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LEAP-based energy demand and emissions modelling for low-carbon transport in Khon Kaen province, Thailand

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Abstract. Climate change mitigation in Thailand requires urgent transformation of energy-intensive sectors, notably transport in rapidly urbanizing provinces. Khon Kaen, a central economic hub in northeastern Thailand, faces increasing energy demand and transport-related greenhouse gas (GHG) emissions driven by rising private vehicle ownership and limited public transit integration. This study applies the Low Emissions Analysis Platform (LEAP) to model long-term energy demand and GHG emissions under two scenarios: Business-as-Usual (BAU) and Low-Carbon Scenario (LCS). A bottom-up vehicle stock turnover approach was combined with socioeconomic projections to simulate transport energy consumption from 2024 to 2050. The LCS integrates electric vehicle (EV) promotion, expansion of Light Rail Transit (LRT), Double-Track Rail (DTR) and High-Speed Rail (HSR), and implementation of Transit-Oriented Development (TOD) strategies. Results show that, compared with BAU, the LCS can reduce transport-related GHG emissions by 62.9% by 2050 and final energy demand by 43.5%, reflecting a substantial shift from fossil fuels toward electricity and biofuels. Under the LCS, adoption of EVs is projected to reach 100% of new passenger car sales by 2050, supported by the electrification of rail transport and decreased Vehicle Kilometres Travelled through TOD-based planning. These findings confirm that locally calibrated, integrated transport and land-use measures can significantly support Thailand's national targets for carbon neutrality by 2050 and net-zero emissions by 2065. The modelling framework may potentially transferable to other mid-sized cities and provides evidence-based guidance for low-carbon urban transport planning.

Keywords: LEAP model; low-carbon transport; energy modelling; greenhouse gas emissions; electric vehicles; transit-oriented development.

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1. Introduction

Climate change is one of the most pressing global challenges, with greenhouse gas (GHG) emissions from energy consumption identified as the dominant driver. The Intergovernmental Panel on Climate Change (IPCC, 2018) reports that energy-related activities account for approximately 76% of global GHG emissions. In response, international agreements such as the Paris Agreement seek to limit global temperature rise to 1.5-2°C and achieve carbon neutrality by mid-century (IPCC, 2021).

Thailand has aligned itself with these global ambitions by progressively enhancing its climate commitments. In its 2nd Nationally Determined Contribution (NDC), submitted in 2022, Thailand pledged to reduce GHG emissions by 30% from the projected business-as-usual (BAU) level by 2030, a significant increase from the 20-25% reduction target in its first NDC, submitted in 2015. Furthermore, the 2022 update indicates that this mitigation contribution could rise to 40% with sufficient international support, including technology transfer, financial assistance, and capacity building (Thailand, 2022). These commitments are embedded in national strategic frameworks, including the 20-Year National Strategy (2018–2037) and the 13th National Economic and Social Development Plan (2023–2027), which together frame Thailand's long-term low-carbon transition (NESDC, 2018; NESDC, 2023).

Within this national policy context, Khon Kaen Province has emerged as a dynamic case for low-carbon urban transformation. As a rapidly growing urban hub in Northeast Thailand, Khon Kaen is pursuing a Smart City vision focused on improving public transportation, expanding renewable energy use, and enhancing energy efficiency (KKM, 2023). Notable initiatives include the planned Light Rail Transit (LRT) system, Transit Oriented Development (TOD), and promotion of electric vehicles (EVs) (S6-5 Group, 2014; Chindaprasirt *et al.*, 2024). These initiatives position Khon Kaen as one of the few provincial cities in Thailand where large-scale rail investment, TOD implementation, and EV promotion are being pursued in parallel, making it a particularly suitable case for integrated transport–energy modelling.

Translating Thailand's national climate commitments into effective provincial action requires robust, locally calibrated energy modelling to evaluate future scenarios, policy impacts, and mitigation pathways (GIZ, 2023). The Low Emissions Analysis Platform (LEAP) has been widely applied in national and subnational studies to assess long-term energy demand and

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emissions, with previous applications in Nakhon Ratchasima (Tippichai, Teungchai, and Fukuda, 2023) and Rayong Province (Lunsamrong and Tippichai, 2022) demonstrating its utility for policy evaluation and strategic planning.

Despite substantial progress in transport energy modelling and GHG assessment, existing research in Thailand remains concentrated on national-level analyses or major metropolitan areas. Consequently, mid-sized provincial cities such as Khon Kaen—where demographic expansion, urbanisation, and rapid motorisation are reshaping mobility and energy demand—remain largely underrepresented in quantitative modelling. Although policy-oriented studies such as the Low Carbon Society (LCS) and Low-Carbon Model Town (LCMT) assessments outline strategic mitigation directions (JGSEE *et al.*, 2013; APERC, 2022), they do not employ bottom-up modelling or quantify how emerging transport and land-use transitions jointly influence long-term emissions.

Furthermore, major infrastructure investments—including Light Rail Transit (LRT), High-Speed Rail (HSR), and Transit-Oriented Development (TOD)—have been repeatedly emphasised in provincial development plans as critical drivers of future modal shift and spatial restructuring. Yet, their combined impacts on transport energy consumption and GHG emissions have not been evaluated within an integrated modelling framework (KKSC, 2022). In addition, provincial datasets such as sectoral final energy consumption and transport activity statistics remain underutilised in previous studies, resulting in projections that are insufficiently tailored to Khon Kaen's local demographic and fleet characteristics.

To address these gaps, this study applies the LEAP model to the transport sector covering road and rail transport in Khon Kaen Province, which currently accounts for the largest share of total final energy consumption. Two scenarios are evaluated:

1. Business-as-Usual (BAU) - assuming continuation of historical trends without major interventions.
2. Low-Carbon Scenario (LCS) - incorporating EVs adoption, the development of double track railway (DTR), expansion of LRT and High-Speed Rail (HSR), and implementation of Transit-Oriented Development (TOD) principles to encourage modal shift.

This study aims to quantify future energy demand and greenhouse gas emissions from the transport sector in Khon Kaen Province under a Business-as-Usual (BAU) scenario and a Low-Carbon Scenario (LCS), to assess the mitigation potential of integrated low-carbon transport measures—including vehicle electrification, rail expansion, and transit-oriented development—and to provide a policy-relevant and replicable modelling framework to support provincial and national decarbonisation strategies.

By focusing on a mid-sized provincial city with strong growth potential, this research contributes to the understanding of how localized scenario modelling can inform both subnational decarbonization strategies and national climate policy integration.

2. Khon Kaen's Transition toward a Low-Carbon City: Policy Integration and Local Initiatives

Khon Kaen Province is undergoing rapid urban, economic, and infrastructural transformation, positioning itself as a strategic node in the Greater Mekong Subregion (GMS) and an emerging leader in low-carbon city development in Thailand. This transition is supported by long-standing research on the city's carbon profile and mitigation potential, reinforced by national policy alignment and international cooperation (JGSEE *et al.*, 2013; TDRI, 2018).

2.1 Provincial Policies and Strategic Plans Driving Khon Kaen toward a Low-Carbon

2.1.1 Smart City Vision and Low-Carbon Goals

Khon Kaen's Smart City vision is anchored in major national frameworks, including the 20-Year National Strategy (2018-2037) and Thailand's Climate Change Master Plan 2015-2050, as well as the country's Updated Nationally Determined Contribution (NDC) submitted under the Paris Agreement. These national strategies collectively promote environmentally responsible development, greenhouse gas mitigation, and the adoption of clean and efficient energy technologies (ONEP, 2015; ONEP, 2022; NESDC, 2018). Complementary sectoral plans, such as the Energy Efficiency Plan (EEP 2018-2037), further reinforce national commitments to transition toward low-carbon energy systems (MOE, 2015).

In 2016, Khon Kaen was designated by the Thai government as one of the country's Smart City pilot areas, initiating a multi-domain development agenda centred on mobility, energy, environment, and digital integration (TDRI, 2018; APERC, 2022). Within this framework, Smart Mobility focuses on improving transport accessibility through investments in light rail and bus systems, while Smart Energy prioritises renewable energy, smart grids, and energy-efficient buildings. Environmental goals are pursued through waste reduction, urban greening, and measures to strengthen climate resilience, alongside broader Smart Living, Smart Economy, and Smart Citizen initiatives that support social and economic well-being. Together, these elements form the foundation of Khon Kaen's long-term transformation strategy as set out in the city's master plan.

Since 2021, the provincial government has emphasized Smart Environment, Smart Mobility, and Smart Energy as its primary development pillars, embedding low-carbon objectives into local development plans and reinforcing policy reform. This includes strengthening the policy linkages between technological innovation, energy transition, and climate resilience (TGC, 2021; KKSC, 2022; Prateeppornnarong, 2025).

2.1.2 Khon Kaen Smart City Master Plan 2029

The Khon Kaen Smart City Master Plan (2021–2029) sets out a clear direction for using digital infrastructure to improve the quality of life while addressing environmental concerns. Within the Smart Energy component, the plan focuses on expanding solar rooftop systems, promoting waste-to-energy generation, and introducing smart grid technologies to support more decentralised and efficient energy management. These efforts are further supported by community-scale renewable energy projects, particularly solar photovoltaic and biomass initiatives, which aim to reduce dependence on fossil fuels and enhance local energy resilience (KKSC, 2022; APERC, 2022).

2.1.3 Integration of National and Provincial Planning

Khon Kaen's development strategies are closely aligned with Thailand's national energy and climate policy framework. The province's low-carbon transition is shaped by the country's Nationally Determined Contributions, which commit to at least a 30% reduction in greenhouse gas emissions by 2030, with the potential to increase to 40% subject to international support (ONEP, 2022). This direction is reinforced by the Long-Term Low Emission Development Strategy, which sets a national pathway toward carbon neutrality by 2050 and net-zero emissions by 2065 (Thailand, 2022). In addition, national energy-sector policies—particularly the draft Energy Efficiency

Plan and the Alternative Energy Development Plan—provide operational guidance by prioritising renewable energy expansion, transport electrification, and improvements in energy efficiency (DEDE, 2024a; 2024b).

By embedding these national targets into provincial operational plans, Khon Kaen ensures that local initiatives-such as EV charging infrastructure, LRT deployment, and renewable energy integration-directly reinforce national climate objectives (NDCP, 2022; Thailand, 2022; UNFCCC, 2020).

2.1.4 Key Projects Supporting Low-Carbon Objectives

The province is actively implementing infrastructure and policy measures to operate its low-carbon vision:

1. Light Rail Transit (LRT) - Initiated in 2017 and now entering the construction phase, with the first line designed to connect major economic and residential zones. The system is expected to shift a substantial share of trips from private vehicles to mass transit (Long *et al*., 2018; KKSC, 2022; Chindaprasirt *et al*., 2024).
2. Smart Grid Development - Strengthening the capacity for household- and municipal-level renewable energy integration, improving energy reliability, and enabling demand-side energy management (KKSC, 2022).
3. IoT-based Energy and Environmental Management - Using sensors and data analytics for real-time optimisation of energy use, waste management, and air-quality monitoring (APERC, 2022).
4. Khon Kaen City Bus Project - Operating clean-energy, air-conditioned buses along key corridors to improve accessibility and reduce motorcycle and private-car trips (TDRI, 2018; KKSC, 2022).
5. Transit-Oriented Development (TOD) - Implementing land-use restructuring around major transport nodes to promote high-density, mixed-use, and pedestrian-friendly environments, thereby lowering travel distances and car dependency (Klungboonkrong, *et al*., 2017; Chindaprasirt, *et al*., 2024).

2.2 Research, Policy Context, and Transport System Overview

2.2.1 Low-Carbon City Concepts and Urban Energy Management

The Low-Carbon City (LCC) concept is a policy framework aimed at reducing urban GHG emissions through both technological innovation and behavioral change. Its core strategies commonly include the expansion of public transport, the promotion of active mobility (walking and cycling), the scaling-up of electric vehicle (EV) adoption, and the generation of energy from local renewable sources (Dienst *et al*., 2013; JGSEE *et al*., 2013; Wang, Du and Liu, 2025).

Effective implementation of the LCC concept requires systematic monitoring and evaluation using tools such as the City Carbon Footprint (CCF), which measures sectoral emissions and informs local policy adjustments. In Thailand, cities such as Khon Kaen, Nakhon Ratchasima, and Koh Samui have piloted LCC initiatives with technical and institutional support from TGO, UNDP, and the APEC Low-Carbon Model Town programme (DEDE, 2018; UNDP, 2020; APERC, 2022).

2.2.2 Tools for Energy and Emissions Analysis

Energy and environmental policy planning increasingly depends on analytical tools capable of simulating complex future scenarios-particularly in urban contexts where energy consumption and human behavior interact dynamically. One of the most widely adopted tools is the Low Emissions Analysis Platform (LEAP), developed by the Stockholm Environment Institute (SEI). LEAP enables detailed modelling of energy use and GHG emissions under alternative scenarios-such as Business-as-Usual (BAU) and Low-Carbon Scenario (LCS)-and has been widely applied in both national and subnational planning contexts (SEI, 2024).

In the transport sector, bottom-up modelling approaches are essential for estimating emissions by vehicle type, incorporating travel-behavior data and operational characteristics. For example, the Multimodal Travel Demand Model (MTDM) has been applied in studies of the Light Rail Transit (LRT) project and Transit-Oriented Development (TOD) initiatives in Khon Kaen to assess the environmental impacts of proposed urban development strategies (Klungboonkrong *et al*., 2017; Chindaprasirt *et al*., 2024).

Complementary tools such as the Extended Snapshot Tool (ExSS) integrate multi-sectoral datasets-covering energy, waste, agriculture, and land use-to generate comprehensive assessments of urban carbon footprints. Notably, the Khon Kaen Towards Low Carbon Society study conducted by the Joint Graduate School of Energy and Environment (JGSEE) applied both ExSS and the Asia-Pacific Integrated Model (AIM) to evaluate provincial-level emissions and identify targeted mitigation measures (JGSEE *et al*., 2013).

Selecting the most appropriate model requires careful consideration of data availability, methodological complexity, and policy relevance. Moreover, integrating these tools with reliable, high-resolution local datasets can substantially enhance the accuracy of energy planning and the effectiveness of emissions-management strategies at the provincial scale (Ferrando *et al*., 2021; Kachirayil *et al*., 2022).

2.2.3 National and Local Policy Frameworks on Energy Reduction

Thailand's policies to reduce energy consumption and transport-related GHG emissions are closely aligned with global sustainable development agendas, most notably the Paris Agreement and its associated Nationally Determined Contributions (NDCs). Under its NDCs, Thailand has committed to reducing GHG emissions by at least 30% from the business-as-usual (BAU) level by 2030, with potential for deeper cuts subject to international support (Thailand, 2022).

From an infrastructure perspective, Khon Kaen is strategically positioned along the Bangkok-Nong Khai mainline railway (Double-track railway, DTR), which spans 139.9 kilometers through several districts section and comprises 12 stations. In 2021, this route recorded a passenger volume of approximately 136,000 (SRT, 2022). The planned Thai-Chinese High-Speed Rail (HSR) project will further strengthen Khon Kaen's connectivity by linking it with Bangkok, Nakhon Ratchasima, Udon Thani, and Nong Khai, forming part of a transregional rail corridor that will connect Thailand to Laos and China (OTP, 2020).

At the provincial level, the Khon Kaen Smart City Master Plan 2029 provides a practical framework for translating national climate and energy objectives into local action. The plan places strong emphasis on Smart Mobility and Smart Energy by advancing sustainable public transport through the deployment of light rail transit, encouraging electric vehicle adoption via incentives and charging infrastructure, and promoting transit-oriented development to better integrate land use and transport while reducing overall travel demand (Klungboonkrong *et al*., 2017). These transport-focused measures are complemented by the expansion of solar rooftop programmes across both public and private sectors to accelerate the uptake of renewable energy (KKSC, 2022).

In addition, Khon Kaen is one of the pilot cities under the UNDP-Low Carbon City (LCS) Project, which focuses on strengthening local capacity in energy planning, waste management, and sustainable mobility behavior change (Faiboun, *et al*., 2020; UNDP, 2020). Together, these national and local frameworks create a robust policy foundation for Khon Kaen's low-carbon transition. They facilitate localized innovation in clean energy and sustainable transport, while reinforcing Thailand's broader commitments to carbon neutrality and global climate targets (Table 1).

2.2.4 Energy and Transportation Situation in Khon Kaen Province

Khon Kaen is a major urban center in northeastern Thailand, serving as a hub for regional economic development, transportation, and smart city initiatives. These functions significantly influence the province's energy consumption patterns and associated greenhouse gas (GHG) emissions, particularly in the transport sector, which continues to expand in parallel with population growth, rising vehicle registrations, and ongoing infrastructure development (JGSEE *et al*., 2013; TDRI, 2018).

Provincial energy reports from 2008 to 2023 indicate a substantial increase in electricity consumption in both the residential and industrial sectors. By 2023, total final energy consumption exceeded 125 kilotonnes of oil equivalent (ktoe)—almost double the level recorded in 2008. The transport sector, dominated by liquefied petroleum gas (LPG) and other fossil fuels, remains the largest contributor to overall energy demand (DOEB, 2024).

In transportation, Khon Kaen registered 58,257 new vehicles in 2024, with motorcycles accounting for the majority share (approximately 44,000 units). Battery electric vehicles (BEVs) reached 1,599 units, representing about 2.7% of total new registrations, reflecting an early but growing shift toward low-emission mobility (DLT, 2024).

Population and household statistics further underscore the province's rapid urbanization. In 2023, Khon Kaen's population stood at approximately 1.78 million, with around 28.6% residing in municipal areas. This rising urban density has contributed to higher travel demand, placing additional pressure on energy infrastructure and mobility systems (KKM, 2023).

To address these challenges, Khon Kaen has launched several major transport initiatives, most notably the Light Rail Transit (LRT) system. The LRT is expected to significantly reduce private car use and transport-related emissions. Several studies estimate that sustained implementation of the LRT, combined with Transit-Oriented Development (TOD) strategies, could cut CO_2 emissions by more than 60,000 tonnes annually by 2049 (Faiboun, *et al*., 2020; Chindaprasirt *et al*., 2024).

These energy and transport trends provide essential empirical inputs for local policy formulation and scenario-based modelling, offering a robust foundation for assessing Khon Kaen's potential contributions to Thailand's broader climate and low-carbon objectives through data-driven, low-carbon urban planning (JGSEE *et al*., 2013; Klungboonkrong *et al*., 2017).

2.2.5 Research and Case Studies Relevant to Khon Kaen Province

Khon Kaen has attracted growing academic and policy interest as a pilot city for sustainable development and low-carbon urban transformation. Its combination of rapid urbanization, strategic location, and proactive planning has made it a preferred study for energy planning and transport system management in both national and international research (JGSEE *et al*., 2013; TDRI, 2018).

One notable initiative is the project "Khon Kaen - Towards a Low Carbon Society", led by the Joint Graduate School of Energy and Environment (JGSEE) in partnership with Kyoto University and other Japanese stakeholders. This study evaluated GHG mitigation potential across key sectors, including energy, waste management, agriculture, and land use/forestry. A comparative scenario analysis between Business-as-Usual (BAU) and Carbon Mitigation (CM) pathways indicated that emissions could be reduced by up to 28% by 2050 under the CM scenario (JGSEE *et al*., 2013).

At the national level, the UNDP and Thailand Greenhouse Gas Management Organization (TGO) launched the "Achieving Low Carbon Growth in Cities through Sustainable Urban Systems" initiative, designating Khon Kaen as one of four pilot

Table 1
National and Local Strategies Related to Energy and Transport Policy for Low-Carbon Urban Planning in Khon Kaen

Policy Level	Logical Framework		
	Plan / Strategy	Goals / Key Objectives	Relevance to Khon Kaen
National Level	20-Year National Strategy (2018-2037)	Promote safe, energy-efficient, and environmentally friendly transport systems	Guides LRT and EV development in major urban centers such as Khon Kaen
	Energy Efficiency Plan (Draft EEP2024)	Improve energy efficiency by 30% by 2037	Supports transition from internal combustion engines (ICE) to EVs and mass transit
	Alternative Energy Development Plan (Draft AEDP2024)	Increase the share of renewable electricity in total electricity generation to 50% by 2037	Encourages Solar Rooftop and community-scale renewable energy in the province
	Nationally Determined Contributions (NDCs)	Reduce GHG emissions by at least 30% by 2030 (compared to BAU)	Provides emissions reduction targets guiding energy and transport policy in Khon Kaen
	Master Plan for Sustainable Transport System and Mitigation of Climate Change Impacts (2013–2030)	Reduce transport-sector greenhouse gas emissions by 20-25% (potentially up to 36%) by 2030	Supports road-to-rail modal shifts, promotes electric vehicles, and uses biofuels
Local Level	Khon Kaen Smart City Master Plan 2029	Emphasize Smart Mobility and Smart Energy	Implements LRT, EVs, TOD, and renewable energy integration at the municipal level
	Khon Kaen Smart City Plan	Reduce GHG by at least 10%, expand green areas, and develop IoT infrastructure	Supports urban sustainability, GMS economic corridor development, and logistics innovation
International Cooperation	UNDP-LCS Project (Khon Kaen Pilot)	Develop low-carbon city models in four major Thai cities	Positions Khon Kaen as a demonstration city under UNDP and TGO's urban decarbonization program

Source: Adapted from JGSEE (2013); OTP (2013); ONEP (2015); NESDC (2018); TGC (2021); UNDP, (2020); KKSC (2022); NESDC (2023); DEDE (2024a); and DEDE (2024b).

cities. This program sought to advance energy-efficient transport systems, stimulate low-carbon investments, and integrate assessments of environmental outcomes with local governance capacity building (UNDPE, 2019; Faiboun, *et al.*, 2020).

Locally, the Khon Kaen Smart City Master Plan 2029 positions Smart Mobility and Smart Energy as strategic priorities. The plan identifies key measures such as the implementation of Light Rail Transit (LRT), Transit-Oriented Development (TOD), promotion of electric vehicles (EVs), installation of solar rooftops, and deployment of Internet-of-Things (IoT) technologies to optimize energy use and reduce urban emissions (KKSC, 2022).

In addition, Khon Kaen University (Chindaprasirt *et al.*, 2024) conducted a policy-focused study using bottom-up modelling and the Multimodal Travel Demand Model (MTDM) to estimate GHG emissions from proposed LRT with TOD projects, and EVs adoption in Khon Kaen. The analysis revealed how alternative urban development models produce varying environmental impacts, reinforcing the importance of evidence-based modelling in urban planning (Klungboonkrong *et al.*, 2017).

Collectively, these research efforts and case studies demonstrate the feasibility and practical relevance of Khon Kaen as a model for urban energy transition and low-carbon transport development. The empirical findings provide a robust foundation for shaping local policy and guiding long-term sustainability strategies (JGSEE *et al.*, 2013; Tippichai *et al.*, 2023).

2.3 State-of-the-Art Methods for Transport Energy and GHG Modelling

2.3.1 Fleet Turnover and Vehicle Stock Modelling

Recent literature increasingly applies dynamic fleet-turnover modelling to analyze long-term transport emissions. These models track how vehicle stocks evolve over time by incorporating survival functions, retirement rates, and the gradual substitution of internal combustion vehicles with cleaner technologies such as hybrid and battery-electric vehicles. By linking stock evolution with behavioral indicators—particularly vehicle-kilometres travelled—fleet-based models are able to generate realistic projections of energy demand and GHG emissions. Studies published between 2023 and 2025 highlight that fleet-turnover approaches are essential for evaluating the pace of electrification and its potential contribution to mitigation pathways under various policy and economic conditions (ICCT, 2025).

2.3.2 Well-to-Wheel (WTW) and Fuel Pathway Emission Models

Well-to-Wheel (WTW) modelling has become the standard method for estimating transport-sector emissions because it captures both upstream fuel production (Well-to-Tank) and vehicle operation (Tank-to-Wheel). This whole-cycle approach is especially important for analysing electric vehicles, hydrogen, and advanced biofuels, as their carbon performance depends heavily on the carbon intensity of electricity generation and fuel supply chains. Recent international assessments emphasize the need to update WTW emission factors to reflect rapidly changing power-sector conditions, including increased penetration of renewable energy and declining grid-emission intensities. These advances enable more accurate comparisons between fossil-based and low-carbon transport options (IEA, 2024; IRENA, 2024).

2.3.3 Transport Energy Demand Forecasting Models

State-of-the-art forecasting models integrate demographic, economic, land-use, and mobility trends to estimate future transport energy demand. Contemporary approaches often combine LEAP's bottom-up accounting structure with statistical learning or econometric forecasting techniques to improve predictive accuracy (Rahman *et al.*, 2023). Scenario-based studies place increasing emphasis on modal-shift dynamics, transit-oriented development (TOD), improvements in public transport, and non-motorised travel. These models provide insights into how urban form, infrastructure investment, and behavioural changes influence energy use and associated emissions over time (Ashik, Rahman, & Kamruzzaman, 2022).

2.3.4 Integrated Low-Carbon Transport Assessment Frameworks

A growing body of research applies integrated assessment frameworks that combine fleet-turnover modelling, WTW emissions analysis, and transport-energy forecasting within a single modelling structure. This integrated perspective allows researchers to examine cross-sector interactions—such as the interplay between transport electrification, power-sector decarbonisation, and biofuel deployment—and to simulate their combined mitigation potential. Regional studies in ASEAN highlight that such integrated frameworks are particularly valuable for rapidly urbanising cities, where transport, energy, and land-use systems evolve simultaneously. These models therefore play a key role in informing long-term strategies for low-carbon transport development (ADB, 2023).

3. Methods

This study employs a quantitative modelling approach using the Low Emissions Analysis Platform (LEAP) to forecast energy demand and greenhouse gas (GHG) emissions in Khon Kaen

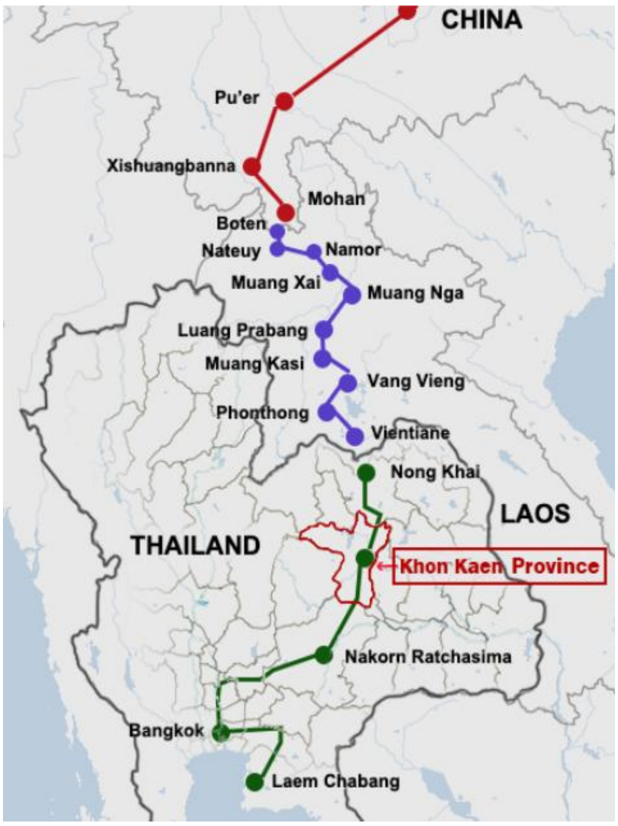

Fig. 1 Location of Khon Kaen Province in relation to Thailand's high-speed rail corridor connecting Bangkok and southern China; provincial boundary added by the authors. *Adapted from China Global South (2025).*

Province's transport sector. The model compares two principal scenarios-Business-as-Usual (BAU) and Low-Carbon Scenario (LCS)-to evaluate the potential impacts of sustainable transport interventions. The methodology integrates transport system data, energy statistics, and socioeconomic indicators to produce evidence-based projections that inform provincial and national policy planning (JGSEE *et al.*, 2013; SEI, 2024).

3.1 Study area

Khon Kaen Province, located in the heart of northeastern Thailand (Fig. 1), spans approximately 10,886 km² and had a population of about 1.78 million in 2024 (KKP, 2024). As a regional hub for commerce, education, healthcare, and transportation within the Greater Mekong Subregion (GMS), the province is well connected via major national highways (Routes 2, 12, 23, and 208), the Bangkok-Nong Khai railway, and an expanding regional airport (OTP, 2020; SRT, 2022).

Rapid urbanization in the central municipality and surrounding peri-urban areas has led to increased final energy consumption, driven by growth in the transport, industrial, and residential sectors. In 2024, total final energy consumption was 725.93 ktoe, with the transport sector contributing the largest share (65.09%), followed by the industrial sector (17.23%), residential sector (13.08%), commercial sector (5.87%), and other sector (1.47%) (DOEB, 2024).

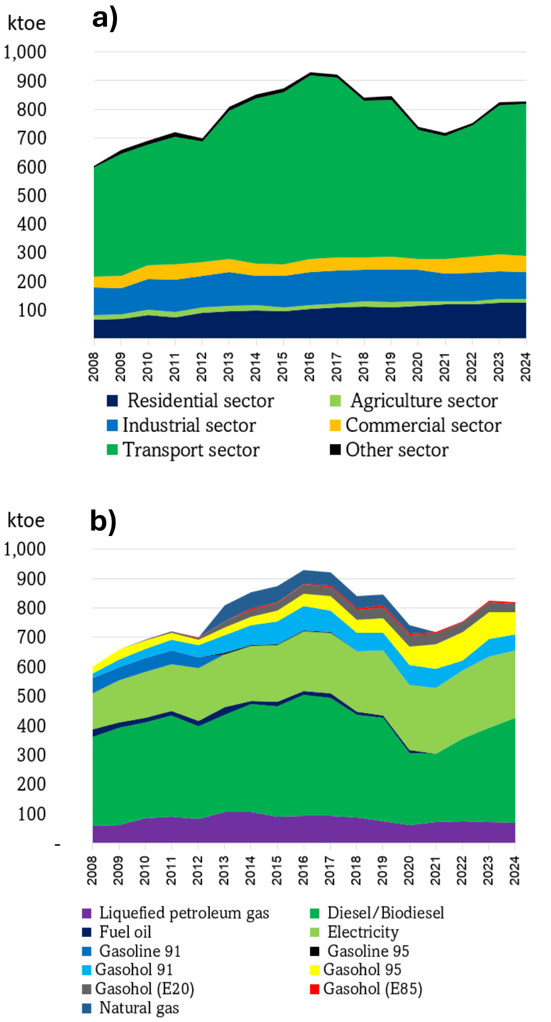

Fig. 2 Khon Kaen's Final Energy Consumption (a) by Sector, and (b) by Fuel Type, 2010-2024.

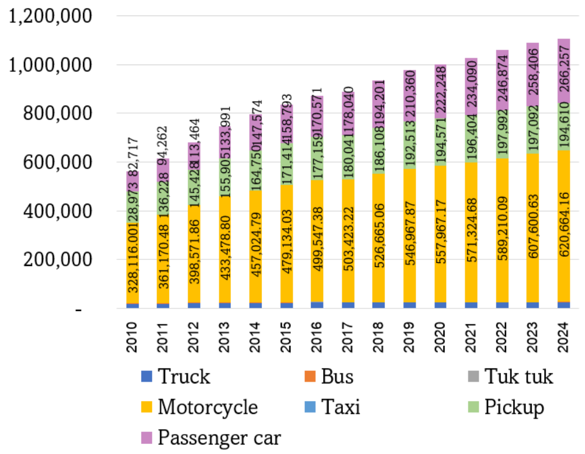

Fig. 3 Vehicle Stock in Khon Kaen Province by Vehicle Type, 2010-2024.

The dominance of the transport sector in energy use, primarily from diesel, gasoline, and gasohol, highlights its critical role in provincial GHG emissions and positions it as a priority for energy efficiency and decarbonization strategies. Historical energy consumption trends from 2010 to 2024, as illustrated in Fig. 2, reveal the sustained dominance of high-speed diesel in Khon Kaen's energy mix, accompanied by a gradual increase in electricity use, primarily driven by rising demand in the residential and industrial sectors (DOEB, 2024; Kanchana, 2024). Consumption of gasohol types (91, 95, and E20) has remained relatively stable over the period, while alternative fuels such as E85 and natural gas have contributed only marginally to the overall energy supply (DOEB, 2024; DMF, 2024; Kanchana, 2024).

Between 2010 and 2024, motorcycles dominated with 60-70% of the fleet, though their share declined slightly in later years. Passenger cars rose from about 15% to over 25%, while pickups increased from around 20% to about 25%. In contrast, buses and tuk-tuks dropped to less than 5% of the total vehicle stock (DLT, 2024; Fig. 3). Together, these patterns provide a robust empirical basis for modelling future energy and emission scenarios (Kanchana, 2024).

3.2 Data Collection and Model Inputs

Data were compiled from multiple sources, classified into three main groups: road transport system, rail transport system, and socioeconomic/demographic data (KKM, 2023).

3.2.1 Road Transport System

Vehicle stock data for Khon Kaen Province were compiled over the period 2010-2024 to construct a time-series database that reflects the dynamics of road-transport development. The dataset was obtained from major institutional sources, including the Department of Land Transport (DLT, 2024), the National Statistical Office, and the Department of Provincial Administration (DOPA, 2024), and records maintained by local administrative authorities (KKP, 2024).

The compiled dataset covers a broad spectrum of vehicle categories such as passenger cars, pickup trucks, taxis, motorcycles, tuk-tuks, buses, and trucks. Each category was further disaggregated by fuel type-gasoline, diesel, LPG/NGV, biodiesel, and electricity-to provide a comprehensive picture of the transport-fuel structure in the province, enabling downstream modelling of energy use and emissions (DMF, 2024; DOEB, 2024).

In addition, the stock of each vehicle category was recorded by vehicle technology, including gasoline, diesel, LPG/NGV, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs), for each year in the time series. This level of detail enables a comprehensive assessment of both fleet composition and fuel-technology structure. The use of multi-year, disaggregated data improves the accuracy of trend analysis and provides a robust basis for calibrating energy models such as LEAP (SEI, 2024) and mathematical functions such as the Gompertz model (Dargay and Gately, 1999; Dargay, Gately and Sommer, 2007), which are subsequently applied to forecast energy demand and greenhouse gas emissions in future scenarios.

Although internal combustion engine (ICE) vehicles continue to dominate, the rising number of electric vehicles (EVs)-including HEVs, PHEVs, and BEVs-reflects an emerging transition toward cleaner energy in the transport sector (GIZ, 2023; Kanchana, 2024). If adequately supported through infrastructure, incentives, and policy measures, this trend could accelerate a systemic shift toward low-carbon mobility (Thailand, 2022).

Based on the time-series data from 2010-2024, Khon Kaen's vehicle fleet has undergone a clear and steady transformation. Passenger cars increased from 82,717 units in 2010 to 266,257 units in 2024, reflecting their sustained role as a dominant mode of personal mobility. Pickup trucks followed a similar upward path, rising from 128,973 units to 194,610 units during the same period.

Motorcycles continue to represent the largest share of the vehicle stock. Their numbers grew from 328,116 units in 2010 to 620,664 units in 2024, underscoring the province's significant dependence on two-wheel transport for both personal and livelihood-related mobility. Taxis also expanded gradually, increasing from 135 units in 2010 to 271 units in 2024. By contrast, some traditional public transport modes (e.g., tuk-tuks and buses) exhibited a decline. Tuk-tuks decreased sharply from 497 units in 2010 to just 33 units in 2024, pointing to a structural shift away from this mode. Buses also declined, from 3,189 units in 2010 to 1,784 units in 2024, reflecting broader challenges in conventional bus-based services.
Meanwhile, trucks-critical for freight operations-grew steadily from 18,229 units in 2010 to 23,953 units in 2024, consistent with the province's expanding economic activities and logistics

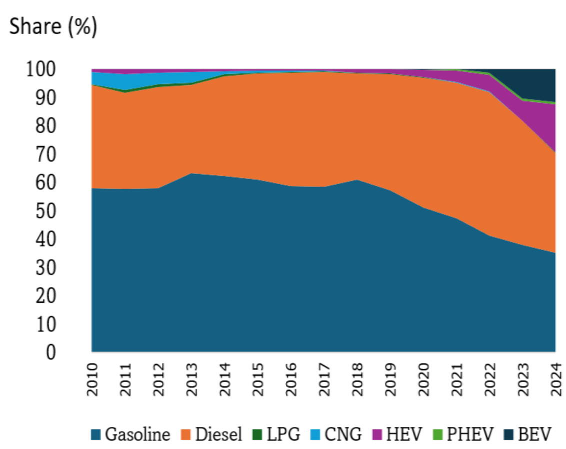

Fig. 4 Passenger Car Sales Share by Vehicle Technology, 2010-2024.

demand (DLT, 2024). As recommended by S6-5 Group (2014), electric truck operations in Khon Kaen could reduce the CO_2 emissions in the urban area. Fig. 4 illustrates the sales share of passenger cars by technology type during 2010-2024. The data show that in 2010, gasoline and diesel vehicles together accounted for nearly 99 percent of total sales, with only a negligible share of hybrid electric vehicles (HEV). Over time, the share of gasoline vehicles declined from about 58 percent in 2010 to roughly 34 percent in 2024, while diesel vehicles decreased from around 36 percent to about 31 percent in the same period (DLT, 2024). In contrast, HEVs gradually expanded their market share, reaching nearly 17 percent of total sales in 2024. Battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) began to enter the market after 2020, together accounting for about 12 percent of sales in 2024 (DLT, 2024). Other fuel types such as LPG and CNG remained below one percent throughout the period. These results indicate an initial diversification of vehicle technologies in the provincial market prior to low-carbon interventions (Kanchana, 2024).

3.2.2 Rail Transport System

This study compiles data on the rail transport system to capture another essential dimension of Khon Kaen's mobility structure. The dataset covers service distances, station numbers, passenger and freight capacity, as well as the integration of Transit-Oriented Development (TOD), which plays a vital role in shaping long-term energy use and CO_2 reduction (OTP, 2020 and 2023; SRT, 2022).

The rail system under study consists of three main components. First, the Bangkok-Nong Khai conventional mainline (Double Track Railway), which spans 139.9 km within Khon Kaen Province, comprises 12 stations, and served approximately 136,000 passengers in 2021 (SRT, 2022). This legacy infrastructure continues to operate throughout the study period, relying predominantly on diesel fuel.

Second, the Thai-Chinese High-Speed Rail (HSR) will link Bangkok, Nakhon Ratchasima, Khon Kaen, Udon Thani, and Nong Khai as part of a regional corridor extending into Laos and China (OTP, 2020 and 2023; SRT, 2022). Construction commenced in the mid-2020s, with operations expected to begin after 2028, powered primarily by electricity.

Third, Khon Kaen is advancing a Light Rail Transit (LRT) project, comprising five planned lines that will connect major hubs such as the main railway station, bus terminals, and Khon Kaen University. Phased operations are anticipated during the 2030s, with planning explicitly aligned to TOD principles aimed at enhancing accessibility, reducing reliance on private cars, and supporting CO_2 mitigation in the long term (TDRI, 2018; Chindaprasirt *et al.*, 2024).

In summary, Khon Kaen Province is served by three distinct railway systems, comprising two intercity systems and one intracity system, each differing in development progress, service characteristics, and long-term strategic roles. The intercity systems include the Bangkok–Nong Khai conventional mainline (Double Track Railway), which currently operates using diesel traction, and the Thai–Chinese High-Speed Rail (HSR), an electric-powered corridor now under construction and expected to commence service after 2028. The province's intracity system is the planned Khon Kaen Light Rail Transit (LRT), designed to expand urban mobility and support Transit-Oriented Development (TOD) initiatives during the 2030s. The development status, technical characteristics, and spatial functions of these three systems are summarized in Table 2.

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Table 2
Timeline of the Rail Development in Khon Kaen

System	Status/Timeline	Operational & Energy Characteristics
DRT (Double Track Railway)	Existing, continuous operation (legacy diesel-based)	Intercity diesel rail; moderate frequency; limited integration with urban modes; high energy intensity.
HSR (Thai-Chinese High-speed Railway)	Construction mid-2020s; operation expected post-2028 (electricity)	Intercity high-speed electric rail; dedicated tracks; long-distance travel demand; low–moderate energy use.
LRT (Khon Kaen Light Rapid Transit)	Planning and investment ongoing; phased operation expected in 2030s (electricity, TOD-based)	Urban light-rail; high service frequency; strong modal-shift potential; integrated with TOD; low energy intensity.

Source: Adapted from OTP (2019, 2023); KKSC (2022); SRT (2022).

In summary, the railway systems serving Khon Kaen—comprising the diesel-based Double-Track Railway (DRT), the electric High-Speed Rail (HSR), and the planned Light Rail Transit (LRT)—illustrate a clear progression from high-energy, legacy operations toward modern, low-carbon rail solutions. The contrast in energy intensity across these systems is substantial: DRT services consume approximately 1.8–2.5 MJ/passenger-km, whereas HSR reduces this requirement to 0.4–0.6 MJ/passenger-km, and LRT performs even more efficiently at 0.25–0.35 MJ/passenger-km. This represents an approximate 70–85% reduction in energy use when shifting from diesel intercity rail to electric urban rail.

When integrated with future TOD sites and enhanced feeder systems, the combined adoption of LRT and HSR is projected to generate a 10–25% modal shift from private vehicles to mass transit over the long term, depending on network coverage and service frequency. These quantitative differences underscore how the evolving rail network can fundamentally reshape mobility patterns, reduce transport-related emissions, and support more sustainable land-use configurations.

Together, these multi-level rail systems—intercity (DRT, HSR) and intra-city (LRT)—provide a robust empirical foundation for developing BAU and LCS scenarios. Their operational characteristics, energy efficiencies, and modal-shift potential ensure that subsequent analyses of energy demand and GHG emissions remain realistic, evidence-based, and aligned with Khon Kaen's long-term mobility trajectory (OTP, 2020, 2023; SRT, 2022; Chindaprasirt *et al.*, 2024**)**

3.3 Energy Demand Forecasting and Scenario Development

The LEAP model simulates energy demand from 2024 (baseline) to 2050 under two main scenarios:

1. Business-as-Usual (BAU) - continuation of existing trends with limited policy intervention.
2. Low-Carbon Scenario (LCS) - integrated measures promoting EV adoption, expansion of LRT and HSR, and TOD-based urban development.

3.3.1 Conceptual Framework and Scenario Assumptions

The modelling framework in this study follows the Avoid–Shift–Improve (ASI) approach, which has been widely adopted in transport decarbonisation policies in Thailand and internationally (Nakamura *et al.*, 2004; OTP, 2019; NDCP, 2022; SEI, 2024).
The ASI concept emphasises three complementary strategies:

- Avoid unnecessary travel through ICT solutions and mixed-use planning.
- Shift travel from private vehicles to public transport systems.
- Improve vehicle efficiency and promote low-carbon technologies.

In subsequent academic work, the ASI framework has been further analysed and expanded to address broader challenges in sustainable and climate-resilient transport systems. Taylor (2021), in Climate Change Adaptation for Transportation Systems, argues that ASI should not be viewed solely as a

Table 3
Applicable fuel-technology combinations for road and rail transport in Khon Kaen Province

Vehicle / Mode	Gasoline*	Diesel*	LPG/CNG	Hybrid	PHEV	BEV
Passenger car	●	●	●	●	●	●
Pickup		●	●			●
Taxi	●	●	●			●
Motorcycle	●		●	●		●
Motorcycle taxi	●		●			●
Tuk-tuk	●		●			●
Bus		●	●	●		●
Truck		●	●			●
Rail (DTR)		●				
Rail (HSR)						●
Rail (LRT)						●

Remark: ● indicates that fuel and technology are applicable.
* Gasoline and diesel include biofuels, i.e., ethanol and biodiesel.

Table 4
Modeling Approaches and Parameters for Road and Rail Transport

	Road Transport	Rail Transport
Modeling approach	• Bottom-up (Stock turnover analysis)	• Top-down
Parameter	• Vehicle stock by technology and fuel, and vehicle age profile in 2010 • Vehicle sales by technology fuel • Fuel economy • Vehicle kilometer-traveled • Survival rate	• Ridership and average kilometer-travel • Freight volume and average kilometer-transport • Energy intensity

mitigation model but as an integrated planning framework that connects emission reduction with long-term climate adaptation. According to Taylor, shifts in travel demand, modal patterns, and technological pathways must be evaluated alongside exposure to climate risks—such as heat extremes, flooding, and infrastructure vulnerability—to ensure that transport planning remains robust under future climatic uncertainties.

This expanded interpretation strengthens the relevance of the ASI framework for rapidly growing provincial cities such as Khon Kaen, where mitigation and adaptation considerations overlap. Incorporating Taylor's insights enables a more comprehensive assessment of how behavioural change, public transport investment, and technological transitions jointly contribute not only to decarbonisation but also to climate resilience.

Table 3 presents the compatibility between different vehicle categories and rail systems in Khon Kaen Province and the types of fuel and technology applicable to each. A dot (●) indicates a valid fuel-technology combination. The table highlights the diversity of fuels in the road transport sector, ranging from conventional fossil fuels such as gasoline and diesel to alternative fuels including LPG, CNG, biofuels, and electricity (DMF, 2024; DOEB, 2024).

In contrast, rail transport still relies predominantly on diesel for conventional services, while new projects such as the High-Speed Rail (HSR) and Light Rail Transit (LRT) are designed to operate primarily on electricity, reflecting a broader transition toward low-carbon transport systems (TDRI, 2018; OTP, 2020 and 2023; SRT, 2022; Chindaprasirt *et al.*, 2024).

Table 4 shows modeling approaches and parameters applied to road and rail transport. The road transport model employs a bottom-up (vehicle stock turnover model) approach, drawing on vehicle stock and age profile, sales by fuel type, fuel economy, vehicle kilometers traveled, and survival rates (Dargay and Gately, 1999; Dargay, Gately and Sommer, 2007). This structure is commonly used to calibrate LEAP-based energy models, ensuring that technology shifts and fleet dynamics are accurately captured (SEI, 2024).

In contrast, the rail transport model applies a top-down approach, based on ridership and average distance traveled, freight volume and distance, and energy intensity (OTP, 2023). These parameters support the development of scenario-based projections for evaluating long-term energy and emissions outcomes.

Table 5 presents the key assumptions underpinning the scenario design, comparing the BAU and LCS pathways (JGSEE *et al.*, 2013). The BAU scenario reflects a continuation of current trends without additional mitigation measures, while developments in other sectors follow existing efficiency programmes In contrast, the LCS scenario integrates measures aligned with national and subnational climate targets, including EV adoption, DTR and HSR expansion, and TOD-based planning (OTP, 2019). For non-transport sectors, the scenario assumes accelerated improvements in energy efficiency and increased renewable energy deployment (JGSEE *et al.*, 2013; NDCP, 2022).

3.3.2 Forecast Variables

The forecasting of energy demand in the transport sector requires a comprehensive set of socioeconomic and technical variables that influence travel behavior and vehicle usage, including population growth, urbanization trends, gross provincial product (GPP), vehicle stock, average travel distance, fuel economy, annual fuel efficiency improvements, and electric vehicle (EV) adoption rates (SEI, 2024; KKP, 2024; NDC Partnership, 2022).

To estimate the evolution of vehicle ownership over time, the Gompertz function is employed as a guiding reference. This empirical model describes the relationship between vehicle ownership and per-capita income using a sigmoidal growth curve, capturing the saturation effect observed in developed countries (Dargay and Gately, 1999). The function is defined as:

Table 5
Scenario and Assumptions

Scenario	Analytical Purpose	Assumptions
Business-as-Usual (BAU)	To project future transport energy use and GHG emissions under current trends without additional mitigation measures	- Continuation of current vehicle sales trends by technology (e.g., BEV sales share reaching 40% by 2050) - Gradual fuel economy improvement following existing national standards (assuming an average annual improvement of 1%) - Limited shift to public transport or alternative modes
Low-Carbon Scenario (LCS)	To assess the impact of integrated low-carbon measures aligned with subnational and national climate targets	- Promotion of EV adoption (i.e., BEV share up to 100% for passenger cars and public transport vehicles—buses and taxis—by 2050) - Expansion of LRT, HSR, and Dual-Track Rail (DTR) systems - Implementation of Transit-Oriented Development (TOD) - Mode shift from private vehicles to public transport - Improved fuel economy for remaining ICE vehicles (assuming an average annual improvement of 2.5%)

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

Where

V_t : vehicle population (vehicles per 1,000 people) in year t,
γ : saturation level of vehicle ownership,
α : shape coefficient,
β : rate coefficient, and
GDP_t : per-capita GDP (purchasing power parity, PPP) in year t.

In this study, the saturation level (γ) is set at 540 vehicles per 1,000 population, representing the long-term upper bound of private vehicle ownership in Khon Kaen Province. The parameters α = -5.897 and β = -0.0138 determine the curvature and income responsiveness of vehicle ownership growth and are calibrated using historical vehicle registration and income data for the period 1995-2022. The calibrated Gompertz function is subsequently applied to project vehicle population trends over the period 2014-2050 and is used consistently under both the Business-as-Usual and Low-Carbon Scenarios.

This formulation is consistent with international empirical studies (Dargay *et al.*, 2007) and serves to validate vehicle growth projections under both BAU and Low Carbon Scenarios. In the context of Khon Kaen, where per-capita income is expected to steadily increase, the Gompertz function provides a logical boundary for modeling the upper limits of private vehicle ownership, especially in the absence of strong public transport incentives.

4. Results and Discussion

4.1 Scenario Simulation Results

This study used the LEAP model to simulate two long-term scenarios for Khon Kaen Province's transport sector (SEI, 2024): Business-as-Usual (BAU) and Low-Carbon Scenario (LCS). The BAU assumes continued growth in private vehicles and fossil fuel use without major policy changes. In contrast, the LCS introduces integrated measures such as EV promotion, expansion of rail transit systems (LRT, DTR, and HSR), and Transit-Oriented Development (TOD) (OTP, 2019 and 2020; Chindaprasirt *et al.*, 2024).

Notably, while car ownership remains similar in early years across both scenarios, the LCS moderates growth over time, consistent with vehicle saturation behaviour observed in international studies (Dargay and Gately, 1999; Dargay *et al.*, 2007). The results underscore the importance of coordinated policy action across transport infrastructure, land use, and vehicle technology-an emphasis aligned with low-carbon transition frameworks adopted in emerging low-carbon cities (Wang *et al.*, 2025; UNFCCC, 2020).

4.1.1 Business-as-Usual Scenario (BAU)

The Business-as-Usual (BAU) scenario represents the reference pathway in which no new policies or behavioural shifts are introduced to curb transport-related energy consumption and greenhouse-gas (GHG) emissions. Private motorization continues to expand in line with income growth, while the contribution of public transport remains marginal. Without further interventions, energy demand rises steadily, reinforcing fossil-fuel dependence and high-carbon mobility patterns.

Under the BAU scenario, vehicle ownership in Khon Kaen Province follows a typical Gompertz motorization curve, increasing from 271 vehicles per 1,000 people in 2023 to 322 in 2030 and 498 in 2050, approaching a long-run saturation of around 540 vehicles per 1,000 people. This growth trajectory mirrors that observed in other emerging urban regions (Wang *et al.*, 2025; IDB, 2013) and highlights the persistence of private-car dominance when no strong policy incentives are introduced.

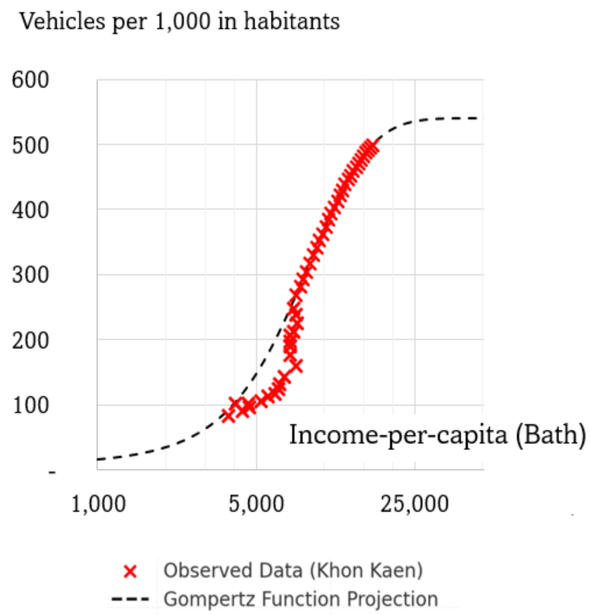

Fig. 5 Khon Kaen's S-curve of Vehicle Ownership.

Fig. 5 compares the observed data points with the Gompertz-based projection. The two curves exhibit reasonably close alignment: ownership accelerates rapidly during periods of income-per-capita expansion and gradually tapers as saturation is approached. This sustained upward trend confirms that, under BAU, road-based private mobility remains the backbone of urban travel, while rail-based systems play only a supporting role. (Dargay and Gately, 1999; Dargay *et al.*, 2007).

Although hybrid and battery-electric vehicles have begun to appear in the provincial fleet, their overall market share remains limited, and internal-combustion-engine (ICE) vehicles continue to dominate Khon Kaen's transport system (DLT, 2024). Between 2023 and 2050, transport-sector energy consumption therefore remains overwhelmingly fossil-fuel-based, driven mainly by gasoline and diesel, which together increase from 686.60 ktoe in 2023 to 879.96 ktoe in 2050 (DOEB, 2024). Electricity consumption rises only marginally from about 0.51 ktoe in 2023 to around 81.27 ktoe in 2050, indicating that electrification alone does not substantially alter the provincial energy trajectory

Planned rail investments such as the Light Rail Transit (LRT) system remain constrained by low ridership and limited integration with surrounding land-use patterns, reducing their potential impact on travel behaviour and energy use (Chindaprasirt *et al.*, 2024). As a result, the benefits of Transit-Oriented Development (TOD) have yet to be realized, and the upward momentum of motorization continues largely unabated.

Fig. 6 illustrates the technological composition of passenger-car stocks under the BAU scenario from 2023 to 2050. Gasoline and diesel vehicles accounted for approximately 93.9 percent of the fleet in 2023 (DLT, 2024), but their share has gradually declined as hybrid-electric (HEV), plug-in hybrid (PHEV), and battery-electric (BEV) vehicles enter the market. Despite this incremental diversification, ICE vehicles remain dominant

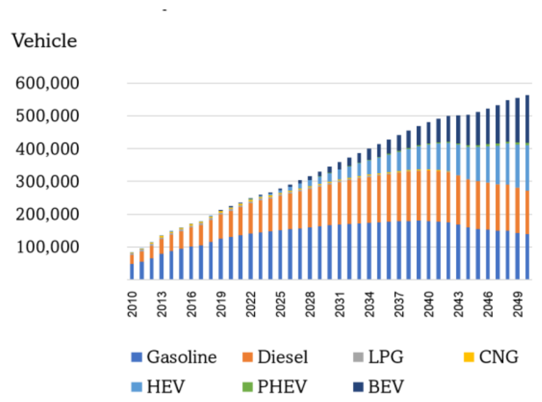

Fig. 6 Passenger Car Stocks by Technology under the BAU.

throughout the projection period, confirming that technological substitution alone does not substantially shift the fossil-fuel trajectory, an outcome consistent with established transport-sector mitigation assessments (IDB, 2013).

Overall, the BAU pathway depicts a conventional urban-transport future in which incremental efficiency gains fail to offset rising demand. By 2050, Khon Kaen's transport energy use reaches approximately 1,085.22 ktoe, while associated GHG emissions rise proportionally—underscoring the necessity of structural interventions such as electrification, TOD, and public-transit expansion, which are examined under the Low-Carbon Scenario (LCS) in the following section (ONEP, 2022).

4.1.2 Low-Carbon Scenario (LCS)

The Low-Carbon Scenario (LCS) demonstrates the potential for structural transformation of Khon Kaen's transport sector through integrated policy interventions. Compared with BAU, the LCS incorporates accelerated electric-vehicle (EV) adoption, rail expansion (LRT, DTR, and HSR), and Transit-Oriented Development (TOD) to reduce fossil-fuel dependency and promote sustainable mobility, consistent with international long-term low-emission development strategies (UNFCCC, 2020).

Under this scenario, total final energy demand in the transport sector declines over the long term, decreasing from 836.29 ktoe in 2023 to 610.49 ktoe in 2050, representing a reduction of 43.5 percent relative to the BAU scenario. Road transport remains dominant in the early years but steadily declines as public transit becomes more accessible and electricity replaces a growing share of petroleum fuels. These behavioural and structural shifts, particularly the rise of electrified rail, align with empirical findings from low-carbon-city pilot studies demonstrating improvements in transport-sector energy efficiency when electrification and modal shift are implemented together (Wang, *et al.*, 2025). Over the same period, final energy demand from rail transport increases from approximately 0.54 ktoe in 2023 to 16.55 ktoe in 2050, reflecting the growing role of electrified LRT, DTR, and HSR systems.

By 2050, non-electricity energy use in transport declines to 372.13 ktoe, comprising gasoline, diesel, B100, ethanol, CNG, and LPG, while electricity consumption in the transport sector rises to 238.36 ktoe, accounting for nearly 39.0 percent of total transport energy demand (Fig. 7). This transition highlights the expanding role of electricity-based mobility in Khon Kaen's transport system and aligns with Thailand's long-term carbon-neutrality objectives.

A key differentiator of the LCS scenario is the rapid acceleration in BEV sales. From a negligible share of about 1% in 2022, BEV sales are projected to reach 50% of new passenger-car sales by 2030, 85% by 2040, and approximately 100% by 2050. Plug-in hybrid vehicles (PHEVs) maintain a small and relatively stable share, while conventional hybrids (HEVs) gradually decline as BEV technology matures and battery costs fall. These market shifts correspond with Thailand's national target of increasing zero-emission vehicle production to 30% by 2030 and reflect strong policy support through tax incentives and investment in charging infrastructure (ONEP, 2022).

Electrification of rail transport further reinforces this outcome. As the High-Speed Rail (HSR), Double-Track Rail (DTR), and Light Rail Transit (LRT) systems become operational, the combined final energy demand of rail transport grows at an average annual rate of approximately 13–14% over the modelling period, supplied almost entirely by electricity (Fig. 8). Together with BEV expansion in the road sector, this dual transition positions electricity as the backbone of Khon Kaen's transport-energy system.

In conclusion, the LCS scenario demonstrates a clear decoupling between economic growth and energy demand. Compared with BAU, it achieves a 62.9% reduction in transport-related GHG emissions by 2050, while moderating the long-term growth of private vehicle ownership (448 vehicles per 1,000 people in 2050 vs. 498 under BAU). Combined with large-scale rail investment, TOD development, and EV-promotion policies, these results confirm that Khon Kaen's transport transition under LCS delivers not only emission reductions but also broader co-benefits in energy efficiency, urban liveability, and social equity (IDB, 2013).

4.1.3 Reduction of Vehicle Kilometers Traveled (VKT)

The reduction of travel activity constitutes a critical mechanism through which the Low-Carbon Scenario (LCS) achieves energy and emission savings. Slower growth in private-vehicle ownership under the LCS, 498 vehicles per 1,000

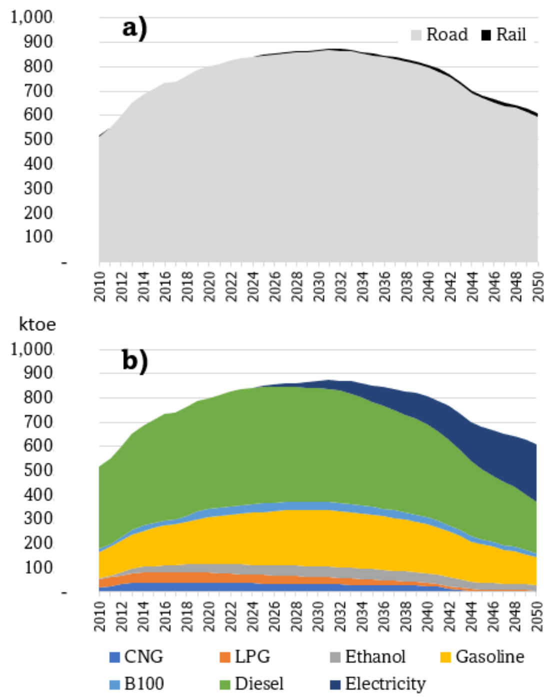

Fig. 7 Final Energy Demand (a) by Mode, and (b) by Energy Type under the LCS, 2010-2050.

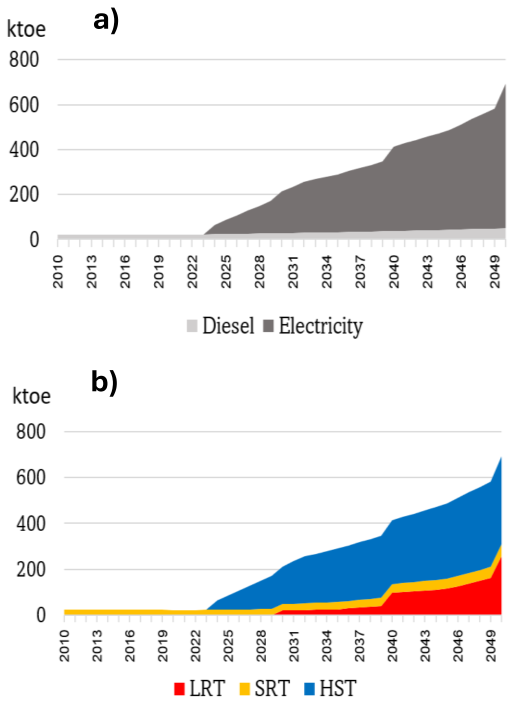

Fig. 8 Rail Transport Final Energy Demand (a) by Energy, and (b) by Rail Type under the LCS, 2010-2050.

people in BAU compared with 448 in LCS by 2050, translates directly into lower levels of mobility demand across Khon Kaen Province. This gradual behavioural and structural moderation of car dependence reflects the combined influence of economic factors, rail system expansion (DTR, HSR, and LRT), and Transit-Oriented Development (TOD) initiatives that reshape travel behaviour and trip distribution.

According to the LEAP-based simulation, the total passenger-car Vehicle Kilometres Travelled (VKT) under the LCS scenario diverges progressively from the Business-as-Usual (BAU) pathway. In 2030, total VKT is projected at 4,486.41 million km under LCS compared with 4,525.24 million km under BAU-equivalent to a 0.86% reduction. The difference expands over time as integrated low-carbon policies begin to take effect: by 2040, the reduction reaches 2.86%, and by 2050, the gap widens to more than 7.37%, with 7,150.59 million km under LCS versus 7,719.90 million km under BAU (Table 6). These outcomes are consistent with international long-term low-emission development strategies that emphasise demand reduction through modal shift and electrification (UNFCCC, 2020).

The growing divergence between the two scenarios demonstrates that the effectiveness of LCS interventions strengthens cumulatively over time. Three interrelated mechanisms account for this pattern.

- Rail-based mobility expansion—including the Light Rail Transit (LRT), High-Speed Rail (HSR), and Double-Track Railway (DTR)—increases network capacity, improves service reliability, and shifts passenger demand from private cars to mass transit.
- Electric-vehicle (EV) adoption reduces the marginal cost of travel and encourages modal integration between private and public transport modes, supporting a broader transition toward low-emission mobility (S6-5 Group, 2014; Chindaprasirt, *et al.*, 2024; Wang, *et al.*, 2025).
- Transit-Oriented Development (TOD) shortens trip distances, supports mixed-use urban development, and promotes walking and cycling (S6-5 Group, 2014; Chindaprasirt, *et al.*, 2024), while enhanced bus and paratransit systems (e.g., minibuses, tuk-tuks) provide essential first-mile/last-mile connectivity and reinforce modal shift toward public transport.

By 2050, total VKT under the LCS is approximately 10% lower than under BAU, confirming that sustainable transport measures can decouple mobility growth from both population and economic expansion. The LCS thus embodies a transition not only in vehicle technology but also in mobility behaviour and spatial planning.

From a policy perspective, these results underscore that demand management is as vital as technological advancement in achieving decarbonization. While EV deployment and electrified rail systems reduce the carbon intensity of travel, complementary demand-side policies-such as land-use zoning around LRT corridors, improved pedestrian connectivity, and incentives for public-transit ridership-directly constrain total travel activity at its source. The synergy between behavioural change and clean technology establishes Khon Kaen's LCS pathway as a practical and replicable model for low-carbon urban mobility in emerging cities of Thailand.

4.2 Discussion

A key outcome of the scenario analysis is the progressively widening divergence between Khon Kaen's Business-as-Usual (BAU) and Low-Carbon (LCS) pathways. While early-stage differences in vehicle ownership are relatively small-322 and 318 vehicles per 1,000 people in 2030-the gap expands significantly by 2050, reaching 498 in BAU and 448 in LCS. This long-term moderation in motorization reflects both behavioural adaptation and structural change resulting from electrification, Transit-Oriented Development (TOD), and rail-based mobility investments. The following discussion interprets these results through four dimensions: policy relevance, key instruments, comparative insights, and limitations.

Table 6
Vehicle Kilometres Travelled (VKT) in Khon Kaen Province: BAU vs LCS.

Year	VKT (BAU) million km	VKT (LCS) million km	Reduction (million km)	Reduction (%)
2030	4,525.24	4,486.41	38.83	0.86%
2040	6,374.59	6,192.45	182.14	2.86%
2050	7,719.90	7,150.59	569.31	7.37%

Source: Author's calculation based on LEAP modelling and Gompertz projections (2025).

4.2.1 Policy Relevance

The scenario results generated by the LEAP model can be directly translated into concrete and actionable policy measures. Provincial authorities can prioritize EV charging deployment, TOD-based zoning around LRT and HSR stations, and demand-management measures, such as parking reform and first–last-mile integration. To achieve effective integration and policy synergy, a combination of "pull" measures and selective "push" policies (e.g., parking management and access control) should be considered in medium-sized cities, even where transport challenges are less acute than in mega-cities (Chindaprasirt *et al*., 2024). At the national level, these findings support alignment with Thailand's Long-Term Low Emission Development Strategy (LT-LEDS) and the updated Nationally Determined Contribution (NDC) targets and potentially provide a transferable decision-support framework for other mid-sized cities. The LCS scenario provides a practical sub-national framework for advancing Thailand's national decarbonization targets under the LT-LEDS and the NDC. These alignments are consistent with Thailand's most recent climate policy commitments, which emphasize strengthened mitigation action at both the national and provincial levels (ONEP, 2022; UNFCCC, 2020). The modelled 63% reduction in transport-related GHG emissions by 2050 demonstrates that regional initiatives-when coordinated with national strategies- can make substantial contributions to the country's carbon-neutrality agenda.

Achieving this transition requires multi-level governance that links national energy policy, provincial planning, and municipal implementation. Electrification of the Light Rail Transit (LRT), Double-Track Rail (DTR), and High-Speed Rail (HSR) systems must coincide with urban-planning reforms, including TOD zoning, parking-space regulation, and incentives that encourage modal shift. Without such integration, efficiency gains from cleaner technology may be offset by rebound effects in travel demand, underscoring the importance of coordinated policy design across administrative levels (Banister, 2011).

Beyond rail expansion, broader policy packages are essential to ensure that low-carbon mobility outcomes materialize across all transport modes. Active-transport improvements—such as safer pedestrian corridors, protected bicycle lanes, and urban-green connectivity—can reinforce short-distance modal shift and complement TOD site enhancements. Electric trucks and freight electrification represent another critical lever, given the increasing role of logistics and goods movement in urban-provincial emissions. Furthermore, park-and-ride facilities, ITS-based traffic management, and feeder systems (including buses, minibuses, and paratransit) are instrumental in strengthening first-mile/last-mile connectivity and maximizing the utilization of rail and public-transport networks.

Taken together, these integrated measures highlight the importance of combining rail transit, land-use planning, zero-emission vehicle strategies, and multi-modal support systems into a coherent policy package. Such a comprehensive approach can help ensure that the decarbonization benefits achieved under the LCS scenario are both durable and scalable across Thailand's emerging provincial cities.

4.2.2 Key Policy Instruments

Successful realization of the LCS pathway depends on three complementary groups of policy instruments:

1.Fiscal and financial measures

Purchase rebates and tax exemptions for Battery Electric Vehicles (BEVs), concessional loans for charging infrastructure, and progressive fuel-tax mechanisms are widely recognized as effective incentives for accelerating low-carbon technology uptake (GIZ, 2023; APERC, 2022).

2.Regulatory and institutional measures

Establishment of low-emission zones, updated vehicle-registration and inspection schemes, and mandatory efficiency standards for public and freight fleets align with international transport-sector mitigation frameworks (IDB, 2013).

3.Urban-planning and behavioural measures

TOD-based zoning, improvement of first-/last-mile connectivity, and expansion of pedestrian and cycling networks around transit corridors have been shown to reshape mobility patterns and reduce car dependence in emerging Asian cities (Klungboonkrong *et al*., 2017; Prateeppornnarong, 2025).

Evidence from Japan's Top Runner Program and Singapore's Green Transport Master Plan shows that long-term policy consistency, rather than short-term subsidies, drives durable investment and behavioural change in the transport sector. For Khon Kaen, combining fiscal incentives with regulatory certainty and urban-design enforcement will be crucial to maintaining momentum under the low-carbon transition (TDRI, 2018).

4.2.3 Comparison with Related Studies

To assess the feasibility and policy relevance of the Low-Carbon Scenario (LCS) in Khon Kaen, it is useful to compare the results with similar case studies from other mid-sized cities, both domestically and internationally. Notably, cities such as Chiang Mai and Nakhon Ratchasima have initiated pilot-scale public transit and EV promotion programs. Preliminary findings from those initiatives indicate that coordinated interventions, particularly those combining rail infrastructure, EV incentives, and land use integration, can positively influence travel behavior and reduce fossil fuel dependency.

According to a 2022 report by Thailand's Energy Policy and Planning Office (EPPO), scenario simulations for similar urban settings suggest that a well-integrated package of EV deployment and TOD development could reduce transport-related GHG emissions by 20-35% over a 20-year period. These results are closely aligned with the 28% reduction projected for Khon Kaen under the LCS scenario.

Internationally, the city of Changwon in South Korea serves as a useful benchmark. Since the early 2010s, it has implemented a combined strategy involving LRT expansion, EV promotion, and TOD-based zoning reforms (APERC, 2022). This integrated approach has not only stabilized the growth of private vehicle ownership but also resulted in sustained emissions reductions in the transport sector. Such examples reinforce the idea that Khon Kaen's LCS pathway is not only theoretically sound, but also practically achievable when contextualized within broader urban transitions globally.

In summary, the scenario outcomes for Khon Kaen are consistent with successful examples elsewhere, reinforcing the notion that similar structural reforms can deliver measurable environmental and social benefits-provided that implementation is systematic, adaptive, and well-supported by public institutions.

4.2.4 Limitations

Despite the strengths of the LEAP modeling approach, the present study is subject to several limitations that should be acknowledged when interpreting the results:

1. Data and Assumptions

The model relies on historical statistical data and projected trends. However, sudden technological disruptions (e.g., rapid EV battery innovation) or major economic shifts (e.g., fuel-price shocks, global crises) may significantly alter these trends in ways not captured by the model. Similar concerns regarding data uncertainty and structural assumptions are documented in urban energy-system modeling literature (Ferrando *et al*., 2021). In addition to battery electric vehicles, hydrogen fuel cell electric vehicles (FCEVs) may play a complementary role in the long term, particularly for heavy-duty and long-distance transport. From a well-to-wheel perspective, battery-electric cars are generally more energy-efficient than FCEVs, as hydrogen pathways entail additional conversion and compression losses during production, storage, and distribution (IEA, 2019). Thailand's Draft AEDP2024 (DEDE, 2024b) sets a national target for hydrogen utilization in the transport sector at just 4 ktoe by 2037. However, this figure is relatively insignificant compared with the anticipated road transport energy demand in Khon Kaen Province, which is projected to reach approximately 840 ktoe in the same year. However, due to the absence of hydrogen production and refuelling infrastructure at the provincial level, FCEVs were excluded from the determined LEAP scenarios.

2. Behavioral Dynamics

The simulation does not fully account for complex behavioral responses, such as consumer hesitancy toward EVs, social preferences for private mobility, or cultural resistance to public transport. Additionally, behavioural shocks arising from extraordinary events—most notably the COVID-19 pandemic—are not incorporated into the model, even though such disruptions have been shown to temporarily alter travel demand, risk perceptions, teleworking patterns, and public-transport ridership. These behavioural uncertainties can significantly influence the real-world impact of any policy intervention, as highlighted in low-carbon urban-transition studies (Dienst *et al*., 2013).

3. Sectoral Interdependence

The model focuses solely on the transport sector and does not explicitly simulate interactions with the electricity sector-for example, increased electricity demand from EV adoption or shifts in the carbon intensity of power generation that would affect net GHG reductions. Integrated energy-system studies have emphasized that such cross-sectoral linkages can substantially alter long-term mitigation outcomes (Kachirayil *et al*., 2022).

4. Policy Implementation Uncertainty

The model assumes that all policy measures under LCS can be deployed on schedule and operate at optimal effectiveness. In practice, however, policy timelines are often affected by political dynamics, institutional capacity, and economic constraints, which may delay or reduce the impact of certain interventions.

Recognizing these limitations is essential to ensure the responsible use of the scenario results. Future work should aim to refine the modeling framework by incorporating dynamic behavioral modules, multi-sectoral linkages, and adaptive timelines for policy roll-out. Such improvements would enhance the robustness and policy relevance of energy-climate modeling at the provincial level.

Overall, the scenario simulation confirms that Khon Kaen Province has substantial potential to decarbonize its transport sector through coordinated policy, infrastructure, and technology measures. By 2050, the Low-Carbon Scenario (LCS) achieves a 63% reduction in transport-related GHG emissions compared to the Business-as-Usual (BAU) pathway, while significantly lowering fossil fuel dependence and increasing the share of electricity and biofuels in the energy mix. These results underscore the importance of integrated planning that combines electric vehicle (EV) adoption, expansion of rail-based public transport, and Transit-Oriented Development (TOD) principles. The magnitude of emissions reduction also demonstrates that provincial-scale interventions, when aligned with national strategies, can make a meaningful contribution to Thailand's carbon neutrality and net-zero targets. This evidence sets the stage for the concluding section, which synthesizes the study's findings and outlines how the Khon Kaen modelling framework may potentially be adapted for other cities pursuing low-carbon transport transitions.

5. Conclusion

This study employed the Low Emissions Analysis Platform (LEAP) to simulate long-term energy demand and greenhouse gas (GHG) emissions from the transport sector in Khon Kaen Province under two scenarios: Business-as-Usual (BAU) and Low-Carbon Scenario (LCS). The results indicate that the LCS—integrating electric vehicle (EV) adoption, expansion of Light Rail Transit (LRT), Double-Track Rail (DTR), and High-Speed Rail (HSR), and implementation of Transit-Oriented Development (TOD) strategies—can reduce transport-related GHG emissions by approximately 63% by 2050 compared to BAU. This substantial mitigation outcome is accompanied by increased energy efficiency, a significant shift from fossil fuels toward electricity and biofuels, and a gradual decoupling of mobility growth from energy demand.

While the analysis focuses on battery-electric vehicles and electrified rail as the primary mitigation pathways under current conditions, future research should explore the role of emerging technologies, such as hydrogen fuel cell electric vehicles (FCEVs), particularly for freight and heavy-duty transport. As hydrogen infrastructure and clean fuel supply chains mature, such technologies may complement electrification in achieving greater emissions reductions. Overall, this research confirms that integrated transport and land-use planning, supported by robust energy modelling, can play a decisive role in advancing low-carbon transport development and supporting Thailand's long-term carbon neutrality and net-zero ambitions.

Achieving high emissions reductions in mid-sized provincial cities requires a multi-pronged approach that integrates technological transformation with infrastructure investment and enforceable urban-planning reforms. The results confirm that integrated policy measures—such as EV incentives, rail electrification, and TOD-based land use planning—can yield transformative impacts when supported by long-term institutional commitment and multi-level governance. These provincial-scale findings reinforce Thailand's national carbon neutrality and net-zero frameworks, demonstrating that locally calibrated interventions can make meaningful contributions to national climate strategies.

Finally, the modelling framework developed in this study may potentially be transferable and adapted for other mid-sized provincial areas in Thailand and emerging economies with comparable development trajectories. This includes applications to regions that are expanding both inter-city and intra-city railway systems, where the interaction between long-distance rail, urban rail transit, and local mobility choices is becoming increasingly important. Future research should enhance the modelling approach by incorporating dynamic behavioral responses, cross-sectoral interdependencies (particularly with the power sector), and policy implementation uncertainties. Strengthening these modelling components would improve the robustness of provincial-level sustainable energy and climate planning.

Overall, Khon Kaen's low-carbon transport transition—as examined through the LCS—demonstrates the feasibility and strategic value of integrated energy–mobility planning, providing a replicable pathway toward sustainable, low-emission urban futures.

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