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Transport Scenario Study for Carbon Neutral and Resilient Urban Planning in Phuket using LEAP Model

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ABSTRACT

Phuket's economy is a key contributor to Thailand's GDP, largely due to its thriving tourism industry supported by floating population from provinces and abroad. The city's transport infrastructure is challenged by traffic congestion, flood risks, and the need for carbon neutrality. The increase in number of vehicles and their impact on transport infrastructure are affecting these issues. This paper uses the Low Emission Analysis Platform (LEAP) to study Phuket's land transport sector and develop strategies for resilient and carbon-neutral urban planning. Three scenarios are introduced: business as usual, updated target, and carbon neutral. The study predicts vehicle numbers, energy demand by vehicle and fuel type, and emissions for each scenario. A notable difference is observed between updated target and carbon-neutral scenarios due to increase in biofuel share and electricity decarbonization. The transition toward a higher blend of biofuel, combined with electric vehicles powered by clean energy sources will create a pathway toward emission reduction. Yet, the number of vehicles remains unchanged, requiring further actions to ease congestion. Solutions like improved "last-mile" transport and Nature-Based Solutions (NbS) can further cut emissions and boost efficiency.

1. INTRODUCTION

The city of Phuket contributes around one percent to Thailand's GDP [1]. The share of tourism-related incomes in Phuket's gross provincial product (GPP) is around 91 percent [1]. This sector has consistently played an important role in Phuket's economic landscape [2]. The tourist industry attracts people from other provinces in Thailand and abroad. Phuket's transportation system currently faces three intertwined challenges: traffic congestion, flood concern, and the need to achieve carbon neutrality. The increase in number of vehicles will result in traffic congestion which becomes even worse during flood and consequently increase the emissions [3], [4]. This accelerates climate change which exacerbates future flooding [5]. There have been several initiatives in the province that aimed to address the issues. The Sustainable Urban Transport Heritage in Phuket (SUTRHE) project in Phuket focused on urban growth and traffic issues, aiming to propose sustainable mobility system despite the slowly developed public transport [6]. It was found that connectivity and infrastructure play a crucial role in bolstering the island's economy. However, the challenges related to congestion and sustainability remain [7].

Thailand's 30@30 Policy aim to shift from internal combustion engine (ICE) vehicles to electric vehicles (EV). This policy aims to establish Thailand as a regional leader in EV manufacturing and transform the nation towards a low-carbon society [8], [9]. In Phuket, the number of electric vehicles has already increased significantly due to this policy, and this trend is likely to continue [10]. The projected rise in EVs will undoubtedly impact energy demand and greenhouse gas (GHG) emissions. However, the overall growth in vehicle numbers, regardless of fuel type, requires extensive discussion on the impact of transportation on urban planning and infrastructure development.

This paper conducted scenario study for the transport sector in Phuket using Low Emission Analysis Platform (LEAP). LEAP offers users a variety of built-in calculation methods and allows modeling through user-defined formulas, which makes it the best candidate for this study [11]. In addition, LEAP provides several benefits, including low initial data requirements and intuitive presentation of the outcomes [12]. Three scenarios are introduced, namely business as usual (BAU) scenario, updated target scenario, and carbon neutral scenario. BAU scenario helps establish baseline information as it assumes the current trends will continue the way they have been. Updated target scenario helps depict how the future would be if all policies are attained. Carbon neutral scenario will guide the way towards carbon neutrality in 2050. The results

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contribute to future resilient transport infrastructure and the attainment of carbon neutrality in Phuket.

2. METHODOLOGY

Figure 1 illustrates the methodological framework of this study. The process begins with developing an input matrix, scenarios to be depicted, and data to be gathered. Then, LEAP is used to perform the calculations of the three scenarios. Finally, the results from difference scenarios are compared to identify key insights. Based on this comparison, recommendations are derived.

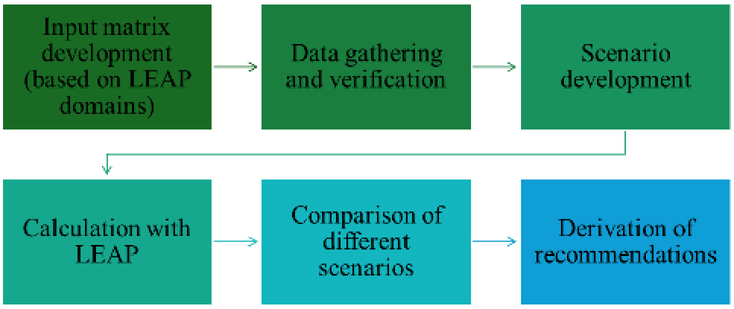

Fig. 1. Methodology framework.

2.1 LEAP

Analyses of number of vehicles, energy demand and GHG emissions in this research were conducted with the Low Emissions Analysis Platform (LEAP) which was developed at Stockholm Environment Institute (SEI). The tool has been adopted by thousands of organizations, and at least 37 countries used LEAP to help develop their Nationally Determined Contributions (NDC) [13]. It helps policymakers and relevant stakeholders in energy sector evaluate the impact of various energy policies, environmental modeling, scenario exploration and emission reduction strategies [14]. Its flexibility and user friendliness allows users to easily create and compare multiple energy scenarios [12]. LEAP also has low initial data requirements and offers intuitive presentation of the outcomes [15]. The ability to integrate with diverse data sources, such as national statistics and energy databases, make it a suitable tool for analyzing energy systems' emission and projecting number of vehicles.

2.2 Bottom-up Approach

There are generally two modelling approaches for GHG emissions projection: top-down and bottom-up [15]. Top-down models use economic data for predictions, while bottom-up models focus on specific technologies for exploring purposes [16]. The bottom-up approach offers detailed insights into emission sources and reduction methods but requires significant data. Top-down models capture the overview of the emissions though it can miss localized variations due to the reliance on aggregated data [13]. Bottom-up approach was selected considering the study's goals. It allows deeper investigation of energy use, vehicle counts, and pollution levels.

2.3 Input Matrix Development

Figure 2 illustrates the data structure used for the calculation. The data is used to estimate the number of vehicles (vehicle ownership), energy demand, and emissions. The calculation classifies vehicles into: Four-wheelers (private and public), Two- and three-wheelers (private and public), Buses (private and public), and Trucks. The fuel types for each category vary based on the usage in Thailand:

- Four-wheelers (private and public): gasoline, ethanol, diesel, biodiesel, electricity
- Two- and three-wheelers (private and public): gasoline, ethanol, electricity
- Buses (private and public): gasoline, ethanol, diesel, biodiesel, LPG, electricity
- Trucks: gasoline, ethanol, diesel, biodiesel, LPG, electricity

The number of vehicles can be projected using historical data, GDP per capita, and vehicle growth model. Energy demand is estimated using vehicle kilometers traveled [17], fuel consumption [17], and number of vehicles. Multiplying energy demand by the emission factor yields the final emission.

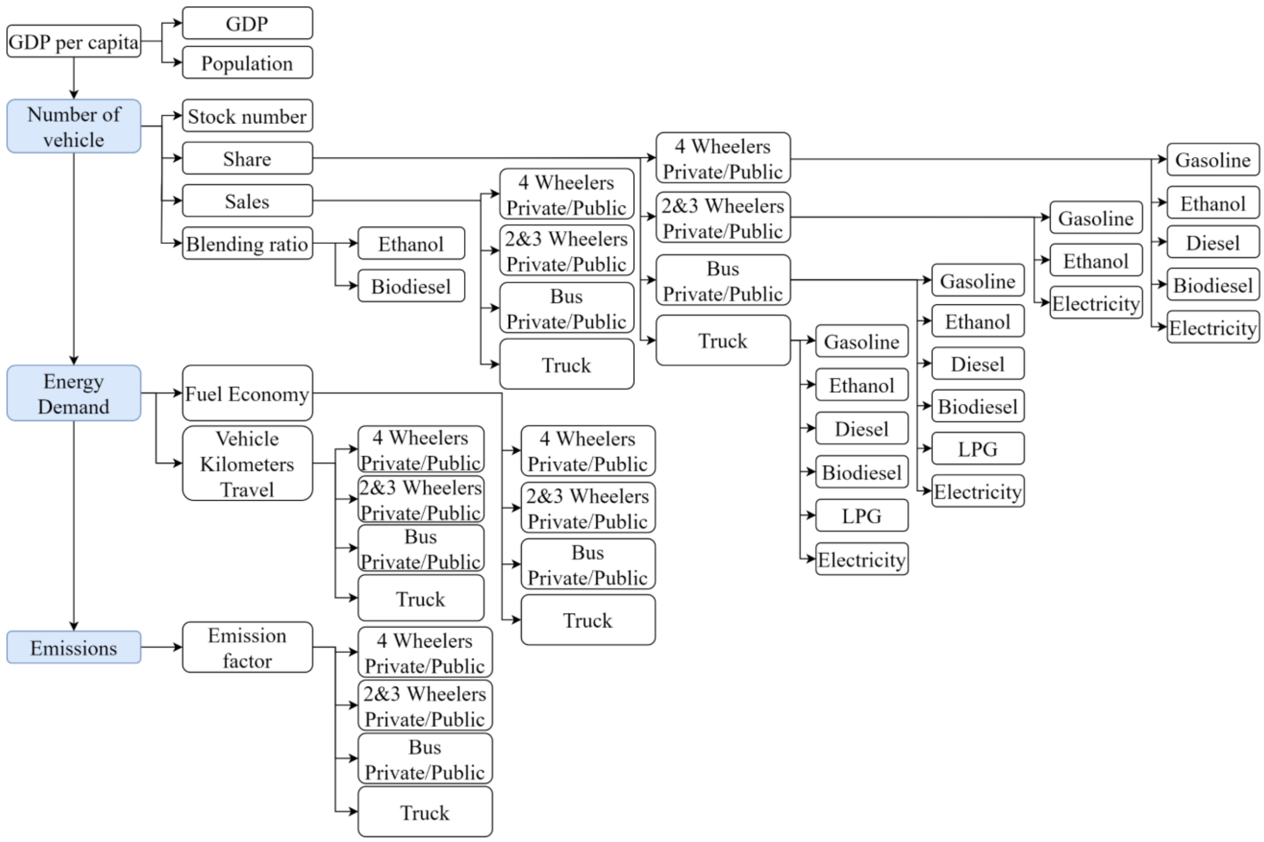

Fig. 2. Data structure for the calculation.

Table 1. Vehicle ownership model for each vehicle type.

Vehicle Category	Vehicle ownership model	R^2
4W Private	$\ln\left(\frac{VO}{812-VO}\right)=8.1798\cdot10^{-4}+5.0492\cdot10^{-1}\cdot\ln\left(GPPpCap\right)$	0.96
4W Public	$\ln\left(\frac{VO}{812-VO}\right)=1.1014\cdot10^{-2}+1.7527\cdot10^{-2}\cdot\ln\left(GPPpCap\right)$	0.53
2 and 3W Private	$\ln\left(\frac{VO}{600-VO}\right)=1.1033\cdot10^{-1}+0.3076\cdot\ln\left(GPPpCap\right)$	0.97
2 and 3W Public	$\ln\left(\frac{VO}{600-VO}\right)=3.8348\cdot10^{3}-1.0549\cdot\ln\left(GPPpCap\right)$	0.95
Bus Private	$VO=-9.7025\cdot\ln\left(GDPpCap\right)+0.4511$	0.93
Bus Public	$VO=14.1171\cdot\ln\left(GDPpCap\right)-166.9103$	0.98
Truck	$VO=-1.2766\cdot\ln\left(GDPpCap\right)+23.5739$	0.63

2.4 LEAP Calculation

2.4.1 Number of vehicle model development

Economic development has historically been linked to increased transportation demand, notably for road vehicles [18]-[20]. This paper describes vehicle ownership models using logistic and logarithmic functions [21], [22]. The logistic vehicle-ownership (*VO*) model is based on the maximum saturation level of cars per capita (*S*) [19].

$$\ln\left(\frac{S-VO}{VO}\right)=a+b\ln\left(GPPpCap\right) \quad (1)$$

where, *S* is the saturation level of *VO* (per 1000 population), *GPPpCap* is the GPP per capita (THB/person), *a* and *b* are coefficients from curve fitting with historical data. The saturation level of four-wheelers is 812 [18] while two- and three-wheelers is 600 [17]. The vehicle ownership of each vehicle type is shown in Table 1. The vehicle ownership model is based on the equation initially developed by Buttom *et al.* [19]

to model vehicle ownership in low- and middle-income countries, which is then modified by Dargay [18] to better fit with current data while retaining the original structure. Phuket provincial data is utilized to determine the constants for these equations.

2.4.2 Energy consumption

LEAP calculates energy consumption of vehicles by fuel types as:

$$ED = \sum NV_{i,j} \cdot FC_{i,j} \cdot VKT_i \tag{2}$$

where i represents the specific vehicle segment or technology under consideration, j denotes the type of fuel or energy used, NV is the number of vehicles based on vehicle ownership model and vehicle sales, FC refers to the fuel consumption (measured in fuel units per kilometer), and VKT is the vehicle kilometers traveled (km). Both FC and VKT are assumed to remain constant throughout the entire timeframe across all scenarios. The values of these parameters are based on UNESCAP's survey study on electric land-based public transport in Thailand [23].

2.4.3 Emission

GHG emissions can be calculated by multiplying the energy demand with the emission factor which gives emissions quantity per unit consumed energy.

$$Emission = \sum ED_j(t) \cdot EF_{jk}(t) \tag{3}$$

where ED_j is the energy demand of fuel category j and EF_{jk} is the emission factor of pollutant type k under fuel category j in year t.

2.5 Scenario Development

The development of scenarios began by examining total emission possibilities across all sectors as shown in Figure 3. Given the global push towards sustainability, a scenario with high carbon emissions was deemed improbable. The focus shifted to four remaining scenarios: business-as-usual (BAU), updated targets, carbon neutral, and net-zero emissions. The analysis then narrowed down to the energy sector, with emphasis on transportation. The net-zero scenario which accounts for emissions other than carbon dioxide (CO_2) seems to be irrelevant. Similarly, achieving carbon neutral without considering carbon absorption also appears unrealistic. The most likely scenarios for further quantitative analysis were identified as BAU scenario, the updated target scenario, and carbon neutral with LULUCF scenario.

The description of each scenario is provided in Table 2 corresponding to three important parameters, namely number of vehicles, energy demand, and emissions. In BAU scenario, LEAP calculates based on the current trends. This scenario reflects the current trajectory of transportation development without any policy or technological intervention. The projection is based on the existing data sets. Energy demand follows the current trend with a mix of conventional fuels, including biodiesel B7 and gasohol blends (E10, E20, and E85). Electric vehicle (EV) adoption is projected using linear extrapolation. Fuel efficiency is assumed to be constant in all scenarios. The updated target scenario builds upon the BAU scenario by incorporating advancements in energy technology and policy targets. The new registered vehicles will likely be electric vehicles and the overall energy efficiency will increase corresponding to EV 30@30 policy and the Energy Efficiency Plan 2018 (EEP 2018) [23,24]. The emission factor of BAU and updated target scenarios is based on tier 2 emissions from IPCC database and remains constant across the timeframe. Carbon neutral scenario represents an ambitious transformation towards sustainable and low-emission transport. This scenario includes significant modal shifts to public and shared transportation options, such as cable cars, trams, and public buses. Biofuel blending targets increased significantly. It also assumes widespread adoption of high-blend biofuels (B85 and E100 by 2050) and 100% transition to electric vehicles for light-duty vehicles (4-wheel and 2 and 3-wheelers) by 2035, and 50% for buses and trucks electrified by the same year. The emission factor from electricity is also set to approach zero [26].

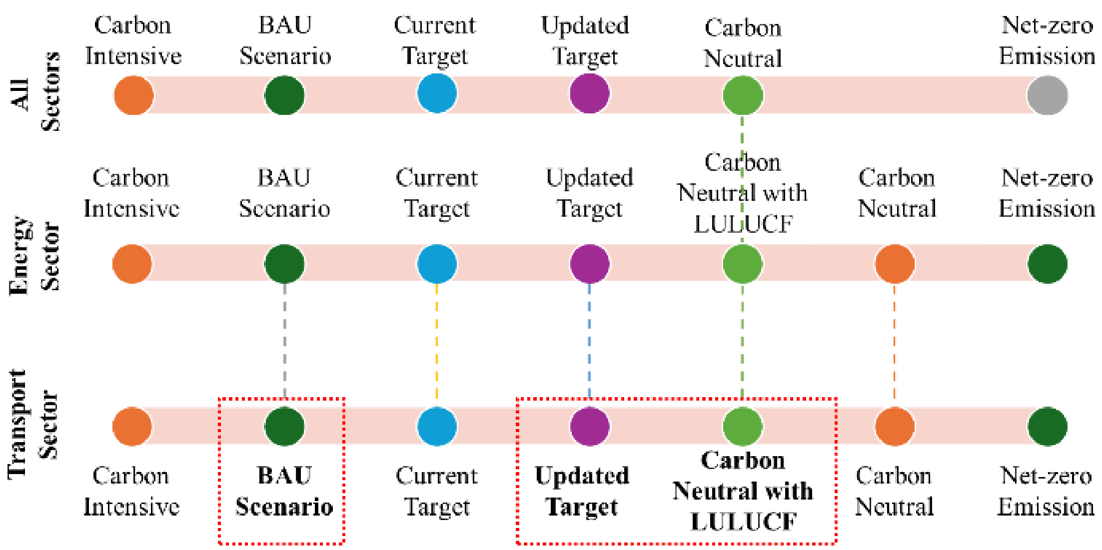

Fig. 3. Scenario planning.

Table 2. Scenario description.

Parameter	BAU	Updated Target	Carbon Neutral
Number of vehicles	Input taken from registered number x factor to account for vehicles from Bangkok and neighboring provinces		Modal shift: cable car, tram, and public bus*
Energy demand	Biodiesel: B7 Gasohol: E10, E20, E85 EV: linear extrapolation Efficiency: ↑	Biodiesel: B7 Gasohol: E10, E20, E85 EV: 30@30↑↑ Efficiency: ↑	Biofuel: E85 and B100 in 2050 EV: 4W, 2 and 3W: 100% in 2035 Bus, truck: 50% in 2035 Efficiency: ↑
Emission	Current tier 2 emission factor		Tier 2 emission factor become 0 at 2050 (Electricity emission factor = 0)

3. RESULTS

3.1 Business as Usual (BAU) Scenario

- Number of vehicles by vehicle and fuel type

In this scenario, the number of vehicles keeps increasing with the GPP per capita. The big portions of vehicles in this scenario are private two- and three-wheelers and private four wheelers as shown in Figure 4.

- Energy demand by vehicle and fuel type

The energy demand increases significantly as it is strongly related to the number of vehicles. Even though the number of public buses is small in Figure 4, the energy demand is comparable to private two- and three-wheelers due to large VKT and bad fuel economy. The remaining energy demand is mostly from private four-wheelers, private two- and three- wheelers and public four-wheelers (taxi) as shown in Figure 5.

- Carbon emission by vehicle and fuel type

In this scenario, liquid fuel, including gasoline, ethanol, diesel, and biodiesel, account for more than 90% of energy demand as shown in Figure 6. Gasoline consumption is the highest due to its use in private four-wheeled vehicles and private two- and three-wheeled vehicles. Diesel follows closely, primarily used in Sport Utility Vehicle (SUV) and Pick-up Passenger Vehicle (PPV) heavy-duty vehicles. The shares of biodiesel and ethanol follow the Orders issued by Ministry of Transport. The share of electricity is nearly negligible.

Emissions follow the same trend as energy demand. As shown in Figure 7, private four-wheelers, private two- and three-wheelers, and public buses are the biggest contributors to the emissions. While the contribution from public buses remains relatively constant, emissions from private four-wheelers and private two- and three-wheelers double. Figure 8 further clarifies that gasoline and diesel are the primary sources of these emissions.

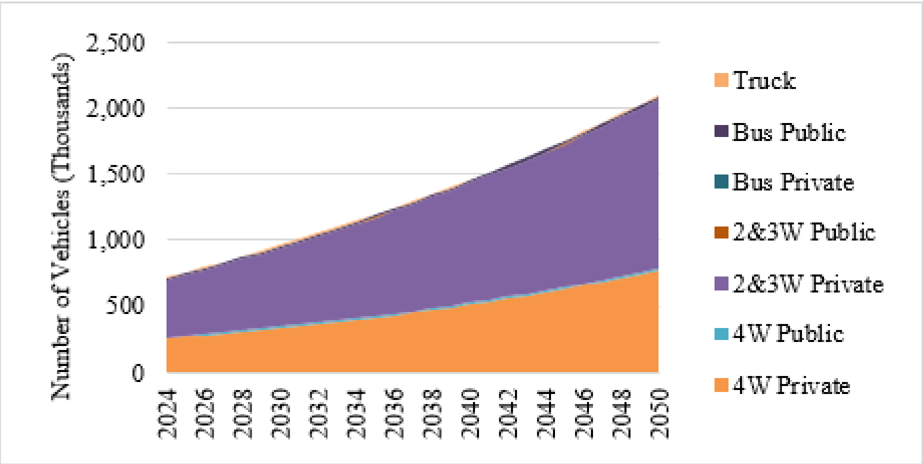

Fig. 4. Number of vehicles by vehicle type in BAU scenario.

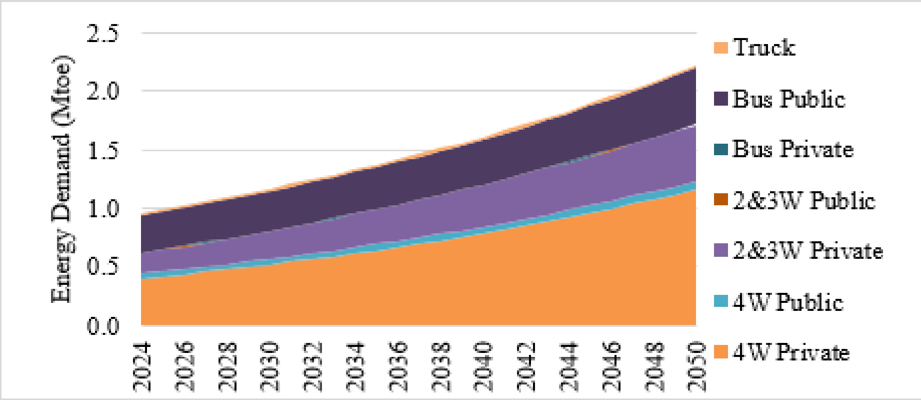

Fig. 5. Energy demand by vehicle type in BAU scenario.

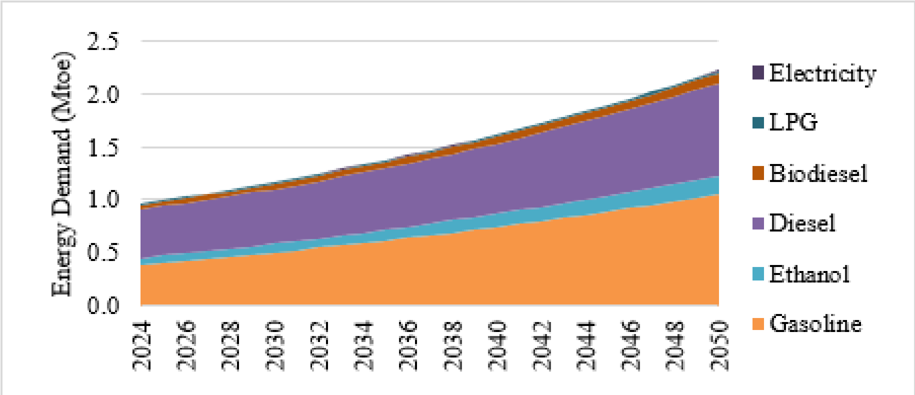

Fig. 6. Energy Demand by fuel type in BAU scenario.

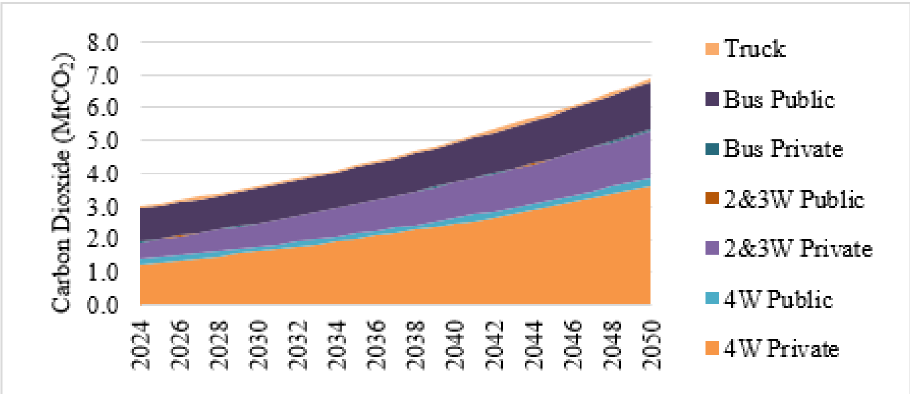

Fig. 7. Carbon emission by vehicle type in BAU scenario.

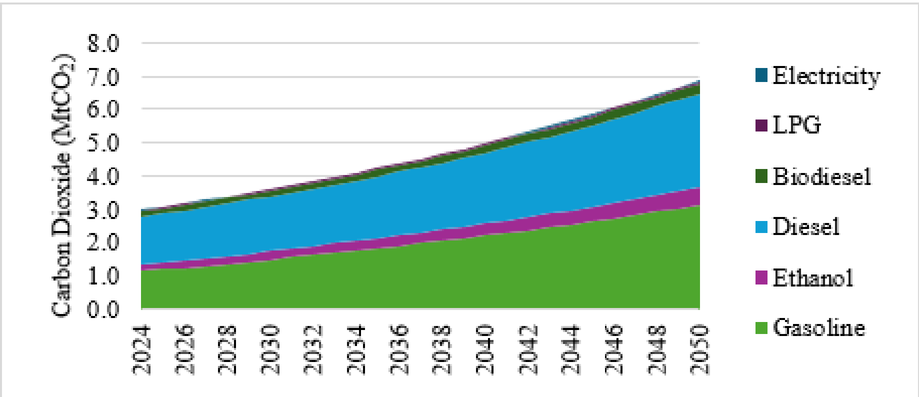

Fig. 8. Carbon emission by fuel type in BAU scenario.

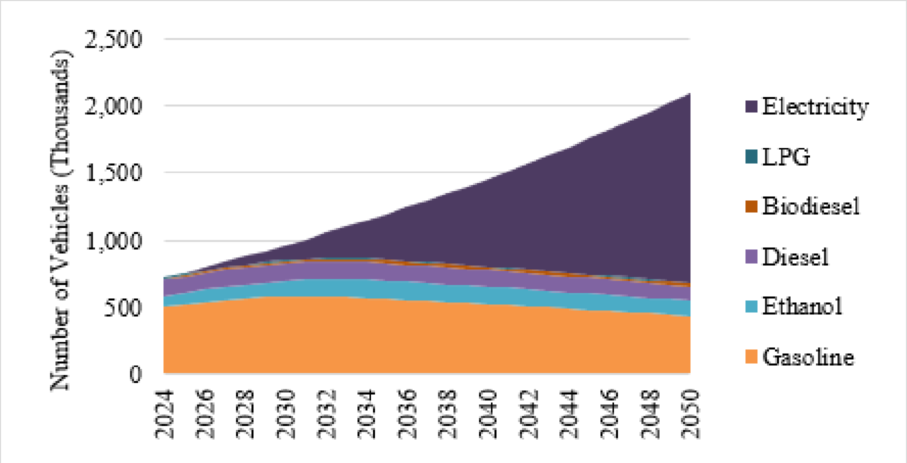

Fig. 9. Number of vehicles by fuel type in updated target scenario.

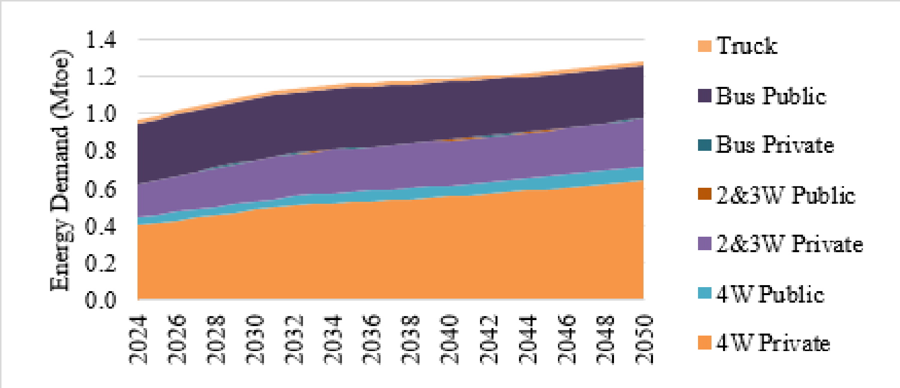

Fig. 10. Energy demand by vehicle type in updated target scenario.

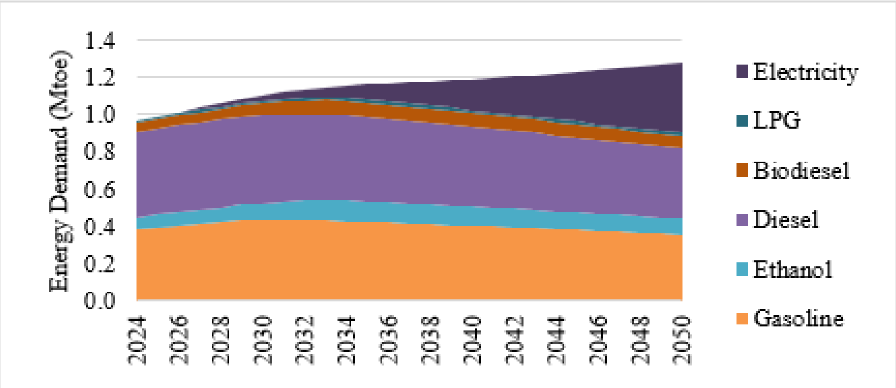

Fig. 11. Energy demand by fuel type in updated target scenario.

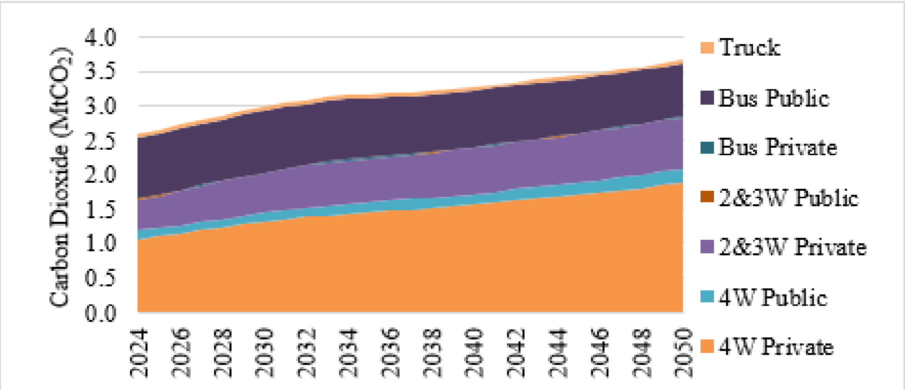

Fig. 12. Carbon emission by vehicle type in updated target scenario.

3.2 Updated Target Scenario

- Number of vehicles by vehicle and fuel type

Since the policy to limit vehicle ownership has not been introduced, the total number of vehicles is the same as BAU scenario (see Figure 4). However, as shown in Figure 9, electric vehicles are projected to cover more than half of all vehicles by 2050 due to 30@30 policy [8].

- Energy demand by vehicle and fuel type

Figure 10 shows a significant decrease in energy demand by 43% in 2050 compared to BAU scenario. This trend is attributed to fuel efficiency improvements achieved through the implementation of EEP 2018 [25] and EV 30@30 initiative. Figure 11 highlights that by 2050, electricity will contribute to one-third of the total energy demand, while the contribution of gasoline and diesel will remain relatively constant.

- Carbon emission by vehicle and fuel type

As shown in Figure 12, most emissions come from private four-wheelers, private two- and three-wheelers, and public buses. Similar to the previous scenario, emissions are closely related with energy demand. Thus, three main fuel sources contributing to the majority of carbon dioxide emissions are gasoline, diesel, and electricity which correspond well to Fig 11. The emission from electricity is significantly high since the electricity mix remains the same as BAU scenario.

3.3 Carbon Neutral Scenario

- Number of vehicles by vehicle and fuel type

In the carbon-neutral scenario, the number of vehicles remains the same as other scenarios. Figure 13 shows that by 2050, the electric vehicles' share is more than half of the total vehicle stock. Diesel vehicles are entirely replaced by biodiesel, while gasoline use continues due to the 85% ethanol blending.

- Energy demand by vehicle and fuel type

Energy demand follows the same trend, with private four-wheeled vehicles consuming nearly half of the total, followed by private two- and three-wheeled vehicles and public buses, as illustrated in Figure 14. Furthermore, Figure 15 shows that electricity, biodiesel, and ethanol dominate the energy demand. In this scenario, biodiesel and ethanol continue to play their important roles even though the number of electric vehicles increase in the future. In this context, biofuels are not seen as competing with electrification. It powers older internal combustion engines (ICE) vehicles which will remain in use due to Thailand's relatively low vehicle retirement rate.

- Carbon emission by vehicle and fuel type

The carbon-neutral scenario shows a continuous decline in emissions after 2037 which is the end of AEDP [24] and EEP [25] due to improvement in fuel efficiency and electrical grid decarbonization. Figure 16 indicates that private four-wheelers remain the largest source of emissions in 2050, followed by private two- and three-wheelers. Figure 17 highlights the success of the transition to clean energy, with zero emissions from electricity generation and widespread adoption of biodiesel.

Figure 18 shows the summary of emissions in all scenarios and sub-scenarios. Emissions significantly decrease in the updated target scenario because of policies promoting biofuel blending and encouraging the adoption of electric vehicles. Decarbonizing electricity generation further reduces emissions. The emission reductions from public transport projects, such as cable car, small public bus promotion, and tram development were insubstantial at provincial level, though they promote adoption of sustainable behavior towards carbon neutral future at local level.

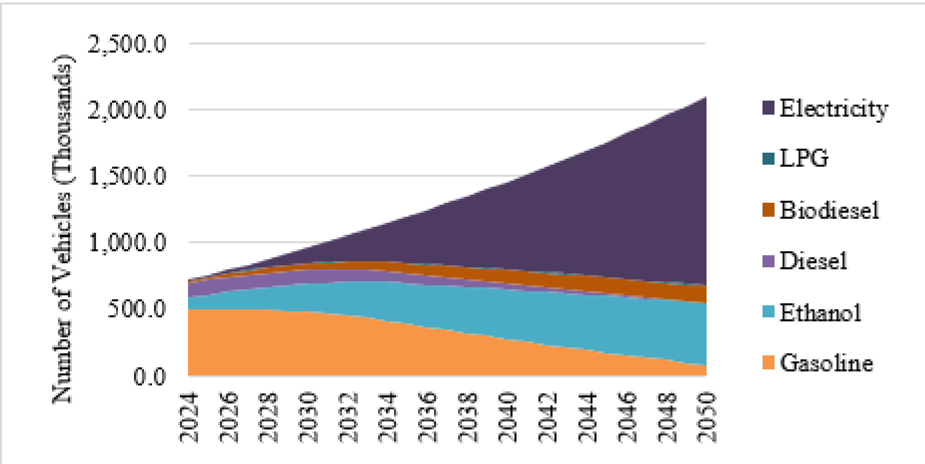

Fig. 13. Number of vehicles by fuel type in carbon neutral scenario.

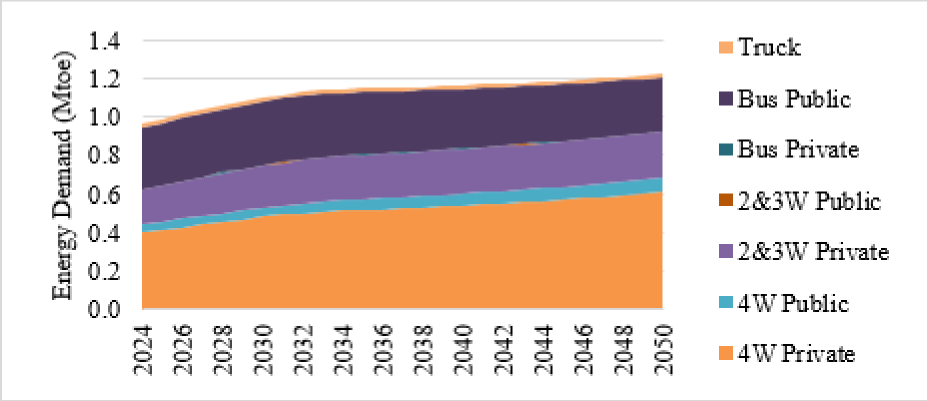

Fig. 14. Energy demand by vehicle type in carbon neutral scenario.

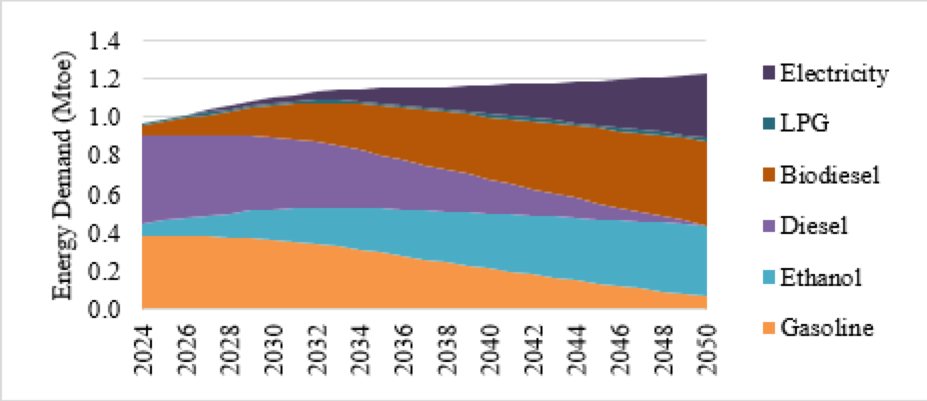

Fig. 15. Energy demand by fuel type in carbon neutral scenario.

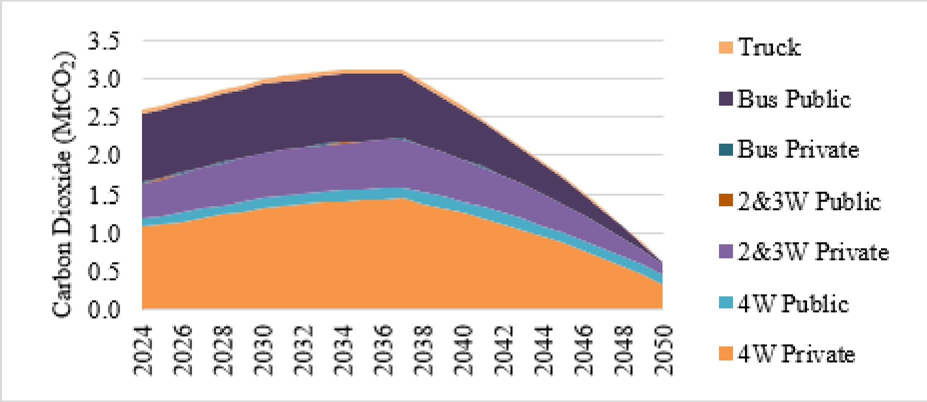

Fig. 16. Carbon emission by vehicle type in carbon neutral scenario.

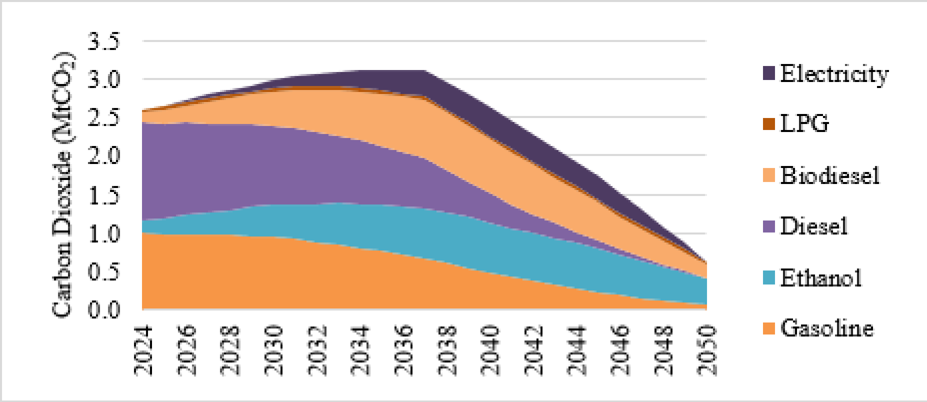

Fig. 17. Carbon emission by fuel type in carbon neutral scenario.

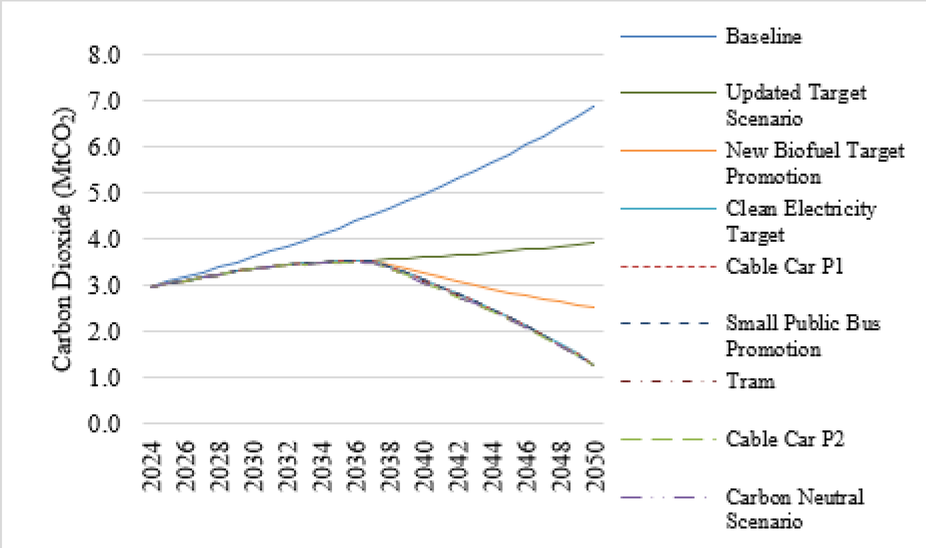

Fig. 18. Emission of different scenarios.

4. LIMITATIONS AND DATA GAPS

As this study only considers population and GDP as macroeconomic inputs into the LEAP program, the validity of the prediction period for the calculation is limited. This is because the results can be entirely shifted if household income trends change or people's preferences shift.

Total energy consumption for a specific transportation mode is calculated using a bottom-up approach. The method offers the advantage of breaking down energy consumption by activity. However, it demands a substantial amount of data input. The acquisition of provincial-level data for bottom-up approaches presents significant challenges. Therefore, country-level data are utilized when provincial-level data are unavailable.

5. CONCLUSION

This study employed Low Emission Analysis Platform (LEAP) to conduct a scenario analysis of Phuket's transportation sector to develop strategies for resilient and carbon-neutral urban planning. Three scenarios – business-as-usual, updated target, and carbon neutral – were explored to understand the potential impact of different policy choices. It was found that Phuket's growing population led to a rise in vehicle emissions. However, the study presents a promising path forward. There is a significant difference between the updated target scenario and carbon neutral scenario. This is driven by the shift towards biofuels and electric vehicles, especially electric cars powered by clean energy sources. These technologies can significantly reduce emissions. Additionally, promoting public transportation through cable cars, small public buses, and trams will decrease vehicle use in the long term. Promoting carbon sink through Land Use, Land-Use Change, and Forestry (LULUCF) can address remaining challenges and create a more sustainable transportation system for Phuket.

The study also showed that the existing vehicle stock remains unchanged. Additional measures are needed to address traffic congestion by decreasing vehicle numbers in Phuket. Furthermore, with several projects underway to achieve carbon neutrality, the province should also implement "last mile" solutions that improve mobility for public transportation users. One potential countermeasure is Nature-Based Solutions (NbS), which can additionally decrease energy demand and emissions.

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