%
Other bioenergy	154.7 (7.7)	232.8 (5.2)	1.33%	193.2 (7.3)	0.72%
Total	2,018.6 (100)	4,464.4 (100)	2.59%	2,659.9 (100)	0.89%

Remark: AAGR is an average annual growth rate compared to the base year; numbers in the baskets are percent shares, and other bioenergy includes biomass, biogas and charcoal.

differentiated due to the highlights of energy efficiency and electrification of mobility policies. In particular, share of ethanol in gasoline-based fuel was about 15%, while share of biodiesel in diesel-based fuel was about 7%, throughout the study period. The share of electric vehicles in 2050 will be higher than one-third of total passenger cars stock as shown in Fig. 9. The electrification of passenger cars will result in lowering demand for gasoline and ethanol in 2050 than the base year in the LCS case (see Table 10).

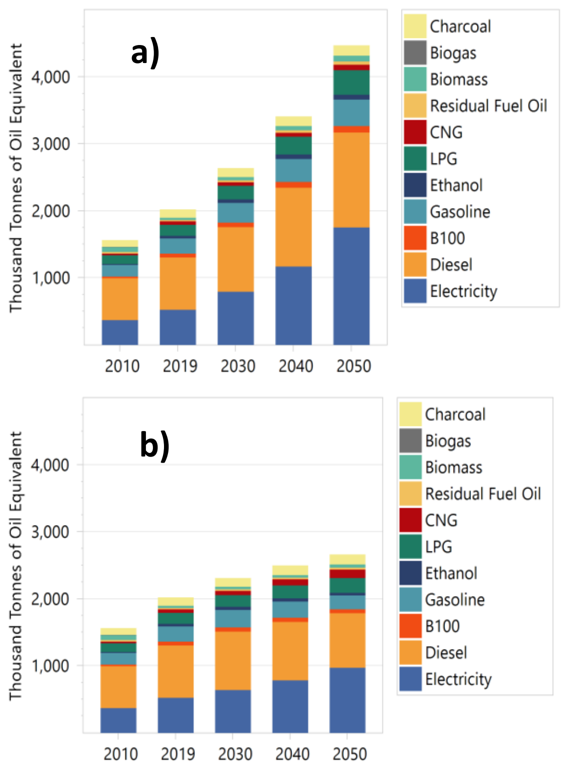

Fig. 5 Final energy demand by fuel type in (a) BAU and (b) LCS scenarios

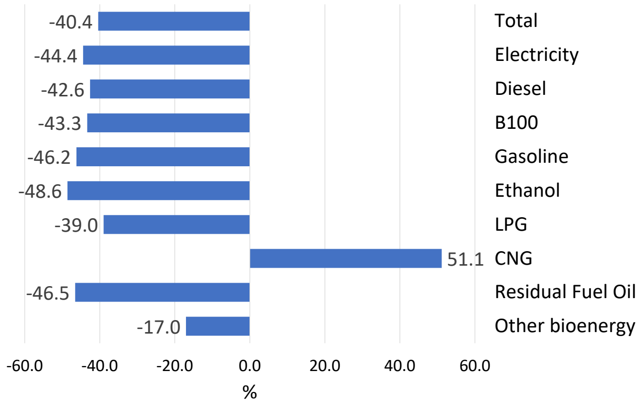

Fig. 6 Percent change of the final energy demand in LCS compared to BAU by fuel type

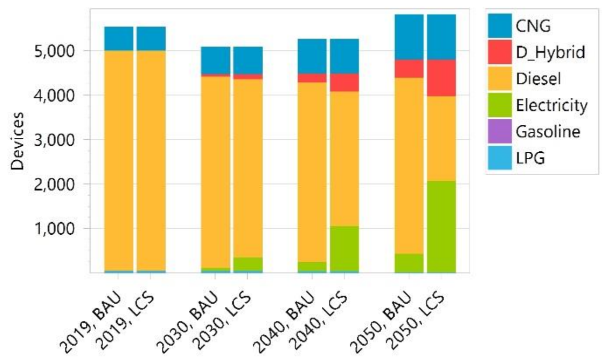

Fig. 7 Stock of public buses by vehicle technology and fuel

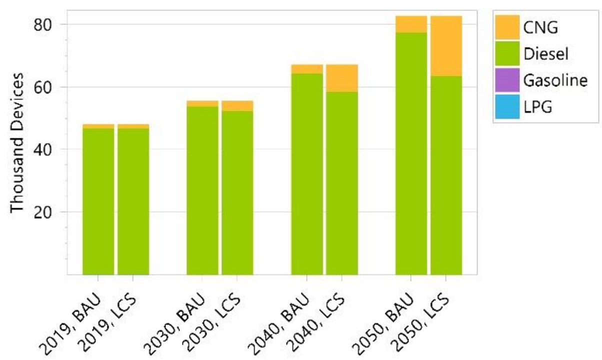

Fig. 8 Stock of trucks by vehicle technology and fuel

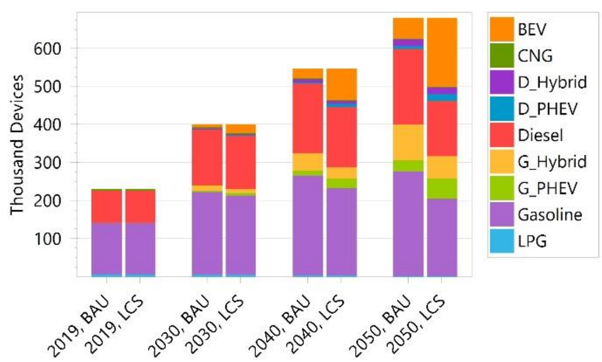

Fig. 9 Stock of passenger cars by vehicle technology and fuel

4.3. CO_2 emissions from energy consumption by the economic sector in BAU and LCS scenarios

The modeling results show that CO_2 emissions from energy consumption in Nakhon Ratchasima Province in 2050 in the BAU case will be 6,926.7 ktCO_2eq, higher than in the base year (3,704.5 ktCO_2eq in 2019) 1.87 times or increasing with an AAGR of 2.04% (lower than the growth of final energy demand), as shown in Table 11. The transport sector shares about 78.9% of total CO_2 emissions in 2050, with the lowest AAGR of 1.74%. In the LCS case, CO_2 emissions in 2050 will be 4,141.8 ktCO_2eq, or 1.12 times compared to the base year. It grows only 0.36% per year. The transport sector still has the largest share of CO_2 emissions and contributes to the most CO_2 emissions reduction with a share of 77.7%, or 2,163.4 ktCO_2eq. Interestingly, the CO_2 emissions in Nakhon Ratchasima Province in the LCS case will peak before 2050, around 2038, at 4,246.6 ktCO_2eq (see Fig. 10 and 11). However, it notes that electricity consumption in each sector is not calculated for CO_2 emissions on the demand side. In the case of accounting for the CO_2 emissions from electricity consumption, the proportion of CO_2 emissions of the commercial sectors such as the building and household sector will be higher than the calculation shown in Table 11 and Fig. 10.

Table 11
Results of CO_2 emissions from energy consumption by the economic sector

(Unit: ktCO_2eq)

	Base year	BAU		LCS	
	2019	2050	AAGR	2050	AAGR
Transport	3,205.4 (86.5)	5,467.7 (78.9)	1.74%	3,304.2 (79.8)	0.10%
Industry	178.3 (4.8)	445.7 (6.4)	3.00%	238.3 (5.8)	0.94%
Building	54.5 (1.5)	332.0 (4.8)	6.00%	177.5 (4.3)	3.88%
Household	162.3 (4.4)	421.4 (6.1)	3.13%	282.9 (6.8)	1.81%
Other	103.9 (2.8)	259.9 (3.8)	3.00%	138.9 (3.4)	0.94%
Total	3,704.5 (100)	6,927.7 (100)	2.04%	4,141.8 (100)	0.36%

Remark: AAGR is an average annual growth rate compared to the base year; and numbers in the baskets are percent shares.

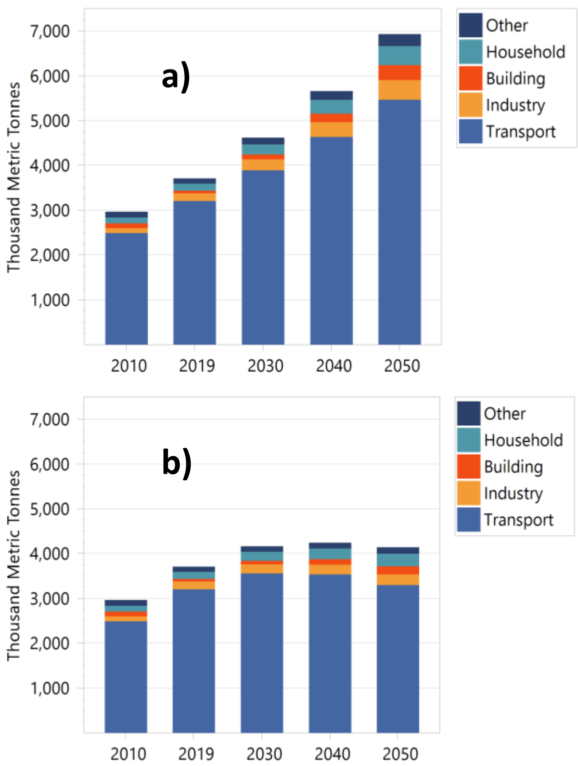

Fig. 10 CO_2 emissions from energy consumption by the economic sector in (a) BAU and (b) LCS scenarios

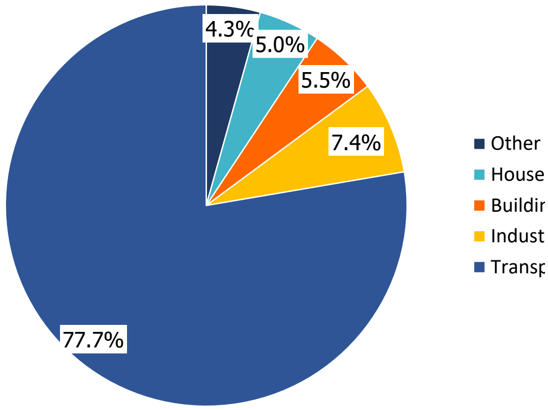

Fig. 11 Contribution of the CO_2 emissions reductions in LCS compared to BAU by economic sector

5. Conclusion

Using LEAP software to forecast energy demand for Nakhon Ratchasima Province between Business-as-Usual (BAU) Scenario and Low-carbon Scenario (LCS) enables us to see the possible potential for GHG emission reductions to meet its low-carbon city goal. In the Low Carbon Scenario, energy demand in Nakhon Ratchasima Province in 2050 will be lower than in the BAU scenario by 1,804.5 ktoe, or about 40.4%. The transport sector will play an important role in energy reduction potentials in LCS compared to BAU, with a 40.7% share of the energy reduction, followed by the industry sector with 28.0%, the household sector with 17.6%, the building sector with 11.2%, and the other sector with 2.5%. Due to the rich data of vehicle registration statistics in Thailand, this study could model the transport sector by using the vehicle stock turnover analysis technique which penetration of high energy efficiency vehicles such as electric vehicles can be captured systematically. This demonstrates the critical importance of policies that promote low-emission vehicles and a modal shift to public transportation. Electrification in all sectors is definitely required to increase the efficiency of energy use. Therefore, the next important issue is which energy should be used to generate electricity. Specifically, electricity generation should come from low-carbon energy such as solar power, wind, biomass, and so on. In the LCS case, CO_2 emissions will be lower than in the BAU case by about 40.2%, which is in line with energy demand reduction. The result shows that energy demand in Nakhon Ratchasima Province will increase gradually up to 2050, but we will see CO_2 emissions peak around 2038. This information is very useful for decision-makers and stakeholders at a provincial level to react to climate change. If most of the cities have their own modeling tools to evaluate and monitor their plans for climate change mitigation, Thailand's government would ensure its commitment to achieving the national targets of carbon neutrality and net-zero emissions as announced.

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