# ANALYSIS OF LARGE-SCALE ELECTRIC VEHICLE PROMOTION PLAN BY CONSIDERING THE ENERGY MIX AND SUSTAINABILITY OF THAILAND

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# การวิเคราะห์แผนการส่งเสริมยานยนต์ไฟฟ้าขนาดมหัพภาคโดยพิจารณาการบูรณาการพลังงานและความยั่งยืนของประเทศไทย

นายอโศก เปาเดล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาปรัชญาดุษฎีบัณฑิต
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ปีการศึกษา 2566

# ANALYSIS OF LARGE-SCALE ELECTRIC VEHICLE PROMOTION PLAN BY CONSIDERING THE ENERGY MIX AND SUSTAINABILITY OF THAILAND

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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คำสำคัญ : การส่งผ่านยานยนต์ไฟฟ้า/ พลังงานแบบผสมผสาน/ การปล่อยก๊าซเรือนกระจก/ ระบบโครงข่ายไฟฟ้าประเทศไทย

วิทยานิพนธ์นี้นำเสนอกรอบงานเพื่อวิเคราะห์แนวโน้มการใช้ยานยนต์ไฟฟ้า ข้อกังวลของสาธารณชน ความต้องการพลังงาน การปล่อยก๊าซเรือนกระจก และความต้องการพลังงานในอนาคตของประเทศไทย นำไปเปรียบเทียบกับแผนพัฒนาพลังงาน PDP2018r1 เพื่อประเมินความสอดคล้องกับนโยบายการเปลี่ยนผ่านยานยนต์ไฟฟ้า โดยประเทศไทยตั้งเป้าให้ยานยนต์ใหม่ 30% ต้องปราศจากการปล่อยก๊าซเรือนกระจกภายในปี 2573 และมีแผนจะห้ามจำหน่ายยานยนต์ที่ใช้เครื่องยนต์สันดาปภายในหลังปี 2578 ในวิทยานิพนธ์นี้ได้แบ่งออกเป็น 4 ส่วนประกอบด้วย 1) ประเด็นที่เกี่ยวข้องกับการนำยานยนต์ไฟฟ้ามาใช้ : เป็นการวิเคราะห์โดยประยุกต์ใช้แนวทางการตัดสินใจแบบหลายเกณฑ์ร่วมกับวิธีการวิเคราะห์แบบลำดับชั้น เพื่อระบุและจัดลำดับอุปสรรคต่อการนำยานยนต์ไฟฟ้ามาใช้ ตามการถ่วงน้ำหนักลำดับความสำคัญที่สัมพันธ์กัน 2) การคาดการณ์สต็อกรถยนต์ในอนาคต: โดยการพัฒนาโมเดล Vehicle Ownership (VO) การถดถอยแบบ log-linear ที่มีตัวแปรทางเศรษฐมิติถูกนำมาใช้ในการพัฒนาแบบจำลอง VO 3) การใช้แพลตฟอร์ม Low Emission Analysis Platform (LEAP) จำลองความต้องการพลังงาน ส่วนผสมเชื้อเพลิง และการปล่อยก๊าซเรือนกระจกในสถานการณ์ต่าง ๆ 4) การคำนวณความต้องการพลังงานไฟฟ้าสูงสุดเปรียบเทียบกับแผนพลังงาน PDP2018r1 สำหรับประเมินผลกระทบของการส่งผ่านยานยนต์ไฟฟ้าต่อการวางแผนการผลิตไฟฟ้า จากการสำรวจความคิดเห็นของผู้เชี่ยวชาญในแวดวงวิชาการ ภาครัฐและอุตสาหกรรมยานยนต์ไฟฟ้า พบว่าราคาซื้อและราคาการขายต่อเป็นปัจจัยหลักในการนำยานยนต์ไฟฟ้ามาใช้ ตามมาด้วยปัญหาการบำรุงรักษาและแบตเตอรี่ นอกจากนี้สถานีชาร์จสาธารณะแบบอัดประจุเร็วก็เป็นอุปัจจัยสำคัญเช่นกัน สิ่งที่น่าสนใจคือผู้เชี่ยวชาญปฏิเสธการอุดหนุนโดยตรงเพื่อลดต้นทุน โดยสนับสนุนการพัฒนาอุตสาหกรรมและการขยายขนาดแทน ค่า VO มีความสัมพันธ์กับการเติบโตของ GDP และราคาเชื้อเพลิง ซึ่งคาดการณ์ว่าจะมีรถยนต์อยู่ที่ 384 และ 344 คันต่อ

1,000 คน ภายในปี 2583 (จาก 250 คนในปี 2563) หากมีการเติบโตของ GDP อยู่ที่ 5% และ 3% ตามลำดับ โดยสมมติว่าอัตราเงินเฟ้อยังคงอยู่ภายใน 2-3% ตามเป้าหมายของธนาคารแห่งประเทศไทย โดยใช้การเติบโตของ GDP และการเปลี่ยนผ่านของยานยนต์ไฟฟ้าอย่างแข็งขัน (ไม่มียานพาหนะ IC หลังปี 2578 เทียบกับนโยบาย ยานยนต์ไฟฟ้า 30@30) เป็นฐาน ส่งผลให้มี 5 สถานการณ์: GDP3A, GDP3M, GDP5A, GDP5M และ Business As Usual (BAU) สำหรับวิเคราะห์ ผลลัพธ์แสดงให้เห็นว่าความต้องการพลังงานจะลดลงในทุกสถานการณ์เมื่อเทียบกับ BAU ในปี 2583 เนื่องจากการประหยัดน้ำมันเชื้อเพลิงที่ดีขึ้น แนวโน้มตามมาด้วยการปล่อยก๊าซเรือนกระจก ส่วนแบ่งการใช้ไฟฟ้าพบว่าน้อยกว่าหนึ่งในสาม แม้แต่ในสถานการณ์การเปลี่ยนแปลงรุนแรงที่สุด (GDP5A) และตรึงไว้ที่ 62.1 TWh ความต้องการสูงสุดเนื่องจากการชาร์จยานยนต์ไฟฟ้านั้นสัมพันธ์กับโหมดการอัดประจุ และการอัดประจุที่บ้านที่ไม่ประสานกันอาจทำให้เกิดภาระอย่างมากต่อระบบการผลิตพลังงานไฟฟ้า การอัดประจุแบบเร็วในที่สาธารณะได้ถูกนำเสนอเป็นแนวทางแก้ไข เพื่อให้รองรับกับการเพิ่มขึ้นของยานยนต์ไฟฟ้า การพัฒนาโครงสร้างพื้นฐานการอัดประจุในที่สาธารณะเป็นสิ่งที่จำเป็น เนื่องจากจะช่วยลดภาระโหลด และจำกัดความจำเป็นของสร้างระบบผลิตพลังงานไฟฟ้า นโยบาย PDP2018r1 ดูเหมือนจะสามารถรองรับความต้องการยานยนต์ไฟฟ้าได้ แต่อาจต้องมีการแก้ไขเพิ่มเติมให้สอดคล้องกับนโยบายการส่งเสริมรถยนต์ไฟฟ้าในอนาคต นอกจากนี้ อาจบังคับใช้มาตรฐานการปล่อยมลพิษที่เข้มงวดขึ้นเพื่อจำกัดการปล่อยก๊าซเรือนกระจก เนื่องจากยานพาหนะเครื่องยนต์สันดาปจะยังคงอยู่บนท้องถนนไกลเกินกว่าปี 2583 ดังนั้นผลการวิจัยจึงนำเสนอมุมมองที่ครอบคลุมเกี่ยวกับความพยายามในการใช้พลังงานไฟฟ้าในอนาคตของ LDV และเป็นพื้นฐานสำหรับการปรับตัวเพิ่มเติมเมื่อเทคโนโลยีพัฒนาขึ้น

สาขาวิชา วิศวกรรมไฟฟ้า
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ASHOK PAUDEL: ANALYSIS OF LARGE-SCALE ELECTRIC VEHICLE PROMOTION PLAN BY CONSIDERING THE ENERGY MIX AND SUSTAINABILITY OF THAILAND
THESIS ADVISOR: Asst. Prof. Boonruang Marungsri, D.Eng., 153 pages.

Keyword: EV transition/ Energy mix/ GHG emission/ Thai power system

This thesis proposes a framework to analyze the prospects of EV adoption, public concerns, energy demand, emissions, and future power needs in Thailand. It also compares results with PDP2018r1 to assess alignment with the EV transition policy. Thailand aims for 30% of new vehicles to be zero-emission by 2030 and plans to ban internal combustion vehicle sales after 2035. This study involves four distinct steps. Firstly, the issues related to EV adoption are analyzed. The approach of multi-criteria decision-making with an analytical hierarchical method is employed to identify and rank the barriers to EV adoption by their relative priority weightage. Secondly, future vehicle stock is projected by developing the Vehicle Ownership (VO) model. Log-linear regression with econometric variables is used to develop VO models. Furthermore, the Low Emission Analysis Platform (LEAP) simulates the energy demand, fuel mix, and emission in various scenarios. Finally, the peak power demand is calculated and compared to PDP2018r1 to assess the impact of EV transmission on power generation planning. A survey of experts in academia, government, and the EV industry identifies investment and resale value as the primary barriers to EV adoption, followed by maintenance and battery issues. Public fast charging stations are also a significant barrier. Interestingly, experts reject direct subsidies to lower costs, advocating for industry development and scaling instead. Vehicle ownership (VO) correlates with GDP growth and fuel inflation, projecting 384 and 344 vehicles per 1,000 people by 2040 (from 250 in 2020) with 5% and 3% GDP growth, respectively, assuming inflation stays within the Bank of Thailand’s 2-3% target. Scenarios based on GDP growth and EV transition aggressiveness (no ICE vehicles post-2035 vs. EV 30@30 policy) are analyzed, resulting in five scenarios: GDP3A, GDP3M, GDP5A, GDP5M, and business as usual (BAU).

The result shows that the energy demand will decrease in all scenarios compared to BAU in 2040 due to an improved fuel economy, a trend followed by emissions. The share of electricity is less than a third in even the most aggressive transition scenario (GDP5A) and pegged at 62.1TWh. Peak demand due to EV charging is tied to the charging mode, and uncoordinated home charging might pose significant stress to the generation system. Public fast charging can offer viable solutions. For excessive EV transition to succeed, proper development of public charging infrastructure is essential as it helps to reduce peak load and limits the necessity of new power generation infrastructures. The PDP2018r1 appears to serve the EV demand, but further revision might be required to be in sync with the EV promotion policy. Additionally, tougher emission standards could be enforced to limit emissions, as IC vehicles will still be on the road far beyond 2040. Thus, the results present a comprehensive view of the prospective electrification attempt of LDVs and provide the basis for further refinement as the technology evolves.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| EV | Electric Vehicle |
| IEA | International Energy Agency |
| ICE | Internal Combustion Engine |
| PDP | Power Development Plan |
| AEDP | Alternative Energy Development Plan |
| ECP | Energy Conservation Plan |
| AQI | Air Quality Index |
| $MtCO_2eq$ | Million Tonnes of Carbon Dioxide Equivalent |
| ZEV | Zero Emission Vehicle |
| BOI | Thailand Board of Investment |
| AOT | Airports of Thailand |
| THB | Thai Baht |
| FAME | Faster Adoption and Manufacturing of Hybrid and EVs |
| LDV | Light Duty Vehicle |
| EGAT | Electricity Generation Authority of Thailand |
| IPP | Independent Energy Producers |
| ktoe | Thousand Tonnes of Oil Equivalent |
| MEA | Metropolitan Energy Authority |
| PEA | Provincial Energy Authority |
| EPPO | Energy Policy and Planning Office |
| IRP | Integrated Resource Planning |
| DSM | Demand Side Management |
| IRSP | Integrated Resource Strategic Planning |
| GDP | Gross Domestic Product |
| ISRP-SG | Integrated Resource Strategic Planning – Smart Grid |
| MARKAL | Market Allocation |

# LIST OF ABBREVIATIONS (continued)

| | |
|---|---|
| MESSAGE | Model for Energy Supply Strategy Alternatives and Their General Environmental Impact |
| LEAP | Low Emission Analysis Platform |
| GAMS | General Algebraic Modelling System |
| RES | Renewable Energy Resources |
| EFOM | Energy Flow Optimization Model |
| TIMES | The Integrated MARKAL-EFOM System |
| SEI | Stockholm Environment Institute |
| TED | Technology and Environment Database |
| KMDI | Logarithmic Mean Divisia Index |
| MCDM | Multi-Criteria Decision Making |
| TOPSIS | Technique for Order of Preference by Similarity to Ideal Solution |
| VIKOR | VlseKriterijumskaOptimizacija I KomprominsnoResenj |
| CBR | Case-Based Reasoning |
| MULTIMOORA | Multi-Objective Optimization by Ratio Analysis plus full Multiplicative Form |
| AHP | Analytical Hierarchical Process |
| CR | Consistency Ratio |
| CI | Consistency Index |
| RI | Random Index |
| PCI | Per Capita Income |
| POPden | Population Density |
| FP | Fuel Price |
| VO | Vehicle Ownership per 1000 Population |
| MBE | Mean Bias Error |
| RMSE | Root Mean Square Error |
| ED | Energy Demand |
| DLT | Department of Land Transport of Thailand |

# LIST OF ABBREVIATIONS (continued)

| | |
|---|---|
| FE | Fuel Economy |
| VKT | Vehicle Kilometer Travelled |
| HEV | Hybrid Electric Vehicle |
| BEV | Battery Electric Vehicle |
| SOC | State Of Charge |
| PDP | Probability Density Function |
| BPMS | Business Performance Management Singapore |
| BAU | Business As Usual |
| PDP2018r1 | Power Development Plan 2018 Revision 1 |

# LIST OF SYMBOLS AND NOTATIONS

| | |
|---|---|
| $D_{i,t}$ | Energy demand in economic sector *i* in *t* period |
| $\gamma$ | Constant or base demand |
| $b_{i,j}$ | Coefficient related to the sector *i* with explanatory variable *j* |
| $X_{i,j,t}$ | Activity level of variable *j* |
| $A$ | Pairwise comparison matrix |
| $A'$ | Normalized pairwise comparison matrix |
| $W$ | Weightage of criteria or alternative member |
| $\lambda_{max}$ | Largest eigenvalue of the pairwise comparison matrix |
| $n$ | Number of criteria or alternatives |
| $VO_{1000}$ | Vehicle ownership per 1000 population |
| $S$ | Saturation level of vehicle ownership |
| $\beta_0, \beta_1, \beta_2, \beta_3$ | Intercept and Coefficients of PCI, POPden, and FE, respectively |
| $ED_{i,j}$ | Energy demand by *j*-type vehicle with *i*-type fuel |
| $N_{stock\ i,j}$ | The stock of *j*-type vehicles with *i*-type fuel |
| $VKT_i$ | Vehicle kilometer traveled by *j*-type vehicle |
| $FE_{i,j}$ | Fuel economy of *j*-type vehicle with *i*-fuel |
| $v$ | Vintage year |
| $N_{sale\ i,j}\ (v)$ | New vehicle sale in vintage year $v$ |
| $a$ | Vehicle age |
| $S_{i,j}(a)$ | The survival rate of vehicle |
| $Emission_{i,j,k}$ | Emission *k* from fuel *i* of vehicle type *j* |
| $EF_{i,j,k}$ | Emission factor |
| $\emptyset_{i,j,k,\alpha}$ | emission degradation factor for emission *k* on $\alpha$ year |
| $x_{i,j}$ | Daily travel distance of $i^{th}$ vehicle of type *j* |
| $\mu_{d,j}$ | Mean daily travel distance of *j*-type vehicle. |
| $\sigma_{d,j}$ | The standard deviation of travel distance |

# LIST OF SYMBOLS AND NOTATIONS (continued)

| | |
|---|---|
| $d_{i,j}$ | Distance covered |
| $D_j$ | Full driving Range |
| $\eta$ | Efficiency (Charging and discharging assumed equal) |
| $Tst_{i,j}$ | Starting time of charge of $i^{th}$ EV of type $j$ |
| $\mu_{st,j}$ | Mean of starting time of charge. |
| $\sigma_{st,j}$ | Standard deviation |
| $tch_{i,j}$ | Charging time of $i^{th}$ vehicle of type $j$ |
| $BP_{i,j}$ | Battery capacity |
| $CP_{j,j}$ | Charging power |
| $Tend_{i,j}$ | End time of charging |
| $P_{EV\ i,j}(t)$ | Charging load at time $t$ due to $i^{th}$ vehicle of type $j$ |
| $P_{EV}(t)$ | Total EV charging demand |
| $P_{existing}(t)$ | Existing power demand at time $t$ |
| $P_T(T)$ | Total demand to be served after adding EV charging load |

# CHAPTER I

# INTRODUCTION

## 1.1 Electric vehicle and disruptive technologies

Climate change is the major global problem of the current century, and the substitution of fossil fuels is the need of the hour. Emission reduction policy and technology development are at an unprecedented rate. Electrifying the transport sector is a hot topic worldwide, generally referred to as green or clean transport. Countries are investing in electric vehicles (EVs) technology and introducing new policies to increase the share of EVs in their vehicle fleet. According to the International Energy Agency (IEA), under a standard policy scenario, the EV share will be as much as 7% in 2030 and may reach about 12% if a sustainable development scenario (Clean Energy Ministerial, n.d.) and 30% if the EV30@30 initiative becomes a reality (Office of National Higher Education Science Research and Innovation Policy Council, n.d.). Thailand is not far behind in this race in the EV roadmap (Thananusak et al., 2021). They have announced that one-third of the newly registered vehicles in 2030 would be zero-emission vehicles, later upgraded to 50% (Thailand Energy Efficiency Situation 2018, 2018). Emission is not the sole driver behind the transition from internal combustion engine (ICE) vehicles to EVs; energy efficiency and lower energy demand are essential driving forces. The official projection of the Thai government is that the final energy demand will be as high as 182700 ktoe in 2036, and the government is committed to lowering that value by 51700 ktoe by implementing energy efficiency measures. In 2018, the transportation sector had the highest share of 39.4% in final energy demand (Thailand Energy Efficiency Situation 2018, 2018); on the contrary, this sector also has the highest potential of reducing demand by energy efficiency, numerically estimated as 44.7% of total energy conservation potential (Saisirirat et al., 2013).

In such a scenario, EVs will increase progressively in the coming years. Higher EV penetration in the transport fleet means higher electricity demand. The utility must ensure an adequate quantity of electricity, maintaining the quality of service. A proper demand estimation is required to visualize the system's security. Some previous research has projected the EV energy demand to be around 12000 GWhr in 2030 (Saisirirat et al., 2013); however, those analyses were carried out before introducing the EV roadmap in 2015, which was updated to set an ambition to be fully electric in 2035. In this context, it is safe to assume that the share of EVs will increase steadily to meet the government's emission and energy efficiency targets. However, some articles criticize the current approach and doubt the plan's success, which does not emphasize social-economic aspects and an alternative approach like a safe and efficient public mobility system and decarbonization of the power sector (Selvakkumaran et al., 2019) (Chantharaphaha, 2020).

## 1.2 Problem statement

Power system expansion planning has always been tedious as its uncertainties are very high. Conventional generation and transmission expansion planning methodologies have only emphasized investment and running costs. It is again theorized that demand-side management may significantly enhance supply quality and limit the generation requirement. The improved efficiency of conversion technologies also added to this. Integrated Resource Planning (IRP) was born to optimize supply and demand. Later on, emission and climate concerns became the primary aspect of any power development planning process. Renewable technology advancements and the reduced price of solar and wind-like technologies have opened a new window toward integrating renewable energy into the national grid.

Considering all these facts, the Government of Thailand has developed its long-term energy policy. These policies include the Power Development Plan 2015 (PDP, 2015), Alternative Energy Development Policy (AEDP), and Energy Conservation Plan (ECP). These policies were formulated during or before 2015 and are still in effect.

However, the current power system situation is not as simple as the policies have predicted. Thailand now has an excess of generation capacity, but again, those capacities are from thermal power plants, and the government has decided to phase out those before 2030.

On top of that, the government has made an ambitious plan to transition to electric personnel vehicles after 2035. This may imbalance the power generation and energy mix scenario as presented in those policies requiring frequent reassessment. So, this is an attempt to reevaluate the Thai energy system based on previous power development plans and disruptive technologies, climate mitigation measures, and relevant policies. However, this report only deals with the land transportation sector based on the government EV promotion scheme; detailed cost-benefit analysis and sectoral analysis of the remaining sector are assumed to be future work.

## 1.3 Research Objective

The objective of this research is listed below:

1. To develop an EV ownership model and project the number of EVs to be powered in the future based on econometrics and prevailing issues.
2. To determine the EV charging load (daily load curve based on charging mode and starting time of charging).
3. To evaluate the effectiveness of the Government EV promotion roadmap regarding emission targets and subsequent energy transition (oil to electricity).

## 1.4 Scope and limitation

This research work is intended to explain and explore the possibilities of a renewable-based Thai energy system within and beyond PDP 2015. However, current work is limited to passenger land transport based on the government EV plan. The scope and limitations are listed below:

Scope

1. Analysis of historical vehicle registration and future projection
2. Analysis of future energy requirement based upon government EV plan (peak load)
3. Future energy mix projection
4. Estimating standard greenhouse gas emissions in business and the government EV plan scenarios.

Limitations

1. It does not take into account air, train, and freight transport
2. The vehicle survival profile is realized from various sources located in ASEAN, considering South East Asian context
3. Macro-economic situation and frequent policy changes may happen in the future
4. The analysis of other sectors like industrial and commercial to form national energy policy is not in this scope, though it is the major work to be done in the future

## 1.5 Thesis procedure

The basic outline of the thesis procedure is presented below:

1. Vehicle data from the Department of Land Transport, econometric data from various sources, fuel economy, and other information from previous publications were collected.
2. Conduct online interviews by using a questionnaire to collect data about AHP.
3. Develop vehicle ownership model and project future vehicle stock

4. Develop a model in Low Emission Analysis Platform (LEAP) and form EV penetration scenarios
5. Calculate energy demand, energy mix, and emissions
6. Project additional peak demand and compare with PDP2018.

## 1.6 Thesis organization

This thesis consists of 5 chapters and presents a detailed description of the research project. Chapter 1 discusses the basic introduction, problems related to EV transition, and research objectives. Chapter 2 details Thailand's power policy, scenario, history, previous research, and perspectives on future energy transition and planning procedures. It also describes various tools of energy modeling and their application. Chapter 3 presents the methodology involved in this research. Detailed mathematical analysis of the vehicle ownership model, mathematical modeling of the LEAP model, and peak demand calculation are presented in this chapter. This also explains the AHP procedure. Chapter 4 presents a detailed analysis of the results, and finally, Chapter 5 consists of a conclusion and future work.

## 1.7 Chapter Summary

Chapter 1 presents a general introduction to electric vehicles and their importance in response to climate issues and their impact on the electrical system. This chapter also discusses the research's objectives, scopes, and limitations.

# CHAPTER II

# LITERATURE REVIEWS

## 2.1 Chapter introduction

Air pollution is one of the significant environmental problems that Thailand has faced for a long time. Bangkok and the surrounding area's air quality index (AQI) makes daily headlines in winter. Studies have suggested that the major contributors to this pollution are dust particles, some particulate matter, typically PM 2.5, and other greenhouse gases. Moreover, the primary sources of the emission of these pollutants are internal combustion engines, factory chimneys, and the burning of agricultural residues. The Pollution Control Department of Thailand suggests that the major contributors of PM2.5 are IC engines and weather patterns. Generally, the most severe level of AQI (WHO recommends a 24-hour average should not exceed 25 µg/m3) occurs from December to February due to airflow stagnation or similar weather phenomena. Traffic congestion also exasperates the situation, leading from bad to worst. Again, the Thai government has committed to reaching the net zero target by 2065 and is also projected to reach the peak emission level in 2030 (370 MtCO2eq), down to 250 MtCO2eq in 2050. In this context, limiting the ICs and their emissions is necessary, which undoubtedly suggests the electrification of the vehicle fleet and is not a new approach (Alahyari et al., 2019).

However, electrifying the vehicle fleet comes with its problems. First of all, it increases the electricity demand, and if any clean energy source cannot supply the additional demand, then only the pollution of one area will be relocated to another place, but the problem will remain unchallenged. On the other hand, such a transition may adversely affect transportation services, manufacturing, and, eventually, the nation's economy (Li et al., 2019). Also, the impact of charging demand may seriously interrupt the reliable operation of the existing distribution system, leading to complete chaos. Primarily, these issues are related to the proper planning of the EV load distribution in the locality, time of charge, mode of charging, voltage and current level of charging, location of charging center etc. (Grahn et al., 2011). This thesis intends to provide information about Thailand's energy demand emission and peak power demand due to the future large-scale EV transition. A detailed review of relevant literature is provided in this chapter

## 2.2 Review of electric vehicle situation

Electric vehicles (EVs) are now considered to be a new-age technology. EV technology has gained prominence in recent years primarily due to the concern about carbon emissions from internal combustion engine (ICE) vehicles. Even though the technology is still maturing, it has already proliferated the vehicle market worldwide. This is partly driven by the incentives provided by the governments to limit emissions. According to the global EV outlook 2024 published by the International Energy Agency, about 40 million electric cars have been registered worldwide until 2023, as shown in Figure 2.1. The growth in the last five years has been exceptionally high. In the last five years, the stock of electric cars rose from about 5 million to 40 million. Such high growth shows electric cars' overall acceptance and market penetration. Figure 2.1 also shows the remarkable progress of China in the electric car sector. Almost half of all stock is in China, followed by the European Union and the United States.

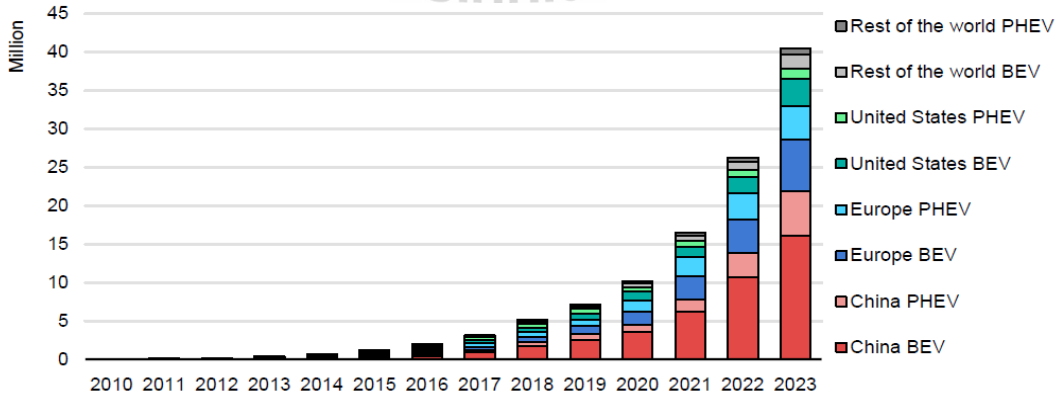


**Figure 2.1 Global stock of EV cars** (International Energy Agency, 2024)

The annual sales of EV cars have also skyrocketed in recent years. In 2023, about 14 million EV cars were registered globally. Without a surprise, China is leading in this number as more than 8 million vehicles are sold in China. Apart from the actual number of sales, the most important factor is sales share. It represents the speed and the direction of EV penetration in the market. Figure 2.2 shows annual vehicle sales and sales share in the leading EV market.

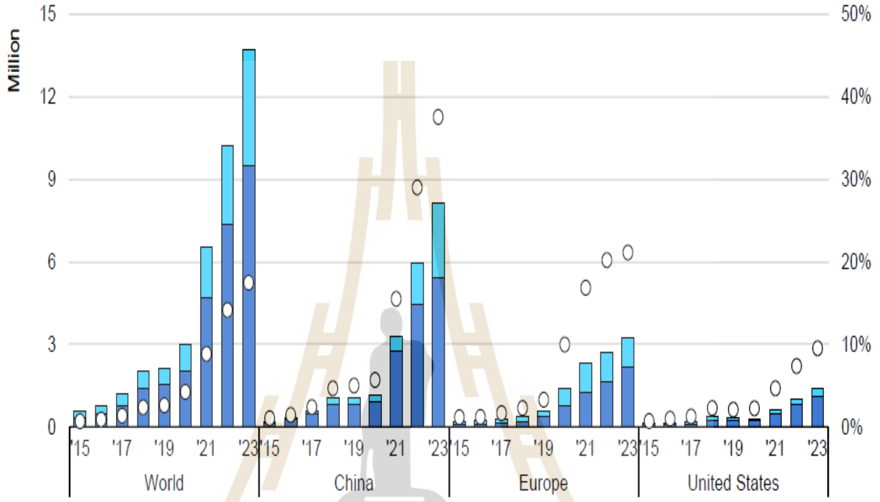


**Figure 2.2 Annual EV car sale and sale share** (International Energy Agency, 2024)

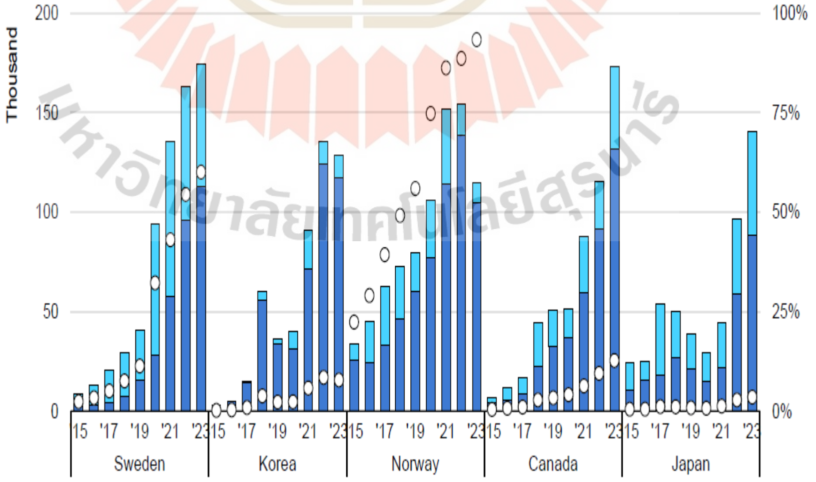


**Figure 2.3 New EV sales and EV sale share in select countries** (International Energy Agency, 2024)

Global sales share is around 16% in 2023, as shown in Figure 2.2. EV accounts for about 39% of car sales in China in 2023. Additionally, the annual growth rate is remarkably higher than in other markets. The EV sales share in Europe is around 20%, and the annual growth rate has slowed in the last year. The United States is the third largest EV market in the world, but the EV sales share is still in the single digits. However, a few countries like Norway and Sweden are on the verge of achieving total electricity soon as their EV sales share is about 90% and 60% in 2023, respectively, as shown in Figure 2.3. On the other hand, EV sales share in other OECD countries, like Japan, Canada, South Korea, etc., is still in the lower tens, suggesting a significant concentration of EVs in some markets.

## 2.3 EV promotion policies adopted by select countries

Countries are keen on transitioning to electric mobility and formulating policies to enhance the speed of such transition. As a new-age technology, EVs require additional support in various fields like research and development, industrialization, market competitiveness etc. even though the policy differs from country to country depending on their priority and the local situation, a commonality among such policies is evident. Primarily, such policies either focus on providing direct purchase subsidies to the consumer or investment incentives and tax benefits to the manufacturers. Finally, they offer indirect incentives like relaxation in parking or other local vehicle regulations to the EV owner. A comparative study of the EV promotion policy of selective countries is presented in Table 2.1.

## 2.4 EV promotion policy and activities in Thailand

Thailand's foremost initiative for promoting Zero Emission Vehicles (ZEV) is the 30@30 policy. This wide-ranging policy addresses vehicle production, battery and infrastructure development, taxation, incentives, and EV standards. The goal is to manufacture 725,000 cars and trucks, 675,000 motorcycles, and 34,000 buses and heavy trucks by 2030 (Energy Policy and Planning Office, n.d.)., as well as to convert existing vehicles like boats, tricycles, and motorcycles to electric power.

A key component of this policy is expanding charging infrastructure, aiming to establish approximately 12,000 public fast chargers and 1,450 battery swapping stations. The Thailand Board of Investment (BOI), tasked with facilitating significant investments, has rolled out specific schemes to attract investment in EV manufacturing. These include corporate income tax exemptions and reduced import duties for certain products (Thailand Board of Investment, 2023)..

Several market stimulus measures have been implemented to boost market demand and bolster manufacturer confidence. For example, the Airport of Thailand (AOT) intends to increase its use of EVs, but only electric vehicles are allowed in heritage sites, and EVs are favored in economic zones. The most impactful incentive is the financial subsidy for individual EV purchasers. In August 2022, the Thai government sanctioned a 2.9-billion-baht subsidy program to provide monetary benefits to new EV buyers (“Cabinet Approves 2.9bn Baht EV Sale Subsidy,” 2022). This program offers a subsidy of 150,000 Thai Baht (THB) for vehicles with a seating capacity of 10 or more, a battery capacity of 30 kWh or greater, and 70,000 THB for vehicles with a battery capacity below 30 kWh. Domestically produced pickup trucks are eligible for this subsidy if their price is under 2 million baht. Additionally, battery-powered motorcycles qualify for a subsidy of 18,000 THB.

A study of the new EV registration in Thailand shows that the EV promotion policy put forward by the Royal Thai government is working successfully. In 2023, more than 80000 new EV cars were registered in Thailand, with a sales share of nearly 10% for the first time, as shown in Figure 2.4. The sales volume is nearly four times higher than the previous year's registration. Such a rise in annual registration after the enaction of the new incentive policy indicates that Thai people have positive regard for EVs and are willing to transition away from ICE vehicles, but the cost issue is a barrier, and some kind of arrangement is necessary. Figure 2.4 also describes Thailand’s excellence in the EV adoption field compared to its regional peers.

Conversely, Thailand's current public charging infrastructure for electric vehicles (EVs) is insufficient compared to global standards. On average, 65 vehicles share one charging point in Thailand, whereas the global average is 10, indicating a significant shortage of charging points, as shown in Figure 3.5. Additionally, Thailand's charging power available per vehicle is about 0.5 kW, substantially lower than the global average of 2.5 kW and dramatically less than China's 33.5 kW per light-duty vehicle. This low charging power results in slower charging times, discouraging EV adoption. Thailand should invest heavily in developing its public charging infrastructure to address these issues and support the transition to electric vehicles. Improved infrastructure will reduce the vehicle-to-charging point ratio and increase available charging power per vehicle, making EVs more viable for consumers and promoting sustainable transportation in the country. The stated policy of installing public charging points and battery charging stations might alleviate this problem of EV charging.

Table 2.1 EV promotion policy of select countries

| SN | Country | Activity | Reference |
|---|---|---|---|
| 1 | India | ■ Faster adoption and manufacturing of hybrid and electric vehicles (FAME) scheme<br>■ Offers tax incentives for the manufacturing of EV parts and sub-parts. | (Ministry of Heavy Industries Government of India, n.d.) |
| 2 | Australia | ■ Future Fuels Fund,<br>■ 250 million A$ funds support industries to develop EV charging stations and hydrogen refueling infrastructure | (Australian Government Department of Climate Change Energy, Environment and Water, n.d.) |
| 3 | New Zealand | ■ Clean Car Discount: Governments offer rebates and punish with fees depending upon per kilometer carbon emission during vehicle registration. | (New Zealand Transport Agency, n.d.) |
| 4 | France | ■ Ecological bonus scheme, Subsidy up to 27% of the purchase price, 50%-100 % rebate in registration fee<br>■ EVs are eligible to get Green Pass, allowing them to be parked for up to 2 hours free of charge in a few municipalities. | (European Alternative Fuels Observatory, n.d.-a) |
| 5 | Japan | ■ Green Growth Strategy 2021 states 100% electrification of LDV by 2030. Provides purchase subsidies to buyers and tax incentives to manufacturers.<br>■ The maximum purchase subsidy limit is 800000 Japanese Yen. | (International Energy Agency, 2023),(Kohn et al., 2022) |

Table 2.1 EV promotion policy of select countries (continued)

| SN | Country | Activity | Reference |
|---|---|---|---|
| 6 | China | ■ A formula determines the subsidy amount, which depends on factors like range, battery energy density, and energy consumption. Many cities and local governments also offer non-monetary benefits like parking access, exemption from congestion and pollution restrictions, etc. | (Kohn et al., 2022),(Li et al., 2020) |
| 7 | Germany | ■ Purchase subsidy, Discount on registration fees, Investment in public charging infrastructure | (European Alternative Fuels Observatory, n.d.-b) |
| 8 | United Kingdom | ■ Grants towards the purchase of light commercial vehicles, taxis, and Heavy-Duty Vehicles (HEV), Investment in charging infrastructure, and ban on petrol and diesel cars by 2030 | (Government of the United Kingdom, 2035) |
| 9 | Canada | ■ Grants towards EV purchase, lease, and installment of the charging station.<br>■ Phase out plan for buses and HEVs | (Government of Canada, n.d.) |
| 10 | United States | ■ Various states have announced a ban on the sale of IC cars after 2035. States have prepared their fuel transition activities and budgeting.<br>■ Up to 7500$ federal tax credit from 2023 to 2032 | (Internal Revenue Service United States Government, n.d.; Joint Office of Energy and Transportation, n.d.) |

Table 2.1 EV promotion policy of select countries (continued)

| SN | Country | Activity | Reference |
|---|---|---|---|
| 11 | Indonesia | ■ Indonesia is more focused on developing the country's EV ecosystem.<br>■ Offers tax benefits to manufacturers depending on the amount of local components used in the final product.<br>■ Manufacturing of electric two-wheelers is given more importance in the short term. | (Cabinet Secretariat of the Republic of Indonesia, n.d.) |

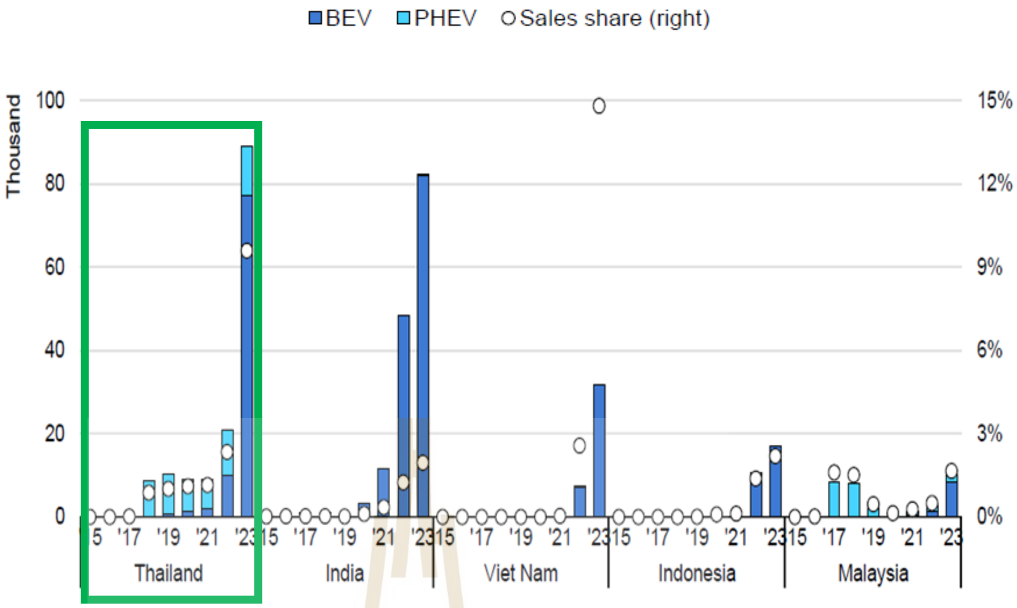


Figure 2.4 EV sale situation in Thailand and its neighborhood

(International Energy Agency, 2024)

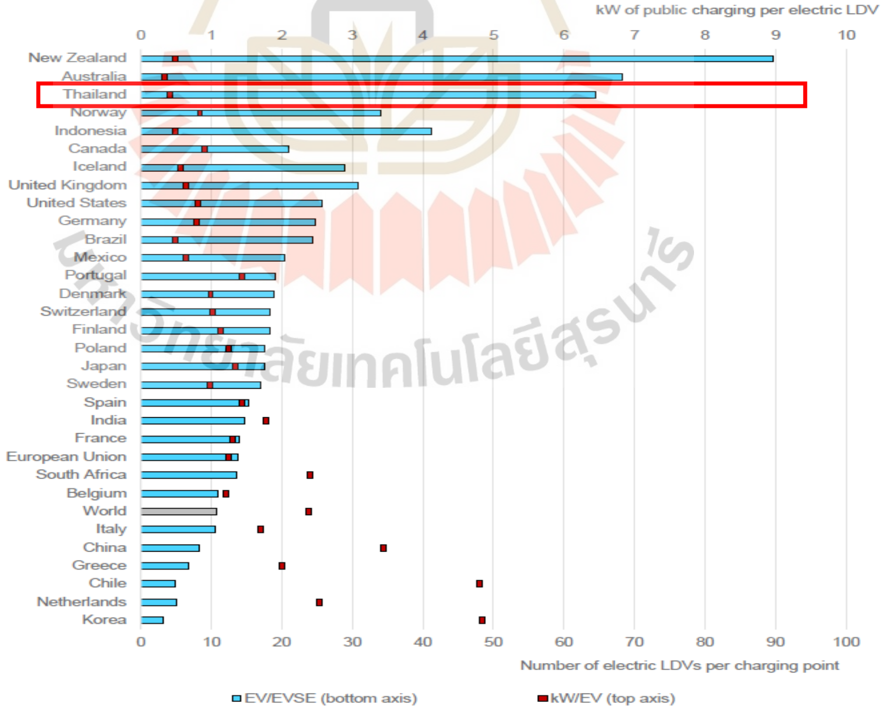


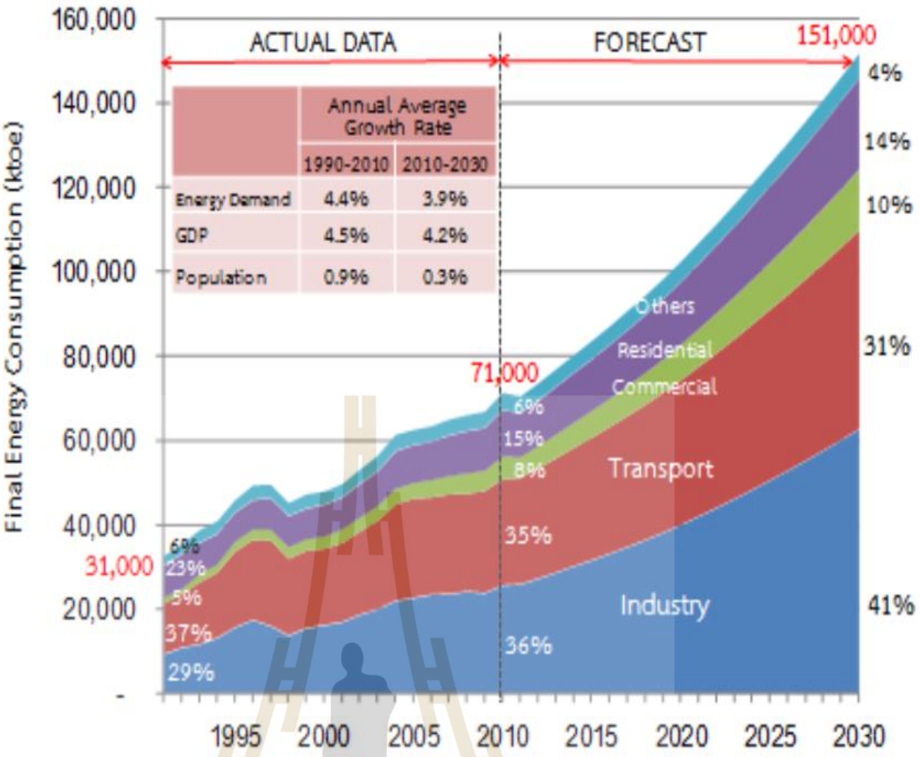
**Figure 2.5 Availability of charging options in select countries** (International Energy Agency, 2024)

## 2.5 Thailand power system

Thailand has a very long history of electricity. Field marshal Chao Phraya Surasakdi Montri first introduced electricity on 20 September 1884. A couple of years later, the first electrical infrastructure was installed in New Jersey, USA, on 31 December 1879 (Electricity Generating Authority of Thailand (EGAT), n.d.). Thailand has witnessed a mammoth revolution in the energy sector since then. As per the 2014 data, the country's total installed capacity reached 37612 MW. The Electricity Generation Authority of Thailand (EGAT) is the state's largest energy producer, accounting for 41.2% of total generation. The remaining is contributed by private or independent energy producers (IPP), small power producers, and tiny power producers and imports from neighboring nations; the share of the stakeholders, as mentioned above in total capacity is 35%, 12%, 5.4%, and 6.4%, respectively. The primary technology used in the country is a combined cycle, thermal, and renewable energy technology. Only 8476 MW of energy is produced from renewable resources, indicating a heavy dependency on fossil fuels. Thailand has a high potential for solar power generation, and minimizing such a considerable dependency should be possible.

## 2.6 Official Energy Demand Forecast

Thailand is an emerging economy, and the energy demand increases daily. The country's energy demand in 2031 is expected to be double that of 2010 if the growth rate and population growth are assumed to be 4.2% and 0.3%, respectively. The annual energy demand will increase by 3.9% in that scenario. Commercial and industrial sectors will be the foremost energy consumers. Figure 2.6 represents the trend of energy consumption and an expected demand that includes thermal and electrical energy.



| | Annual Average Growth Rate | |
|---|---|---|
| | 1990-2010 | 2010-2030 |
| Energy Demand | 4.4% | 3.9% |
| GDP | 4.5% | 4.2% |
| Population | 0.9% | 0.3% |

**Figure 2.6 The trend of future energy demand considering the base year of 1988** (EEDP2011)

This massive energy demand will pose many challenges like system security, emission, energy cost, and international competition and conflict. Thailand's natural energy resources are insufficient to meet the demand, resulting in energy dependency on other countries. Due to the ever-changing global politics and dynamics, geo-economic conflicts such as dependency will seriously affect the country's economic activities and security.

The solution to energy demand can be done by using more resources or utilizing the same resources more efficiently. The Ministry of Energy has developed an energy conservation or efficiency plan called the Energy Efficiency Development Plan 2011, which mainly emphasizes reduced or more efficient energy use. Implementing such a plan is expected to lower the total energy demand by at least 20% in 2030, considering the same growth rates in Figure 2.7.

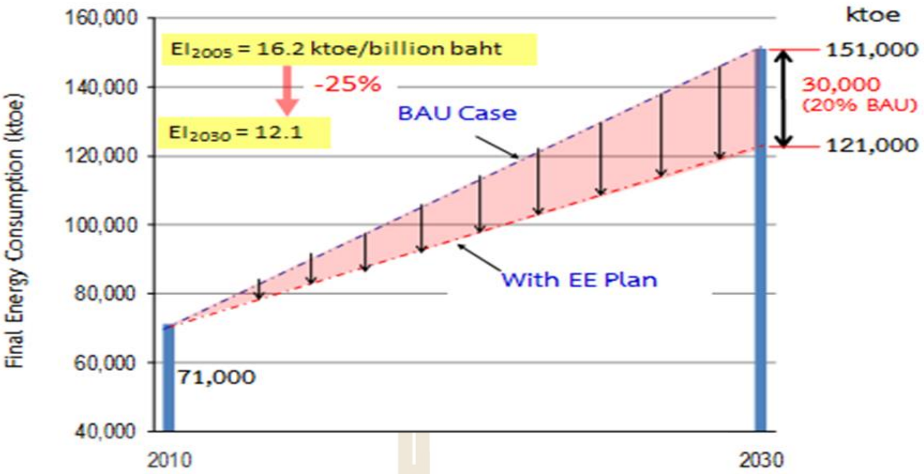


Figure 2.7 Target of the energy conservation plan (EEDP2011)

Energy efficiency project has numerous benefits like low emission, low running cost, and requiring fewer infrastructures. However, the significant advantage is that it requires less generation (if we consider electrical energy and are solely interested in that). Table 2.2 shows the expected savings in electrical energy requirements by implementing the energy efficiency programs, and this data should be considered during capacity expansion analysis. Power Development Plan 2015 (PDP2015) is implemented to match future demand, as explained in the following section.

Table 2.2 Possible energy saving in the year 2030 by implementing energy efficiency programs

| **Share of Energy Saving by Economic Sector in 2030. Economic Sector** | Technical Potential | | | **Specified Target (ktoe)** | **Share (%)** |
|---|---|---|---|---|---|
| | Heat (Ktoe) | Electricity (GWh) | Total (Ktoe) | | |
| Transportation | 16,250 | - | 16,250 | 13,400 | 44.7 |
| Industry | 10,950 | 33,500 | 13,790 | 11,300 | 37.7 |
| Large Commercial Building | 410 | 27,420 | 2,740 | 2,300 | 7.6 |
| Small Commercial Building & Residential | 1,690 | 23,220 | 3,670 | 3,000 | 10.0 |
| **Total** | **29,300** | **84,140** | **36,450** | **30,000** | **100** |

## 2.7 Power development plan 2015 and power development plan 2018

According to the Power Development Plan 2015 (PDP2015) (Energy Policy and Planning Office, 2015), it is expected that the installed capacity in 2036 will reach 70335MW, i.e., the addition of another 57459MW in the next 20-plus years; however, one-fifth of the total power will be generated from renewable resources in 2036, which is more than double the current 8%. Nevertheless, the expected power addition from renewable resources is 21648MW only, just above 37%, indicating the nation still lacks commitments to reducing non-renewable energy dependency.

The most interesting insight of PDP2015 is that it has officially advocated small-scale solar generation at the individual household level. Solar rooftop-like programs are expected to shore in the coming years. Domestic renewable energy generation is forecasted to reach about 12105 MW from 2015 to 2036, about 57% of the expected renewable generation; this indicates the nation's willingness to incorporate a distributed generation-based energy system.

The total generation expansion during the period of 2015 to 2036 is as follows:

| | | |
|---|---|---|
| a. | Existing capacity as of December 2014: | 37,612 MW |
| b. | New capacity during 2015-2036 | 57,459 MW |
| c. | Retired capacity during 2015-2036 | -24,736 MW |
| d. | Total capacity in 2036: | 70,335 MW |

The PDP2015 has undergone reviews at regular intervals. In 2018, an update was made to existing policy, i.e., PDP2015, and presented in a new power development plan 2018 (PDP2018). PDP2018 has considered existing distributed resources in various country areas and their possible utilization, either absent or inadequately mentioned in the previous plan, PDP2015. PDP2015 mainly focuses on power generation and transmission infrastructure development, but distribution has been given relatively lower importance. PDP2018 provides the guidelines for energy system management from 2018 to 2037. Some significant features of the PDP2018 are listed below:

I. Proper importance has been given to all aspects of the power system: generation, transmission distribution with adequate regional sectionalization, and regional stability criteria.
II. Least cost generation expansion based Flexible grid management approach
III. Importance to green energy and energy efficiency
IV. Smart utility, smart prosumer, smart grid

The power generation capacity of Thailand as of December 2017, as given in PDP2018, is shown in Table 2.3.

**Table 2.3: Existing power generation scenario of Thailand**

| S.N. | Technology type | Capacity (MW) | Percentage |
|---|---|---|---|
| 1 | Combined heat | 20398 | 44.3 |
| 2 | Thermal plant | 8567 | 18.6 |
| 3 | Cogeneration | 5816 | 12.6 |
| 4 | Renewable energy | 10949 | 23.8 |
| 5 | Diesel plant | 60 | 0.1 |
| 6 | import from Malaysia | 300 | 0.6 |
|  | Total | 46090 | 100.0 |

According to PDP2018, the total generation capacity is expected to be around 77,211 MW. To reach that mark, new plants with a capacity of 56431 MW will be added during the 20 years, and 25310 MW of existing plants will be retired. Further technology-wise division of proposed generation capacity is provided below:

| | | |
|---|---|---|
| I. | Renewable Energy Power Plant | 20,766 MW |
| II. | Pumped Hydro Power Plant | 500 MW |
| III. | Cogeneration Power Plant | 2,112 MW |
| IV. | Combined Cycle Power Plant | 13,156 MW |

| | | |
|---|---|---|
| V. | Coal/lignite power plants | 1,740 MW |
| VI. | Electricity Import | 5,857 MW |
| VII. | New/Replacement Power Plant | 8,300 MW |
| VIII. | Energy Conservation Measures | 4,000 MW |
| IX. | Total | 56,431 MW |

The government has prioritized renewable energy expansion planning as around 44.7 % of newly added capacity will be from renewable or alternative energy resources (including pumped hydro and energy conservation measures). However, the construction of a new coal-fired plant and not mentioning the technology of the replacement plant still raises questions about the government's commitment to climate change and decarbonization of the power system.

## 2.8 Alternative Energy Development Plan: AEDP 2015

Ministry of Energy has developed the Thailand Integrated Energy Blueprint (TIEB) with a focus on:

1) Energy security to supply energy in response to the energy demand, which is consistent with

a) the rate of economic growth, population growth, urbanization

b) Diversified energy to the appropriate resources.

2) Economy,

a) Considering the energy costs are reasonable and not an obstacle to the economic and social development of the country in the long term.

b) In line with costs and the tax burden, reforms in fuel price structure are reasonable to level up to national energy utilization performance to promote energy efficiency.

3) Ecology,

a) increased domestic renewable energy production and introduction of more efficient technologies to reduce the impact on the environment and community

TIEB includes PDP 2015, The Energy Efficiency Development Plan (EEDP), The Alternative Energy Development Plan (AEDP), The Oil Development Plan, and The Gas Development Plan. The target energy mix according to the PDP 2015 is presented in Table 2.4.

**Table 2.4 Thailand Renewable Energy Mix**

| **Fuels** | **Status at the end of 2014 (MW)** | **Target at 2036 (MW)** |
|---|---|---|
| 1. MSW | 65.72 | 500.00 |
| 2. Industrial Waste | - | 50.00 |
| 3. Biomass | 2,451.82 | 5,570.00 |
| 4. Biogas (WW/SW) | 311.50 | 600.00 |
| 5. Small Hydro | 142.01 | 376.00 |
| 6. Biogas (Energy Crop) | - | 680.00 |
| 7. Wind | 224.47 | 3,002.00 |
| 8. Solar | 1,298.51 | 6,000.00 |
| 9. Large Hydro | - | 2,906.40 |
| **Total install capacity (MW)** | **4,494.03** | **19,684.40** |
| Electrical Energy (Million Units) | 17,217 | 65,588.07 |
| Total Electrical Energy Demand (Million Units) | 174,467 | 326,119.00 |
| **Share of RE in Electricity Generation (%)** | **9.87** | **20.11** |

## 2.9 Transmission and Distribution Expansion

EGAT is the power producer responsible for bulk energy buying from IPP and managing the national grid. Managing transmission lines and power dispatch also falls within its jurisdiction. EGAT operates the transmission line of various voltage levels. Thailand's current transmission voltage level is 115kV, 132kV, 230kV, and 500 kV. The total length of all transmission lines is just above 33 thousand circuit kilometers and is dominated by 115 kV lines, constituting 56.95% of the total length. The cumulative power transfer capacity is 106889 MVA.

The Energy Regulatory Commission is the regulatory body in the power trading sector and is responsible for national electricity tariffs (Provincial Electricity Authority (PEA), 2018). The Provincial Electricity Authority (PEA) and Metropolitan Electricity Authority (MEA) are two government-owned utilities responsible for distributing energy. MEA distributes power in Bangkok, Nonthaburi, Samut Prakan provinces, and other places, which is PEA's responsibility. Both utilities buy electricity from EGAT and distribute it to the consumers according to their demand. The primary distribution voltage level used by PEA is 22kV. Some private companies are also allowed to sell energy directly to the consumer.

Utilizing local resources to produce energy will benefit the community and nation; considering these facts, PEA has started research and investment in microgrid technology. The radial distribution system is the most commonly used distribution model in Thailand. As the policy enhances a distributed generation-based distribution system, PEA has developed an exemplary microgrid network of solar PV, micro-hydro, and battery storage at Khun Pai village of Chiang Mai province (Kasirawat et al., 2017).

## 2.10 Final energy supply by fuel

The Energy Policy and Planning Office (EPPO) under the Ministry of Energy is responsible for policy planning, monitoring, and evaluating the energy market of the kingdom. It publishes the statistics and indices periodically. The annual “Thailand Energy Situation and Efficiency Situation” is one of the essential reports published annually, which summarizes the sector-wise energy consumption, year-on-year change, and type of fuel use with essential macroeconomic variables. The latest edition is for 2020; although the year is heavily affected by the COVID-19 pandemic, the data is still relevant to this research. The report's summary is presented here to help understand the present condition of Thailand's energy sector.

The total final energy consumption in 2020 is about 77340 ktoe, about 10% lower than the previous year (85708 ktoe), mainly due to the COVID-19 pandemic. The transportation sector is the single energy consumer, accounting for about 38.4%, followed by the industrial sector, which has a share of 37.3% of total consumption. Residential (13.1%), commercial (8.2%), and agricultural sectors (3%) account for the rest of the energy consumption. From the supply side perspective, the agriculture sector is heavily dominated by petroleum products, accounting for 2283 ktoe out of 2318 ktoe (98.5%), and electricity supplies the rest (35 ktoe). This may not be surprising since all agricultural equipment and processes exclusively use petroleum as fuel. However, a direct opposite scenario is evident in the case of the commercial sector, where electricity supplies more than 90% (5776 of 6336 ktoe) and petroleum products fulfill the rest. Residential sector energy demand is supplied by both electricity and petroleum products with a share of 44.5% (4521 of 10150 ktoe) and 18%. The remaining energy demand is realized using biomass products like wood, charcoal, paddy husk, etc. This indicates ample space for the expansion of electricity in rural communities and rural electrification. Since most biomass energy is used for cooking in rural households, an effective electricity expansion policy may help reduce wood demand and deforestation, smoke-related health issues, and carbon emissions.

The transportation sector, which is the most energy-hungry, is supplied by three primary sources: petroleum, natural gas, and electricity, with a share of 95.7%, 4%, and the rest, respectively. Even though the proportion of electricity is virtually nonexistent, it is growing at a respectable rate and will continue to grow as the government elects to electrify the transport sector rapidly. Estimating the extent of such fuel transition is one of the most critical aspects of this research.

## 2.11 Rationale Behind Generation Expansion Planning

Electrical energy is the backbone of any nation's development. Economic activities are mainly dependent on the continuous supply of adequate energy. The industrialization of a nation is not possible without the electrical energy supply. As a result, the electricity demand is surging day by day. To make matters worse for the planner, internal combustion engine-driven vehicles are declining, and electric vehicles (EV) are becoming more common, drastically increasing the electricity demand. Hence, ensuring an adequate energy supply has become a nightmare for the system planner. Electrical energy generation is a very long and tedious process involving numerous planning and subsequent execution work, hence taking time. Generally, a generation system is designed considering the increasing demand for a particular duration, and after that time, another facility will be built. However, due to the evolution of disruptive technologies like EVs, such projections are no longer helpful. The demand forecasting must include social, economic, technological, environmental, and policy changes as possible influences.

## 2.12 Economics of Energy System Expansion

The first task in the planning process is to project the tentative demand that should be supplied during the planning period. The second and most important is to assess the economic aspect of the project. The analysis must consider the power plant's operation and fuel cost, capital cost, technical parameters, power supply reliability criteria, and power generation system operation practices to determine the expansion cost. However, the process of overall energy planning is challenging. New technologies are being developed, economic and social parameters frequently change, and fuel pricing is volatile. Hence, an effective energy planning program is a dynamic process repeated periodically and adjusted according to varying scenarios. The approximate definition of the energy planning process can be given as the systematic assembly and analysis of information about energy supply and demand and the presentation of this information to decision-makers who must choose an appropriate course of action (IEC 1985).

**The systematic energy planning process should include the following steps:**

**Definition of goal:** It deals with the objective of the planning, which may be any or all of preparing capital investment programs and policy decisions and identifying the vulnerability in the current system due to technological change and other uncertainties.

**Determination of approach to be taken:** it deals with the direction of the planning process. The analysis's scope, planning horizon, and scale are fixed here.

**Identifying the required information:** The analysis and decision variables are selected according to the scope, and various methods are used to collect the data related to the variables. Essential decision variables are reliability, system investment cost, and socio-economic parameters.

**Selecting the analytical process or the model:** the appropriate analytical method is chosen here. It may be optimization, statistical analysis, etc.

**Carry out the analysis:** to the analysis using the collected data.

**Concludes the result:** derive a conclusion based on the result obtained after the analysis. It is already said that the planning process is not linear. Frequent adjustments are made depending on the situation, so a step may be repeated several times to achieve the desired level of satisfaction.

Energy system planning is very similar to electrical system planning. So, the steps described above are equally applicable to electrical system planning. Economic growth is the major driving factor in any energy development plan. So, economic analysis is the first step in any planning process. On the contrary, availability and the quality of energy supply drive the country's economic growth, so these two aspects are interrelated. The fundamental issues considered during planning are GDP, sectoral economics, etc. Analyzing macroeconomics, population consumption behavior, and sectoral economics provides the basic level of activity that will determine energy demand. However, as mentioned earlier, the parameters' values are usually not expressed in energy units, so the primary work is determining the equivalent energy demand. One of the most frequently used methods of energy demand forecasting is to relate current fuel and electricity consumption to economic activity and apply economic growth rates to energy use. Because it is a simple procedure and requires only the minimum amount of data, On the opposite side, this approach does not consider the effect of new technology like energy efficiency methods. The popular alternatives in this area are considering the actual energy consumed or billed since the valuable energy is billable. The fundamental driving factors and their subsequent variables are given in Table 2.5

The planner develops different alternatives based on the above factors. However, the choice of driving parameters depends on the project's requirement, and more factors might be added or removed from the list presented above.

After developing the various alternatives, its impact on various sectors must be evaluated. Fundamental decision variables are the amount of energy supplied, investment and operation cost, environmental issues, contribution to economic development, etc.

Table 2.5 Factors Affecting Energy System Modelling

| Factors | variables |
|---|---|
| Economic growth | Rate of growth |
| | Structure of economic growth |
| International energy prices | Price of crude oil |
| | Price of petroleum products |
| | Price of coal |
| | Price of gas |
| | Price of nuclear fuel |
| Domestic energy price policy | Subsidies |
| | Taxes |
| | Price controls |
| Conservation program | Business-as-usual conservation efforts |
| | Moderate conservation program |
| | Aggressive conservation program |
| Renewable resource program | No particular emphasis |
| | Incentive program |
| Supply system configuration | Least-cost system |
| | Restrictions on certain imports |
| | Requirement for diversification |
| | Emphasis on Indigenous supplies |
| | Choice of specific technologies |

## 2.13 Issues related to the generation system

### 2.13.1 Demand

The demand to be served is the first parameter to be considered during generation expansion planning. Both power and energy demand must be projected with an acceptable margin of error. Demand forecasting is associated with mainly two types of uncertainty; the first one is the randomness of the data, such as consumption characteristics, weather uncertainty, etc.; the second type of uncertainty is related to the future loading characteristics due to socio-economic change, which results in a wide range of fluctuations in demand that is projected in the present.

### 2.13.2 Technology

Generation technology is changing very rapidly. Previously, steam power plants were the dominating technology in electrical power systems, but now the development of renewable technology and battery storage technology is unprecedented, and environmental concern is also rising. The planning process must give a clear direction to select a particular approach with a solid argument.

### 2.13.3 Reliability

The electric power system is prone to contingencies, and the supply may sometimes get interrupted. An acceptable level of confidence related to the supply or availability of energy is required to ensure an economic gain. So, the planning must include various reliability-related issues like a forced outage, maintenance, failure, etc.

## 2.14 Demand forecasting

The process of projecting based on current data is known as forecasting. If the projected electrical power demand that may occur at any time in the future based on past data is made, such projection is known as demand projection or demand forecasting. Demand forecasting is a fundamental issue related to the planning of any electrical system.

Forecasting is a systematic process involving various factors that follow basic guidelines.

### Identify the cause

To achieve accurate forecasting, identification of the cause is a fundamental requirement. Generally, a correlation between demand and time projects some value, but that may not produce the most accurate projection. A better approach should be to identify the reason behind the demand at that time. For example, demand may depend on the weather, the growth of industry, etc. After identifying why the fluctuation in demand occurs, correlations among the factors can be calculated.

**Concise and functional**

The forecasting process should be concise and clearly defined. The objective of forecasting should be applicable or ready to use. Forecasting should not include many factors that may not be useful and create ambiguity.

**Sensitivity**

Sensitivity analysis provides information about the characteristics and the extent of influence of any cause on the final solution. The forecasting considers numerous causes; sensitivity analysis shows the most influential cause and the potential alternatives.

## 2.15 Forecasting methodology

### 2.15.1 Time series analysis

The most common forecasting technique is time series analysis. This method establishes a pattern of demand variation concerning time, and the projection is made by scaling that cyclical pattern. It generally requires less data, but some algorithms are complicated and require tons of data.

### 2.15.2 Econometric model

The econometric model differs from time series analysis because it includes more dependable variables that ultimately affect the electrical energy demand. It considers different economic activities or sectors and their subsequent impact on energy demand. A general model is given in equation 2.1

$$D_{i,t} = \gamma + \sum_{j}^{n} b_{i,j} X_{i,j,t} \tag{2.1}$$

$D_{i,t}$ = energy demand in sector ***i*** at period ***t***

$\gamma$ = constant or base demand

$b_{i,j}$ = coefficient related to the sector $\boldsymbol{i}$ with variable $\boldsymbol{j}$

$X_{i,j,t}$ = the level of activity for explanatory variable $\boldsymbol{j}$, like the price of fuel

Time series and econometric analyses both have an acceptable level of accuracy in predicting the changes in the variables. However, in a similar analysis condition, the econometric model is generally preferred since it can help analyze the cause of change, which will help generalize the demand and change in other factors like income or revenue caused by the change in demand.

### 2.15.3 End-use model

It is the most frequently used forecasting methodology employed by many utilities. This method is different from others because it focuses on every action that may require energy (end-use). First, primary energy use actions are categorized, and then the energy requirement for that action is recorded. After that, some mathematical relations are established. For example, a broad category of household is first assumed, and then different actions inside the household are considered, such as cooking, space heating, lighting, etc. Finally, the energy required for that particular action is also identified. It looks like cooking using an induction cooker, with a rating of 1kW and an efficiency of 80%. Since this method is highly descriptive of every possible energy use in the system, forecasting accuracy might be better than other methods. On the contrary, not all data might be available, and it requires time and resources, limiting its benefits.

## 2.16 Integrated resource planning (IRP)

As the name suggests, IRP is the planning process that integrates various aspects of the energy system to develop the most cost-effective and sustainable energy system. It was primarily formulated after the energy crisis in 1970 and has undergone colossal modification and development. IRP focuses on supply and demand-side resources to meet the expected demand with an acceptable reliability limit but minimum cost. Different organizations and authors give various definitions. According to the United States Agency for International Development, IRP is the "planning process to meet users demand for electricity in a way that satisfies the various objectives for resource use  (The Tellus Institute, n.d.). The following are the most common objectives of IRP:

i. Fulfill overall national development goal

ii. Load demand should be served effectively

iii. Quality of supply

iv. Minimize the cost of generation transmission in both short and long-term

v. Minimum environmental impact or sustainable

vi. Enhance energy security by minimizing the use of external resources.

vii. Economic benefits to the affected area or people.

viii. Minimize foreign exchange costs.

However, every planning process differs, and the objectives may vary accordingly. IRP is a mandatory planning approach in various US states and is applied worldwide, though their objectives may differ. The objectives presented in the above list are conflicting, like minimum cost and low environmental impact, so planners choose based on their requirements. The common IRP framework is shown in Figure 2.8.

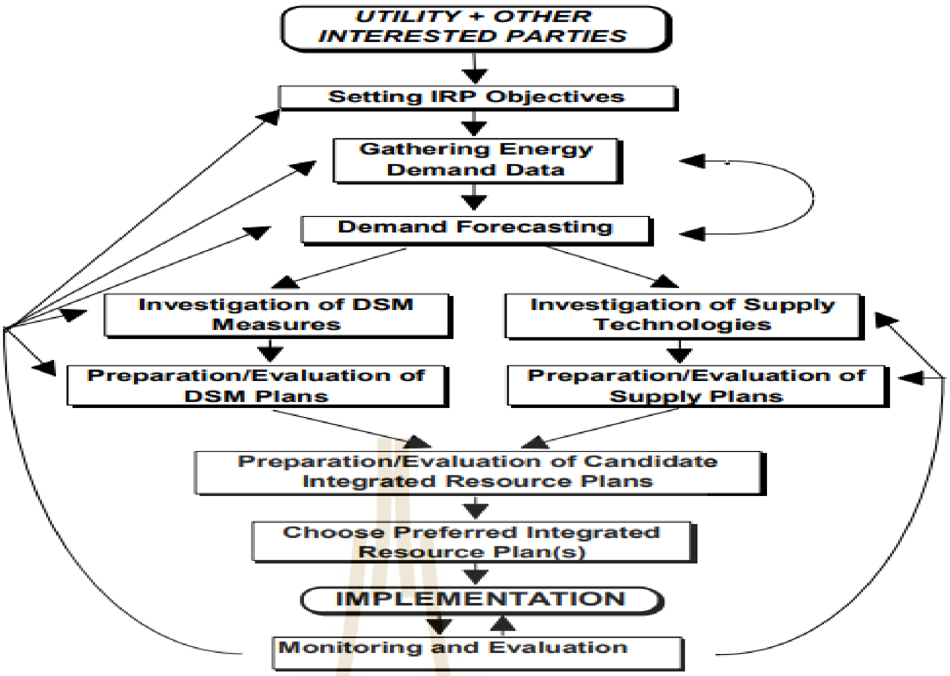


**Figure 2.8: Process of IRP** (The Tellus Institute, n.d.)

IRP has changed the traditional view of power system expansion planning, in which adding new generators was more critical. Since the IRS incorporates Demand Side Management (DSM), optimization in supply and demand sides is possible, leading to cheaper expansion costs. However, the power system has undergone deregulation. The separation of generating companies and distributors caused problems in implementing the IRP process since the two companies have conflicting interests, ultimately separating the DSM from IRP. On the contrary, the regulator can still enforce some regulations such that two companies can come together. This is achieved by sectionalizing the power system and strategically aligning the Generation Company and Distribution Company. This concept is integrated resource strategic planning (IRSP) ( Hu et al., 2010). In IRSP, supply-side and demand-side optimization is carried out under a virtual power plant concept. A virtual power plant is an alternative mathematical construct in the system that is more energy-efficient than the existing one. Later on, emission became a more critical aspect of energy system planning, and the low carbon emission model was also developed. IRSP planning is a nonlinear programming problem that various methods can solve. The IRSP-based global power system analysis demonstrated the massive possibility of reducing carbon emissions from both the supply and demand sides ( Hu et al., 2010).

The article (Yassin et al., 2004) presents a case study of ISPs in a city in Egypt. It incorporates both supply and demand-side management options and combinations. An econometric forecasting methodology was used to forecast the load in which sectoral GDP and energy intensity are considered for industrial and commercial customers. In contrast, population and per capita energy consumption are used to forecast the demand in the residential sector. Different energy efficiency plans were proposed and integrated with the demand side to make various decision options depending on the weightage of both the supply and demand sides. The interconnection of regional power grids is another essential aspect of the power system expansion planning process. It facilitates the system to become more contingent and resilient. Initially, IRSP did not incorporate this aspect, but later development added this feature, enabling more and more renewable resources in the power system. The IRSP, with the addition of a smart grid to facilitate distributed renewable resource integration, is called the IRSP Smart Grid (IRSP- SG). IRSP-SG helps reduce greenhouse emissions by utilizing renewable resources. It also provides better optimization results by incorporating regional grids into one, and more efficient DSM programs are also possible. A case study of the interconnection of the regional Chinese power grid with IRSP-SG methodology is provided by (Zheng et al., 2014) to optimize the generation cost, transmission grid cost, energy efficiency cost, and emission cost. The result shows the massive potential of saving energy and reducing greenhouse gas emissions. A similar result is evident in Henan province (wang et al., 2017).

Even though IRSP is the planning methodology dealing with both the supply and demand side, the importance and detailed analysis of the demand side is often limited. This is due to the complexity and uncertainty of the demand. Generally, a load duration cure is used to account for the loading pattern during the study, which will give a good result in an extensive system (national or regional level) but miss the opportunity for more efficient demand-side management schemes like peak shaving and load shifting. This shortcoming makes the IRSP unattractive in small grids or smart microgrids. In a microgrid, loads are limited and relatively predictable so chronological hourly data can be used for a more efficient planning process than the load duration method. This predictability of load enables more rigorous demand-side management programs. Such a program can be integrated into IRSP so that the conventional IRSP can be utilized in a microgrid (Zhu et al., 2015).

## 2.17 Energy system planning models and software

Conventional energy planning models become increasingly obsolete after the energy crisis in the 1970s. New system planning approaches have started to appear in the literature. IRP is one of them. However, due to the complexities of nonlinear programming and the lack of user-friendly algorithms, many companies and research centers have started developing some ready-to-implement energy models and tools. These models are user-friendly, reduce the programming time, the mathematical model is already formulated, and the necessary parameters can be altered depending on the user's requirement. The most appealing feature of these models is that they are very flexible and can be modified to add new variables or features like environmental issues or socioeconomic parameters. Some of the models commonly available now are the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), MARKet ALlocation (MARKAL), Least Emissions Analysis Platform LEAP, etc. (Pfenninger et al., 2014), (Perissi et al., 2021).

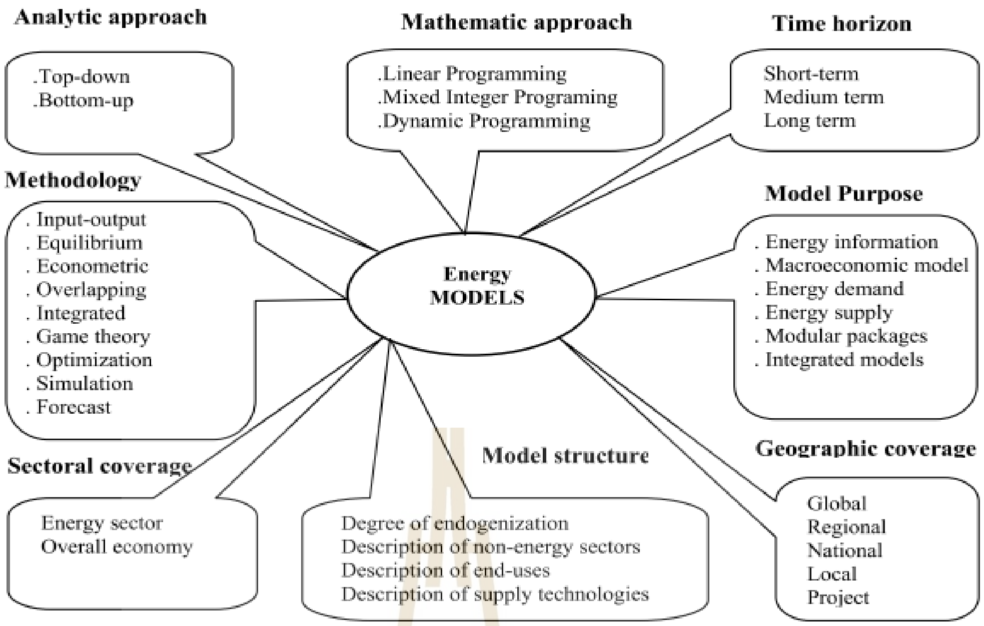


**Figure 2.9: Characteristics of an energy model** (Nguyen, 2005)

Figure 2.9 presents the basic framework of distinguishing characteristics of different software and tools. Even though each model and tool differ in coverage, analysis method, analytical approach, etc., a general model can be explained as shown in the figure. The model selection should be based on the preliminary result required, the primary data available, and the nature of the study. A particular model primarily provides the best result in certain areas through the general application of the model, which is acceptable. For example, forecasting demand, emission-oriented or process-oriented, and the size of the research area (regional, national, etc.) are different aspects of energy system planning (Lund, 2010).

A brief explanation of the models listed here is given below:

### 2.17.1 Model for energy supply strategy alternatives and their General Environmental Impact (MESSAGE):

The MESSAGE model is a dynamic framework for energy, environmental, engineering, and economic research developed by the Institute for Applied System Analysis (IIASA) in Australia in the 1980s, which has undergone various updates and modifications to suit contemporary requirements. It is a linear programming-based optimization algorithm. MESSAGE-ix is a Python-based open-source model that is an extension of MESSAGE methodology. This can be used for medium- to long-term planning scenarios, and all types of generations, such as thermal, renewable, energy storage, etc., can be simulated. The MESSAGE model emphasizes the generation side, and those inputs are detailed and extensive, but the demand side inputs are relatively bulky or accumulated. The results are a multi-technology strategy to minimize the emission based on the least-cost portfolio of the relevant technology. Energy consumption is directly related to macroeconomic data. The energy intensity of GDP energy price will affect the national energy policy. So, the MESSAGE model is generally coupled with MACRO, a short form of macroeconomics, and IIASA also developed the methodology. Various reputed organizations like the World Energy Council, an intergovernmental panel on climate change, the European Commission, etc, widely use this modeling framework.

### 2.17.2 MARKet ALlocation (MARKAL)

MARKAL is the bottom-up cost minimization energy system modeling framework developed by the International Energy Agency employing the General Algebraic Modelling System (GAMS). It covers extensive energy technologies, and the data requirement is excessive. It is generally used for the planning process of about 50 to 60 years, though it can result in acceptable results with a concise duration of five years (Mendes et al., 2011). Many modifications were made after its first development in the 1980s to satisfy the dynamic nature of the energy system and planning priorities. A later development links it with the MACRO model to develop a model rich in energy technology and complicated macroeconomic problems and scenarios (Shakya et al., 2012).

MARKAL models use a Reference Energy System (RES) model, a set of possibilities through which any resource can be delivered to the user, for example, coal and its transformation to supply electricity to a user. MARKAL model only generates optimal output if all the demand is satisfied at every time of the planning horizon. The Integrated MARKAL-EFOM (Energy Flow Optimization Model), popularly known as TIMES, is the later development of MARKAL, which IEA developed with its collaborative partners. TIMES is a bottom-up model and optimizes the system to generate the least cost alternatives using linear programming optimization techniques based on user-specified constraints for a medium to long period.

### 2.17.3 Low Emissions Analysis Platform (LEAP)

The Low Emission Analysis Platform (LEAP) simulates the transition scenarios. LEAP is the scenario-based analysis tool developed by the Stockholm Environment Institute (SEI) and is commonly used in academics to simulate the various dimensions of energy systems. It is generally used to simulate energy demand, energy generation, the cost involved in energy production, replacement analysis, comparison of alternative energy production options, related environmental impact, etc. LEAP may use any bottom-up, end-use, top-down macroeconomic approach, etc., to simulate the various aspects of the energy system (Fathi, 2016). It is beneficial in short to medium-term operational planning and long-term expansion planning. It has a Technology and Environment Database (TED), the library of techno-economic and environmental characteristics of numerous energy technologies defined by credible international organizations working in climate change and global energy safety and security, like IEA, the Intergovernmental Panel on Climate Change, etc. This database makes it easier to compute and verify the environmental impact of various energy production technologies globally and make policy decisions locally. In simple words, LEAP is an optimization framework used for energy system analysis (Heaps, 2021).

The typical planning horizon is between 20 and 50 years, though there is no limit to the number of years to be analyzed. LEAP's most crucial feature is allowing the basic time unit (year) to be sliced into various numbers like a month, seasons, days, and even time of day, significantly improving the load dispatch analysis. A typical block diagram of the LEAP software environment is presented in Figure 2.10.

Only necessary items and features can be selected to formulate a scenario, ignoring the rest. This makes LEAP one of the easiest to customize energy modeling software.

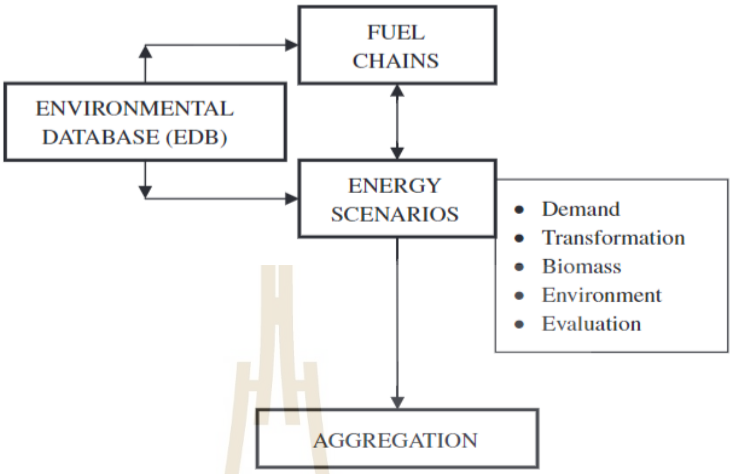


Figure 2.10 Block diagram of LEAP environment

Table 2.6 compares the three most common energy modeling tools based on various criteria. Even though MARKAL is sometimes preferred over LEAP, MARKAL is less desirable in this research because of its extensive data requirement.

Table 2.6 Comparative study of some of the simulation platform

| Criteria | MARKAL | LEAP | EFOM |
|---|---|---|---|
| Methodology | Linear optimization | Accounting | Linear optimization |
| Simulated area | National | Regional to global | Regional or national |
| Technology included | Extensive | Predefined extensive list | Extensive |
| Digital competency | High | High to very high | Moderate |
| Economic Transition | Not covered | Not covered | Presented with user-defined scenario |
| Data required | Excessive | Can be limited | Excessive |

## 2.18 Energy information system or energy database

Energy information systems collect historical statistics related to the energy system. They primarily deal with energy consumption, production, and transformation from one form to another. They also include techno-economic data, climate data, etc. IEA, the US Department of Energy, and the Intergovernmental Panel on Climate Change are examples of energy databases. As mentioned earlier, TED of LEAP includes data on around 1000 technologies from the institutions.

## 2.19 Review of previous research using the LEAP model

Azerbaijan's LEAP-based energy modeling from 2015 to 2030 is presented in (Felver, 2020). It considers the current scenario and the government commitment to emission reduction or the Paris Agreement commitment to reduce emissions by 2030 by 35%. This shows that commitment will not be achieved without a more assertive approach, even though the total energy consumption of renewable energy shares has reached 20%. LEAP model forecasting future energy system composition based on the different inputs provided in different scenarios. However, this may not be sufficient to choose a particular scenario for further development.

Further scrutiny of the alternatives should be carried out based on cost, reliability, and other factors. The article (Mirjat et al., 2018) provides further decision-making procedures based on the results obtained from LEAP. Generally, the LEAP software is used for regional or national-level energy planning; it is equally accepted and capable of analyzing a small geographical area. On top of that, the usual LEAP analysis does not consider the scenario's economic cost or the alternative technologies. This shortcoming is dealt with by combining the marginal abatement cost curve with LEAP (Hu et al., 2019). Demand-side management (DSM) is another crucial aspect of power system management; a proper DSM would reduce the peak load demand. LEAP is used by (Shrestha and Nakarmi, 2015) to analyze the prospect of demand-side management in Nepal. It employs an end-use energy forecasting model using log-linear regression (for elasticity calculation). This research was carried out during a particular time when the nation was facing a severe power shortage due to a lack of generation capacity. However, the situation has drastically changed, and generation is considerably higher than demand in recent times during the wet season, so the result might not be applicable in this changing scenario. The least-cost generation expansion methodology is the most commonly used planning procedure in the past, but such an approach may not yield the best result on the climate front. An analysis of the Australian power system has shown that adopting government climate commitment will require a higher investment than the amount required in the least cost method. However, a policy like a carbon tax might benefit the economy in the long term (Vincent et al., 2019).

On the other hand, nuclear energy could be more economical both economically and environmentally, as shown in (Cai & Guo, 2018), at least in the Chinese scenario furthermore (Zhang et al., 2020) discuss the often neglected difficulty level of implementing each alternative scenario similar approach is evident in (Kuldna et al., 2015) in case of Estonian context. The usual practice in planning is to generalize the demand change in a single value like GDP or value addition on a sectoral basis. However, it gives a perfect result but misses the opportunity to identify the primary cause or the aspect of such change. The Logarithmic Mean Divisia Index (LMDI) methodology helps divide energy consumption into its constituent aspects: scale, structure, and efficiency. Scale effects deal with the expansion or scaling of the economy, and structure effect is related to the change and adjustment of the current structure and resources. Finally, the efficiency effect describes the potential energy conversion efficiency or technology change. LEAP can simulate the sensitivity of each effect or identify the most dominant effect in demand (Wang et al., 2017). LEAP can also be used in emission control analysis apart from the electric power system. Transportation emission reduction scenarios are analyzed in (Maduekwe et al., 2020) but do not include the electric vehicle transition option and subsequent demand created in the power grid.

## 2.20 Previous research in Thailand

Many papers discuss the energy use pattern and the alternative perspective of the future of the Thai power system. However, they are relatively old, and the recent government policies have taken more strong climate commitments and renewable targets, so the result might not be favorable anymore. Kusumadewi et al. (2017) present the effect of renewable targets prescribed by PDP 2015 on Thailand's Paris commitment. It evaluates the scenario of fulfilling 100% of the target renewable integration, 50% of the target, and 25% of renewable target integration. Results showed that if the renewable target is fully met, emissions will be reduced by 41.71% if only 50% of the target renewable is added to the system. The emission will be reduced by 23.75%, and if only 25% of projected renewable integration is possible, then the emission will be reduced by about 10% compared to the business-as-usual scenario. It shows that the 50% target renewable integration will meet the government's climate commitment. However, this is only concerned with power sector emissions, not national ones. The analysis period is 2005 to 2030. The major shortcoming is that it does not include a government EV road map. Similar scenarios are analyzed for extended periods (2010-2035), and the results are almost consistent (Kusumadewi, Winyuchakrit, & Limmeechokchai, 2017). It also argues that if new technologies like hydrogen fuel and tidal energy are considered, the decarbonization of power systems will be achieved much earlier, but it does not provide the economic and financial analysis of such transformation. A bottom-up econometric approach-based integrated planning model for the Bangkok metropolitan area is presented (Phdungsilp, 2010). The critical takeaway of this research is that the transportation sector has the highest emission reduction potential. Even though the study period is from 2000 to 2025, it presents a more extensive overview of energy-related issues around Bangkok, which can be extrapolated nationwide with recent trends and government policies. These results are similar to the more recent studies, which also show that transportation and industries are two major energy consumers and possess the highest potential to reduce consumption either by energy efficiency or by policy intervention like the promotion of mass transit instead of private vehicles (Traivivatana & Wangjiraniran, 2019).

## 2.21 Chapter Summary

Chapter 2 deals with the relevant theory, previous research, and government plan related to the future power system development. Topics discussed in this chapter are listed below:

1. Review of PDP2015 and 2018PDP as well as AEDP and EEP of Thailand. PDP2018 expects more than 77000 MW of installed capacity, of which renewable sources will supply more than 20000 MW.
2. Process, methods requirements, and rationale of integrated energy planning
3. Tools used in integrated energy planning their characteristics and comparison of most popular tools.
4. Detailed review of LEAP software and its usage in the world and Thailand.

# CHAPTER III

# RESEARCH METHODOLOGY

## 3.1 Introduction of the research architecture

The primary objective of this thesis is to determine the electrical energy and peak power demand caused by the electrification of the LDV section of the Thai transportation sector. It also aims to calculate emissions and analyze whether the additional demand can be accommodated with the existing power development plan or if some adjustment in such planning is required. Furthermore, barriers to large-scale EV transition in Thailand are also studied.

This study involves several intermediate steps to achieve the objectives mentioned above. Figure 3.1 presents the overall architecture of the steps involved in this thesis. Firstly, Reviewing existing energy policy and EV transition programs and activities in Thailand is the first stage of the research. This provides a basic understanding of the shortcomings of the existing policy and prospects. A review of planning methodologies is also essential to determine the approach to be taken in analyzing the future scenario. The analysis involves four separate modules identifying barriers to large-scale EV transition, determining future EV stock, establishing an energy forecasting model using LEAP software, and determining peak power demand using the Monte Carlo simulation method.

A detailed analysis of each module, along with the necessary literature, mathematical expression, and modeling, is provided in subsequent sections. Section 3.2 deals with barriers to EV transition and related methodologies, and details of future vehicle registration are provided in section 3.3. Sections 3.4 and 3.5 explain the details of the energy transition model used in LEAP and the charging load determination model, respectively.

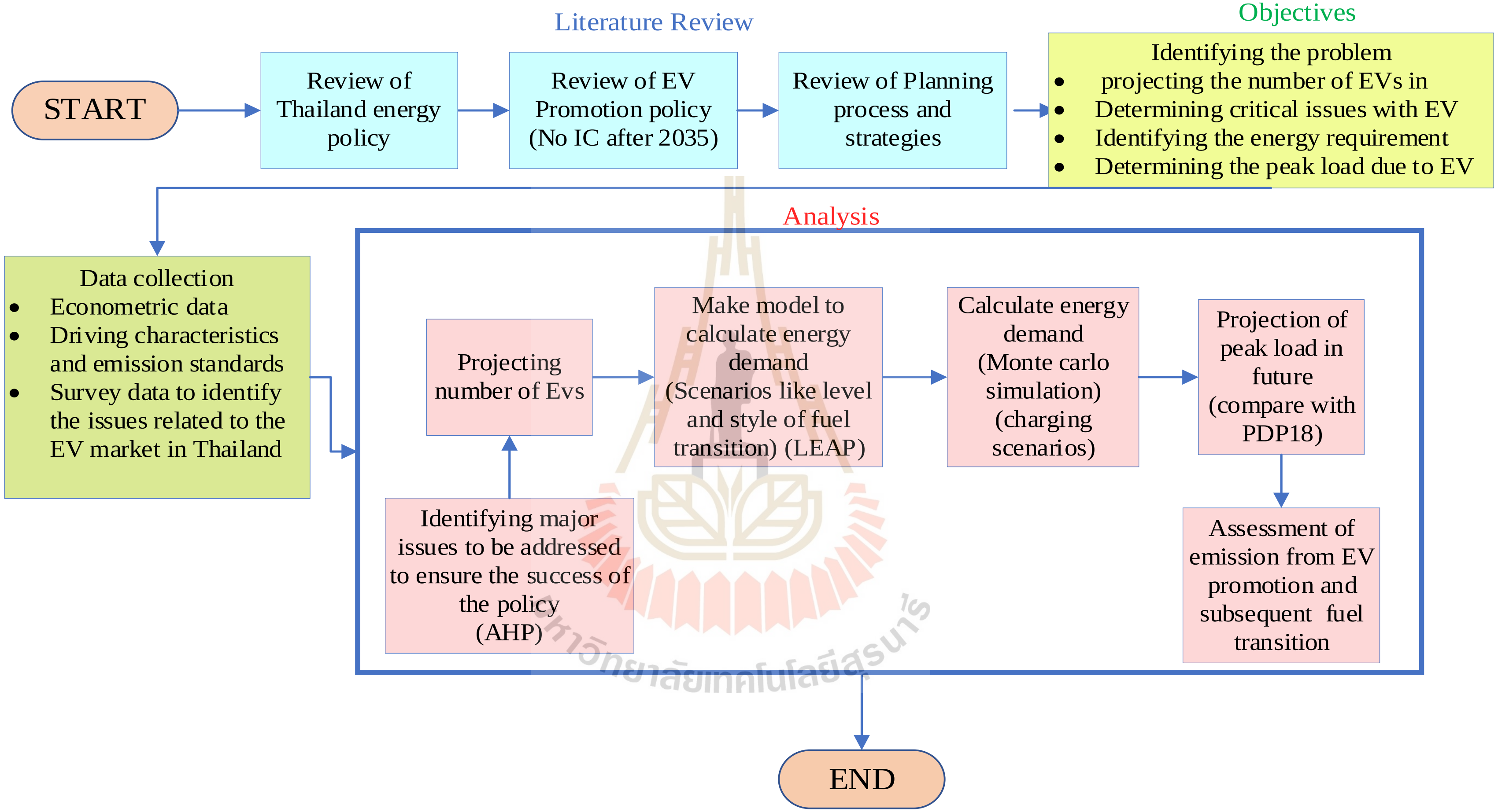


Figure 3.1 Overall architecture of thesis

## 3.2 Issues with Electric Vehicles.

It is not a surprise that EVs have become the talk of the town in recent times as countries are searching for more sustainable and emission-free mobility options. On the contrary, the criticism it has generated is also substantial. IC technology is a relatively mature technology, and the domination of IC in the vehicle market is absolute; hence, consumers' skepticism about the emerging technology is understandable. However, EV technology has much more severe issues than the lack of consumer enthusiasm to accept it. Whenever a credible alternative and benefit arises in the market, consumers will appreciate it, as evident from the growing demand for EVs globally. The issues related to the EVs are listed in Table 3.1.

### 3.2.1 Multi-Criteria Decision Making (MCDM)

A literature survey and comparative study of different EV markets can identify potential issues that might act as a barrier to large-scale EV penetration. However, determining the relative importance of such an issue in a particular market is the most critical aspect. Multicriteria decision-making (MCDM) methodology helps to solve such problems. MCDM is a decision-making algorithm used to identify or rank the best alternatives. MCDM methods are used where a single optimal solution either does not exist or is not practicable; hence, the decision maker's preferential opinions are employed (Taherdoost & Madanchian, 2023). MCDM can be used in quantitative and qualitative analyses involving multiple criteria to make informed decisions. Almost all MCDM methodologies involve some critical components in the decision-making process, as mentioned below:

**Selection of alternatives:** these are the individual options to be ranked or chosen from the available options.

Table 3.1 Issues related to EV promotion

| Issue | Problem | Explanation | Reference |
|---|---|---|---|
| Consumer-level (cost) | Investment cost and after-sell value | The investment cost of EVs is considerably higher than that of IC cars. Subsidy in any form may help to motivate consumers. Similarly, the consumer might be worried about the resell value as the vehicle can be considered a capital investment. | Lee, 2014 |
|  | Maintenance cost | Since the EV technology is still in the initial stage, the maintenance cost is relatively higher, and the servicing facility and the technician are higher and not readily available. | Sanguesa et al., 2021 |
|  | Electricity price | The fuel cost (electricity) must be competitive. | Leontitsis, Pagge, 2007 |
| Technical level (Manufacturer) | Battery technology | Battery technology is still maturing, and the type of battery (Lithium Ion (Li-Ion), Molten Salt (Na-NiCl2), Nickel Metal Hydride (Ni-MH) and Lithium Sulphur (Li-S)) etc., and their performance determines the attractiveness of the EV. | Iclodean et al. 2017 |

Table 3.1 Issues related to EV promotion (continued)

| Issue | Problem | Explanation | Reference |
|---|---|---|---|
| Technical level (Manufacturer) | Charging technology | Charging time, charging type (on/off board, fast charging station), charging rate, and charging method (constant current, constant voltage, intelligent charging control) are some of the most critical aspects of the EV. | Brenna et al., 2020 |
| | Performance of EV | Driving range, maximum power, speed, safety, etc, are the points of concern to the consumer. | Lee & Govindan, 2014 |
| Policy level | Public infrastructure | Charging stations and service centers, road safety, etc. | Barter et al., 2015 |
| | Domestic infrastructure | Home charging possibility (the policy maker must ensure sufficient voltage level, adequate supply etc., to motivate the public) | Kongklaew, 2021 |
| | Financing | Incentives and subsidies in terms of monetary or tax benefit | Alotaibi, 2022 |

**Setting criteria:** This sets the rule by which alternatives are to be compared or used to group the alternatives under certain conditions; cost criteria can be divided into multiple cost alternatives like investment cost, running cost, etc.

**Calculating weights:** The main objective of the MCDM methodology is to assign certain numerical weights to make a comparison among alternatives.

**Decision-making:** this includes both the stakeholders and the people whose preferences are to be analyzed during the decision-making process

There are various MCDM techniques available in the literature; a brief list of a few techniques is given below:

**Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS):** This method is used to identify the best option among a set of alternatives. It was developed by Hwang and Yoon in 1981. The primary goal of TOPSIS is to determine the alternative closest to the ideal solution and farthest from the anti-ideal solution. There are three distances in the TOPSIS method – Manhattan distance, Tchebycheff distance, and Euclidean distance (Rahim et al., 2018).

**VlseKriterijumskaOptimizacija I KompromisnoResenj (VIKOR):** It is a compensatory version of TOPSIS that is based on minimizing the distance to the ideal solution using a linear normalization approach. The Euclidean distance is used in this method (Zlaugotne et al., 2020).

**Case-Based Reasoning (CBR):** A problem-solving methodology that leverages past experiences to address new challenges. Instead of relying solely on general rules or models, CBR utilizes specific instances of previously encountered and resolved cases to inform decision-making. Each case in CBR includes a problem description, the solution applied, and the outcome achieved. These cases are stored in a repository known as a case base. When faced with a new problem, CBR systems retrieve the most similar past cases from the case base, adapt the solutions to fit the new context, test and refine the adapted solutions, and finally store the new experience as a new case for future use. This approach is convenient for customer support, medical diagnosis, legal reasoning, technical support, and design engineering. CBR offers significant advantages, such as improving efficiency by reusing past solutions and continually learning from new experiences. However, it also presents challenges, including the need for diligent maintenance of the case base and the complexity of adapting past solutions to new problems. CBR mimics human reasoning by solving new problems based on historical knowledge, making it a valuable tool in various fields where past experiences are crucial for problem-solving.

**Multi-objective optimization by Ratio Analysis plus Full Multiplicative Form (MULTIMOORA)** is a comprehensive multi-criteria decision-making (MCDM) method that integrates three distinct approaches to evaluate and rank alternatives based on multiple criteria (Aytaç Adalı & Tuş Işık, 2017). Developed by Brauers and Zavadskas, MULTIMOORA is known for its robustness and simplicity in handling complex decision-making problems. The three approaches it incorporates are the Ratio System, the Reference Point Approach, and the Full Multiplicative Form, each offering a unique perspective on evaluating alternatives.

The Ratio System normalizes the decision matrix and calculates a performance score for each alternative by dividing its normalized value by the sum of normalized values across all criteria. This method ranks alternatives based on these calculated ratios, with higher ratios indicating better alternatives. The Reference Point Approach, on the other hand, compares each alternative against a reference point, typically representing the best values for each criterion. It calculates the distance of each alternative from these reference points, using the Tchebycheff metric to measure the maximum deviation. Alternatives are ranked based on distance from the reference point, with smaller distances indicating better options.

The Full Multiplicative Form method evaluates alternatives by multiplying the normalized values of all criteria for each alternative to obtain an aggregated performance score. Alternatives are then ranked based on these scores, with higher scores indicating better performance. The final step in MULTIMOORA involves integrating the rankings from all three methods to provide a comprehensive evaluation. This aggregated ranking offers a robust and thorough decision-making tool by combining the strengths of each approach.

MULTIMOORA is widely applicable in fields such as engineering, economics, environmental management, and healthcare, where it helps in selecting the best designs, investment options, sustainable practices, or healthcare policies. Its key advantages include robustness, simplicity, and flexibility. However, it can be computationally intensive and relies heavily on the quality of input data.

**Analytical Hierarchical Process (AHP):** One of the most popular techniques used in the multi-criteria decision-making process. The credit for developing the current form of AHP is given to Dr. Thomas Saaty. This tool helps planners make complex decisions based on the priority of the various alternatives (Saaty & Katz, 1990). Since it is a tool involved in multi-level decision-making and evaluating multi-criteria alternatives, its results rank different alternatives in importance or weight. It ranks and assigns weight to alternatives at every decision level, and finally, a global ranking is provided after aggregating the weights of each decision variable. Generally, AHP is defined in 4 levels but can be modified according to the need. The first level is the goal of the decision, level 2 is the main criteria, level 3 is the sub-criteria of the decision, and the final level is alternatives to be examined. Due to its simplicity, it is widely used in various sectors, primarily in sustainability, like sustainable agriculture, manufacturing, investment, banking, and service sectors (Siekelova et al., 2021),(Nejad et al., 2021). Modifications like fuzzy AHP ((Jayawickrama et al., 2017)) have been developed to get higher accuracy whenever extra high-level precision and accuracy are required. On the downside, it increases the computation complexities, and the data requirement is relatively high, which may increase the chance of errors.

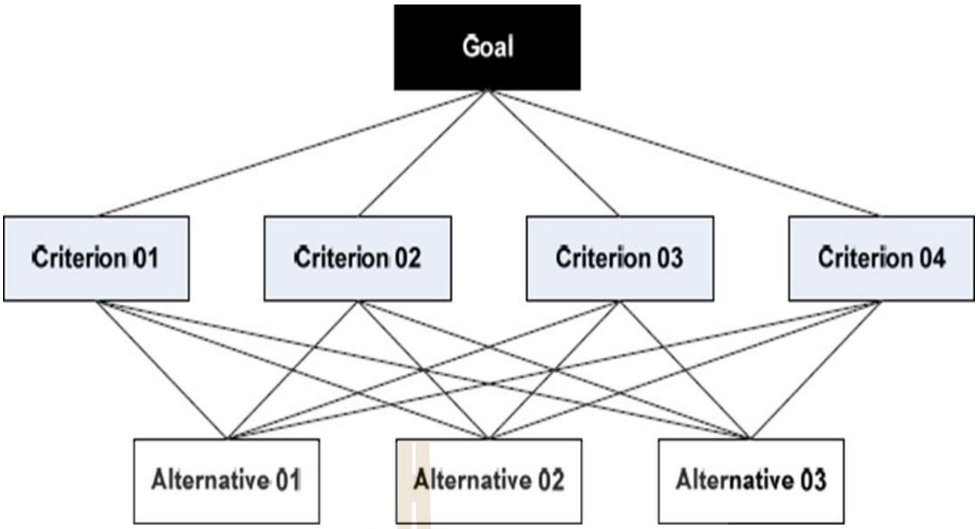


Figure 3.2 Basic structure of AHP

### 3.2.2 AHP methodology

AHP employs the process of pairwise comparison, i.e., each criterion and sub-criteria are compared to themselves. This is done based on the input provided, which is the number assigned by the human according to their preferences. Such preference is ranked in odd numbers from 1 to 9, known as Saaty's scale of importance. 1 means two criteria have equal importance, 9 means one is extremely important to the other, as shown in Table 3.2, and the reciprocal value represents the opposite comparison. Figure 3.2 presents the basic structure of AHP, and Figure 3.3 depicts the flowchart of the AHP methodology.

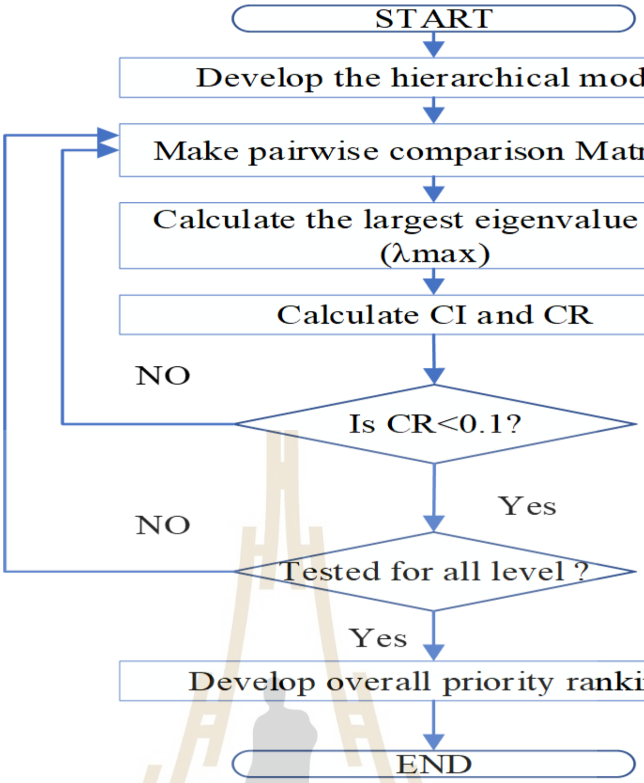


Figure 3.3 Flowchart of AHP methodology

Table 3.2 Saaty’s scale of importance

| SN | Saaty’s scale value | Description |
|---|---|---|
| 1 | 1 | Equal importance |
| 2 | 3 | Moderate importance |
| 3 | 5 | Strong importance |
| 4 | 7 | Very strong importance |
| 5 | 9 | Extremely important |
| 6 | 2,4,6,8 | Intermediate importance used if compromise has to be made (rarely used) |

The first step in AHP is to generate a pairwise comparison matrix.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \tag{3.1}$$

Normalizing the matrix A to get the priority matrix

Normalization involves summing the individual column and dividing individual members of a column by the total sum of the respective column

$$A' = \begin{bmatrix} a'_{11} & a'_{12} & \dots & a'_{1n} \\ a'_{21} & a'_{22} & \dots & a'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a'_{n1} & a'_{n2} & \dots & a'_{nn} \end{bmatrix} \tag{3.2}$$

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad \text{i, j} = 1,2, \dots \text{n}$$

If we average across the row, it gives the principal eigenvalue (since it is already normalized)

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{3.3}$$

$$w_{j=} \frac{\sum_{j=1}^{n} a_{ij}}{n} \quad \text{i, j} = 1,2, \dots \text{n}$$

Now, using the eigenvalue equality (scatty's proposition)

$$Aw = \lambda_{max} w = w' = \begin{bmatrix} w'_1 \\ w'_2 \\ \vdots \\ w'_n \end{bmatrix} \tag{3.4}$$

$$\lambda_{max} = \frac{1}{n} \left( \frac{w'_1}{w_1} + \frac{w'_2}{w_2} + \dots + \frac{w'_n}{w_n} \right) \tag{3.5}$$

Where $w$ is the vector, and $w'$ is the value of criterion i, $\lambda_{max}$ is the largest eigenvalue of pairwise comparison matrix.

Now, calculating consistency index (CI)

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.6}$$

CI indicates an inconsistency level in data, and CI = 0 means the data is relatively consistent. However, a small level of inconsistency is accepted. The consistency ratio (CR), the ratio of CI to random index (RI), is calculated to determine the acceptable level of inconsistency. The RI recommended by Saaty is presented in Table 3.3.

$$CR = \frac{CI}{RI} \tag{3.7}$$

Table 3.3 RI values

| n | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.4 | 1.45 | 1.49 |

### 3.2.3 Data collection and questionnaire

AHP analysis requires a pairwise comparison between individual members of the hierarchy. Generally, such comparisons are made by experts via interviews. In this study, an online interview of experts working in academics, EV businesses, and government policy was conducted with the help of Google Forms. The questionnaire designed for this study is presented in Appendix G. However, the comparison table is also shown in Table 3.4. Experts are requested to compare issues listed in a row by their relative importance. A total of 32 respondents participated in this interview. The list of participants is presented in Appendix G.

Table 3.4 Pairwise comparison table

| SN | Issue | Preference | | | | | | | | | | | | | | | | | Issue |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | More important than | | | | | | | | Equal | Less important than | | | | | | | | |
| | | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | Cost | | | | | | | | | | | | | | | | | | Technical Issue |
| 2 | Cost | | | | | | | | | | | | | | | | | | Policy Issue |
| 3 | Technical issue | | | | | | | | | | | | | | | | | | Policy Issue |
| 4 | Investment and after sale cost | | | | | | | | | | | | | | | | | | Maintenance cost |
| 5 | Investment and after sale cost | | | | | | | | | | | | | | | | | | Fuel (electricity) cost |
| 6 | Maintenance cost | | | | | | | | | | | | | | | | | | Fuel cost |
| 7 | Battery related issue | | | | | | | | | | | | | | | | | | Availability of service center |
| 8 | Battery related issue | | | | | | | | | | | | | | | | | | Performance (reliability, safety) |
| 9 | Availability of service center | | | | | | | | | | | | | | | | | | Performance (reliability, safety) |
| 10 | Public infrastructures (charging stations etc.) | | | | | | | | | | | | | | | | | | Private infrastructure (home charging etc) |
| 11 | Public Infrastructure | | | | | | | | | | | | | | | | | | Financing (tax exemption etc) |
| 12 | Private infrastructures | | | | | | | | | | | | | | | | | | Financing |

## 3.3 Projection of Future vehicle registration (econometric analysis)

Estimating vehicle registration in the future is a difficult task. The vehicle buying decision of a person depends upon various factors, like income, necessity, technology, availability of public transport, etc. This study considers the planning horizon from 2016 to 2040. Since the forecasting duration is significantly longer, the more accurate methodologies used for short-term forecasting might not be helpful. A vehicle ownership model is developed to forecast future vehicle registration. The time series forecasting method has been widely applied for long-term forecasting applications. ARIMA models predict future car sales in articles (Irhami & Farizal, 2021; Shakti et al., 2017). Holtz’s method could be more accurate than ARIMA's as its exponential smoothing method might help to assign weights holistically to previous data (Leenawong & Chaikajonwat, 2022). However, the most trusted method of forecasting for such a prolonged duration is found to be log-linear regression due to its simplicity, low data requirement as well as the macroeconomic factors are found to be highly correlated to vehicle purchase in the number of previous studies (Button & Hine, n.d.; Sillaparcharn, 2007; Wattana & Wattana, 2022). Models generally use macroeconomic indicators like per capita income, population and population density, urbanization, fuel cost, taxation, etc. This article considers three dependent variables, nominal per capita income (PCI), population density (POPden), and the average retail fuel price (FP), to predict vehicle ownership per thousand people. The concept of saturation level is also introduced, making the model quasi-logistic.

A log-linear regression model establishes a relationship between independent variables and dependent variables. The model equation of log-linear regression is given below:

$$ln\left(\frac{VO_{1000}}{S - VO_{1000}}\right) = \beta_0 + \beta_1\, ln\, PCI + \beta_2\, ln\, POPden + \beta_3\, ln\, FP + \varepsilon \qquad (3.8)$$

Where,

$VO_{1000}$ = vehicle ownership per 1000 population, $S$ = saturation level, $\beta_1, \beta_2$, and $\beta_3$ = coefficient of respective variables

The rationale behind the implementation of loglinear regression is that its coefficient represents the elasticity of the dependent variable concerning the independent variable, or elasticity is the measure of the sensitivity of one variable to another. The coefficient $\beta_1$ represents the expected percentage change in y if PCI is changed by 1%. Similarly, the sign of the coefficient indicates the direction of the change. If PCI is changed by a%, then the dependent parameter will also change by a* $\beta_1$ %.

The goodness of fits between predicted and actual fuel consumption can be indicated by determining the coefficient of determination ($R^2$). The formulas to calculate the mean bias error (MBE), RMSE, and coefficient of determination ($R^2$) are presented below:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(y_{f,i} - y_{o,i}) \tag{3.9}$$

Where MBE is the percentage of a mean bias error of estimation, $y_{f,i}$ is a forecasted value, $y_{o,i}$ is an observed value, $\bar{y}$ is a mean of the observed values, and n is number of data sets.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{f,i} - y_{o,i})^2} \tag{3.10}$$

Where RMSE is the percentage of a root mean squared error of estimation.

$$R^2 = 1 - \frac{Sum\ of\ squares\ regression\ (SSR)}{Sum\ of\ squares\ total\ \ (SST)}$$

(3.11)

$$= 1 - \frac{\sum_{i=1}^{n}(y_{o,i} - y_{f,i})^2}{\sum_{i=1}^{n}(y_{o,i} - \bar{y})^2}$$

Where $R^2$ is the coefficient of determination and is the square of the correlation coefficient (r).

**Table 3.5 Saturation level of vehicle ownership in some countries (Chollacoop et al. 2009), (Chollacoop et al. 2010), (Laoonual et al. 2013)**

| **Countries** | **Saturation levels (cars per 1000 population)** |
|---|---|
| US | 852 |
| Malaysia | 827 |
| Thailand | 812 |
| Indonesia | 808 |
| China | 807 |
| Japan | 732 |
| Germany | 728 |
| UK | 707 |
| Korea | 642 |

The saturation level is the maximum number of vehicles per thousand population. This number depends on the country's economic condition and cannot be predetermined. The vehicle saturation level of selective countries is presented in Table 3.5. Determining saturation level is a research topic in itself and is out of the scope of this study. The saturation level is chosen to maximize the goodness of fit, considering available information from previous studies and data of countries with comparable economic development.

## 3.4 Energy Forecasting Model

The energy demand (ED) model used in the LEAP (stock turnover model) is primarily based on the number of vehicles (total stock at a time t), vehicle kilometers traveled (VKT), and the fuel economy (FE) of the vehicle. ED model can be expressed as follows:

$$ED_{i,j} = N_{stock\ i,j} \times VKT_i \times FE_{i,j} \tag{3.12}$$

Where $\boldsymbol{i}$ represents the type of fuel used in the vehicle and $\boldsymbol{j}$ represents the category of the vehicles. The Department of Land Transport of Thailand registers the same categories of vehicles under various service designations; for example, taxis are registered under fixed-route, hotel, and tour taxis. For the simplicity of the calculations, such similar vehicles are grouped into six types of vehicles, which include cars (less than seven passengers), personnel utility vehicles (including cars of more than seven-passenger capacity, minivans, and pickup), tricycle and tuk-tuk, bikes (personal and public), taxi and bus (fixed route as well as non-fixed route). Besides buses and bikes, all groups can be categorized into the more common Light Driving Vehicles (LDV) designation.

The total stock of each vehicle type and fuel type can be determined as shown in equation (3.13), which depends on the number of vehicle sales and the survival rate of the vehicle.

$$N_{stock\ i,j} = \sum_{v=1}^{t} N_{sale\ i,j}\ (v) \times\ S_{i,j}(a) \tag{3.13}$$

Where, $N_{sale\ i,j}\ (v)$ is the number of new vehicles that were sold in vintage year $v$, and $S_{i,j}(a)$ is the survival rate of vehicle type j with fuel i with age $a\ (a =$ t-vintage year $(v)$). The overall block diagram of the modeling process is given in Figure. 3.4.

The driving dynamics of different vehicle types vary greatly, influenced by factors such as urban or rural driving conditions and the vehicle's purpose. Data on driving characteristics are sourced from prior publications (Limanond et al., 2010; Pongthanaisawan & Limmeechokchai, 2007), while vehicle-specific information like registration numbers, annual mileage, and fuel types are gathered from the Department of Land Transport (DLT) web portal of the Thai government. A sample VKT profile of car driving in the provincial and urban areas is given in Figure 3.5.

DLT records reveal a variety of fuel designations for registered vehicles, including gasoline, diesel, CNG, LPG, and hybrids. Some vehicles are dual-fueled, such as CNG-gasoline or CNG-diesel, while older models may use benzene. Thailand leads in adopting policies like ethanol blending (Bloyd, 2017), termed gasohol, which has varying blends like 5%, 10%, and 20%. Biodiesel with different blending grades is also prevalent. To simplify the analysis, these fuels are categorized into groups:

a. Gasoline: Vehicles registered under gasoline designation.
b. Diesel: Vehicles primarily use diesel fuel.
c. CNG: Vehicles using CNG as primary fuel or in dual-fuel configurations.
d. LPG: Vehicles primarily fueled by LPG.
e. Gasoline (Hybrid): Hybrid electric vehicles assumed to be gasoline-powered.
f. Electricity: Includes battery electric and plugin electric vehicles.

Fuel economy is another critical issue when deterring vehicle energy demand. FE may vary according to the manufacturer, model, fuel used, type of vehicle and utility, driving condition, and age. Usually, regulators define minimum FE standards to be met to be road-worthy. In the case of Thailand, such regulation is not strictly defined; rather, it is regulated by market force (most miniature FE vehicles will not be market-friendly). Since Japanese manufacturers dominate the Thai automaker sector and the market, the FE is expected to be similar to that of IEA non-European members, which is 9km/l (Bank, 2009).

On the contrary, the ASEAN fuel economy roadmap predicts the FE of LDV of Thailand to be 13.3km/lge (ASEAN Secretariat, 2019). Since Thailand is the leading vehicle manufacturer, various brands are available. Some popular gasoline and plugin hybrid car brands in Thailand are Toyota, Mazda, Hyundai, and Nissan. Whereas Nissan, BYD, Tesla, etc. are leading brands in the battery electric market. Table 3.6 presents the FE values used in this study.

Table 3.6 Fuel Economy of Various type of vehicles

| Vehicle | FE km/lge | | | Reference |
|---|---|---|---|---|
| LDV | ICE | HEV | BEV | (ASEAN Secretariat, 2019) |
| | 12 | 18 | 47 | |

Emission calculation assumes emission as the function of distance traveled and energy consumption. Total emission from a particular vehicle type using specific fuel is the product of total energy consumed, emission factor, and emission degradation factor. The emission factor is the maximum allowable emission prescribed by the regulating authority. Countries adopt different standards according to their specific environments. The Thailand Euro-IV emission standard has been in effect since 2012, succeeding Euro-III (enforced in 2005) and Euro-II (promulgated 1999). The government is soon preparing to move to a tougher emission standard, Euro-V. The emission degradation factor represents the effect of higher emissions as the engine ages. However, this phenomenon depends on actual driving patterns, road, and environmental conditions and is difficult to realize for various car types.

Additionally, vehicle survivability predicts minimal chances of an old vehicle that might have significantly altered its emission factor. Owing to this consideration, the emission factor is assumed to remain constant throughout their service on the road. The mathematical formula used to calculate emission is given in equation 3.14

$$Emission_{i,j,k} = ED_{i,j} \times EF_{i,j,k} \times \emptyset_{i,j,k,\alpha} \tag{3.14}$$

Where, $\boldsymbol{Emission_{i,j,k}}$= Emission $\boldsymbol{k}$ from fuel $\boldsymbol{i}$ of vehicle type $\boldsymbol{j}$

$EF_{i,j,k}$= Emission factor

$\emptyset_{i,j,k,\alpha}$= emission degradation factor for k type emission from $\boldsymbol{i}$ fuel of $\boldsymbol{j}$ category vehicle on $\alpha$ year ($\alpha$=t-$v$).

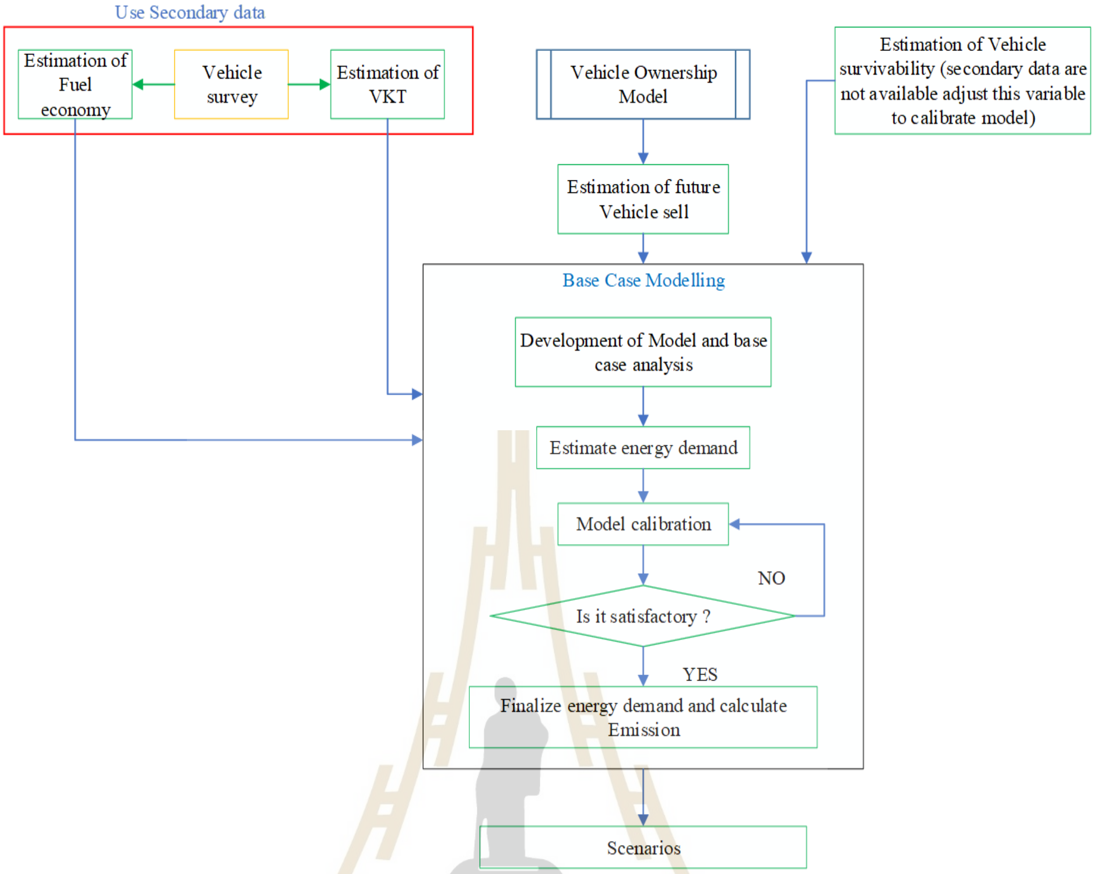


Figure 3.4 Energy modeling flowchart

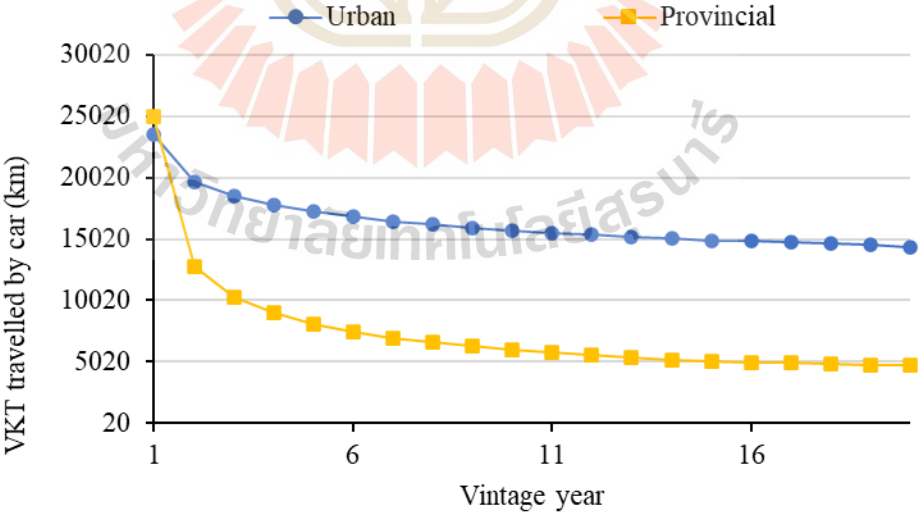


Figure 3.5 VKT profile by age of a car in the provincial and urban area

## 3.5 EV charging load

The EV charging load is a multivariate probabilistic model based on the Monte-Carlo simulation, in which EV charging behavior is a survey work. The Monte-Carlo simulation evaluates charging demand, as shown in Figure 3.6. Figure 3.6 shows a procedure to evaluate an EV charging demand, comprising two parts: Monte-Carlo simulation and charging demand calculation. The Monte-Carlo simulation used survey data to evaluate daily mileage, charging mode, and plug-in time to determine initial SOC and charging duration.

The EV charging behavior evaluation is a random variable that includes driving patterns and daily distances. A multivariate probabilistic model is used to evaluate charging demand based on survey and statistical data. Daily travel distance, plug-in duration, and the probability that an EV will recharge are uncertainty variables considered while predicting the need for 24-hour EV charging. An uncertainly of each EV is defined as a probability distribution function (PDF) which the PDF of daily distance can be defined into two types, including log-normal distribution type and normal distribution type, as respectively expressed by Equation 3.15 – 3.16

$$f_d(x_{i,j}) = \frac{1}{x_{i,j}\sigma_{d,j}\sqrt{2\pi}} e^{\left(-\frac{(\ln x_{i,j} - \mu_{d,j})^2}{2\sigma_{d,j}^2}\right)} \tag{3.15}$$

$$f_d(x_{i,j}) = \frac{1}{\sigma_{d,j}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{(x_{i,j} - \mu_{d,j})^2}{\sigma_{d,j}^2}\right)} \tag{3.16}$$

Where $x_{i,j}$ = daily driving distance of $i^{th}$ EV.

$j$ = EV type

$\mu_{d,j}$ = mean driving distance

$\sigma_{d,j}$ = standard deviation of driving distance

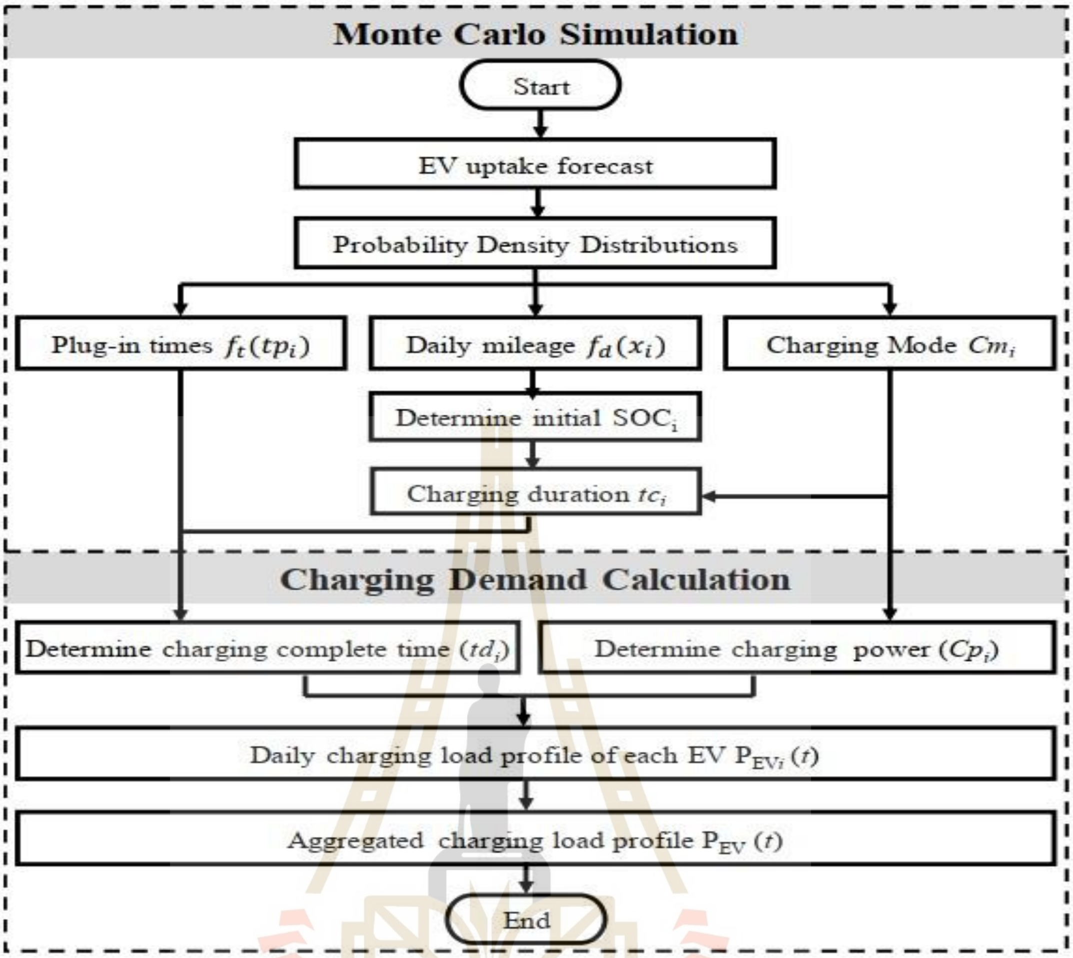


Fig. 3.6 Flowchart of EV load determination using Monte Carlo simulation (Adianto et al., 2022)

SOC of EV battery can be given by

$$soc_{i,j} = 1 - \frac{d_{i,j}}{D_j \eta} \tag{3.17}$$

$d_{i,j}$ = distance covered

$D_j$ = full driving capacity with 100% battery charged

$\eta$ = efficiency of battery (discharging)

The starting time of charging is another critical factor. The uncertainly of the plug-in time of each EV is a random variable in the form of a normal probability distribution function, which is expressed by Eq 2.14

$$f(Tst_{i,j}) = \frac{1}{\sigma_{st,j}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{(tst_{i,j}-\mu_{st,j})^2}{\sigma_{st,j}^2}\right)} \tag{3.18}$$

Where,

$Tst_{i,j}$ = starting time of plug-in or charging of $i^{th}$ vehicle of type $j$

$\mu_{st,j}$ = Mean of starting time of charge

$\sigma_{st,j}$ = Standard deviation of starting time of charge

now, the required charging time can be given as

$$tch_{i,j} = (1 - SOC_{i,j})\frac{BP_{i,j}}{CP_{i,j} \times \eta} \tag{3.19}$$

Where, $tch_{i,j}$ = charging time

$BP_{i,j}$= battery capacity (Whr)

$CP_{i,j}$ = charging rate

$\eta$ = efficiency of charger or overall charging efficiency

now, the end of charging time $Tend_{i,j}$ is defined by

$$Tend_{i,j} = Tst_{i,j} + tch_{i,j} \tag{3.20}$$

Now, the charging load at $t$ can be calculated as

$$P_{EV\ i,j}(t) = \begin{cases} CP_{i,j} & : Tst < t < Tend \\ 0 & : \quad otherwise \end{cases} \tag{3.21}$$

Aggregated demand at time ***t*** is the sum of the charging load of all vehicles and is given by

$$P_{EV}(t) = \sum_{j=1}^{N_{types}} \sum_{i=1}^{N_{EV}} P_{EV\ i,j}(t) \tag{3.22}$$

Since the charging load is the additional load to the existing demand curve, the final load curve can only be generated by adding EV load to the base load curve (existing load curve).

$$P_T(T) = P_{existing}(t) + P_{EV}(t) \tag{3.23}$$

## 3.6 Chapter Summary

Chapter 3 deals with the details of the methodology used in the study. The major feature of the chapter is listed below:

I. Development of vehicle ownership model based on log-linear regression and its mathematical explanation.
II. Detailed modeling of energy demand and emissions from vehicles used in the LEAP software. (Mathematical interpretation of LEAP model).
III. Mathematical modeling of peak demand estimation using the Monte Carlo method.
IV. Explanation of AHP, the process involved in AHP analysis, mathematical explanations, survey methodology, and questionnaire.

# CHAPTER IV

# RESULTS AND DISCUSSION

## 4.1 Barriers to large-scale EV adoption (AHP analysis)

Thailand is committed to enhancing large-scale EV promotion soon. However, it has its limitations and concerns. Firstly, EVs are new-age technology, so their acceptance and penetration in the market might depend on the customers' willingness. Assessing people's opinions about EVs is logical if the vision of electric mobility is to come true.

A survey has been conducted to determine the prevalent issues linked to wider EV adoption in Thailand. This survey primarily emphasizes the viewpoint of three major stakeholders, including academics, the EV industry, and government functionaries responsible for formulating EV promotion strategies and policies. A total of 32 experts with sufficient experience in their respective fields have been included in this study. The calculation is made using MS Excel and cross-verified with the model developed by Business Performance Management Singapore (BPMS) according to the methodology explained in section 3.2.2. The hierarchy formulation of the issues analyzed in this thesis is given in Figure 4.1. It has three main criteria: Cost, technical, and policy issues. Each criteria category has sub-issues related to the main criteria group. Cost criteria have three sub-criteria: investment and after-sales, maintenance, and fuel costs (electricity tariffs). Technical issues are divided into three subcategories: battery-related issues, availability of service centers and spare parts, and finally, the performance of vehicle specification (range, reliability, safety etc.). The policy criteria issues also contain three sub-criteria. Public infrastructure mainly focuses on policies related to expanding public fast charging stations etc. Private infrastructure deals with policies related to enhanced home charging infrastructures. Financing is primarily related to the subsidy and tax rebates.

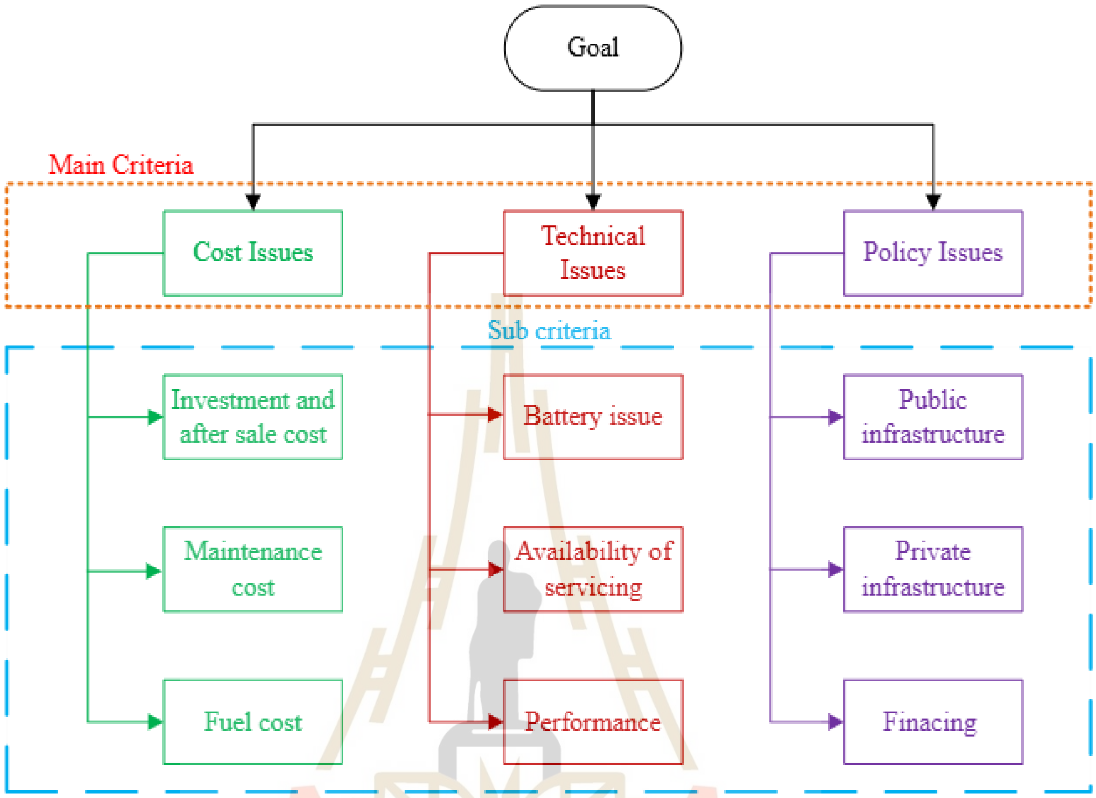


Figure 4.1 AHP hierarchy structure

AHP methodology determines the relative weightage of each criteria category member and subcategory member. The details of the calculation procedure, as well as priority weight, are explained below:

### 4.1.1 Weights of Main Criteria Categories

First and foremost, a survey was conducted, and the response to the questionnaire was recorded. In the questionnaire, participants are requested to compare two issues of the same group, known as pairwise comparison. For example, cost issues and technical issues were compared by each participant, and they identified more essential issues, given their magnitude of importance. Similarly, all members of sub-criteria are also compared with each other.

Since multiple participants are present in the survey and their preference in identifying the more critical issues among the list varies significantly, the pairwise comparison matrix is formed by taking the geometrical means of all responses.

The comparison matrix, known as the pairwise comparison matrix for main criteria members, is shown in Table 4.1

**Table 4.1 Pairwise comparison matrix of main criteria members**

| | Cost | Technical | Policy |
|---|---|---|---|
| Cost | 1 | 4.39 | 6.87 |
| Technical | 0.23 | 1 | 3.63 |
| policy | 0.15 | 0.27 | 1 |
| | Sum = 1.38 | 5.66 | 11.50 |

After forming the pairwise comparison matrix is normalized by dividing each column member by the sum of individual columns.

The normalized matrix is $\begin{bmatrix} 0.728 & 0.7748 & 0.5972 \\ 0.1658 & 0.1765 & 0.3158 \\ 0.1059 & 0.0485 & 0.086 \end{bmatrix}$

The normalized priority weightage is equal to the average of each row of elements, as explained in equation 3.3.

The normalized weight is $\begin{bmatrix} 0.700 \\ 0.219 \\ 0.081 \end{bmatrix}$

The above-mentioned normalized priority weight (Priority vector) must be checked for consistency. The eigenvector method is used to test consistency. According to equation 3.4, the following criteria should be valid.

$$Aw = \lambda_{max} w = w' = \begin{bmatrix} w'_1 \\ w'_2 \\ \vdots \\ w'_n \end{bmatrix}$$

Where A is the comparison matrix, and $\lambda_{max}$ is the largest eigenvalue. And hence, $\lambda_{max}$ can be calculated using equation 3.5.

Here, $w' = \begin{bmatrix} 2.21 \\ 0.67 \\ 0.24 \end{bmatrix}$ and finally $\lambda_{max}$ is calculated to be 3.08

Furthermore, the consistency index and ratio are calculated using equations 3.6 and 3.7, respectively, and found to be 0.04 and 0.069, respectively.

The priority weightage calculated earlier is consistent since the consistency ratio is less than 0.1.

The result suggests that cost is a significant factor that might impact the EV market since it has the highest weightage at 70%. Cost is followed by technical performance with 21.9% weightage, and policy-level issues appear to be the least important issue to the experts, obtaining only 8.1% overall weightage among the three main criteria. The consistency ratio (CR) is 0.069. The weights of the main criteria are tabulated in Table 4.2. Similarly, the priority weights of sub-criteria under different criteria categories are also calculated.

**Table 4.2 Priority weight of main criteria**

| Criteria Categories | Priority weight (%) | Rank |
|---|---|---|
| Cost Issues | 70% | 1 |
| Technical Issues | 21.9% | 2 |
| Policy Issues | 8.1% | 3 |

### 4.1.2 Priority weight of sub-criteria of criterion cost

There are three supporting issues related to cost: investment and after-sale cost, maintenance cost, and finally, fuel cost (electricity tariff). AHP analysis results show that investment and after-sales costs have the highest weight (60.5%), followed by maintenance costs (25.7%). Electricity tariffs do not appear to have much impact since their weight in the hierarchy is about 13.8%. CR of this calculation is less than 0.06. Table 4.3 lists the weights and ranks of each sub-criteria within cost criteria.

Table 4.3 Priority weight of sub-criteria under criteria cost

| Sub criteria | Priority weight (%) | Rank |
|---|---|---|
| Investment and after-sale value | 60.5% | 1 |
| Maintenance cost | 25.7% | 2 |
| Fuel (Electricity) cost | 13.8% | 3 |

### 4.1.3 Priority weight of sub-criteria of criterion technical and policy issue

Tables 4.4 and 4.5 lists the priority weight of sub-criteria under technical and policy criteria, respectively. Expert opinion suggests battery-related issues are the most prominent issues under the technical barrier category. The priority weight of the battery-related issue (63.9%) is about three times higher than that of the service center, and spare parts (22.5%) rank second in the priority hierarchy. With 13.6% priority, weightage performance-related issues are ranked in the third. Analysis can safely be termed as consistent since CR is about 0.08. The priority weightage of sub-criteria under policy criteria is almost the same as that of the other two criteria. Public infrastructure seems to be the most impactful issue, with an overwhelming weightage of 67.5%; second place, the private infrastructure issue has a 22.5% priority weightage. Experts have ranked financing, which deals with government subsidies, tax rebates, etc., as the least impactful issue related to EV market penetration, as the priority weightage is only 13.6%. The consistency ratio of the analysis is 0.006.

Table 4.4 Priority weight of sub-criteria of Technical Issues

| Sub Criteria | Priority weight (%) | Rank |
|---|---|---|
| Battery related issues | 63.9% | 1 |
| Service center and spare parts | 22.5% | 2 |
| Performance | 13.6% | 3 |

Table 4.5 Priority weight of sub-criteria of policy issues

| Sub criteria | Priority weight (%) | Rank |
|---|---|---|
| Public Infrastructure | 67.5% | 1 |
| Private Infrastructure | 20.3% | 2 |
| Financing | 12.2% | 3 |

### 4.1.4 Global priority weightage and priority order

Global priority order represents the overall priority weightage of sub-criteria and is calculated by multiplying criteria weightage with sub-criteria weight. This gives information about the overall impact of a particular sub-criterion on the EV market penetration. Table 4.6 presents the global weightage of each sub-criterion, and Figure 4.2 describes the ranking of the issues according to their priority weightage. According to the result, Investment and after-sales costs are the most critical barriers to higher EV penetration in Thailand, with 42.5% weightage. Maintenance costs and battery-related issues follow this. Experts believe the private infrastructure and government financing might not impact future EV purchases since their priority weightage is less than 5%.

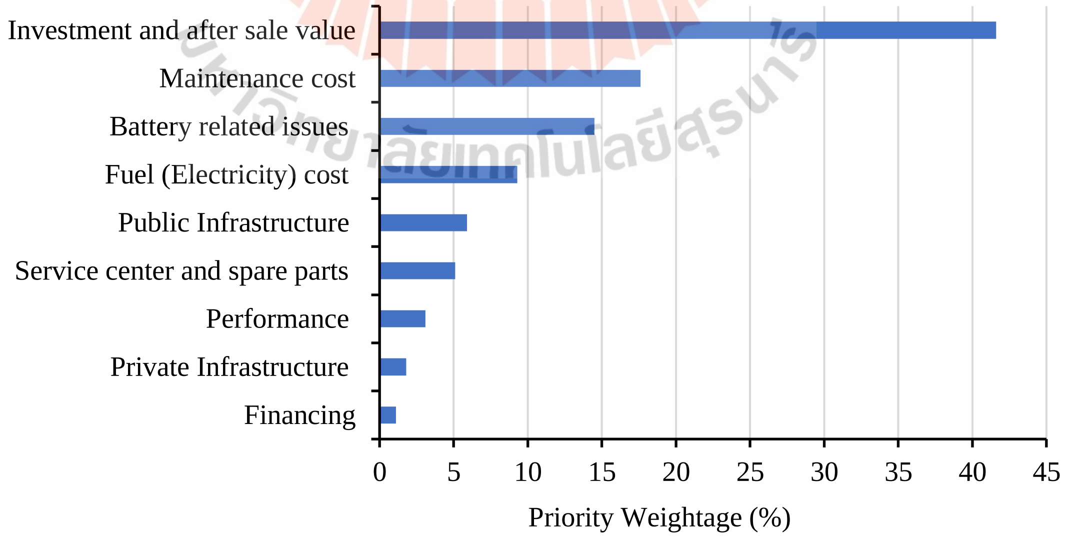


Figure 4.2 Priority weightage and ranking of issues related to EV promotion

Table 4.6 Global weightage of issues related to EV promotion.

| Main criteria weightage | Sub criteria weightage | Global weightage |
|---|---|---|
| Cost Issue (0.70) | Investment and after-sale value (0.605) | 0.4252 |
| | Maintenance cost (0.257) | 0.1801 |
| | Fuel (Electricity) cost (0.138) | 0.0947 |
| Technical issues (0.228) | Battery related issues (0.639) | 0.1402 |
| | Service center and spare parts (0.225) | 0.04953 |
| | Performance (0.136) | 0.02958 |
| Policy issues (0.081) | Public Infrastructure (0.675) | 0.0544 |
| | Private Infrastructure (0.203) | 0.0163 |
| | Financing (0.122) | 0.011 |

## 4.2 Interpretation of the AHP Result

Nine issues that might negatively impact large-scale EV integration in the Thai transport system are analyzed using the AHP methodology. The result ranks such issues according to their importance in buying EVs over conventional vehicles. Respondents overwhelmingly agree on the paramount importance of cost-related issues. The expert also gives technical performance and parameters relatively higher importance, but the policy issue appears to be relatively mundane in front of the more severe issue of cost and technical excellence.

Investment and after-sale value are the most critical factors that might impact EV purchase decisions, followed by maintenance costs. However, experts do not assign much importance to finance from the government through tax incentives or direct cash handouts, which will reduce EV prices to customers. Such observation might appear to be contradictory at first sight. Deeper scrutiny of the result presents an alternative viewpoint. Electricity cost and public infrastructure are ranked 4th and 5th most influential in the final priority order, and financing is placed at the bottom. Expert believes direct purchase subsidy might help in the short run, but large-scale penetration on the market cannot be achieved by subsidizing on an individual basis; if the government improves public infrastructures (charging stations, servicing, etc.) and makes sure electricity prices remain affordable, then people will be more likely to opt for EV over conventional vehicles. The high cost of EVs can be reduced using economy of scale rather than direct personal subsidy. The resource allocated for the purchase subsidy should be redirected towards developing the EV industry, which, in turn, reduces the overall purchase and maintenance costs.

Surprisingly, the performance of EVs is ranked in the bottom third, just above private infrastructure and below the service center and spare parts. This might be due to the familiarity with the specifications of EV and the respondent’s faith in such performance characteristics. Experts are satisfied with the driving features like experience, design, safety, interiors etc., and believe they are comparable to the existing vehicles. However, battery-related issues (range, reliability, charging time) still significantly hinder the EV market. Solutions to these concerns should be the primary priority of EV manufacturers to gain a higher market share.

One crucial observation related to the charging phenomenon is that Public infrastructure is much higher than private infrastructure, suggesting people are more likely to charge their vehicles in public fast charging stations rather than in their homes. Faster charging technology and charging stations are necessary for electrifying a significant portion of the transport fleet. The observation also provides a crucial insight into subsequent charging load and power demand. If home charging is not the preferred method of charging and public charging becomes dominant, the peak demand can be significantly reduced as the demand caused by the simultaneous plugin of the large number of EVs will be minimized. Such demands will be distributed throughout the day rather than concentrating on a short timeframe when people return home for a charge. This information is paramount when planning energy system expansion and system security.

## 4.3 Vehicle ownership model

The vehicle ownership model presented in section 3.3 was solved with the help of MATLAB statistical module using the vehicle stock at the end of the year from 1995 to 2020, obtained from the Department of Land Transport. PCI and population density data is collected from the World Bank database (The World Bank, n.d.). Finally, the historical record of the fuel price is realized from the Bank of Thailand records (Bank of Thailand, n.d.). It is to be noted that the vehicle is retired after 20 years of service. Figures 4.3 and 4.4 present the data on PCI regarding current local prices in local currency, population density, and fuel prices, respectively.

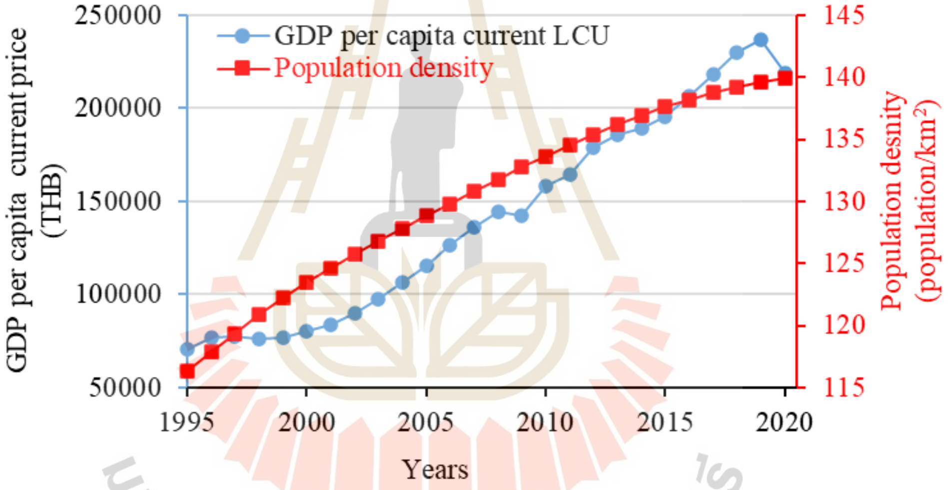


Figure 4.3 Data of PCI in current local currency

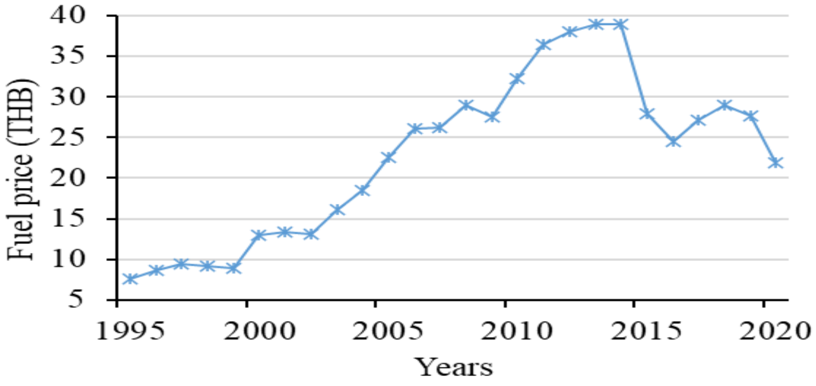


Figure 4.4 Historical fuel price

Table 4.7 Parameters of the vehicle ownership model

| parameter | coefficient | p Value |
|---|---|---|
| $\beta_0$ | -44.346 | $1.3377\times10^{-8}$ |
| $\beta_1$ | 0.70569 | $6.9\times10^{-4}$ |
| $\beta_2$ | 7.4199 | $3.79\times10^{-5}$ |
| $\beta_3$ | -0.43314 | $1.0354\times10^{-6}$ |

Table 4.7 presents the fitting parameters of equation 3.8. The $R^2$ and adjusted $R^2$ values are 0.982 and 0.98, respectively. Additionally, MAPE is calculated to be 4.1072. The saturation level is assumed to be 600, which fits the data most accurately.

Referring to Table 4.7, it can be concluded that the most significant variable in the equation is population density since its coefficient is the highest. It also has a positive coefficient, signifying a positive correlation. However, Thailand's population is almost stagnant and starts a gradual decline around 2030, and it might not be the primary determining factor in the future simply because of its extremely narrow range of variation. On the contrary, the PCI and fuel price coefficients are 0.70569 and -0.43314, indicating positive and negative correlations, respectively. These two factors might be the most influential in determining future vehicle market growth. Figure 4.5 shows the result of the regression model. The MAPE of the analysis is equal to 4.1.

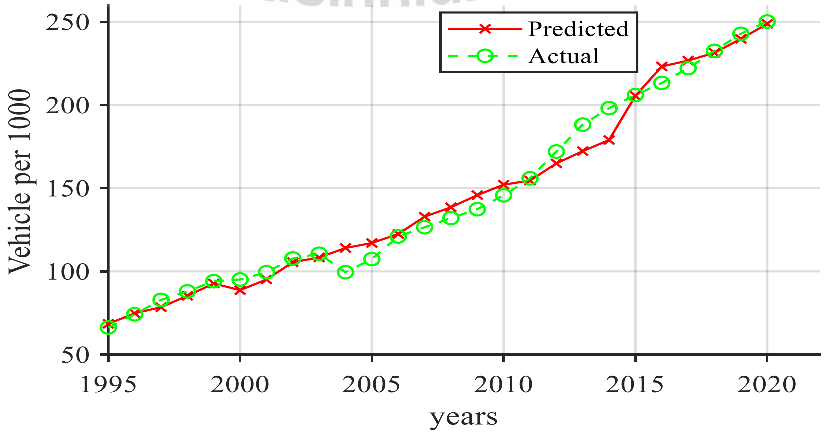


Figure 4.5 Vehicle ownership 1995-2020 (Actual vs Predicted)

Finally, the vehicle ownership model can be given as follows:

$$ln\left(\frac{VO_{1000}}{600 - VO_{1000}}\right) = -44.346 + 0.70569\, ln\, PCI$$

$$+7.4199\, ln\, POPden + -0.43314\, ln\, FP$$

Since the model is dependent on PCI, two growth scenarios are considered. It is considered that the economy will grow by 5% in the high-growth scenario and 3% in the medium-growth scenario. These numbers follow medium-term growth forecasts by different international organizations, including the IMF and the World Bank. The Bank of Thailand's inflation target is pegged at 2%, so data is also considered for evaluating fuel costs in the future. Figure 4.6 shows the projected vehicle ownership per 1000 population in two growth scenarios. The vehicle per 1000 population is projected to be about 384 in the GDP5 scenario and 344 in the GDP3 scenario, respectively. The PCI in 2020 is 223437 Baht, as given by the National Statistical Office of Thailand. The total number of vehicles in 2040 will be about 26.5 million and 24.2 million in the GDP5 and GDP3 scenarios, respectively, as presented in Figure 4.7.

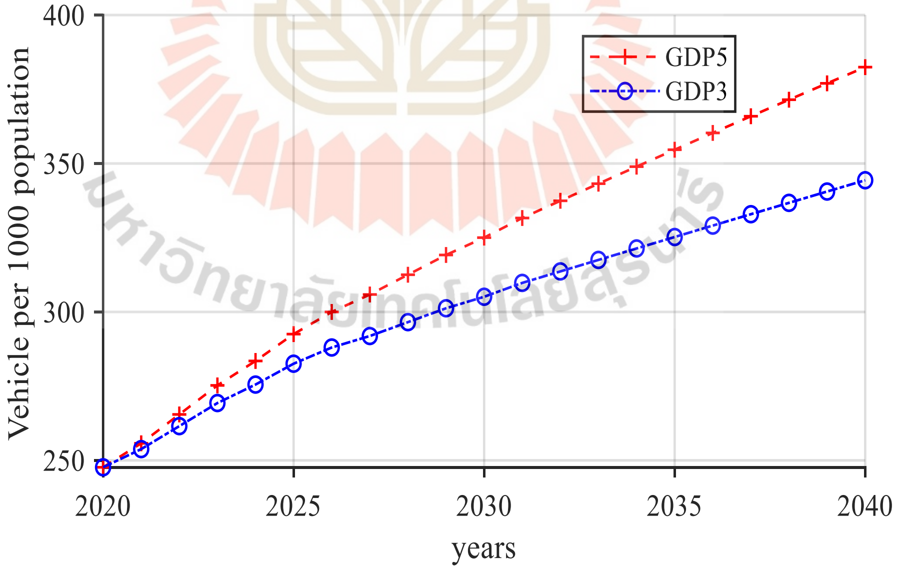


Figure 4.6 Future vehicle ownership projection

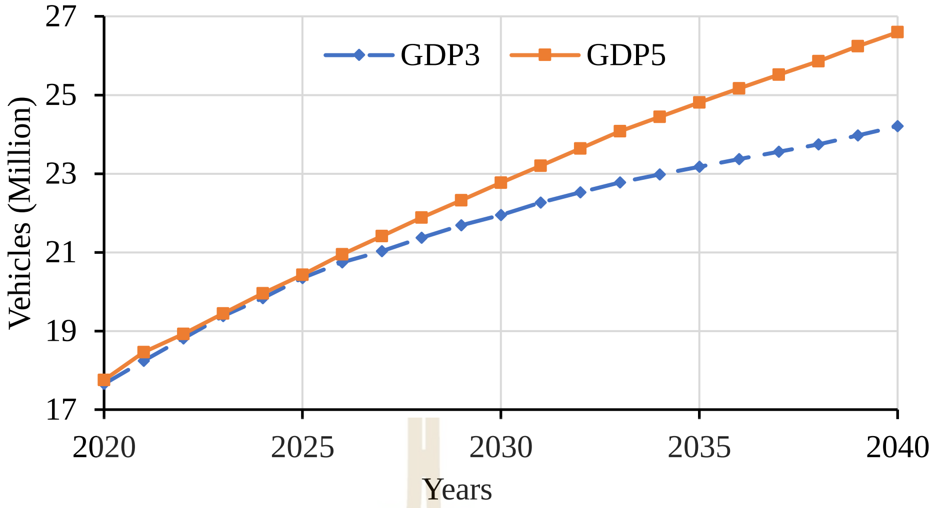


Figure 4.7 Projected vehicle number.

The Department of Transport also maintains the record on a regional basis. Thailand has seven regions: Bangkok, central, east, northeast, north, west, and south. The proportion of vehicles in each region is not constant throughout history. Without a surprise, Bangkok leads the chart with almost 37% of total vehicles, which has been consistent since 2008. On the other hand, the share of the central region dropped to 5.2% in 2020 from 6.1% in 2008, and a significant increase was noted in the northeast region over the same period. Figure 4.8 presents the proportion of vehicles in each region from 2008 until 2020 and the projected share until 2040, considering the trend remains unchanged. The dotted line represents the future projection.  The northeast region, which is relatively rural compared to other regions, is expected to increase its share from around 18% in 2020 to about 21% in 2040. This is due to its potential for economic growth and higher future income.

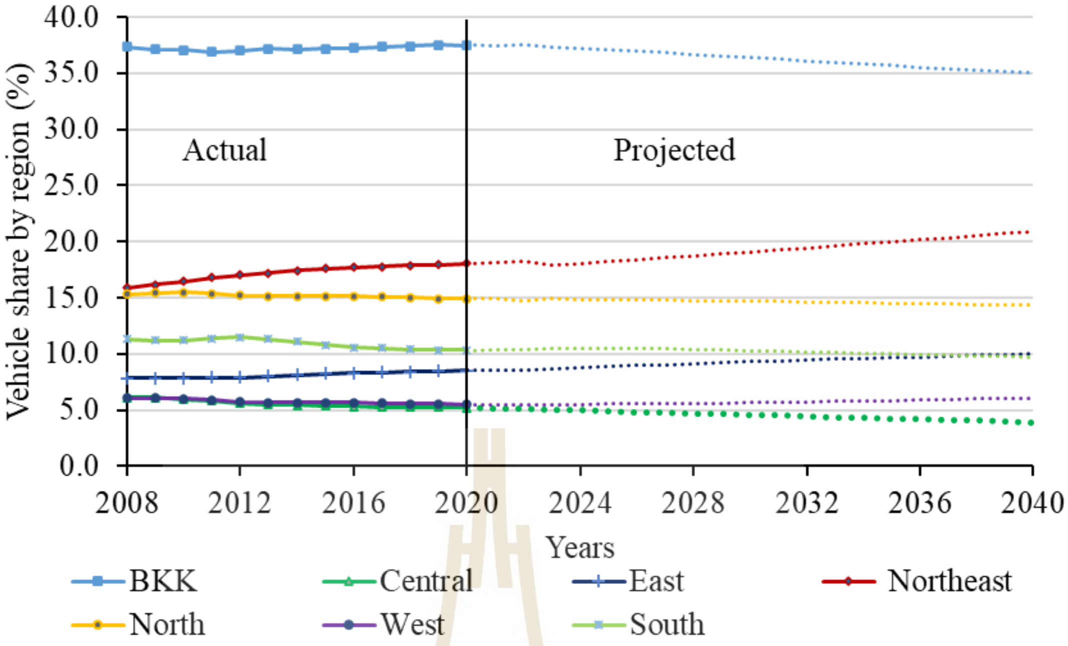


Figure 4.8 Proportion of vehicle stock by region

## 4.4 Future Energy consumption projection

### 4.4.1 Simulation setup and scenario description.

The LEAP software tool is widely used in various fields, such as integrated energy modeling, water resource management, emissions estimation from different activities, and generation expansion planning as an optimization tool. In this study, authors have employed LEAP software Version 2020.1.0.103 (64-bit) on a PC equipped with an Intel(R) Core (TM) i5-1135G7 processor running at 2.40 GHz to implement the methodology described in Section 3.2.

This study examines vehicles, including those seating up to seven passengers, pickup trucks, taxis, and minivans. Historical vehicle stocks for each category across seven regions of Thailand were sourced from DLT. The seven regions are Bangkok, Eastern, Central, Northeastern, Northern, Western, and Southern. Initially, the total number of vehicles in the country is calculated using a vehicle ownership model and then distributed proportionally across each region based on historical trends and future potential. Two scenarios—high and low growth—are considered for projecting future vehicle ownership, as well as the business-as-usual (BAU) scenario.

The high-growth scenario assumes a real GDP growth of 5%, while the low-growth scenario assumes 3%.

Additionally, a 2% inflation rate (aligned with the Bank of Thailand's 2%-3% inflation target) is factored in for fuel costs. Additionally, two more scenarios related to the pace of EV adoption are also considered within scenarios. In an aggressive EV adoption model, it is considered that 50% of all newly registered vehicles will be EVs in 2030, and by 2035, it will be fully electric. This is the current government policy. On the other hand, a more moderate EV adoption target is also considered. In the moderate EV adoption scenario, the EV share in vehicle registration is pegged at 30% in 2030, 50% in 2035, and 100% in 2040. The specifics of these scenarios are detailed in Table 4.8.

Table 4.8 Description of scenarios

| Scenarios | Description | Notation used |
|---|---|---|
| Business as usual | Continuation of the current trend without any policy intervention | BAU |
| High growth and aggressive transition | 5% GDP growth and new EV registration target of 50% by 2030 and 100% by 2035 | GDP5A |
| High growth and Moderate transition | 5% GDP growth and new EV registration target of 30% by 2030, 50% by 2035 and 100% by 2040 | GDP5M |
| Low growth and Aggressive transition | 5% GDP growth and new EV registration target of 50% by 2030 and 100% by 2035 | GDP3A |
| Low growth and Moderate transition | 3% GDP growth and new EV registration target of 30% by 2030, 50% by 2035 and 100% by 2040 | GDP3M |

### 4.4.2 Future energy projection

In the BAU scenario, total energy consumption is estimated to reach 271 TWh by 2040. This represents a 27% increase compared to the base year energy consumption of 213 TWh, as depicted in Figure 4.9. Conversely, the GDP3A scenario projects the lowest energy demand at 184 TWh. This lower demand is attributed to fewer vehicles despite a relatively higher proportion of electric vehicles (EVs).

Energy demand across all scenarios is expected to rise initially, peaking at different points before eventually declining, except for the BAU scenario, where energy demand continues to rise. The timing of this peak is contingent on the number of internal combustion (ICE) vehicles in each scenario. Scenarios with a higher number of IC vehicles tend to peak later.

In the early years of the projections, the proportion of IC vehicles is significantly high. However, as time progresses, the share of EVs in the vehicle fleet increases, which helps to moderate the overall energy demand. By 2040, the energy demand in the GDP5A scenario is nearly the same as the base year's demand despite having the most significant number of vehicles compared to the BAU and GDP3 scenarios. This is due to EVs' increased efficiency and lower energy consumption than IC vehicles.

The projected energy consumption trends highlight the impact of different vehicle compositions on overall energy demand. In scenarios with higher GDP growth, such as the GDP5A scenario, the adoption of EVs plays a critical role in stabilizing energy consumption levels despite an increase in the total number of vehicles. With its continued reliance on IC vehicles, the BAU scenario shows a steady increase in energy demand without a subsequent decrease.

These results underscore the importance of transitioning to EVs to manage and potentially reduce future energy consumption. The varying peak times and energy demands across scenarios demonstrate the significant influence of vehicle type and composition on energy consumption.

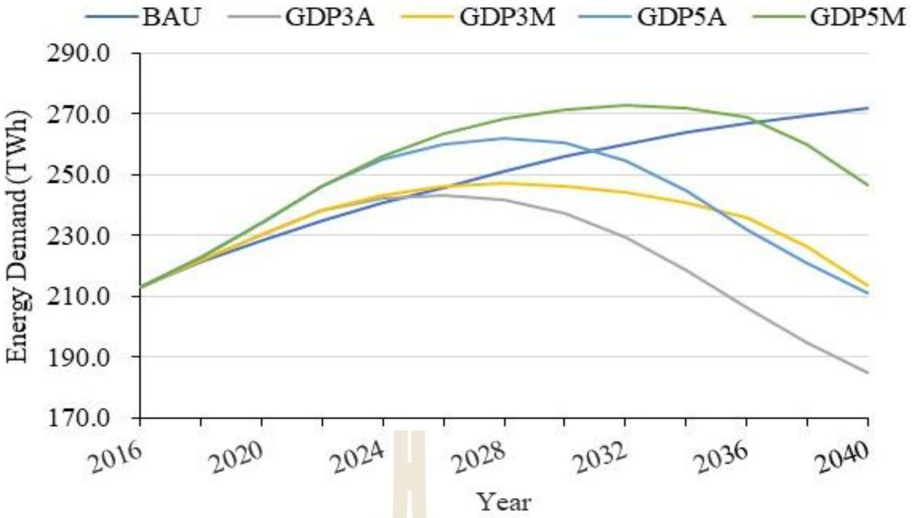


Figure 4.9 Annual energy demand by scenarios

Fuel composition is a crucial aspect of this simulation. Figures 4.10 to 14 illustrate the percentage share of each fuel type in the final energy demand. Despite the increasing number of newly registered electric vehicles (EVs), internal combustion (ICE) vehicles will remain dominant for a considerable time. Even in the most aggressive EV transition scenario (GDP5A), fossil fuels will account for more than 70% of the energy demand in 2040.

In the BAU scenario, electricity will meet less than 3% of energy demand in 2040. The share of electricity in the total energy mix for scenarios GDP3M, GDP5M, GDP3A, and GDP5A is projected to be 16.4%, 17.6%, 27.1%, and 29.4%, respectively. Diesel's share will significantly decrease in the later years due to EVs' much higher fuel economy than diesel engines. Gasoline will experience a less dramatic decline in share compared to diesel. This is because some vehicles will be hybrids that primarily use gasoline. Additionally, LPG and CNG are expected to see a marginal upward trend in almost all scenarios. This analysis underscores the ongoing reliance on fossil fuels despite the growth in EV adoption.

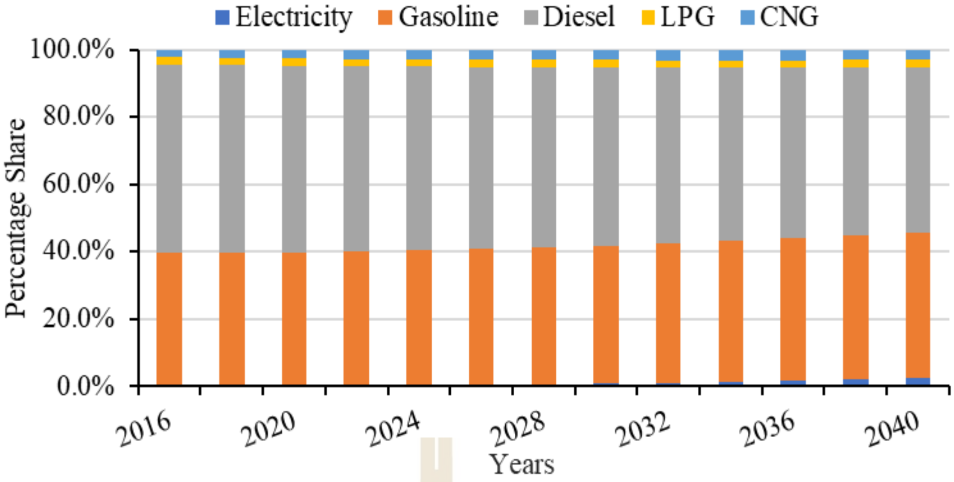


Figure 4.10 Fuel composition in BAU scenario

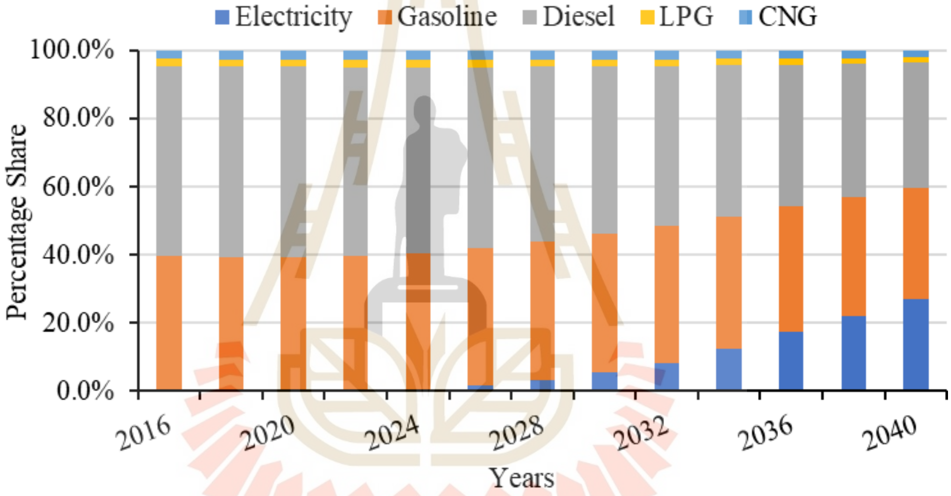


Figure 4.11 Fuel composition in GDP3A scenario

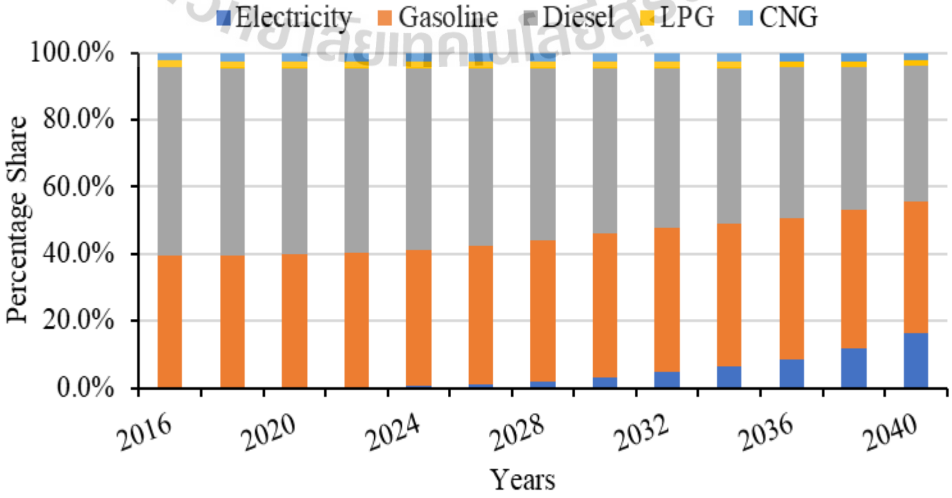


Figure 4.12 Fuel composition in GDP3M scenario

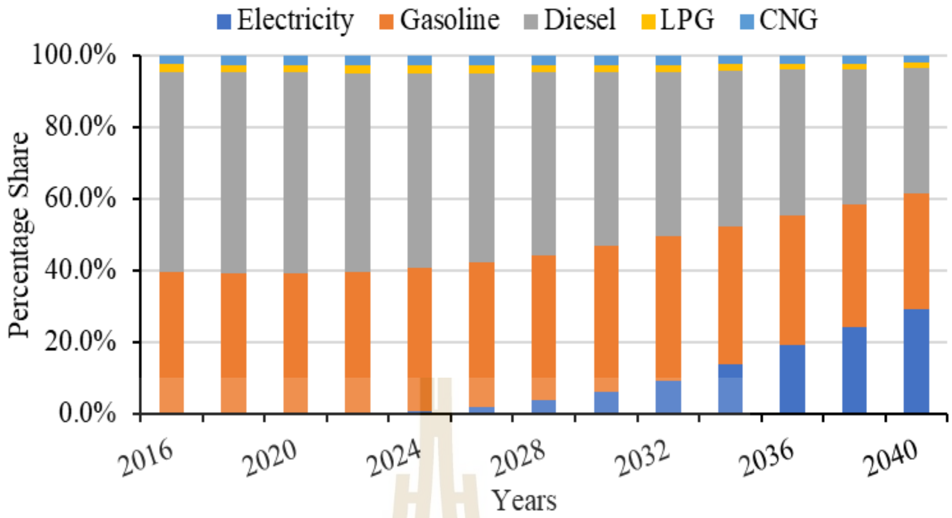


Figure 4.13 Fuel composition in GDP5A scenario

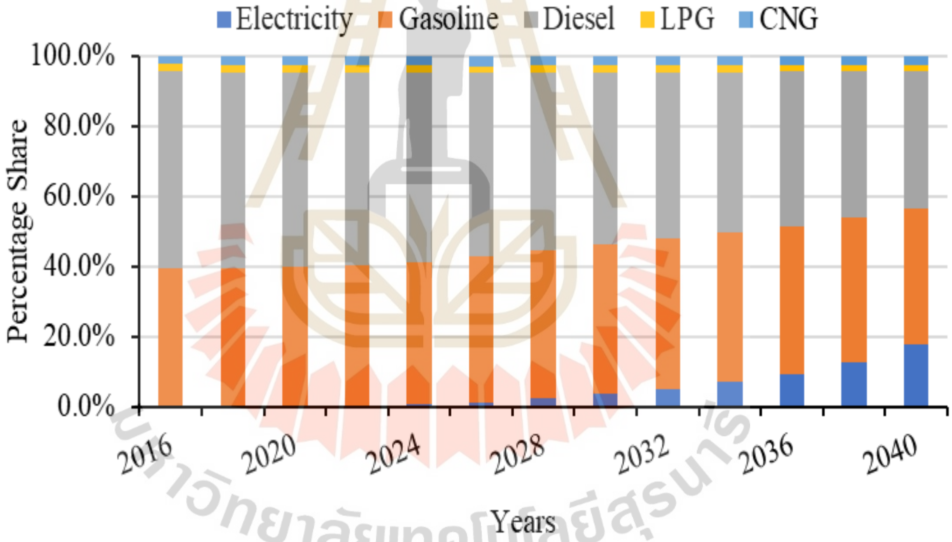


Figure 4.14 Fuel composition in GDP5M scenario

### 4.4.3 Vehicle kilometer traveled (VKT) and model validation

The model can be validated by comparing the VKT traveled calculated using the model with the official VKT projection made by the Ministry of Transportation. Figure 4.15 presents the VKT forecast made by the model. Since the number of vehicles in GDP5A and GDPM are the same. The same phenomenon is evident in the GDP3A and GDP3M scenarios. The model predicts 171 billion vehicle kilometers to be traveled in 2016 and will reach 291 billion (70% growth) in the high growth (GDP5) scenario in 2040; on the other hand, in the low growth scenario, the growth will be about 43.8% during the same period. In the case of BAU, it assumes constant vehicle registration growth and is very close to a low growth scenario. Initially, VKT in GDP3 is marginally higher than BAU, but in later years, BAU will have more VKT than GDP3. This is because of slightly lower vehicle registration in the GDP3 scenario than BAU. Transportation statistics 2018 published in 2020 by the Ministry of Transport Thailand (Ministry of Transportation Thailand, 2020) show the accumulated VKT of cars, taxis, and pickup trucks (LDV) in 2016, 2017, and 2018 is 175.4, 182.2 and 183.4 billion km respectively.

Similarly, the model predicts 171.6, 175.8, and 179.6 billion km in the BAU scenario. Since the vehicle registration number is very similar in all scenarios for those three years, VKT is approximately equal, too. Even though the latest figures are unavailable, a comparison can be made with those three-year data. The MAPE for those three years is 2.58%, suggesting the model is reasonably accurate to approximate various parameters in the future.

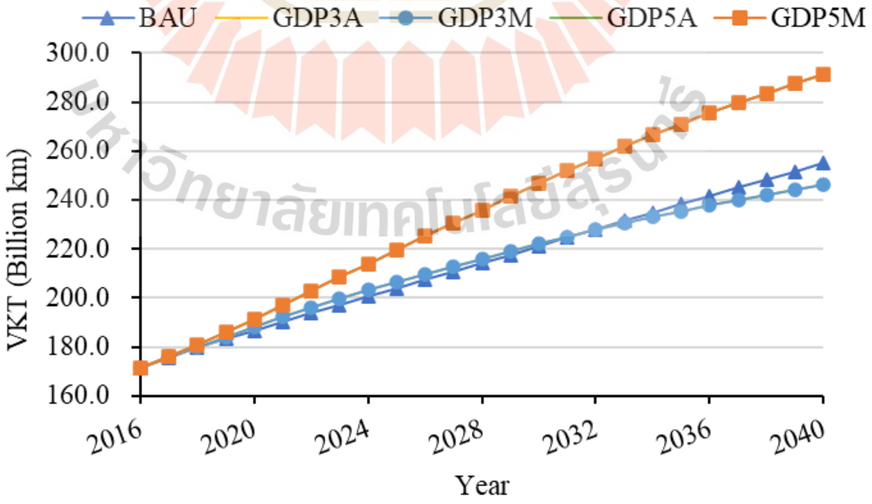


Figure 4.15 VKT projection

### 4.4.4 Electrical energy demand

Table 4.9 provides detailed projections of energy demand growth (in TWh) from 2018 to 2040 under five scenarios: BAU, GDP3A, GDP3M, GDP5A, and GDP5M. Each scenario reflects different assumptions regarding economic growth and adoption rates of electric vehicles (EVs).

In the BAU scenario, characterized by minimal changes in technology and policy, energy demand gradually increases from 0.0 TWh in 2018 to 6.7 TWh by 2040, representing a steady but modest growth trajectory. Contrastingly, under the GDP3A scenario, which assumes moderate economic growth and higher EV adoption rates, energy demand experiences a substantial surge, reaching 50.0 TWh by 2040. This signifies a significant acceleration compared to BAU, with an increase of 43.3 TWh over the projection period.

Moderate economic growth and moderate EV adoption, as depicted in the GDP3M scenario, lead to a more pronounced rise in energy demand, reaching 35.0 TWh by 2040. Although this scenario still exhibits notable growth compared to BAU, it falls short of the rapid expansion seen in GDP3A, indicating the significant influence of EV adoption rates on energy consumption patterns. The increase from 0.3 TWh in 2022 to 35.0 TWh in 2040 highlights this steady growth.

In contrast, the GDP5A scenario, characterized by high economic growth and aggressive EV adoption, forecasts the highest energy demand, soaring to 62.1 TWh by 2040. This represents a substantial increase compared to BAU and GDP3A scenarios, with the highest growth rate observed between 2026 and 2040. The notable acceleration, particularly in the later years of the projection, underscores the combined impact of rapid economic expansion and widespread EV adoption on energy demand.

Combining high economic growth with moderate EV adoption, the GDP5M scenario projects energy demand to rise to 43.5 TWh by 2040. While this growth is lower than GDP5A, it still reflects a significant increase compared to BAU and GDP3M, emphasizing the influence of higher vehicle numbers.

Comparative analysis reveals that scenarios with higher EV adoption rates (GDP3A, GDP5A) exhibit much steeper growth trajectories than those with moderate adoption rates (GDP3M, GDP5M), underscoring the pivotal role of EV adoption in shaping future energy demands. Moreover, the stark contrast between BAU and the more ambitious scenarios highlights the transformative potential of proactive policy measures and technological advancements in mitigating future energy challenges. Strategic planning and targeted interventions are thus essential for effectively managing and optimizing future energy consumption patterns in alignment with sustainability goals and economic development objectives.

This data is crucial during power system expansion planning. Apart from the actual energy demand, the annual growth rate is also essential. During the early years of the fuel transition, the annual growth is consistently higher. However, this may not be an issue for the power system as the growth comes from a low base, and actual demand is incremental at its best. The concern will arise when the previous year's demand is relatively high, and the growth rate is still significantly high. After 2028, demand in every scenario except BAU starts to rise sharply. The growth rate in GDP3M and GDP5M in 2028 is around 26% and 27%, gradually decreasing to about 14% in 2040. Similarly, the annual electricity demand rate in 2028 and 2040 in GDP3A and GDP5A is 32.6%, 33.6%, and 6.9%, 7.1% respectively. Power generation and transmission infrastructure should be planned accordingly to accommodate additional demand.

Table 4.9 Electricity demand by year (TWh)

| Scenario | 2016 | 2020 | 2024 | 2028 | 2032 | 2036 | 2037 | 2040 |
|---|---|---|---|---|---|---|---|---|
| BAU | 0.0 | 0.2 | 0.6 | 1.4 | 2.7 | 4.5 | 5.0 | 6.7 |
| GDP3A | 0.0 | 0.2 | 1.7 | 8.1 | 19.1 | 35.9 | 39.7 | 50.0 |
| GDP3M | 0.0 | 0.2 | 1.2 | 5.1 | 11.3 | 20.0 | 23.2 | 35.0 |
| GDP5A | 0.0 | 0.2 | 2.0 | 9.7 | 23.4 | 44.3 | 49.2 | 62.1 |
| GDP5M | 0.0 | 0.2 | 1.4 | 6.1 | 13.8 | 24.7 | 28.7 | 43.5 |

### 4.4.5 GHG emissions projection

In the realm of emission estimation, the consideration of four primary pollutants—carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM10)—is pivotal for understanding environmental impacts. These pollutants, mainly emitted from various industrial activities and vehicular emissions, pose significant challenges to air quality and public health.

Figure 4.16 - 4.19 offers a detailed insight into the CO2, CO, NOx, and PM10 emissions estimations, providing a comparative analysis across different scenarios. Notably, in the base year, CO2 emissions are recorded at a substantial 45 billion kg. Projections suggest a promising decrease in emissions across most scenarios, underscoring efforts toward environmental sustainability. However, the Business As Usual (BAU) scenario presents a marginal increase of 1 billion kg, signaling potential challenges in mitigating emissions without robust intervention.

The disparity in emissions among scenarios GDP5A, GDP5M, and BAU sheds light on the complex interplay of EV transition and environmental conservation. While GDP5A and GDP5M exhibit higher emissions initially due to a prevalence of internal combustion (ICE) vehicles, the gradual adoption of Electric Vehicles (EVs) leads to a notable decline in emissions over time. This underscores the importance of transitioning towards cleaner energy sources and incentivizing sustainable transportation alternatives.

However, it is imperative to acknowledge the limitations of these estimations, particularly in the absence of further policy interventions. The assumption of stagnant emission standards overlooks the potential impact of stringent regulatory measures. Implementing more robust emission standards could unlock further reductions in emissions, offering a pathway towards achieving environmental targets.

Analyzing CO, NOx, and PM10 emissions unveils intriguing patterns, notably the sharp decline in a particular year attributed to the retirement of vehicles operating under previous emission standards. This phenomenon, occurring precisely 20 years after the promulgation of new standards, highlights the effectiveness of regulatory frameworks in driving environmental progress.

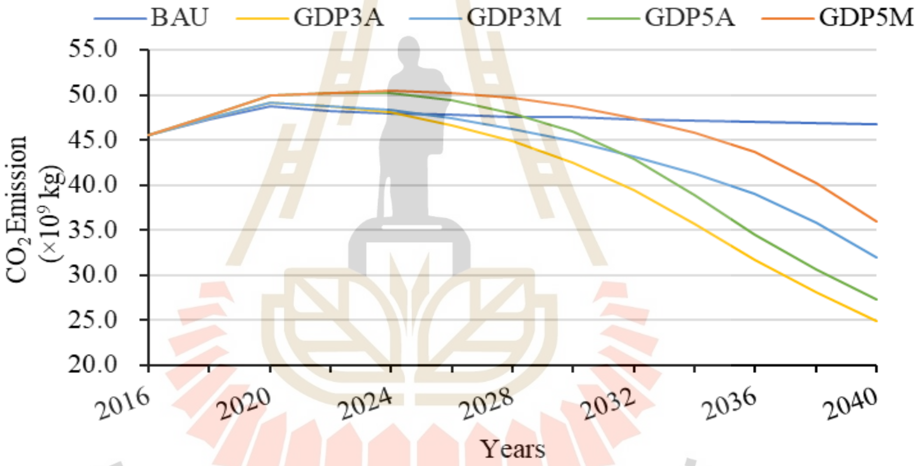


Figure 4.16 Annual $CO_2$ emission by scenario

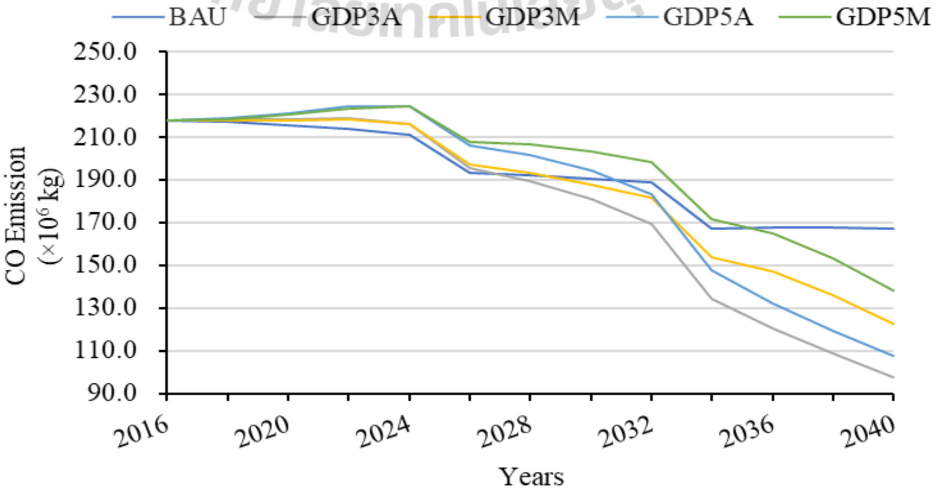


Figure 4.17 Annual CO emission by Scenario

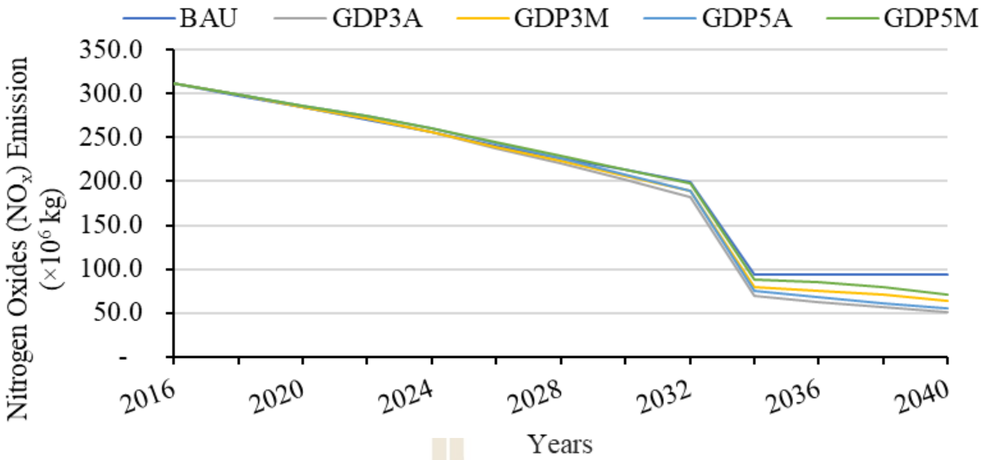


Figure 4.18 Annual $NO_x$ emission by scenario

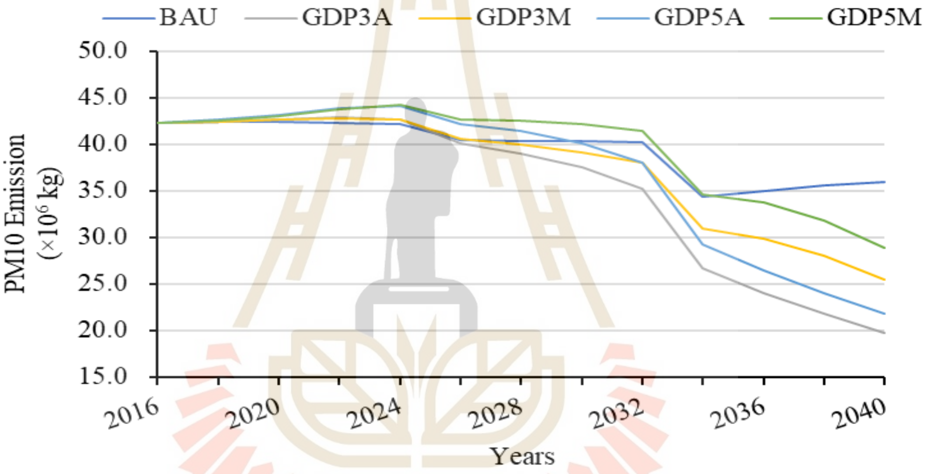


Figure 4.19 Annual PM10 emission by scenario

## 4.5 Charging load determination

Charging load depends on three significant variables: charging rates, charging time, and the battery's State of Charge (SOC). Each of these variables plays a crucial role in determining the overall charging load on the electrical grid. The capacity of the charger defines the charging rate. This means that different chargers, with varying power outputs, can deliver electricity to the battery at different speeds. High-capacity chargers can recharge batteries more quickly, thereby increasing the charging rate. Charging time depends mainly on personal behavior. This includes when and how long individuals choose to charge their vehicles. Factors such as daily schedules, driving habits, and availability of charging stations influence these decisions. Some drivers charge their vehicles overnight, while others do so during the day. The distance influences the SOC of the battery traveled and the vehicle's mileage during discharging. When a vehicle has traveled a long distance, its SOC will be lower, necessitating a longer charging time to replenish the battery.

Additionally, the charging rate affects how quickly the SOC increases during recharging. All these parameters are probabilistic, meaning they vary and can be described by statistical distributions. The number of vehicles needing a charge at any given time and their traveled distances are random variables. However, studies have shown that these variables follow specific probabilistic distributions, allowing for better prediction and modeling. Probabilistic distributions of these variables are explained in section 3.5.

The BYD ATTO 3 is considered the reference vehicle for simulation purposes. This is because it is Thailand's most widely used electric vehicle (EV), making it a representative model for studying charging behaviors. Additionally, the BYD ATTO 3 specifications are not significantly different from other EVs, ensuring that the simulation results are broadly applicable. The specification of BYD ATTO 3 is given in Table 4.10.

The parameters of daily driving distance, starting time of charge, and other relevant data used in Monte Carlo simulation are tabulated in Table 4.11. The starting time of charge follows the normal distribution, whereas the driving distance follows the log's normal distribution. The SOC of the battery is calculated based on the vehicle's driving distance and all-electric range. Distribution parameters are taken from (Adianto et al., 2022) since the driving condition of the ASEAN region is assumed to be similar.

Table 4.10 Battery Specification of BYD ATTO 3

| Parameters | Value |
|---|---|
| Nominal battery capacity | 62kWh |
| Usable battery capacity | 60.5 kWh |
| Range (City/highway mild weather) | 330 km |
| Home charging port | Type 2 |
| Home Charging Power | 11 kW AC |
| Home charging duration | 6.5 Hr |
| Fast charging port | CCS |
| Fast charging power | 73kW DC (10% to 80%) |
| Time to reach 80% SOC | 37 minutes |
| Equivalent fuel efficiency | 2.1 lge/100km |

Table 4.11 Monte Carlo simulation environment

| parameters | Parameter values | remarks |
|---|---|---|
| Starting time of charging | N (18,3) (normal distribution) | Slow home charging |
| | N (9,0.9) (normal distribution) | Slow office charging |
| | Uniform distribution | Fast charging |
| Driving distance | LogN (3.47,0.92) log-normal distribution | Log normal variable |
| Max. iteration | 10000 | |
| Charge efficiency | 90% | |
| Tolerance | 1e-4 | |

### 4.5.1 Monte Carlo simulation Effect of charging mode on load curve

If home charging is employed, it is reasonable to assume that most vehicles will be plugged in during the evening and left to charge throughout the night. This results in a relatively low power demand over an extended period. However, an exceptional peak demand might occur if many vehicles are connected to the grid simultaneously.

In contrast, vehicles will likely be taken to charging stations during the daytime if fast charging is preferred. This scenario creates a higher power demand over shorter durations, which can contribute to peak load times, potentially stressing the electrical grid. However, fast charging stations could operate around the clock, catering to vehicles needing a quick charge at any time, thus spreading out the demand more evenly and smoothing out any peaks. A third charging scheme involves plugging in vehicles at their destination, such as offices, parking lots, or other locations where vehicles are parked for extended periods during the day. Since many personal vehicles, like those considered in this study, are primarily used for commuting, this charging method could shift some of the demand to daytime hours. This could balance the load by utilizing electricity when home demand is typically lower.

However, destination charging faces several operational challenges that might limit its widespread adoption. One major issue is the lack of infrastructure, such as insufficient charging ports and the need for substantial investment to install them. Additionally, varying electricity tariffs, space constraints in urban areas, and the need for efficient management of charging spots further complicate the feasibility of this scheme.

While destination charging presents an attractive solution by distributing the charging load evenly throughout the day, these challenges make it less preferable to home or fast charging options. Addressing these infrastructural and logistical issues would be essential to making destination charging a viable alternative.

All three charging schemes are considered in this study to assess their effect on the daily load curve. However, an assumption is made regarding the destination charging. It is assumed that only 5% of total vehicles will opt for this charging mode, and the rest will choose the other two. The different combinations of these three charging modes in varying proportions result in significantly different load curves.

A demonstration of 10000 vehicle charging is presented in this study, which can be scaled up to generate charging profiles of any more vehicles. Figure 4.20

and Figure 4.21 present the sampling data of the starting time of charge in the home charging scenario and the daily travel distance of 10000 vehicles, respectively.

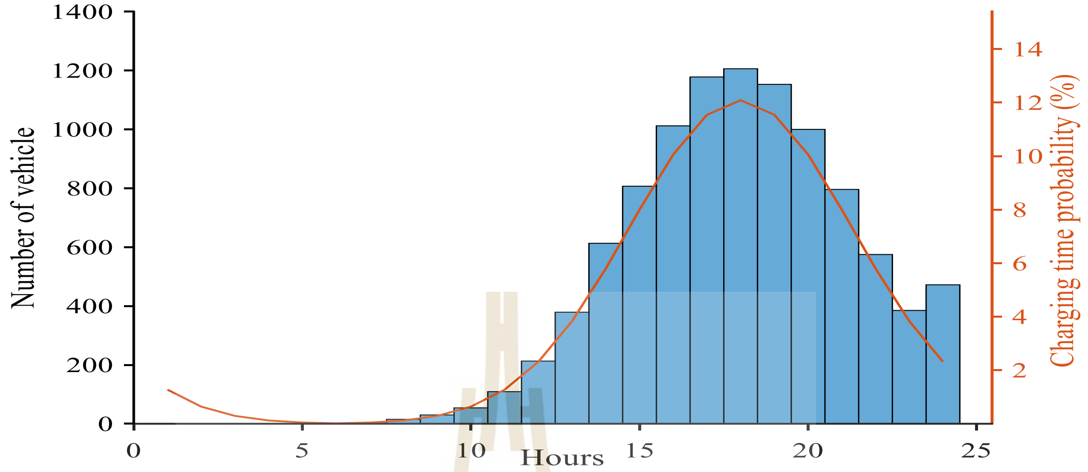


Figure 20 Sampling of starting time of charge for home charging

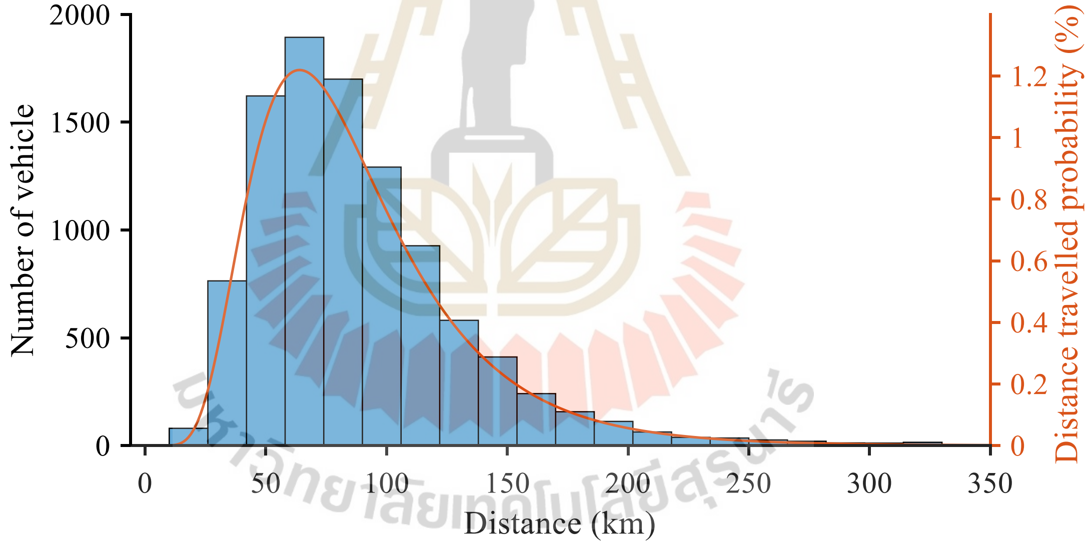


Figure 4.21 Sampling of daily travel distance

Different combinations of charging modes will result in significantly different charging profiles. Such a combination of charging can be formed by assigning a specific number of vehicles to a specific charging mode but using the probabilistic approach to decide the starting time of charging. Figure 4.22 depicts such variation of 10000 EVs. H85P10 in Figure 4.21 means 85% of vehicles opted for home charging mode, 10 % chose public fast charging, and the rest were charged at parking spaces.

If 90 percent of vehicles opted for a public fast charging station, the peak power demand would be about 7.4 MW. Conversely, if only 10 percent of vehicles chose the public fast charging option, the peak power demand would rise to approximately 16.1 MW. It is to be noted that the demand in the 10% home charging scenario starts to peak after 5 PM, after office hours, and peaks around 9 PM. Whereas in 90% of fast charging cases, the peak occurs around 10 AM, sometime after the start of office hours. In the home charging case, all demand accumulates quickly, but fast charging distributes such demand throughout the day.

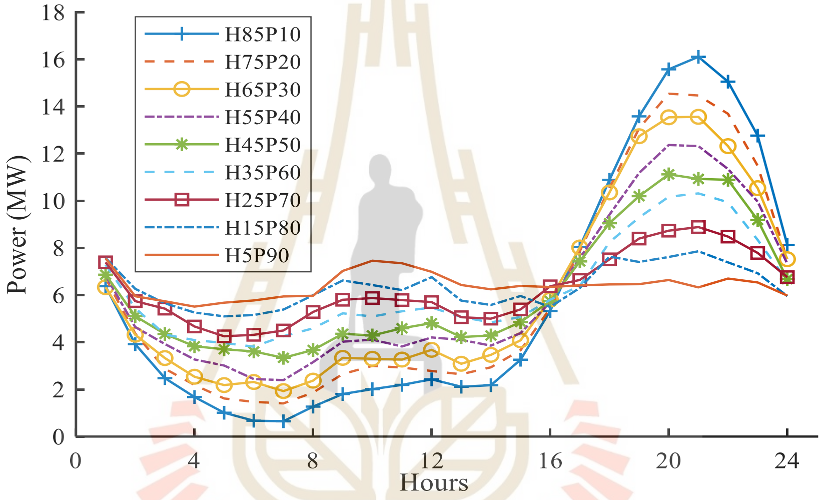


**Figure 4.22 Variation in daily load curve of 10000 vehicles according to charging mode selected**

Given that EV technology is still in its nascent stage and future dynamics cannot be predicted with acceptable accuracy. However, public charging stations are expected to grow exponentially in the coming decade. To address this uncertainty, two extreme conditions are considered: a worst-case scenario with 85 percent home charging and a best-case scenario with 90 percent public charging station usage.

This significant difference in peak power demand underscores the importance of strategic planning in developing charging infrastructure. In the worst-case scenario, with 85 percent of vehicles charging at home, the grid will experience higher stress during the evening and nighttime, as many vehicles are plugged in simultaneously. This scenario demands substantial investments in grid reinforcement and smart charging solutions to manage the increased load effectively.

In the best-case scenario, with 90 percent of vehicles using public charging stations, the peak demand is considerably lower. This distribution allows for more efficient grid utilization, mainly if charging can be managed dynamically to balance daily loads. Public charging stations with high-speed chargers can cater to vehicles during off-peak hours, reducing the overall strain on the electrical infrastructure.

### 4.5.2 Additional Peak Demand

As discussed in the previous section, peak demand and load curves vary dramatically according to the charging schemes. It is complicated to project and optimize the best combination of charging schemes for a long time. Since battery capacity and driving range increase yearly, Faster and more efficient charging technologies are also developing rapidly. In this context, projecting the most optimal demand is complicated and unnecessary. The most important aspect is to determine and prepare for the worst- and best-case scenario. Taking a cue from Figure 4.21, peak load is predicted for two extremes. The best-case scenario is when 90% of EVs opt for fast charging mode, and the worst-case scenario would be 85% home charging. Table 4.12 presents the expected peak demand in the future due to the EV transition in BAU, GDP3A, GDP3M, GDP5A, and GDP5M.

The demand in 2020 across all scenarios is nearly identical due to the total number of vehicles being relatively the same. However, peak demand will increase significantly in all scenarios, as shown in Table 4.12. By 2040, an extra load of more than 21,000 MW will occur in the GDP5A scenario if home charging becomes dominant. In contrast, the demand can be limited to approximately 9348 MW with the extensive use of public fast charging stations. Even in the BAU scenario, 2533MW of additional load will be required in home charging mode, but demand can be restricted below 1108MW simply by employing a fast-charging scheme.

Table 4.12 Additional peak demand estimation based on the selection of charging scheme.

| Scenario | Worst case, additional peak demand (MW) | | | | | Best case, additional peak demand (MW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **2020** | **2025** | **2030** | **2035** | **2040** | **2020** | **2025** | **2030** | **2035** | **2040** |
| **BAU** | 57 | 266 | 721 | 1468 | 2533 | 25 | 116 | 315 | 642 | 1108 |
| **GDP3A** | 59 | 768 | 3742 | 9967 | 17258 | 25 | 336 | 1637 | 4360 | 7550 |
| **GDP3M** | 59 | 535 | 2329 | 5560 | 11613 | 25 | 234 | 1018 | 2432 | 5081 |
| **GDP5A** | 62 | 897 | 4537 | 12265 | 21368 | 27 | 392 | 1985 | 5365 | 9348 |
| **GDP5M** | 62 | 621 | 2817 | 6831 | 14387 | 27 | 271 | 1232 | 2988 | 6294 |

The home charging scheme presents a challenge for system operators and utility providers. The sharp increase in peak demand under the home charging scenario indicates that the current infrastructure would struggle to cope without significant upgrades. On the other hand, expanding the fast-charging infrastructure can help manage and mitigate this demand, ensuring a more stable and balanced load on the grid.

The development of fast-charging infrastructure is essential for realizing the vision of an all-electric vehicle fleet. Various strategies could also support this transition by reducing the reliance on home charging. These include advancements in charging and battery technology, battery swapping schemes, vehicle-to-grid technology, and tariff structures based on time-of-use and real-time pricing. These measures could help discourage excessive home charging, distributing the load evenly across different times and locations.

### 4.5.3 Total power demand and Planned generation capacity

The primary goal of this study is to align the increased energy and peak power demand resulting from integrating additional electric vehicle (EV) loads with the current energy development plan. The existing power development strategy is the

Power Development Plan 2018, revision 1 (PDP2018r1), which outlines the power sector development from 2018 to 2037. Despite the study's calculations extending energy and peak power demand projections up to 2040 in a previous section, Table 4.13 only presents data up to 2037. This limitation is due to the scope of PDP2018r1, which only forecasts up to 2037. This alignment is critical as it ensures that the integration of EVs does not disrupt the planned development and that the infrastructure can support the anticipated demand within the forecast period. The reconciliation process involves a thorough analysis of the projected energy demands and peak power requirements against the backdrop of the PDP2018r1. The widespread perception that the lack of a comprehensive public fast-charging infrastructure is a significant barrier to higher EV adoption in Thailand indicates the minimal likelihood of excessive coordinated home charging. This assumption is based on the expectation that many EVs will be charged at fast charging stations rather than at home. Consequently, the worst-case scenario of an overwhelming surge in home charging demand may not materialize. In this context, the demand projected in best-case scenarios, where EVs are primarily charged at public fast charging stations, can likely be met with a reduced reserve margin. However, even under the most aggressive EV adoption scenario, GDP5A, where electricity accounts for 27% of total energy demand by 2037, the demand will continue to rise steadily in subsequent years. This trend suggests that electricity demand will increase sharply, even in the best-case scenarios, potentially outstripping the planned installed capacity. Thus, despite the projected manageable demand in best-case scenarios, the planned installed capacity under PDP2018r1 may not meet the rising electricity needs driven by an aggressive EV transition. In conclusion, while the PDP2018r1 provides a framework for power sector development, it may fall short of adequately supplying the increased demand resulting from the government's ambitious EV adoption targets. This underscores the necessity for revisiting and potentially revising the power development plan to ensure it can accommodate the projected growth in electricity demand.

Table 4.13 Future EV demand and PDP2018r1 projections (MW)

| Year | Peak demand forecasts | | Scenarios | | | | |
|---|---|---|---|---|---|---|---|
| | | | BAU | GDP3A | GDP3M | GDP5A | GDP5M |
| 2020 | PDP Forecast | | 32732 | 32732 | 32732 | 32732 | 32732 |
| | Demand with EV | Best Case | 32757 | 32757 | 32757 | 32759 | 32759 |
| | | Worst case | 32789 | 32791 | 32791 | 32794 | 32794 |
| | Installed capacity | | 51943 | 51943 | 51943 | 51943 | 51943 |
| 2025 | PDP Forecast | | 38780 | 38780 | 38780 | 38780 | 38780 |
| | Demand with EV | Best Case | 38896 | 39116 | 39014 | 39172 | 39051 |
| | | Worst case | 39046 | 39548 | 39315 | 39677 | 39401 |
| | Installed capacity | | 55845 | 55845 | 55845 | 55845 | 55845 |
| 2030 | PDP Forecast | | 44781 | 44781 | 44781 | 44781 | 44781 |
| | Demand with EV | Best Case | 45096 | 46418 | 45799 | 46766 | 46013 |
| | | Worst case | 45502 | 48523 | 47110 | 49318 | 47598 |
| | Installed capacity | | 62868 | 62868 | 62868 | 62868 | 62868 |

Table 4.13 Future EV demand and PDP2018r1 projections (MW) (continued)

| Year | Peak demand forecasts | | Scenarios | | | | |
|---|---|---|---|---|---|---|---|
| | | | BAU | GDP3A | GDP3M | GDP5A | GDP5M |
| 2035 | PDP Forecast | | 51265 | 51265 | 51265 | 51265 | 51265 |
| | Demand with EV | Best Case | 51907 | 55625 | 53697 | 56630 | 54253 |
| | | Worst case | 52733 | 61232 | 56825 | 63530 | 58096 |
| | Installed capacity | | 74005 | 74005 | 74005 | 74005 | 74005 |
| 2037 | PDP Forecast | | 53997 | 53997 | 53997 | 53997 | 53997 |
| | Demand with EV | Best Case | 54845 | 60034 | 57909 | 61220 | 58759 |
| | | Worst case | 55780 | 67870 | 62139 | 71246 | 64253 |
| | Installed capacity | | 77211 | 77211 | 77211 | 77211 | 77211 |

### 4.5.4 Peak day load profile in 2037

After determining the charging profile in different scenarios, the system load card can be generated by superimposing additional demand with the existing system load, as shown in equation 3.23. The daily load curve of peak day in 2020 is taken as a reference and is upscaled to form the peak day load profile in 2037 (peak demand is given in PDP2018r1). Maximum demand for the Thai power system occurs in April, per EGAT and PEA load profile data. Figure 4.23 presents the peak day load profile 2037 in different economic and charging scenarios. Since additional demand in the BAU scenario is insignificant enough to cause any severe impact on the system, it is not included.

It is evident that the demand is lowest in the morning and rises after 7 AM, peaking around 2P and falling. This load profile suggests substantial commercial as well as industrial demand. Since the evening and night demand is moderate, home charging is possible in some scenarios where vehicle numbers are limited, like in moderated EV transition (GDP3M and GDP5M). However, in an aggressive transition scenario (GDP5Aand GDP3A), the home charging scenario significantly alters the characteristics of the load curve and shifts peak hours from afternoon to evening. The demand for home charging in GDP3A and GDP5A might stress the power system. On the Contrary, in public fast-charging scenarios, the characteristics of the load curve remain consistent, but it adds more demand during peak hours even though the additional demand is relatively lower compared to the home charging scenario.

Studying curves in Figure 4.23, some possible options to meet additional charging demand are listed below:

I. **The most challenging option is to optimize the charging mode** (optimizing the number of EVs to be charged in the charging station and home). It is challenging to achieve as EV charging and discharging flexibility is quite limited on a large scale. **(improve load factor)**

II. **Increasing installed capacity.** Even though the demand for EVs in 2037 can be supplied in most cases, it will rise significantly beyond 2037. So, the addition of capacity is essential. **An interesting observation** from the study is that people are more interested in fast charging and consider the lack of it as a significant barrier to excessive EV adoption. Also, the peak demand occurs during the afternoon in the fast charging scenario, making perfect sense for the higher solar installation, which Thailand is heavily blessed. Since the primary objective of the EV transition is to limit GHG emissions, powering EVs with solar energy fits precisely in a large scheme of things.

## 4.6 Key findings and projections for 2037

Since the end date of PDP2018R1 is 2037, the projection of all variables is referenced to 2037, as shown in Table 4.14. The environmental and electrical energy and peak power demand performance of EV transition policy vary significantly in various scenarios. The vehicle ownership model demonstrates the effect of purchasing power and, hence, the number of vehicles. The active fleet size (max 20 years) will be around 22.5 million in GDP3 and 25.9 million in 2037, respectively. Again, considering the pace of electrification, the proportion of EVs in the total fleet will be maximum at 41.6% in GDP5A, followed by GDP3A (39.7%), GDP5M (24.7%), and GDP3M (22.6%). The EV share will be insignificant in the BAU scenario. Total energy demand is closely tied with the electrification rate, and the share of electricity in the energy mix is maximum in the GDP5A (21.7%) scenario.

The amount of carbon dioxide emission in BAU is maximum, with 47 million metric tons, but varies with the pace of fleet electrification in GDP5M scenario emission, which is only 10% lower than BAU due to the high absolute number of IC vehicles. It was found that the GDP3A scenario can curtail emissions by 36.7% compared to BAU. A similar trend is also evident in the case of PM10 emissions. Installed power generation

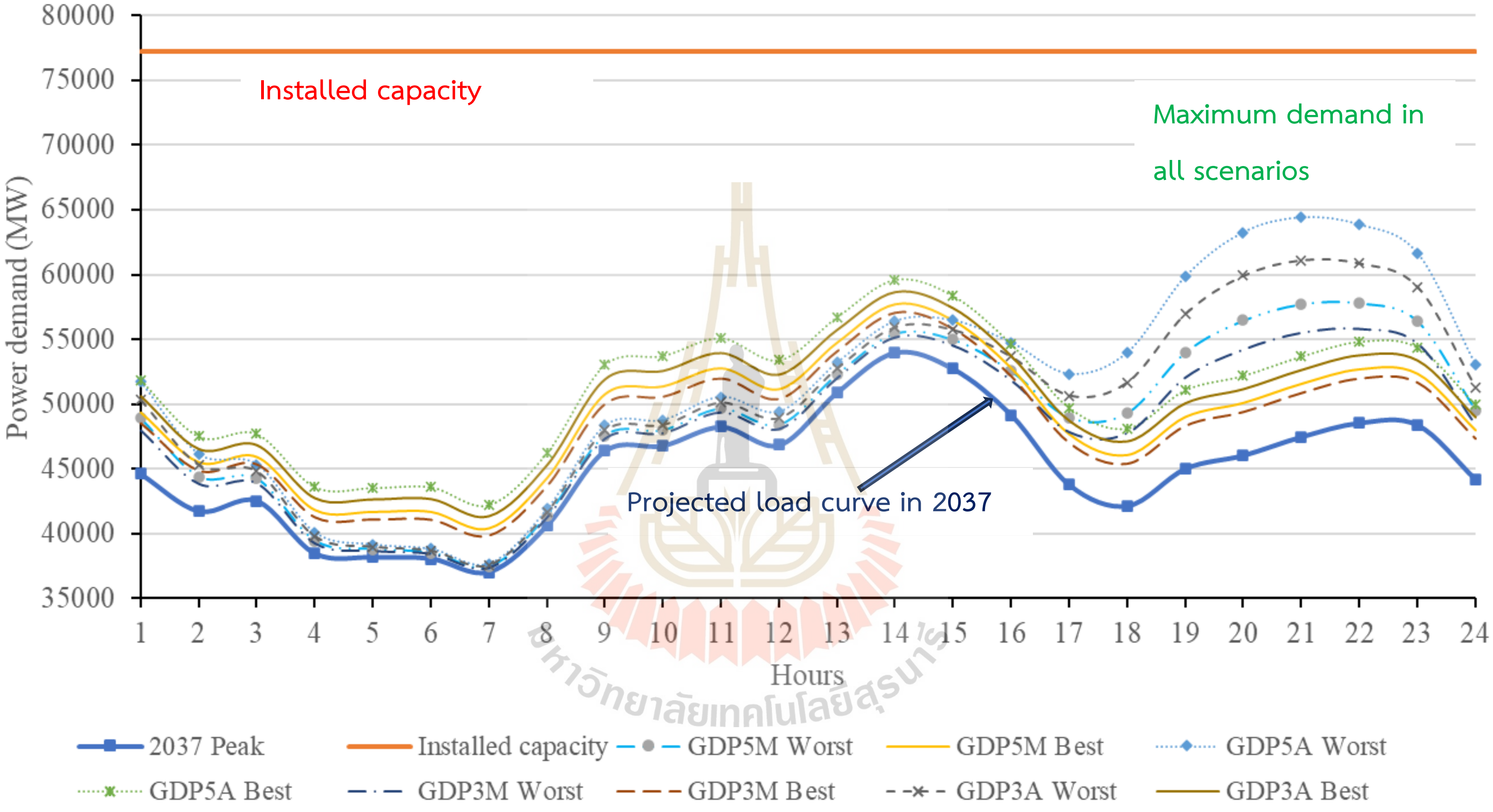


Figure 4.23 Load profile of peak day in various scenarios in 2037

Table 4.14 Summary of findings for year 2037

| scenario | Total number of vehicles (Million) | Number of EVs (Million) (% of total) | Total fleet energy demand (TWh) | Electrical energy (TWh) (% of total) | CO2 (MMt) (% change compared to BAU) | PM10 (TMt) (% change compared to BAU) | PDP2018 peak demand projection | Additional peak power demand (MW) | | Projected peak power demand (MW) | | Installed capacity (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Best | Worst | Best case | Worst | |
| BAU | 22.4 | 1.11<br>**(0.05%)** | 268.4 | 5<br>**(1.9%)** | 47<br>(-) | 35.3<br>(-) | 53997 | 848 | 1783 | 54845 | 55780 | 77211 |
| GDP3A | 22.5 | 8.67<br>**(39.7%)** | 200.3 | 39.7<br>**(19.8%)** | 29.8<br>**(-36.6%)** | 22.9<br>**(-35.1%)** | 53997 | 6037 | 13873 | 60034 | 67870 | 77211 |
| GDP3M | 22.5 | 5.1<br>**(22.6%)** | 231.5 | 23.2<br>**(10.1%)** | 37.5<br>**(-20.2%)** | 29.1<br>**(-17.6%)** | 53997 | 3912 | 8126 | 57909 | 62123 | 77211 |
| GDP5A | 25.9 | 10.78<br>**(41.6%)** | 226.3 | 49.2<br>**(21.74)** | 32.6<br>**(-30.6%)** | 25.2<br>**(-28.6%)** | 53997 | 7223 | 17246 | 61220 | 71246 | 77211 |
| GDP5M | 25.9 | 6.4<br>**(24.7%)** | 265 | 28.7<br>**(10.8%)** | 42.1<br>**(-10.5%)** | 32.9<br>**(-7.8%)** | 53997 | 4762 | 10256 | 58759 | 64253 | 77211 |

Capacity in 2037 is projected to be 77211 MW by PDP2018r1. Which also predicts a peak demand of 53997 MW. A considerable amount of power demand will arise from EV charging, and it might be difficult to accommodate such demand. Even though the peak day load curve appears to suggest the load can be served, the charging behavior of EVs considerably impacts the demand pattern. However, Figure 4.22 suggests a possibility of some amount of home charging of EVs and smoothing out the load curve as the peak demand without EVs occurs in the afternoon hours.

On the contrary, the additional demand will be for electricity generated from fossil fuels, and net emissions from electrification will not be significant. The solution appears to be charging EVs with solar energy in the daytime, which can be done by fast charging. The survey of experts also believes people highly prefer the fast charging option over home charging.

## 4.7 Power generation capacity by fuel type in 2037 (PDP2018r1)

The PDP2018r1 predicts 77211 MW of available generation capacity in 2037, of which 4000 MW will be attributed to energy conservation measures. If that is excluded, the actual generation capacity will be 73211 MW. The composition of capacity by fuel type is given in Figure 4.24. Natural gas-based plants will be the major power plant in Thailand. More than two-fifths of the generation capacity is assigned to natural gas. Coal-based plants will have a 6.6% share in capacity, meaning half of the generation capacity is reserved for fossil fuels. This also suggests that the proportion of these fuels in final energy generation will be significantly higher than renewable energy.

On the renewable front, solar power plants have a 20% capacity share, followed by hydropower and bioenergy, which have an almost equal share of about 10%. However, it is to be noted that bioenergy consists of biomass, municipal waste, and biogas, which has a high level of seasonality in the availability of fuels (like agricultural residue, rice husk, etc.)—suggesting their share in final energy generation to be limited or highly varied across the season.

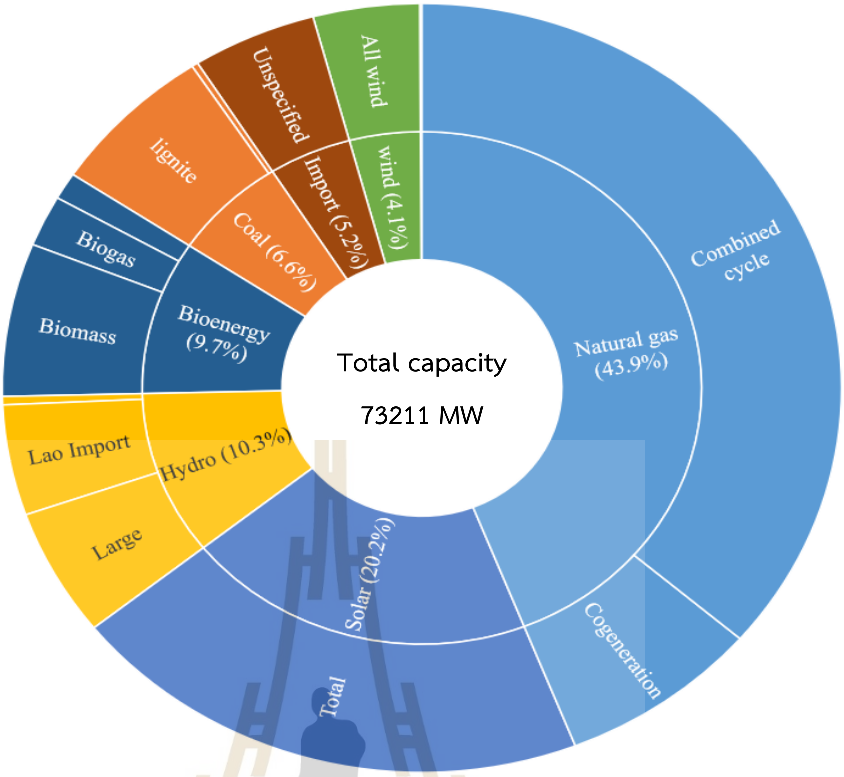


Figure 4.24 Power generation capacity by fuel type in PDP2018r1

Large Hydropower in Thailand is a multipurpose project, and its operation is tied mainly to irrigation requirements. Hence, it usually acts as a peak load provider according to the season, and the possibility of new installation is limited. Consequently, the options for extra energy generation for EV charging become limited to three types of plants: natural gas, solar, and import. Regarding the load curves in Figure 4.23, the generation scheduling and expansion must be reevaluated. A combination of solar plants and natural gas plants might provide a solution. In predominantly fast charging scenarios, the additional peak demand occurs in the afternoon, so solar will play a significant role in supplying energy. However, the amount of generation mix cannot be determined without integrated energy planning considering all sectors and resource availability. Despite that, this study acts as a basis for assessing the impact of EV transition on final energy demand, emission reduction potential, and peak demand.

## 4.8 Validation of the results

The projected vehicle numbers are calculated using this thesis's vehicle ownership model and compared with projections made by previous studies. In a high-growth scenario, the projected number of vehicles in 2040 is approximately 27 million. In contrast, a slower economic growth scenario is expected to limit this number to around 23 million. However, a previous study (Wattana & Wattana, 2022) projected a higher figure for the same year, roughly 14% above the estimate in this paper. This discrepancy could be due to the 20-year vehicle retirement period considered in our study. Another study (Saisirirat et al., 2013) estimated 19 million vehicles for 2030, which is closely aligned with a current projection of 20 million.

The Energy Efficiency Plan (EEP) 2015 has set an energy-saving target of 351 TWh for the entire transportation sector by 2036 (Uthathip et al., 2021). The most aggressive EV promotion scheme could save approximately 36 TWh (around 10%) from the LDV segment alone, underscoring the significant potential of EVs in energy efficiency programs.

It's important to note that electrical power demand accounts for less than one-third of total energy consumption, and this demand is expected to rise beyond 2040. The widespread use of home charging presents challenges for system operators and utilities, emphasizing the need for a robust fast-charging infrastructure. Strategies such as improved charging technology, battery swapping, V2G technology, time-of-use pricing, and real-time tariffs can help mitigate the issues associated with excessive home charging.

## 4.9 Chapter Summary

Chapter 4 describes the result obtained after implementing methodologies explained in Chapter 3. The major highlights of this chapter are listed below:

a. Cost-related issues are the most critical in EV purchase decisions, with investment, after-sale value, and maintenance costs being top factors.

Technical performance is essential, but policy issues and government financing, like tax incentives or cash handouts, are less significant.

b. Experts recommend improving public infrastructure and maintaining affordable electricity prices over offering subsidies. Public charging infrastructure is prioritized over private options, as it reduces peak demand by spreading usage throughout the day.

c. High EV costs can be reduced through economies of scale rather than direct subsidies, and addressing battery-related performance concerns is necessary to increase market share.

d. Vehicle ownership depends on disposable income, population density, and fuel price. In the high growth scenario (GDP5), vehicles per 1000 population will reach 384, and in the moderate growth scenario (GDP3), 344, reflecting increases of 53.6% and 37%, respectively.

e. Projected energy demand for 2040 varies across scenarios, with fossil fuels remaining dominant. Electricity demand in GDP3M, GDP5M, GDP3A, and GDP5A is 35 TWh, 50 TWh, 43.5 TWh, and 62.1 TWh, representing 16.4%, 17.6%, 27.1%, and 29.4% of total demand respectively.

f. Carbon emissions can be reduced by 17% to 45% depending on scenarios except BAU.

g. By 2040, the maximum additional demand in the worst scenario is 21,368 MW, and in the best (public fast charging) scenario, 9,348 MW.

h. If a fast-charging scheme is used on a large scale, the peak hour will fall in the afternoon, making perfect sense for powering EVs with solar energy without requiring expensive storage infrastructures.

i. The PDP2028r1 might be able to meet additional demand caused by EVs if a fast-charging scheme is used predominantly, but if the EV transition is to go according to the government plan, PDP2018r1 requires further revision. It appears that natural gas and solar will power EVs in the future. However, the proportion and amount of each generation source cannot be determined without integrated system optimization considering resource availability and demand.

# CHAPTER V

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

The electrification of the transport fleet, driven by concerns over global warming and climate change, is an emerging global trend. Thailand is actively participating in this movement as a leading economy in the ASEAN region. The country's commitment to the 30@30 initiative, which aims to have 30% of all vehicles be electric by 2030, and its subsequent announcement of a ban on internal combustion (ICE) vehicles after 2035 necessitate a thorough examination of the pace of fuel transition and the potential implications for electrical energy and peak demand.

In light of these ambitious targets, this study develops an Electric Vehicle (EV) transition scenario model utilizing the Long-range Energy Alternatives Planning (LEAP) software. This model enables a detailed analysis of future energy demand and associated emissions under various scenarios. The study projects the energy requirements and assesses the impact on peak power demand, offering critical insights into how Thailand's power infrastructure must evolve to support this transition.

The issues and hindrances related to higher EV transition are also explored using the AHP methodology. A survey has been conducted among experts working in EV-related sectors to determine various barriers obstructing the rapid electrification of transport fleets and their relative importance.

The analysis within this study attempts to understand the broader implications of Thailand’s electrification efforts. It provides a base understanding of the potential challenges and opportunities arising from the shift to EVs, highlighting the need for robust infrastructure development, strategic planning, and policy support to ensure a smooth and sustainable transition. By modeling different scenarios, the study offers a nuanced view of how energy demand might change and what measures could be taken to mitigate any adverse impacts, thereby supporting Thailand's commitment to reducing greenhouse gas emissions and enhancing energy security.

### 5.1.1 Findings and suggestions about issues related to EV transition.

Nine issues potentially affecting large-scale EV integration in Thailand were analyzed using AHP methodology, and the findings of the AHP analysis are listed below:

I. Cost-related issues are the most critical in EV purchase decisions.
II. Technical performance is essential, but policy issues are less significant.
III. Investment and after-sale value are the top factors influencing EV purchase decisions, followed by maintenance cost.
IV. Government financing through tax incentives or direct cash handouts is deemed less critical.
V. Experts suggest improving public infrastructure and maintaining affordable electricity prices over individual subsidies.
VI. Public charging infrastructure is prioritized over private infrastructure.
VII. High EV costs can be reduced through economies of scale rather than direct subsidies.
VIII. EV performance concerns, particularly battery-related issues, need addressing to increase market share.
IX. Public charging reduces peak demand compared to home charging, spreading demand throughout the day.

### 5.1.2 Findings Future Vehicle Ownership Model

The findings of vehicle ownership model and future vehicle registration are listed below:

I. Vehicle ownership depends on disposable income, population density, and fuel price.

II. In the high growth scenario (GDP5), vehicles per 1000 population will reach 384 and 344 in the moderate growth scenario (GDP3), an increase of 53.6% and 37%, respectively.

III. Population density is almost constant between 2020 to 2040. Hence, the primary deciding factor is disposable income and inflation.

### 5.1.3 Future energy demand and energy mix

I. Energy demand will rise initially in all scenarios, peak somewhere between, and start to decrease from base year energy demand. However, demand will not peak and rise continuously in the BAU scenario.

II. The projected energy demand for 2040 in BAU, GDP3A, GDP3M, GDP5A, and GDP5M is 371TWh, 187TWh, 212 TWh, 211 TWh, and 248 TWh, respectively. The base year (2016) demand is 212 TWh.

III. Fossil fuel will supply overwhelming proportions of final energy demand even in the most aggressive EV transition scenario. The demand for electricity in scenarios GDP3M, GDP5M, GDP3A, and GDP5A in 2040 is projected to be 35 TWh, 50 TWh, 43.5 TWh, and 62.1 TWh, accounting for 16.4%, 17.6%, 27.1%, and 29.4%, of total demand respectively.

IV. However, it can be said with confidence that after 2040, the share of electricity will increase significantly as the older ICs are replaced dramatically.

V. Carbon emissions can be reduced by 17% to 45% depending on scenarios except BAU.

### 5.1.4 Findings of Peak Load Projection

I. The charging load, subsequent peak demand, and load profile depend on factors like driving distance, battery capacity, hour of charge, charging power, etc.

II. Home charging by many EVs poses a severe threat to the system as an unusually high peak will be generated quickly. On the contrary, public fast charging can mitigate such problems by distributing daily demand.

III. The maximum additional demand (GDP5A) 2040 in the worst (home charging) and best (public fast charging) scenario is 21368 MW and 9348 MW, respectively. PDP2018r1 might not be able to meet the additional demand without additional revision.

## 5.2 Contributions

The contribution of the research is listed below:

1. It provides a glance at future vehicle ownership based on the econometric parameters. This information can help formulate energy and transport policies.
2. The results also demonstrate the possible energy demand by fuel type in different scenarios and hence help demonstrate the effect of EV transition on fuel demand in the future.
3. It also presents an idea about the probable peak power demand caused by EVs. Furthermore, it successfully demonstrates the importance of fast public charging stations.
4. This research can illustrate the barrier to large-scale EV transition in Thailand through a survey. The cost of the vehicle is the most important deciding factor in the EV purchase decision.
5. The survey findings are vital for policy planners to successfully implement the EV transition policy introduced by the government of Thailand.

## 5.3 Future work

Future research efforts will focus on creating an optimal coordinated charging strategy and revising the power development plan to align with this optimized charging framework. This strategy will emphasize increased integration of renewable energy sources. This analysis aims to understand the net emission reductions achievable by promoting electric vehicles. This evaluation will be instrumental in assessing the effectiveness of the EV program in meeting climate action goals and reducing greenhouse gas emissions. Through these efforts, it can be ensured that the transition to electric vehicles contributes significantly to our environmental sustainability objectives and supports our commitment to combating climate change.

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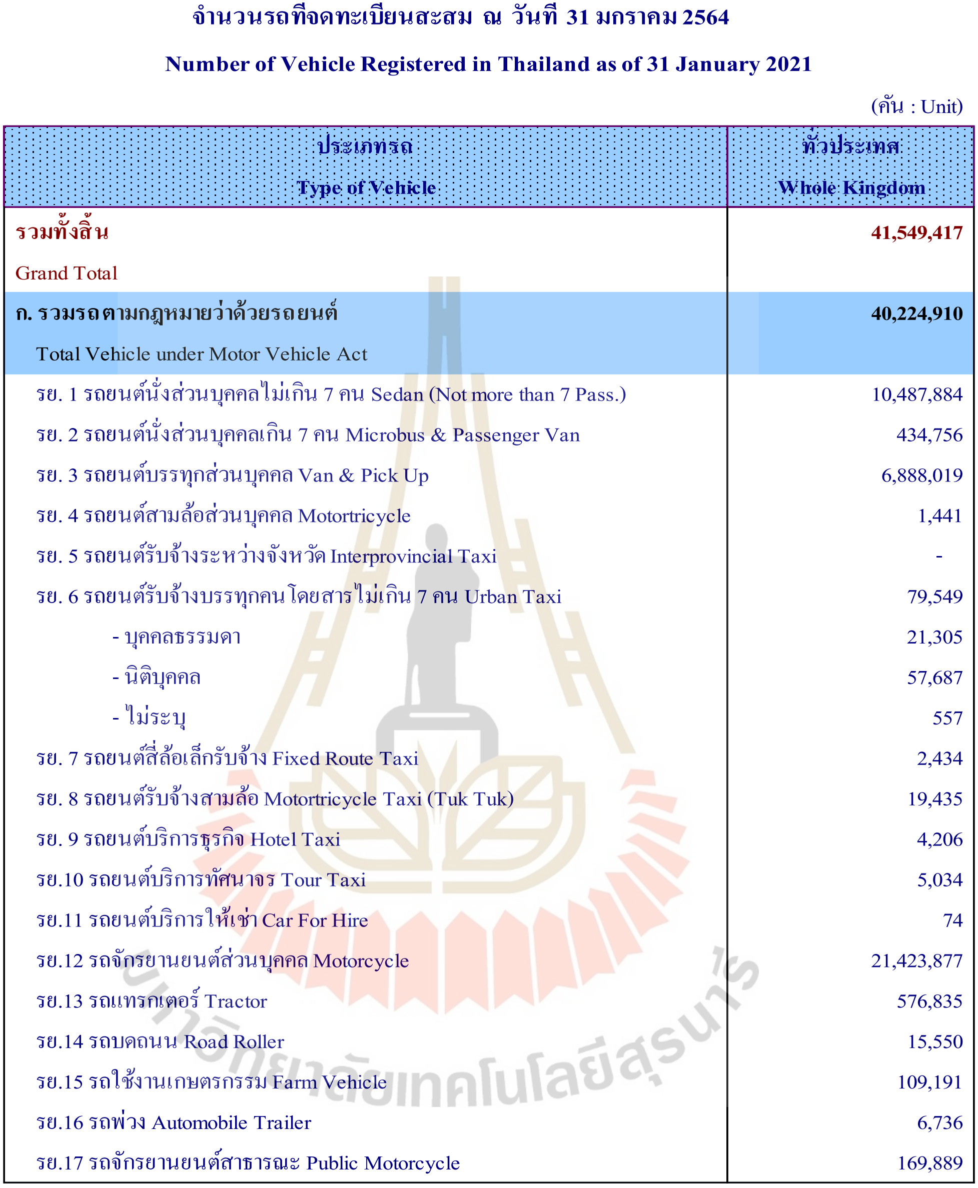
# APPENDIX

# APPENDIX A Sample of yearly vehicle registration data



**จำนวนรถที่จดทะเบียนสะสม ณ วันที่ 31 มกราคม 2564**

**Number of Vehicle Registered in Thailand as of 31 January 2021**

(คัน : Unit)

| ประเภทรถ<br>Type of Vehicle | ทั่วประเทศ<br>Whole Kingdom |
|---|---|
| **รวมทั้งสิ้น**<br>Grand Total | **41,549,417** |
| **ก. รวมรถตามกฎหมายว่าด้วยรถยนต์**<br>Total Vehicle under Motor Vehicle Act | **40,224,910** |
| รย. 1 รถยนต์นั่งส่วนบุคคลไม่เกิน 7 คน Sedan (Not more than 7 Pass.) | 10,487,884 |
| รย. 2 รถยนต์นั่งส่วนบุคคลเกิน 7 คน Microbus & Passenger Van | 434,756 |
| รย. 3 รถยนต์บรรทุกส่วนบุคคล Van & Pick Up | 6,888,019 |
| รย. 4 รถยนต์สามล้อส่วนบุคคล Motortricycle | 1,441 |
| รย. 5 รถยนต์รับจ้างระหว่างจังหวัด Interprovincial Taxi | - |
| รย. 6 รถยนต์รับจ้างบรรทุกคนโดยสารไม่เกิน 7 คน Urban Taxi | 79,549 |
| - บุคคลธรรมดา | 21,305 |
| - นิติบุคคล | 57,687 |
| - ไม่ระบุ | 557 |
| รย. 7 รถยนต์สี่ล้อเล็กรับจ้าง Fixed Route Taxi | 2,434 |
| รย. 8 รถยนต์รับจ้างสามล้อ Motortricycle Taxi (Tuk Tuk) | 19,435 |
| รย. 9 รถยนต์บริการธุรกิจ Hotel Taxi | 4,206 |
| รย.10 รถยนต์บริการทัศนาจร Tour Taxi | 5,034 |
| รย.11 รถยนต์บริการให้เช่า Car For Hire | 74 |
| รย.12 รถจักรยานยนต์ส่วนบุคคล Motorcycle | 21,423,877 |
| รย.13 รถแทรกเตอร์ Tractor | 576,835 |
| รย.14 รถบดถนน Road Roller | 15,550 |
| รย.15 รถใช้งานเกษตรกรรม Farm Vehicle | 109,191 |
| รย.16 รถพ่วง Automobile Trailer | 6,736 |
| รย.17 รถจักรยานยนต์สาธารณะ Public Motorcycle | 169,889 |

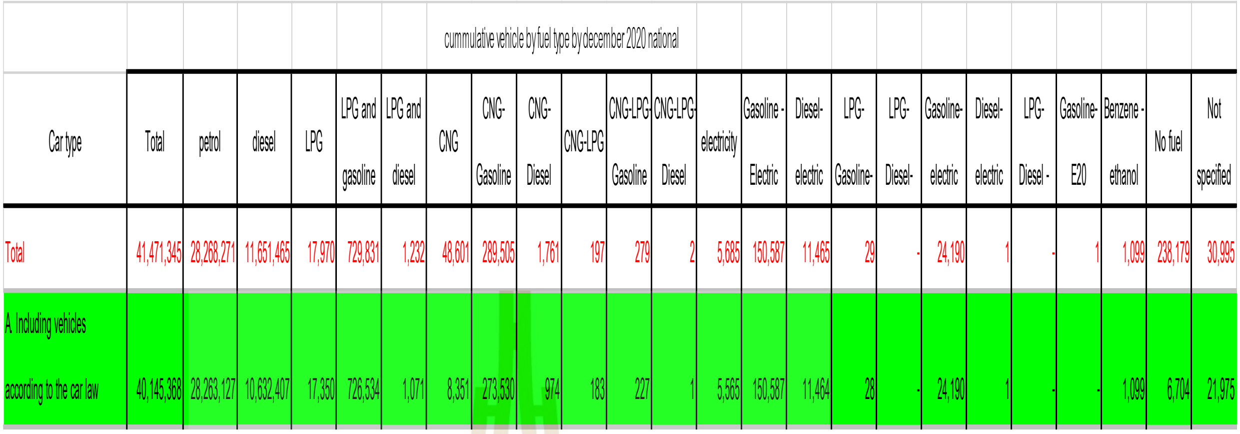
It is evident from the table that the same kind of vehicle, like taxis, are registered in different categories. All such individual categories are combined in this study to form a single type of vehicle.

# APPENDIX B Age of vehicle fleet by 2020

car age by 2020 december

| Car type | Car age | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | <1 year | 1 year | 2 years | 3 years | 4 years | 5 years | 6 years | 7 years | 8 years | 9 years | 10 years | 11 - 15 years | 16 - 20 years | > 20 years | Not specified |
| **Total** | 41,471,345 | 2,358,440 | 2,752,897 | 2,766,789 | 2,663,430 | 2,291,432 | 2,193,645 | 2,263,052 | 2,814,035 | 2,730,685 | 2,102,385 | 1,786,130 | 6,675,614 | 3,606,587 | 4,465,714 | 510 |
| **A. Including cars according to the car law** | 40,145,368 | 2,322,324 | 2,703,879 | 2,712,728 | 2,618,995 | 2,245,694 | 2,148,046 | 2,209,073 | 2,741,394 | 2,677,050 | 2,056,611 | 1,749,329 | 6,503,287 | 3,422,945 | 4,034,013 | - |
| Ror. 1 Private car for up to 7 people | 10,446,505 | 553,063 | 710,489 | 680,314 | 617,368 | 532,429 | 509,856 | 582,356 | 897,038 | 865,691 | 521,017 | 444,733 | 1,494,536 | 914,912 | 1,122,703 | - |
| RAOR. 2 passenger cars more than 7 people | 434,254 | 16,642 | 12,988 | 13,762 | 17,413 | 11,885 | 12,859 | 16,249 | 20,203 | 21,607 | 17,617 | 17,378 | 67,794 | 43,659 | 144,198 | - |
| Ror. 3 Personal trucks | 6,878,050 | 214,094 | 254,690 | 250,924 | 242,863 | 220,580 | 230,197 | 262,272 | 328,339 | 326,287 | 267,710 | 235,890 | 1,336,710 | 867,621 | 1,839,873 | - |
| RA.4 Personal three-wheeled vehicle | 1,478 | 58 | 60 | 62 | 38 | 50 | 73 | 64 | 108 | 60 | 46 | 37 | 157 | 63 | 602 | - |
| RA 5 Automobile for hire between provinces | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| RAOR. 6 Taxi trucks carrying up to 7 passengers | 80,172 | 3,233 | 7,423 | 14,400 | 7,794 | 7,470 | 8,910 | 6,774 | 10,273 | 9,368 | 428 | 194 | 1,070 | 1,359 | 1,476 | - |
| - natural person | 21,322 | 104 | 229 | 744 | 1,019 | 1,919 | 3,226 | 3,203 | 4,962 | 4,292 | 175 | 62 | 177 | 292 | 918 | - |
| - Juristic person | 58,293 | 3,129 | 7,194 | 13,655 | 6,775 | 5,549 | 5,682 | 3,571 | 5,311 | 5,076 | 253 | 132 | 864 | 750 | 352 | - |
| - Not specified | 557 | - | - | 1 | - | 2 | 2 | - | - | - | - | - | 29 | 317 | 206 | - |
| RA. 7 Small four-wheeled vehicle hire (Passengers up to 7 people) | 2,442 | - | - | - | 3 | 13 | 16 | 5 | 22 | 43 | 18 | 40 | 1,090 | 75 | 1,117 | - |
| Ror. 8 Three-wheeled vehicle | 19,459 | 118 | 50 | 39 | 168 | 351 | 57 | 75 | 41 | 14 | 20 | 12 | 1,748 | 53 | 16,713 | - |
| RA 9 Business Cars | 4,243 | 58 | 160 | 479 | 222 | 242 | 209 | 338 | 283 | 243 | 175 | 180 | 803 | 477 | 374 | - |
| RAJ 10 Cars, sightseeing services | 5,118 | 158 | 389 | 268 | 158 | 216 | 330 | 414 | 496 | 424 | 288 | 275 | 1,129 | 445 | 128 | - |
| RAJ. 11 Cars for rent | 76 | 2 | 9 | 21 | 12 | 2 | 1 | 5 | 3 | 3 | 2 | 2 | 10 | 4 | - | - |
| RAJ. 12 Motorcycles | 21,396,980 | 1,474,955 | 1,654,812 | 1,686,105 | 1,673,000 | 1,416,261 | 1,323,677 | 1,271,816 | 1,414,834 | 1,395,876 | 1,208,214 | 1,017,541 | 3,510,637 | 1,554,789 | 794,463 | - |
| RAJ 13 Tractor | 574,789 | 54,055 | 53,227 | 54,202 | 48,118 | 42,740 | 47,970 | 49,979 | 50,576 | 37,945 | 26,022 | 20,814 | 40,950 | 10,839 | 37,352 | - |
| RAJ. 14 road roller | 15,516 | 841 | 562 | 815 | 945 | 1,017 | 795 | 518 | 535 | 403 | 463 | 489 | 1,503 | 1,670 | 4,960 | - |
| RAOT 15 Agricultural vehicles | 109,076 | 394 | 665 | 705 | 884 | 1,063 | 1,511 | 1,757 | 2,543 | 3,371 | 3,196 | 3,126 | 13,011 | 9,514 | 67,336 | - |
| RAJ 16 trailer | 6,704 | 1,067 | 949 | 720 | 618 | 461 | 323 | 249 | 219 | 204 | 369 | 113 | 492 | 64 | 856 | - |
| RAJ 17 Public Motorcycles | 170,506 | 3,586 | 7,406 | 9,912 | 9,391 | 10,914 | 11,262 | 16,202 | 15,881 | 15,511 | 11,026 | 8,505 | 31,647 | 17,401 | 1,862 | - |
| **B. Including vehicles in accordance with the law governing land transport.** | 1,325,977 | 36,116 | 49,018 | 54,061 | 44,435 | 45,738 | 45,599 | 53,979 | 72,641 | 53,635 | 45,774 | 36,801 | 172,327 | 183,642 | 431,701 | 510 |
| **Including buses** | 151,547 | 3,305 | 6,672 | 6,505 | 5,991 | 6,140 | 7,322 | 6,806 | 6,769 | 6,532 | 6,777 | 5,931 | 19,458 | 17,631 | 45,657 | 51 |
| - Including route | 68,758 | 1,090 | 2,740 | 1,391 | 1,341 | 1,514 | 2,077 | 2,227 | 3,114 | 3,518 | 4,166 | 3,633 | 8,700 | 8,177 | 25,043 | 27 |
| Category 1 | 17,035 | 337 | 1,467 | 781 | 424 | 257 | 397 | 367 | 476 | 646 | 936 | 1,080 | 1,730 | 1,767 | 6,362 | 8 |
| Category 2 | 7,919 | 304 | 468 | 159 | 121 | 139 | 320 | 513 | 734 | 737 | 816 | 1,073 | 773 | 495 | 1,267 | - |
| Category 3 | 11,050 | 160 | 339 | 159 | 219 | 303 | 514 | 412 | 620 | 766 | 1,151 | 435 | 1,062 | 1,265 | 3,641 | 4 |
| Category 4 | 31,305 | 289 | 466 | 292 | 576 | 815 | 846 | 935 | 1,284 | 1,369 | 1,261 | 1,045 | 5,135 | 4,633 | 12,347 | 12 |
| International | 39 | - | - | - | 1 | - | - | - | - | - | 2 | - | - | - | 36 | - |
| Not specified | 1,410 | - | - | - | - | - | - | - | - | - | - | - | - | 17 | 1,390 | 3 |
| - including not buses | 69,055 | 1,764 | 3,351 | 4,601 | 4,104 | 4,108 | 4,799 | 4,123 | 3,193 | 2,689 | 2,217 | 1,934 | 8,274 | 6,846 | 17,030 | 22 |
| Not on a regular basis | 69,055 | 1,764 | 3,351 | 4,601 | 4,104 | 4,108 | 4,799 | 4,123 | 3,193 | 2,689 | 2,217 | 1,934 | 8,274 | 6,846 | 17,030 | 22 |
| International | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| - Personal total | 13,734 | 451 | 581 | 513 | 546 | 518 | 446 | 456 | 462 | 325 | 394 | 364 | 2,484 | 2,608 | 3,584 | 2 |
| Personal | 13,734 | 451 | 581 | 513 | 546 | 518 | 446 | 456 | 462 | 325 | 394 | 364 | 2,484 | 2,608 | 3,584 | 2 |
| International | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **Truck included** | 1,173,801 | 32,811 | 42,346 | 47,556 | 38,444 | 39,598 | 38,277 | 47,173 | 65,871 | 47,103 | 38,996 | 30,865 | 152,853 | 165,995 | 385,456 | 457 |
| - including not buses | 361,357 | 15,122 | 22,635 | 26,608 | 18,157 | 17,007 | 16,187 | 19,125 | 28,307 | 21,988 | 15,047 | 12,652 | 51,257 | 39,143 | 58,050 | 72 |
| Not on a regular basis | 361,357 | 15,122 | 22,635 | 26,608 | 18,157 | 17,007 | 16,187 | 19,125 | 28,307 | 21,988 | 15,047 | 12,652 | 51,257 | 39,143 | 58,050 | 72 |
| International | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| - Personal total | 812,444 | 17,689 | 19,711 | 20,948 | 20,287 | 22,591 | 22,090 | 28,048 | 37,564 | 25,115 | 23,949 | 18,213 | 101,596 | 126,852 | 327,406 | 385 |
| Personal | 812,444 | 17,689 | 19,711 | 20,948 | 20,287 | 22,591 | 22,090 | 28,048 | 37,564 | 25,115 | 23,949 | 18,213 | 101,596 | 126,852 | 327,406 | 385 |
| International | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **Include a small car** | 629 | - | - | - | - | - | - | - | 1 | - | 1 | 5 | 16 | 16 | 588 | 2 |

# APPENDIX C Sample of classification of vehicle by fuel type



cummulative vehicle by fuel type by december 2020 national

| Car type | Total | petrol | diesel | LPG | LPG and gasoline | LPG and diesel | CNG | CNG-Gasoline | CNG-Diesel | CNG-LPG | CNG-LPG-Gasoline | CNG-LPG-Diesel | electricity | Gasoline - Electric | Diesel-electric | LPG-Gasoline- | LPG-Diesel- | Gasoline-electric | Diesel-electric | LPG-Diesel - | Gasoline-E20 | Benzene - ethanol | No fuel | Not specified |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total | 41,471,345 | 28,268,271 | 11,651,465 | 17,970 | 729,831 | 1,232 | 48,601 | 289,505 | 1,761 | 197 | 279 | 2 | 5,685 | 150,587 | 11,465 | 29 | - | 24,190 | 1 | - | 1 | 1,099 | 238,179 | 30,995 |
| A. Including vehicles according to the car law | 40,145,368 | 28,263,127 | 10,632,407 | 17,350 | 726,534 | 1,071 | 8,351 | 273,530 | 974 | 183 | 227 | 1 | 5,565 | 150,587 | 11,464 | 28 | - | 24,190 | 1 | - | - | 1,099 | 6,704 | 21,975 |

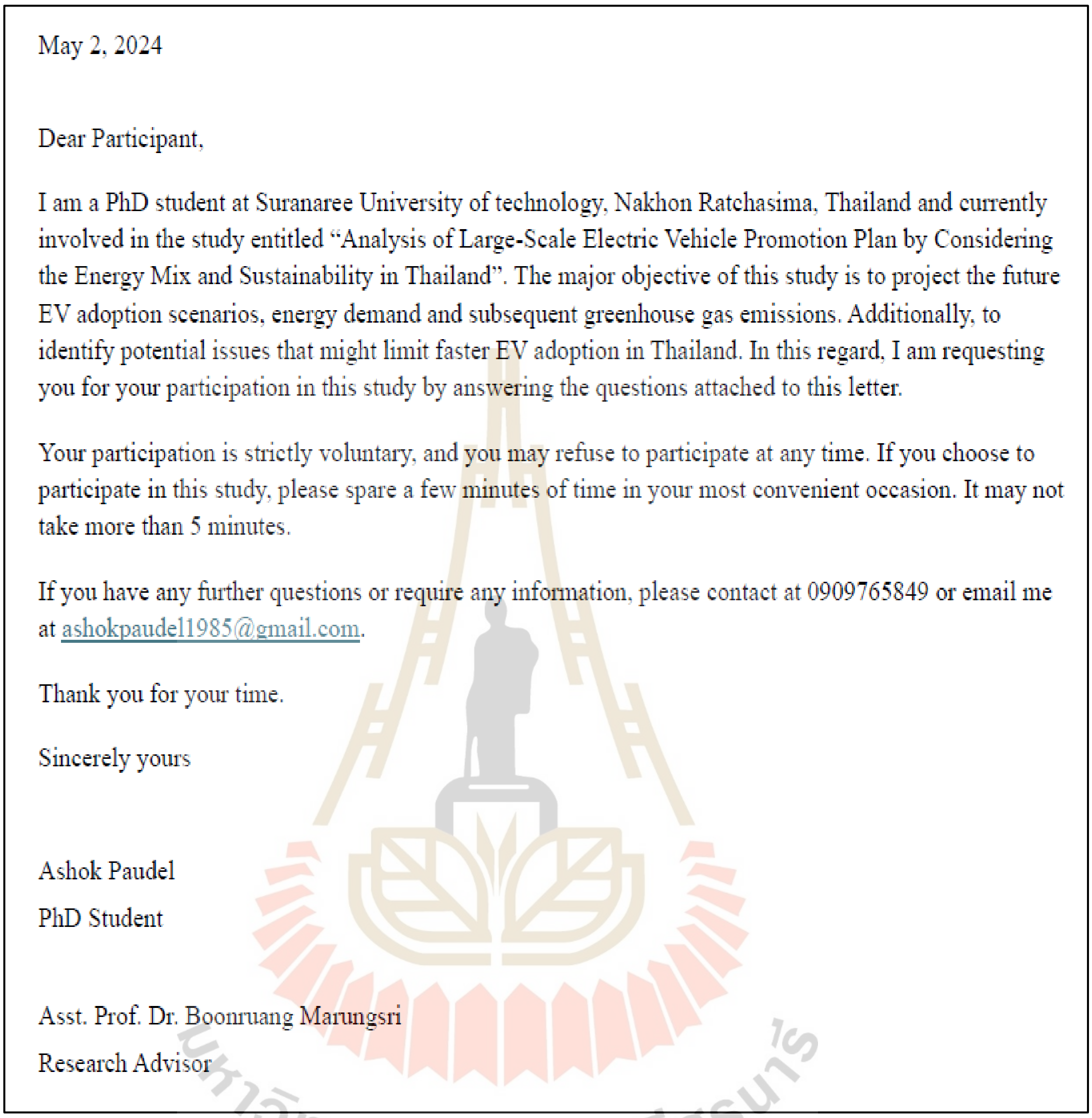
Varieties of fuels are used in different vehicles. In the case of combined fuel like LPG and diesel, the vehicle is considered an LPG-powered vehicle. All hybrid electric vehicles are considered gasoline-electric, as the diesel-electric vehicles are negligible compared to gasoline-electric.

# APPENDIX D Macroeconomic data used in the study

| Years | GDP per capita current LCU | price of fuel current price | population density | vehicle per 1000 pop |
|---|---|---|---|---|
| 1995 | 70973.93 | 7.57 | 116.3163 | 66.31388 |
| 1996 | 77039.02 | 8.6 | 117.8553 | 74.23077 |
| 1997 | 77231.99 | 9.48 | 119.3782 | 82.89348 |
| 1998 | 76144.41 | 9.15 | 120.8581 | 88.00481 |
| 1999 | 76707.6 | 8.96 | 122.2233 | 94.13464 |
| 2000 | 80388.35 | 12.93 | 123.4446 | 95.14937 |
| 2001 | 83975.02 | 13.43 | 124.5863 | 99.48942 |
| 2002 | 89837.22 | 13.12 | 125.7073 | 107.7488 |
| 2003 | 97523.93 | 16.12 | 126.7924 | 110.608 |
| 2004 | 106479.2 | 18.52 | 127.838 | 99.52232 |
| 2005 | 115683 | 22.48 | 128.8367 | 107.4092 |
| 2006 | 126669.2 | 26.05 | 129.8118 | 121.0058 |
| 2007 | 135818.4 | 26.17 | 130.8046 | 126.5526 |
| 2008 | 144173.2 | 28.95 | 131.7862 | 132.0633 |
| 2009 | 142429.5 | 27.49 | 132.7363 | 137.3885 |
| 2010 | 158313.6 | 32.18 | 133.6305 | 145.7127 |
| 2011 | 164553 | 36.42 | 134.4964 | 155.9344 |

| | | | | |
|---|---|---|---|---|
| 2012 | 178685.3 | 37.95 | 135.3658 | 172.0385 |
| 2013 | 185619.7 | 38.95 | 136.191 | 188.2046 |
| 2014 | 189109.9 | 38.94 | 136.9393 | 198.1111 |
| 2015 | 195513.2 | 27.87 | 137.592 | 205.9762 |
| 2016 | 206641.4 | 24.5 | 138.204 | 213.2743 |
| 2017 | 218463.4 | 27.15 | 138.7739 | 222.151 |
| 2018 | 230196.1 | 28.96 | 139.2233 | 232.5278 |
| 2019 | 236894.4 | 27.68 | 139.5756 | 242.7828 |
| 2020 | 218772.2 | 21.93 | 139.9042 | 250.1688 |

# APPENDIX E Request for participation in survey



May 2, 2024

Dear Participant,

I am a PhD student at Suranaree University of technology, Nakhon Ratchasima, Thailand and currently involved in the study entitled “Analysis of Large-Scale Electric Vehicle Promotion Plan by Considering the Energy Mix and Sustainability in Thailand”. The major objective of this study is to project the future EV adoption scenarios, energy demand and subsequent greenhouse gas emissions. Additionally, to identify potential issues that might limit faster EV adoption in Thailand. In this regard, I am requesting you for your participation in this study by answering the questions attached to this letter.

Your participation is strictly voluntary, and you may refuse to participate at any time. If you choose to participate in this study, please spare a few minutes of time in your most convenient occasion. It may not take more than 5 minutes.

If you have any further questions or require any information, please contact at 0909765849 or email me at ashokpaudel1985@gmail.com.

Thank you for your time.

Sincerely yours

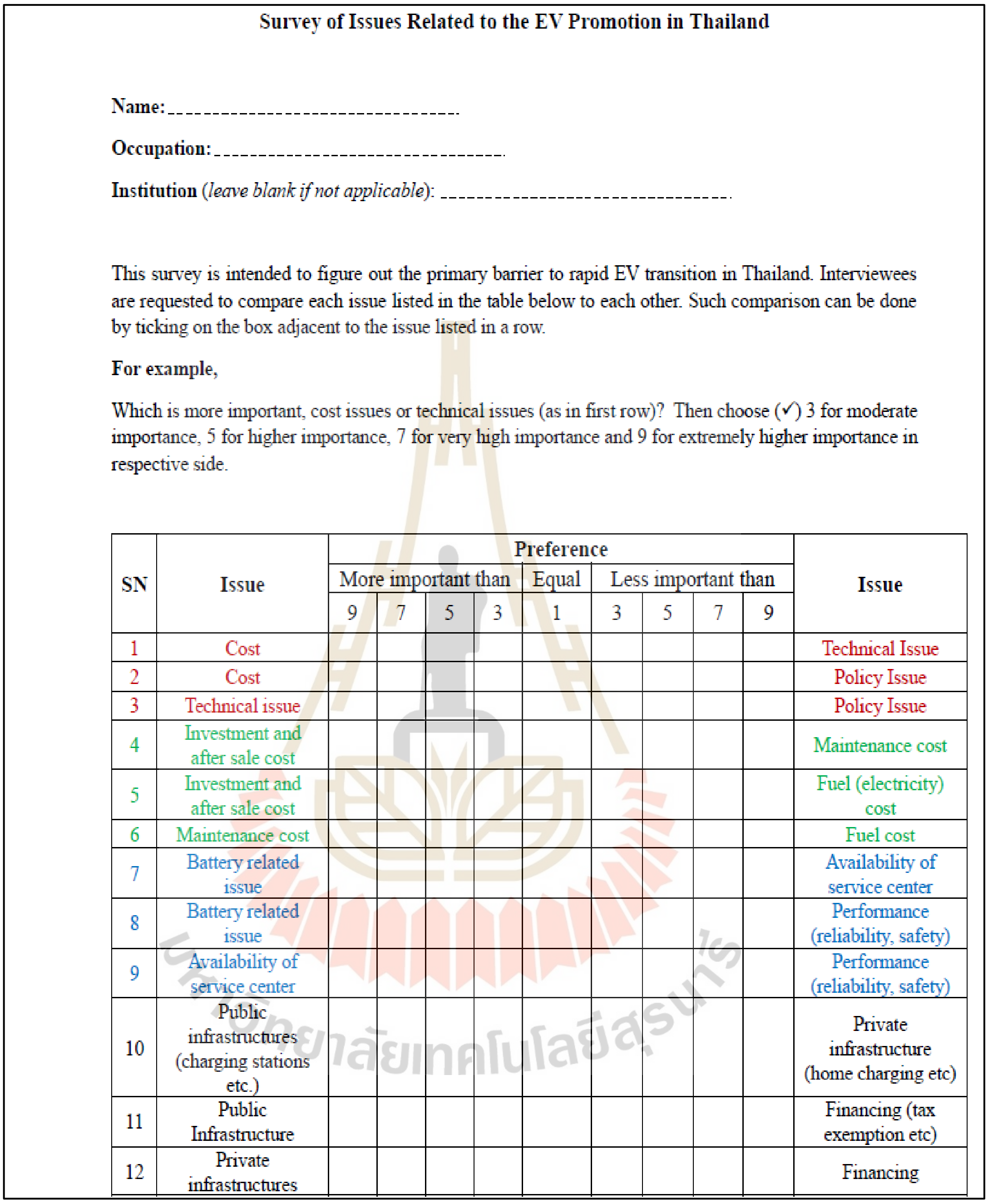
Ashok Paudel

PhD Student

Asst. Prof. Dr. Boonruang Marungsri

Research Advisor

# APPENDIX F AHP questionnaire



**Survey of Issues Related to the EV Promotion in Thailand**

**Name:**________________________________

**Occupation:**________________________________

**Institution** (*leave blank if not applicable*): ________________________________

This survey is intended to figure out the primary barrier to rapid EV transition in Thailand. Interviewees are requested to compare each issue listed in the table below to each other. Such comparison can be done by ticking on the box adjacent to the issue listed in a row.

**For example,**

Which is more important, cost issues or technical issues (as in first row)? Then choose (✓) 3 for moderate importance, 5 for higher importance, 7 for very high importance and 9 for extremely higher importance in respective side.

| **SN** | **Issue** | **Preference** | | | | | | | | | **Issue** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | More important than | | | | Equal | Less important than | | | | |
| | | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | |
| 1 | Cost | | | | | | | | | | Technical Issue |
| 2 | Cost | | | | | | | | | | Policy Issue |
| 3 | Technical issue | | | | | | | | | | Policy Issue |
| 4 | Investment and after sale cost | | | | | | | | | | Maintenance cost |
| 5 | Investment and after sale cost | | | | | | | | | | Fuel (electricity) cost |
| 6 | Maintenance cost | | | | | | | | | | Fuel cost |
| 7 | Battery related issue | | | | | | | | | | Availability of service center |
| 8 | Battery related issue | | | | | | | | | | Performance (reliability, safety) |
| 9 | Availability of service center | | | | | | | | | | Performance (reliability, safety) |
| 10 | Public infrastructures (charging stations etc.) | | | | | | | | | | Private infrastructure (home charging etc) |
| 11 | Public Infrastructure | | | | | | | | | | Financing (tax exemption etc) |
| 12 | Private infrastructures | | | | | | | | | | Financing |

# APPENDIX G AHP questionnaire respondent

| SN | Name | Occupation | SN | Name | Occupation |
|---|---|---|---|---|---|
| 1 | Banyat Boribun | Professor | 17 | Wirat Prasongmongkon | Company employees |
| 2 | Nattakarn Prasertsung | Lecturer | 18 | Grittin tongnum | Engineer |
| 3 | Nattamon | Business owner | 19 | ธีธัช เลาหวิโรจน์ | วิศวกรไฟฟ้า |
| 4 | Anucha | Business owner | 20 | Sanit taodee | Employee |
| 5 | Boonyang Plangklang | Professos | 21 | Pannathon Rodkumnerd | Electrical Engineering |
| 6 | Viput | Professor | 22 | Boontham Poonsamrong | Engineer |
| 7 | Chalermpol | Officer | 23 | Mr.Sathaporn Tongnoi | Electrical Engineer |
| 8 | Wirachai | ราบการ | 24 | ดร.สมฤกษ์ การวิวัฒน์ | Owner |
| 9 | Punluek | Employee | 25 | Yuttana Kongjeen | Teacher |
| 10 | Phattaradol Saengsil | Private Company | 26 | Sontaya Manmai | Officer |
| 11 | สุชีรา อินทร์ศวร | พนักงานบริษัท | 27 | ประพาส โนรี | Owner of IOs Digitech |
| 12 | Suchada Butnark | Freelancer | 28 | Mr Wichitchai Ponhla | Electrical Engineering |
| 13 | NC | Engineer | 29 | Ratthakhet Thiamsri | Engineer |
| 14 | Chanon | Officer | 30 | ยุทธพงษ์ ศรัทธา | พนักงานบริษัทเอกชน |

| | | | | | |
|---|---|---|---|---|---|
| 15 | Apichai Sawisit | Lecturer | 31 | Preecha Chamram | Service Engineer |
| 16 | Thipsuphin Hinsui | Researcher | 32 | Jitphol kuhasantisuk | Engineer |

# APPENDIX H Aggregated Pairwise comparison matrix

1. Pairwise comparison matrix for criteria members (Cost issue, Technical issues, Policy issues)

| | Cost issue | Technical issue | Policy issue |
|---|---|---|---|
| Cost issue | 1 | 4.39 | 6.87 |
| Technical issue | 0.22779 | 1 | 3.633 |
| Policy issues | 0.14556 | 0.275255 | 1 |

2. Pairwise comparison matrix for sub criterions under criteria cost

| | Investment and after sale cost | Maintenance cost | Fuel (electricity) cost |
|---|---|---|---|
| Investment and after sale cost | 1 | 3.1654 | 3.546 |
| Maintenance cost | 0.315916 | 1 | 2.504 |
| Fuel (electricity) cost | 0.282008 | 0.399361 | 1 |

3. Pairwise comparison matrix for sub criterions under criteria technical issues

| | Battery related issue | Availability of service center | Performance (range, reliability, safety) |
|---|---|---|---|
| Battery related issue | 1 | 4.057 | 3.62 |
| Availability of service center | 0.246488 | 1 | 2.31 |
| Performance (range, reliability, safety) | 0.276243 | 0.4329 | 1 |

4. Pairwise comparison matrix for sub criteria under criteria policy issues

| | Public infrastructure | Private infrastructure | Financing (Taxation, subsidy etc) |
|---|---|---|---|
| Cost issue | 1 | 4.544 | 4.42 |
| Technical issue | 0.220070423 | 1 | 2.22 |
| Policy issues | 0.226244344 | 0.45045045 | 1 |

# APPENDIX I Publication

I. Paudel, A. and Marungsri, B. (2023). Impact of Large-Scale Electric Vehicles' Promotion in Thailand Considering Energy Mix, Peak Load, and Greenhouse Gas Emissions. ***Smart Cities***. 6(5), pp. 2619-2638. https://doi.org/10.3390/smartcities6050118

II. Paudel, A. and Marungsri, B. (2023). Analysis of the Effect of the Royal Thai Government's Electric Vehicle Promotion Strategy on Future Energy demand, Energy Mix and Emissions from Passenger Land Transport. ***GMSARN International Journal***. 17(2). pp. 184-191.

III. Paudel, K., Bonraksa, T. and Marungsri, B. (2021). Scenario Analysis of the Electric Vehicle Promotion Roadmap of Royal Thai Government. International Conference on Power, Energy and Innovations (ICPEI), 2021. Nakhon Ratchasima, Thailand, pp. 130-133, doi: 10.1109/ICPEI52436.2021.9690655.

smart cities

MDPI

*Article*

# Impact of Large-Scale Electric Vehicles' Promotion in Thailand Considering Energy Mix, Peak Load, and Greenhouse Gas Emissions

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[2] Department of Electrical Engineering, Rajamangala University of Technology Tawan-Ok, Chanthaburi 22210, Thailand
* Correspondence: watcharakorn_pi@rmutto.ac.th (W.P.); bmshvee@sut.ac.th (B.M.)

**Abstract:** Thailand's policies are in accord with the global drive to electrify transportation vehicle fleets due to climate concerns. This dedication is evident through its adoption of the 30@30 initiative and the planned ban on new internal combustion (IC) engine vehicles by 2035, showcasing a strong commitment. The objective of this study was to utilize the Low Emission Analysis Platform (LEAP) software to model the transition possibilities for electric vehicle (EV). Emphasis was placed on the future of the light-duty vehicle (LDV) sector, encompassing the energy sources, electric power demands, and greenhouse gas (GHG) emissions. Two scenarios were evaluated: one involving rapid economic growth and the other characterized by a more-gradual expansion. The former projection foresees 382 vehicles per thousand people by 2040, while the latter estimate envisions 338 vehicles. In the scenario of high growth, the vehicle stock could surge by 70% (27-million), whereas in the case of low growth, it might experience a 47% rise (23.3-million) compared to the base year (15.8 million). The increased adoption of EVs will lead to a decrease in energy demand owing to improved fuel efficiency. Nonetheless, even in the most-extreme EV scenarios, the proportion of electricity in the energy mix will remain below one-third. While GHG emissions will decrease, there is potential for even greater emission control through the enforcement of stricter emission standards. Significant EV adoption could potentially stress power grids, and the demand for charging might give rise to related challenges. The deployment of public fast charging infrastructure could provide a solution by evenly distributing the load across the day. In the most-rapid EV penetration scenario, a public charging program could cap the demand at 9300 MW, contrasting with the 21,000 MW demand for home charging. Therefore, a recommended approach involves devising an optimal strategy that considers EV adoption, a tariff structure with incentives, and the preparedness of the infrastructure.

**Keywords:** electric vehicle promotion; Thailand; load demand; LEAP; vehicle driving distance; energy demand; emission; zero-emission vehicles

check for updates

**Citation:** Paudel, A.; Pinthurat, W.; Marungsri, B. Impact of Large-Scale Electric Vehicles' Promotion in Thailand Considering Energy Mix, Peak Load, and Emissions. *Smart Cities* **2023**, *6*, 2619–2638. https://doi.org/10.3390/smartcities6050118

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## 1. Introduction

In this century, a major challenge is reducing GHG emissions and implementing climate-change-mitigation measures. Global communities are striving for net-zero commitments to achieve sustainability. Actions such as decarbonizing electrical power, promoting green manufacturing, and enforcing the control of emissions are underway worldwide to achieve net-zero goals. Concerns about the GHGs and micro-pollutants from vehicle exhaust are driving countries to craft policies encouraging zero-emission vehicles (ZEVs). Electric vehicles (EVs) are gaining popularity, with the IEA projecting them to constitute 7% of the vehicle fleet under standard policies and 12% under sustainable policies by 2030 [1]. The Clean Energy Ministerial's "30@30" campaign aims for 30% of new vehicle registrations to be ZEVs by 2030 [2]. Notably, global EV sales rose from 9% in 2021 to 14%

in 2022, a ten-fold increase from 2017 [3]. China leads the EV market, followed by the European Union and the United States.

Countries worldwide are implementing diverse policies to boost EV adoption and establish new EV industry supply chains. Despite variations in their strategies, three common approaches emerge in EV-promotion policies globally. First, direct cash subsidies are offered at the point of sale. Second, incentives and tax rebates are provided to the industry to keep the EV costs affordable and stimulate a burgeoning industry. Third, non-monetary incentives, such as parking access, streamlined registration processes, and exemptions from congestion and pollution restrictions, are utilized. Examples of direct cash transfer schemes include New Zealand's Clean Car Discount, as well as purchase subsidies in France, Germany, the U.K., Canada, the U.S., Japan, and China. India's Faster Adoption and Manufacturing of Hybrid and EVs (FAME) scheme and Australia's Future Fuels Fund are industry-focused incentives. Indonesia and Malaysia have similar policies to attract EV parts and component investment. France's Green Pass and China's Green Sticker scheme are non-monetary promotional initiatives improving road and parking access for EV users. The increasing EV market penetration in these countries suggests that these schemes are effective in achieving their objectives. Notably, some countries such as China are reducing or eliminating point-of-sale subsidies, while Japan has recently increased such incentives. Table 1 summarizes incentives across regions and socio-economic levels to promote EV and ZEV adoption. Common approaches include cash subsidies, tax benefits for manufacturers, and non-monetary perks such as parking access and pollution-related congestion exemptions. The growing EV market share in these countries indicates policy success.

**Table 1.** Illustrative promotion of EVs in selected countries.

| Country | Activity and Promotion | Ref. |
|---|---|---|
| India | (i) Faster Adoption and Manufacturing of Hybrid and EVs (FAME) scheme;<br>(ii) Offers tax incentives in the manufacturing of EV parts and sub-parts. | [4] |
| Australia | (i) Future fuels fund; (ii) AUD 250-million in funds support industries to develop EV charging stations and hydrogen refueling infrastructure. | [5] |
| New Zealand | (i) Clean car discount;<br>(ii) Offers rebates and punishes with fees depending on per-kilometer carbon emission during vehicle registration. | [6] |
| France | (i) Ecological bonus scheme;<br>(ii) Subsidizes up to 27% of purchase price;<br>(iii) 50–100% rebate of registration fee; (iv) EVs are eligible to receive a green pass, allowing them to be parked up to 2 h free of charge in a few municipalities. | [7] |
| Germany | (i) Purchase subsidy;<br>(ii) Discount on registration fees;<br>(iii) Investment in public charging infrastructure. | [8] |
| U.K. | (i) Grants towards the purchase of light commercial vehicles, taxis, and heavy-duty vehicles;<br>(ii) Investment in charging infrastructure; (iii) Ban on petrol and diesel cars by 2030. | [9] |
| Canada | (i) Grants towards EV purchase, lease, as well as installment of charging stations;<br>(ii) Phase out plan for buses and HEVs. | [10] |
| U.S. | (i) Various states have announced a ban on the sale of IC cars after 2035;<br>(ii) States have prepared their fuel transition activities and budgeting;<br>(iii) Up to USD 7500 federal tax credit from 2023 to 2032. | [11,12] |
| Indonesia | (i) More focused on developing EV ecosystem;<br>(ii) Offers tax benefit to manufacturers depending on amount of local components used in the final product;<br>(iii) Manufacturing of electric two wheelers is given more importance in the short term. | [13] |
| Malaysia | (i) Fully green transport by 2030 including LPG, CNG, biofuel, and EVs;<br>(ii) Primary focus is on parts and component development and manufacturing. | [14] |
| Japan | (i) The 2021 Green Growth Strategy aims for 100% LDV electrification by 2030;<br>(ii) Offers purchase subsidies to buyers and tax incentives to manufacturers;<br>(iii) Maximum purchase subsidy limit: JPY 800,000. | [15,16] |
| China | (i) China has been subsidizing new energy vehicles since 2009, adjusting subsidies based on market conditions;<br>(ii) A formula considers factors such as range, battery energy density, and energy consumption to determine subsidy amounts; eligibility criteria are regularly adjusted, and the subsidy program, initially set to end in 2022, has been extended to 2027;<br>(iii) Many cities and local governments offer non-monetary benefits such as parking access and exemptions from congestion and pollution restrictions. | [16,17] |

Thailand, the second-largest ASEAN economy, is a significant player in the automobile industry, with approximately 6% of newly registered LDVs being EVs in 2022 [18]. In 2015, Thailand launched an EV promotion roadmap to enhance EV usage, manufacturing, and capabilities [19]. Thailand is committed to the 30@30 campaign and plans to ban IC vehicle registration after 2035, aligning with more-ambitious goals [20]. Furthermore, Thailand is pursuing policies to boost EV adoption and develop the EV ecosystem. The Thailand Board of Investment (BOI) offers tax incentives for EV manufacturing [21], and a THB 2.9-billion EV subsidy program supports new EV buyers [22]. This subsidy ranges up to THB 150,000 based on passenger and battery capacity. These policies, successful in other countries, are expected to drive increased EV adoption in Thailand, potentially impacting existing energy management policies outlined in the Thailand Integrated Energy Blueprint (TIEB) (2015–2037), which faces challenges in meeting the rising electrical demand from EVs.

By 2030, official energy consumption is projected to be 151 Mtoe, potentially reduced by 30 Mtoe through successful the EEP implementation [20]. Transportation is expected to consume 31% of energy and industry 41%, with the EEP projecting transport's energy-saving potential at 44%. Achieving efficiency targets relies on electrifying fleets, fuel economy improvements, enforcing standards, and eco-driving policies. PDP-2018 guides power systems, adding 52,431 MW generation capacity, including 18,833 MW of renewables. By 2037, there will be an estimated 77,200 MW installed capacity, 54,000 MW peak load, and 367 TWh annual energy demand. The EV transition must align with the TIEB framework, considering its impact on load, stability, and emissions.

The generation composition in the PDP2018 is crucial. In 2018, renewables made up 18% of total capacity, with the rest from fossil fuels. Natural gas accounted for 60% and coal for 19%. By 2037, renewables will comprise 30% of total capacity and coal will drop to 11%, but natural gas will remain dominant at 53%. A concern is the potential addition of new coal-fired power plants after 2030, conflicting with global efforts to discourage them. This may change in future policy revisions. $CO_2$ emissions from power generation are expected to increase by just over 18% from 2018 to 2037.

### 1.1. Related Publications

After the introduction of the EV promotion roadmap, several studies have analyzed various aspects related to EVs in Thailand. These studies have explored public perceptions of EVs and their popularity [23,24], the potential of charging stations [19], and the socioeconomic consequences of promoting EVs [23,25,26]. Together, these articles indicate a consensus that the Thai population is leaning towards adopting EVs. Young people in Thailand are increasingly favoring EVs over IC vehicles due to factors such as vehicle performance, environmental concerns, and social considerations. Yet, significant challenges persist, encompassing insufficient public infrastructure, limited driving range, cost considerations, and concerns about battery lifespan. In response to the insufficient charging infrastructure, potential solutions have been suggested. These solutions mainly involve incentivizing existing gas stations to install charging infrastructure and fostering collaborations between startups and major businesses, such as shopping centers. Furthermore, technical studies have investigated the impact of EV charging on the grid and power quality, with results suggesting that an off-peak charging strategy may be more favorable from a technical standpoint [27]. Studies related to vehicle-to-grid (V2G) and smart-home-based energy management have also surfaced, concentrating on strategies such as time-of-use (ToU) and real-time pricing (RTP) to address domestic demand from the consumer's perspective [28]. While this strategy can assist in managing daily load demand, its overall impact on the entire power system is challenging to assess since smart home technology has not yet widely penetrated the market in Thailand. This suggests that the domestic charging management strategy may not have a significant impact on peak demand or its timing in the near future. Despite these efforts, there is a relative scarcity of macro-level studies addressing long-term energy demand and fuel transition in relation to the growth of EVs and their impact on the electrical generation and supply system. Previous research has frequently focused on the potential emission reductions resulting from increased EV adoption, but it has lacked insights into the enduring effects on the electricity generation and supply system [29–31]. Article [31] criticized the potential emissions benefits of EV promotion, as it could lead to increased emissions from the power sector. However, other studies endorse the electrification of the transportation sector, especially in light of the rapid growth of renewable integration in the power system. Only a handful of studies in the literature have made predictions about the potential transition to EVs and the resulting peak load caused by EV charging. For example, in a scenario involving 1.5-million cars, roughly 35-million motorcycles, and a few thousand electric buses, a scenario with free charging would necessitate approximately 6000 MW of peak demand [27]. In a study spanning the period from 2010 to 2030, it was estimated that approximately 11.5 TWh of electrical energy would be required to charge a fleet consisting of 18.5-million motorcycles and 1.1-million cars, resulting in a peak demand of 10,000 MW [32]. While current conditions differ significantly from those assumed in the article, it is still important to analyze the academic interest in this sector. Extensive energy modeling of the Bangkok metropolitan area demonstrates the potential for introducing EVs and their positive impact on energy-conservation and emission-reduction efforts. Moreover, the expansion of mass rapid transport systems significantly contributes to emission reduction [33,34]. The latest study, utilizing the PDP2018, examined scenarios involving diverse levels of EV adoption, ranging from 1.2-million in 2030 to 15-million in 2037 [35]. The findings suggest that increased electrification of the transportation fleet substantially decreases overall energy demand. Nevertheless, the increased electricity generation still depends on natural gas, underscoring the importance of a robust transition towards renewable energy sources in the final energy mix. Similar doubts about the transition to EVs without simultaneously decarbonizing the electricity-generation sector are widespread, as emphasized in [36,37]. The article [38] contended that, although people generally hold positive views on the potential of EVs to reduce emissions, their skepticism is amplified by the slow integration of renewables into the grid system. Moreover, there are concerns regarding the socioeconomic aspects of private car ownership and their sustainability impact, along with the environmental implications of rare earth mining for battery production and disposal, which require attention. In-depth analyses of vehicle electrification effects in Abu Dhabi City and the Netherlands can be found in [39,40]. A substantial infrastructure investment would be needed if there is excessive demand from EV charging. Moreover, the article [41] examined how EV adoption can foster the development of sustainable communities. Similar analyses in Thailand are vital for evaluating existing policies, formulating new ones if needed, and assessing electrical demand and peak load variations with varying EV penetration. These data will inform optimal charging strategies and long-term power development policy adjustments.

### 1.2. Motivation and Contributions

Given the recent EV penetration targets, it is essential to reevaluate the potential energy demand and peak load associated with EV growth. Determining future charging demand based on the EV penetration pace is crucial for power system planning and reliability. Additionally, assessing the impact of EV promotion on reducing tailpipe emissions is important. This study introduced a scenario-based LEAP model to project future energy demand, fuel mix, and GHG emissions, considering EV growth potential and penetration. Compared to the existing works, the salient features of this paper are listed below:

1. Using econometric data, we constructed a vehicle ownership model to project vehicles per thousand population, contingent upon various future economic growth scenarios.
2. We analyzed energy consumption, fuel mix, and LDV emissions in different scenarios, factoring in the transition pace using the LEAP software tool.
3. Each vehicle type possesses distinct operational traits. In this study, we focused on LDVs primarily used for commuting, excluding taxis. In such instances, charging LDVs concurrently with larger vehicles could lead to excessive demand.
4. Additionally, we also assessed the potential impact of various charging schemes on peak load. Here, Monte Carlo simulation was employed to derive the EV charging load profiles.

### 1.3. Paper Organizations

The rest of the paper is structured as follows. Section 2 explains the methodology implemented in this paper. The details of the proposed scenarios and simulation setup are described in Section 3. Section 4 contains the obtained simulation results. Finally, Section 5 concludes the paper.

## 2. Methodology

Several tools exist for energy system modeling, including TIMES, HOMER, MESSAGE, and LEAP. This study opted for LEAP due to its convenience and independence from a specific environment, unlike the general algebraic modeling system (GAMS) [42]. It is a scenario-focused energy system modeling software from the Stockholm Environment Institute [43]. LEAP, as an optimization framework, finds widespread application in diverse fields including integrated energy modeling, water resource management, emission estimation, and generation expansion planning [44–48]. LEAP employs the accounting method for energy-related activities simulation. Its standout qualities are its flexibility and versatility, serving as a model-building platform adaptable to user needs. Diverse modeling approaches (bottom-up, top-down, end-use, macroeconomic) are feasible. Planning horizons vary from short to long, but LEAP excels in medium-term operational and long-term expansion planning. A key feature is its inbuilt Technology and Environment Database (TED), containing standards and techno-economic, socio-economic, and environmental data from organizations such as IEA and the IPCC. This streamlines analysis, minimizing data input through internal library linkage.

### 2.1. *LEAP Models*

LEAP employs the stock turnover method for calculating energy demand (ED). It necessitates vehicle driving distance (VKT), fuel economy (FE), and the number of vehicles for a specific year, $N_{stock}$. The ED model is mathematically defined as

$$ED_{i,j} = N_{stock\ i,j} \times VKT_i \times FE_{i,j}, \tag{1}$$

where $i$ represents the consumed fuel and $j$ denotes the vehicle type, such as car, SUV, or taxi.

Total energy consumption is the aggregate of all vehicle types' energy consumption and their associated fuel. Focusing on the LDV segment, the study considered cars (up to seven passengers), SUVs, personal trucks, and taxis as the vehicle types. The Department of Land Transport registers similar vehicles in various categories based on the service designation, such as fixed-route taxis and hotel taxis. To simplify the model, these categories are merged and treated as distinct vehicle types.

The total stock of each vehicle and fuel type can be calculated based on vehicle sales and the vehicle's survival rate as

$$N_{stock\ i,j} = \sum_{v=1}^{t} N_{sale\ i,t}(v) \times S_{i,j}(a), \tag{2}$$

where $N_{sale\ i,j}(v)$ is the quantity of new vehicles sold in the given vintage year $v$ and $S_{i,j}(a)$ is the survival rate of the $j$-th vehicle type with fuel $i$ with age $a$ so that $a = t - v$.

The survival rate pertains to the anticipated likelihood of a specific vehicle enduring in operational use, while the survival profile was derived from prior research and documented information [49,50].

Each vehicle type's driving characteristics differ significantly based on urban or rural settings, alongside its utility, which impacts annual mileage. Driving characteristics' data were gathered from prior publications [51,52]. Data related to the vehicle number, annual new registration, fuel type classification, age, etc., was collected from Thailand's Department of Land Transport (DLT) government web portal.

The DLT database indicates diverse fuel registrations, primarily gasoline and diesel, with CNG and LPG also used. Some vehicles have dual-fuel registrations such as CNG = -gasoline or CNG = -diesel. Older vehicles use benzene. Newer registrations include hybrid (gasoline hybrid), plug-in hybrid, and battery electric vehicles (BEVs) in distinct categories. Thailand pioneered the introduction of biodiesel and bioethanol applications and associated policies in Asia [53]. Gasohol, commonly known as ethanol-blended gasoline, is required and offered in various blends, including 5%, 10%, and 20%. Likewise, various biodiesel blends exist, each with slightly different energy content, emission coefficients, and fuel economy compared to gasohol grades. Accounting for these nuances is challenging due to limited data and computational constraints. Thus, these fuels were classified into the following simplified groups.

1. ***Gasoline:***This category includes all vehicles registered under the gasoline designation.
2. ***Diesel:*** Vehicles registered with diesel as their primary fuel.
3. ***CNG:*** Vehicles with CNG as the primary fuel, including those with dual-fuel options such as CNG–gasoline, are grouped due to the government's promotion of CNG through subsidies and tax rebates, driven by its affordability.
4. ***LPG:*** The primary fuel is LPG, with the addition of dual-fuel capabilities.
5. ***Gasoline (Hybrid):*** Gasoline–electric vehicles overwhelmingly dominate the hybrid electric category, leading to the assumption that all hybrid electric vehicles are powered by gasoline.
6. ***Electricity:*** This category includes both battery electric and plug-in EVs.

Fuel economy (FE) is a pivotal factor in determining vehicle energy demand, influenced by factors such as manufacturer, model, fuel type, vehicle type, utility, driving conditions, and age. Regulators typically set minimum fuel economy standards for roadworthiness. In Thailand, these standards are not strictly defined by regulations, but rather influenced by market forces, as vehicles with lower fuel efficiency might not be market-friendly. Given the dominance of Japanese manufacturers in the Thai automaker sector and market, the expected fuel efficiency is comparable to that of non-European members of the IEA, which is 9 km/l [54]. Conversely, the ASEAN fuel economy roadmap forecasts Thailand's LDV fuel efficiency to be 13.3 km/lge [55]. As Thailand leads in both vehicle manufacturing and market, a range of brands are offered. Notable gasoline and plug-in hybrid brands include Toyota, Mazda, Hyundai, and Nissan. In the battery electric market, leading brands encompass Nissan, BYD, Tesla, etc. Table 2 provides the utilized FE values in this study.

**Table 2.** Fuel economy taken from [55].

| Vehicle | Fuel Economy, FE (km/lge) | | |
|---|---|---|---|
| | **IC** | **HEV** | **BEV** |
| LDV | 12 | 18 | 47 |

Emissions are calculated based on travel distance and energy consumption, where total emission for a specific vehicle type and fuel is the product of consumed energy, emission factor, and degradation factor. The emission factor adheres to regulating authority limits set according to country-specific environments. Thailand adopted Euro-IV in 2012, following Euro-III (2005) and Euro-II (1999); Euro-V is upcoming. Emission degradation is influenced by aging engines, but is complex to gauge for diverse vehicle types due to driving, road, and environmental variables. Predicting old vehicle emissions is limited; thus, the emission factor was assumed constant throughout their service. The mathematical formula used to calculate emissions is given as

$$Emission_{i,j,k} = ED_{i,j} \times EF_{i,j,k} \times \phi_{i,j,k,\alpha}, \tag{3}$$

where $Emission_{i,j,k}$ is the $k$-th emission from the $i$-th fuel of the $j$-th vehicle type; $EF_{i,j,k}$ is the emission factor; and $\phi_{i,j,k,\alpha}$ is the emission degradation factor for type $k$ emission from the $i$-th fuel of the $j$-th category vehicle on the $\alpha$-th year such that $\alpha = t - v$.

### 2.2. *Estimation of New Vehicle Registration*

The number of vehicles in a specific year stands as one of the utmost critical factors in (1). This study examined the time frame from 2016 to 2040. Given the extended forecasting period, precise short-term forecasting methods might not be advantageous. A vehicle ownership model was created for future registration predictions. The time series forecasting technique is extensively used for long-term prediction tasks. In the articles [56,57], ARIMA models forecast upcoming car sales. Holtz's method might surpass ARIMA in accuracy due to its exponential smoothing approach, which could comprehensively assign weights to past data [58]. Due to its simplicity and relatively low data requirements, log-linear regression stands as the predominant approach for crafting vehicle ownership models [35,59,60].

Models commonly employ macroeconomic indicators (e.g., per capita income (PCI), population density (POPden), urbanization, fuel price, and taxation) to predict vehicle ownership per thousand population. In this paper, we used three dependent variables (nominal per capita income, population density, and average retail fuel price) and introduced the concept of saturation level, rendering the model quasi-logistic. Testing multiple saturation levels (400, 500, 600, 700, and 800) showed 600 to yield the best-fitting accuracy; thus, it was chosen for final simulation. The mathematical expression of the vehicle ownership model used in this article is given by

$$\ln\left(\frac{VO_{1000}}{S - VO_{1000}}\right) = \beta_0 + \beta_1 \ln PCI + \beta_2 \ln POPden + \beta_3 \ln FP + \epsilon, \quad (4)$$

where $VO_{1000}$ is the vehicle ownership per thousand population; $S$ is the saturation level (600); and $\beta_0$, $\beta_1$, $\beta_2$, and $\beta_3$ are the coefficients of the respective variables.

The vehicle inventory at year-end, spanning 1995 to 2020 and acquired from the Department of Land Transport, can be employed to address (4). The World Bank database gathers data on PCI and population density [61]. Ultimately, the historical fuel price record was sourced from the records of the Bank of Thailand [62]. Table 3 encapsulates the outcomes derived from solving (4). The model exhibited R2 and adjusted R2 values of 0.982 and 0.98, respectively.

**Table 3.** Parameters of the vehicle ownership model.

| Parameter | Coefficient | *p*-Value |
|---|---|---|
| $\beta_0$ | −44.365 | $1.33770 \times 10^{-8}$ |
| $\beta_1$ | 0.70569 | $6.9 \times 10^{-4}$ |
| $\beta_2$ | 7.4199 | $3.79 \times 10^{-5}$ |
| $\beta_3$ | −0.43314 | $1.0354 \times 10^{-6}$ |

### *2.3. Estimation of Charging Load and Charging Scenarios*

Understanding charging behavior is crucial for determining system peak load. Yet, calculating multi-decade peak load and driving traits is challenging due to evolving EV technology and changing parameters such as charging rate, battery capacity, driving behavior, and infrastructure. Short-term strategies and public supercharging shape charging patterns and the ensuing peak load. This article employed a Monte Carlo simulation to derive EV charging load profiles, focusing on three key parameters: daily driving distance, charge start time, and rate. Distance and start time were treated as normally distributed random variables, with their probability density functions (PDFs) in (5) and (6) [63,64]. Charging rate varies based on infrastructure and scheme. Type I is slow charging; Type II is fast; home chargers were all assumed to be Type II. In this article, public fast charging was regarded as supercharging and represented by

$$f_d(x_{i,j}) = \frac{1}{\sigma_{d,j}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x_{i,j} - \mu_{d,j}}{\sigma^2_{d,j}}\right)}, \quad (5)$$

$$f(T_{st_{i,j}}) = \frac{1}{\sigma_{st,j}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t_{st_{i,j}} - \mu_{st,j}}{\sigma^2_{st,j}}\right)}, \quad (6)$$

where $\mu_d$ and $\sigma_d$ are the mean and standard deviation of the *j*-th-type vehicle driving distance, respectively. Similarly, $\mu_{st}$ and $\sigma_{st}$ represent the mean and standard deviation of the starting time of charging of the *i*-th type of vehicle, respectively.

The state-of-charge (SoC) is determined using driving distance and the range provided by the vehicle manufacturer. This can be expressed as

$$SoC_{i,j} = 1 - \frac{d_{i,j}}{D_j \eta}, \quad (7)$$

where $d$ is the covered distance; $D$ signifies the complete driving capacity with a fully charged battery (100%); and $\eta$ denotes the battery efficiency during discharging.

The duration for the battery to reach 100% SoC is presented as

$$t_{ch_{i,j}} = (1 - SoC_{i,j}) \frac{BP_{i,j}}{CP_{i,j} \times \eta}, \quad (8)$$

where $t_{ch_{i,j}}$ is the charging time; $BP_{i,j}$ is the battery capacity (Whr); $CP_{i,j}$ is the charging rate; and $\eta$ is the charger efficiency or overall charging efficiency.

With the known starting time of charge and charging duration, the ending time of charge ($T_{end}$) can be computed as

$$T_{end_{i,j}} = T_{st_{i,j}} + t_{ch_{i,j}}. \quad (9)$$

Now, demand caused by the *i*-th vehicle at time *t* can be given by

$$P_{EV_{i,j}}(t) = \begin{cases} CP_{i,j} : & T_{ST} < T < T_{end} \\ 0 : & \text{otherwise.} \end{cases} \quad (10)$$

Finally, total demand at a particular time can be calculated as

$$P_{EV}(t) = \sum_{j=1}^{N_{types}} \sum_{i=1}^{N_{EV}} P_{EV_{i,j}}(t). \quad (11)$$

## 3. Simulation Setup and Proposed Scenarios

This study included cars (up to seven passengers), pickup trucks, taxis, and minivans. Historical vehicle stocks for each category in Thailand's seven regions were obtained from DLT—Bangkok for the eastern, central, northeastern, northern, western, and southern regions. The total vehicles in the country were first calculated using a vehicle ownership model and, then, allocated proportionally to each region based on historical trends and future potential. Future vehicle ownership was computed under two scenarios: high and low growth, alongside business as usual (BAU). In high-growth scenarios, a real GDP growth of 5% was assumed, while in low-growth scenarios, it was assumed to be 3%. Moreover, a 2% inflation rate (aligned with the Bank of Thailand's inflation target range of 2–3%) was factored in for fuel costs. Table 4 presents an elaboration of the scenarios' particulars. This study comprised three processes (as in Figure 1)): (1) developing a macroeconomic-based vehicle ownership model to derive LDV ownership per thousand population and total kingdom vehicles for a specific year; (2) estimating energy demand, fuel composition, and vehicle emissions through a LEAP simulation model that integrates variables and vehicle numbers from the initial process; (3) determining potential peak EV charging demand by considering driving characteristics, vehicle attributes, and predicted ownership model vehicle numbers.

The LEAP software tool is extensively employed in diverse fields, including integrated energy modeling, water resource management, emissions' estimation from various activities, and generation expansion planning. It serves as an optimization framework in regions worldwide, including China, Europe, Canada, and Australia [45–48].

In this work, we utilized the LEAP software Version 2020.1.0.103 (64 bit) on a PC equipped with an Intel(R) Core (TM) i5-1135G7 processor running at 2.40 GHz to implement the methodology outlined in Section 2.1. This methodology was employed to simulate energy demand, GHG emissions, and fuel composition for the scenarios detailed in Table 4.

Furthermore, we utilized MATLAB R2018b to solve the equations outlined in Section 2.3. To demonstrate the impact of charging schemes on peak load, we selected various combinations of charging modes, ranging from exclusive home charging to widespread public fast charging. For simulation purposes, this article references the Nissan Leaf 2019 EV.

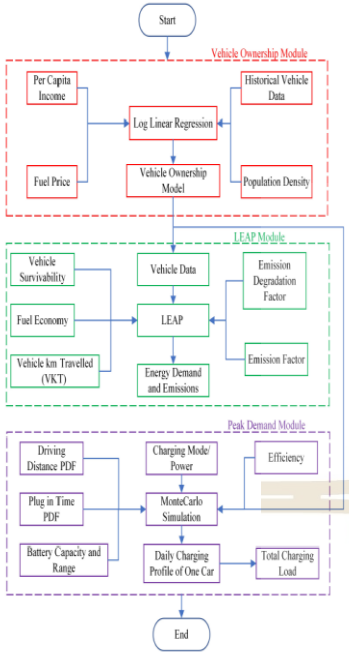

**Figure 1.** Schematic representation delineating the procedural components explored within this study.

**Table 4.** Description of the proposed scenarios.

| No. | Scenarios | Description | Notation |
|---|---|---|---|
| 1 | Business as usual | Continuation of the current trend without any policy intervention. | BAU |
| 2 | High growth and aggressive transition | The objective entails attaining a 5% GDP growth, along with achieving new EV registrations of 50% by 2030 and 100% by 2035. | GDP5A |
| 3 | High growth and moderate transition | Aiming for a 5% GDP growth, the target for new EV registrations includes 30% by 2030, 50% by 2035, and 100% by 2040. | GDP5M |
| 4 | Low growth and aggressive transition | Envisioning a 3% GDP growth, the aspiration is for new EV registrations to attain 50% by 2030 and 100% by 2035. | GDP3A |
| 5 | Low growth and moderate transition | With a projected 3% GDP growth, the objective is to achieve new EV registrations of 30% by 2030, 50% by 2035, and 100% by 2040. | GDP3M |

## 4. Results and Discussion

### 4.1. Simulation Results

In the GDP5 scenario, vehicle ownership in 2040 is projected at approximately 382 per thousand population, while in the GDP3 scenario, it is estimated to be around 338 per thousand population. These figures represent substantial growth of approximately 80% and 59%, respectively, compared to the base year value of 213. Among the three variables, population density exhibits the highest elasticity; however, the Thai population has already peaked and remained relatively stable throughout the study period, resulting in a less-pronounced impact on determining vehicle ownership. Both per capita income and fuel inflation display comparable elasticity values, but with contrasting effects. This implies that a scenario characterized by higher and sustained growth with limited inflationary constraints would be more favorable. Under the BAU scenario, total energy consumption is projected to be 271 TWh in 2040, reflecting a 27% increase compared to the base year energy consumption of 213 TWh (depicted in Figure 2). Notably, the GDP3A scenario is associated with a minimal energy demand of 184 TWh due to fewer vehicles overall, albeit with a relatively higher proportion of EVs. Across all scenarios, energy demand is expected to rise until reaching a peak and, subsequently, decrease in all scenarios except for the BAU scenario. Initially, the proportion of IC vehicles is notably high; over time, the share of EVs in the vehicle fleet increases, contributing to the moderation of energy demand.

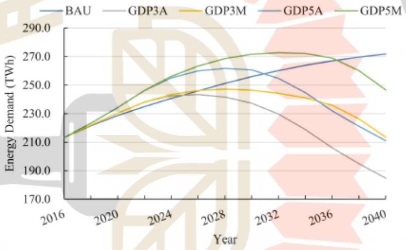

**Figure 2.** Annual energy demand.

Fuel composition is a pivotal consideration within this simulation. Figures 3–7 illustrate the proportionate distribution of each fuel type within the final energy demand. Despite the surge in newly registered EVs, ICVs are projected to maintain dominance over a substantial period. Even in the most-ambitious EV transition scenario (GDP5A) for 2040, fossil fuels are anticipated to contribute to more than 70% of the overall demand. In the BAU scenario, electricity is predicted to account for less than 3% of the demand in 2040. Across scenarios GDP3M, GDP5M, GDP3A, and GDP5A, the share of electricity in the total energy mix is projected to be 16.4%, 17.6%, 27.1%, and 29.4%, respectively. The utilization of diesel sees a notable decline in later years due to the considerably superior fuel efficiency of electric vehicles compared to diesel engines. On the other hand, scenarios show a slight upward trajectory for LPG and CNG consumption.

Table 5 provides a comprehensive depiction of the yearly electricity demand across various scenarios, representing the central parameter of concern in this study. Demand begins to rise after 2022 in all scenarios except for the BAU scenario. The highest projected demand of 62 TWh for 2040 is observed in the GDP5A scenario, closely followed by 50 TWh in GDP3A. This dataset holds pivotal importance for power system expansion planning. Beyond the actual energy demand figures, the annual growth rate is of paramount significance. In the initial stages of the fuel transition, the annual growth consistently exhibits higher rates. However, this aspect may not pose a significant challenge for the power

## 4. Results and Discussion

### *4.1. Simulation Results*

In the GDP5 scenario, vehicle ownership in 2040 is projected at approximately 382 per thousand population, while in the GDP3 scenario, it is estimated to be around 338 per thousand population. These figures represent substantial growth of approximately 80% and 59%, respectively, compared to the base year value of 213. Among the three variables, population density exhibits the highest elasticity; however, the Thai population has already peaked and remained relatively stable throughout the study period, resulting in a less-pronounced impact on determining vehicle ownership. Both per capita income and fuel inflation display comparable elasticity values, but with contrasting effects. This implies that a scenario characterized by higher and sustained growth with limited inflationary constraints would be more favorable. Under the BAU scenario, total energy consumption is projected to be 271 TWh in 2040, reflecting a 27% increase compared to the base year energy consumption of 213 TWh (depicted in Figure 2). Notably, the GDP3A scenario is associated with a minimal energy demand of 184 TWh due to fewer vehicles overall, albeit with a relatively higher proportion of EVs. Across all scenarios, energy demand is expected to rise until reaching a peak and, subsequently, decrease in all scenarios except for the BAU scenario. Initially, the proportion of IC vehicles is notably high; over time, the share of EVs in the vehicle fleet increases, contributing to the moderation of energy demand.

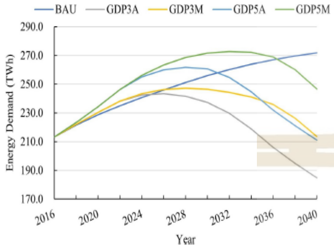

**Figure 2.** Annual energy demand.

Fuel composition is a pivotal consideration within this simulation. Figures 3–7 illustrate the proportionate distribution of each fuel type within the final energy demand. Despite the surge in newly registered EVs, ICVs are projected to maintain dominance over a substantial period. Even in the most-ambitious EV transition scenario (GDP5A) for 2040, fossil fuels are anticipated to contribute to more than 70% of the overall demand. In the BAU scenario, electricity is predicted to account for less than 3% of the demand in 2040. Across scenarios GDP3M, GDP5M, GDP3A, and GDP5A, the share of electricity in the total energy mix is projected to be 16.4%, 17.6%, 27.1%, and 29.4%, respectively. The utilization of diesel sees a notable decline in later years due to the considerably superior fuel efficiency of electric vehicles compared to diesel engines. On the other hand, scenarios show a slight upward trajectory for LPG and CNG consumption.

Table 5 provides a comprehensive depiction of the yearly electricity demand across various scenarios, representing the central parameter of concern in this study. Demand begins to rise after 2022 in all scenarios except for the BAU scenario. The highest projected demand of 62 TWh for 2040 is observed in the GDP5A scenario, closely followed by 50 TWh in GDP3A. This dataset holds pivotal importance for power system expansion planning. Beyond the actual energy demand figures, the annual growth rate is of paramount significance. In the initial stages of the fuel transition, the annual growth consistently exhibits higher rates. However, this aspect may not pose a significant challenge for the power system, as the growth emanates from a low baseline and the actual demand increment is modest at best. Concerns arise when the previous year's demand is relatively high while the growth rate remains notably elevated. After the year 2028, demand across all scenarios, except BAU, embarks on a steep ascent. The growth rate in GDP3M and GDP5M scenarios for the year 2028 hovers around 26% and 27%, subsequently tapering to approximately 14% by 2040. Similarly, the annual growth rates for electricity demand in the years 2028 and 2040 are calculated at 32.6%, 33.6% and 6.9%, 7.1% for GDP3A and GDP5A, respectively. In view of these trends, meticulous planning for power generation and transmission infrastructure becomes imperative to accommodate the mounting additional demand.

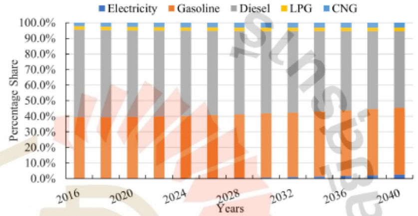

**Figure 3.** Fuel composition in BAU scenario.

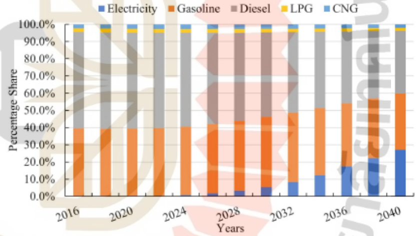

**Figure 4.** Fuel composition in GDP3A scenario.

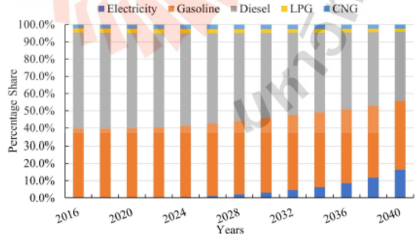

**Figure 5.** Fuel composition in GDP3M scenario.

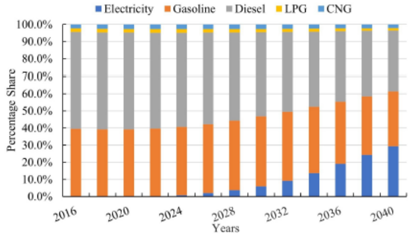

**Figure 6.** Fuel composition in GDP5A scenario.

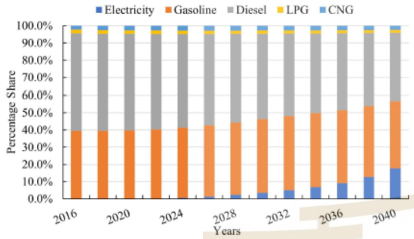

**Figure 7.** Fuel composition in GDP5M scenario.

**Table 5.** Electricity demand by year (TWh).

| Scenarios | 2018 | 2019 | 2020 | 2022 | 2024 | 2026 | 2028 | 2030 | 2032 | 2034 | 2036 | 2038 | 2040 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BAU | 0.0 | 0.1 | 0.2 | 0.3 | 0.6 | 1.0 | 1.4 | 2.0 | 2.7 | 3.5 | 4.5 | 5.5 | 6.7 |
| GDP3A | 0.0 | 0.1 | 0.2 | 0.3 | 1.7 | 4.4 | 8.1 | 12.8 | 19.1 | 27.2 | 35.9 | 43.3 | 50.0 |
| GDP3M | 0.0 | 0.1 | 0.2 | 0.3 | 1.2 | 2.8 | 5.1 | 7.9 | 11.3 | 15.2 | 20.0 | 26.8 | 35.0 |
| GDP5A | 0.0 | 0.1 | 0.2 | 0.4 | 2.0 | 5.2 | 9.7 | 15.6 | 23.4 | 33.4 | 44.3 | 53.7 | 62.1 |
| GDP5M | 0.0 | 0.1 | 0.2 | 0.4 | 1.4 | 3.3 | 6.1 | 9.6 | 13.8 | 18.7 | 24.7 | 33.2 | 43.5 |

Regarding emission estimation, the focus lied on four primary pollutants: carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), and particulate matter (PM10). Figures 8–11 provide an overview of the estimations for $CO_2$, CO, $NO_x$, and PM10 emissions. In the base year, $CO_2$ emissions are approximately 45-billion kg and are projected to exhibit significant declines in all scenarios except for BAU, where a marginal increase of 1-billion kg is anticipated. It is worth noting that both the GDP5A and GDP5M scenarios initially witness higher emissions compared to BAU due to the prevalence of IC vehicles. Nevertheless, as the share of EVs becomes more substantial over time, emissions start to sharply decrease. These estimations were based on the assumption of no further policy interventions related to emission standards. The implementation of more-robust emission standards could result in further emission reductions. Notably, a notable drop is evident in CO, $NO_x$, and PM10 emissions during specific years. This anomaly arises from the retirement of all remaining vehicles adhering to previous emission standards. Such reductions occur precisely 20 years after the introduction of new emission standards to replace the existing ones.

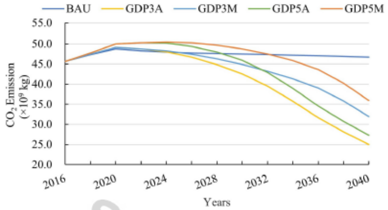

**Figure 8.** $CO_2$ emission projection.

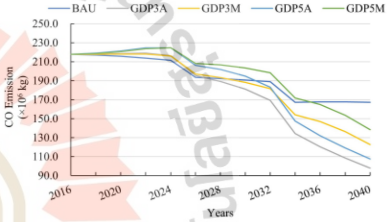

**Figure 9.** CO emission projection.

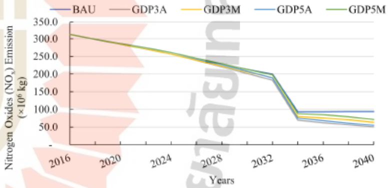

**Figure 10.** $NO_x$ emission estimation.

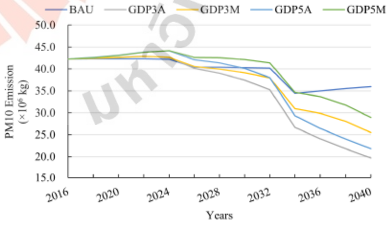

**Figure 11.** PM10 emission projection.

Charging load is contingent on three key variables: charging rates, charging time, and battery SoC. This study considered three charging modes: home charging, office charging, and public charging. The assessment employed the 2019 Nissan Leaf EV battery as a reference and assumed double-speed charging with a Type II charger for both home and office charging. For public charging, it was presumed that the battery will reach up to 80% charge within 30 min. Given the substantial variations in charging rates across each mode, peak demand correspondingly fluctuates. Figure 12 illustrates such variations, displaying the charging load for 10,000 vehicles on a typical day across different combinations of charging modes. It is posited that 5% of vehicles will charge at the office, with the remaining distributed between home and public charging.

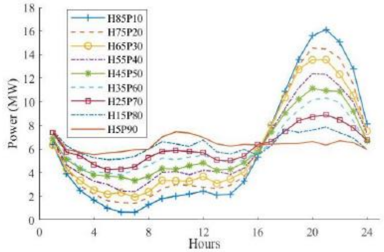

**Figure 12.** Charging demand variation due to the selection of various combinations of charging modes.

Figure 12 displays a substantial range of peak power demand variations. Should 90% of vehicles opt for public charging stations, the peak power demand would be approximately 7.4 MW. In contrast, the adoption of public fast charging by only 10% would result in a peak power demand of approximately 16.1 MW. Optimizing this configuration over an extensive time frame poses considerable challenge due to the evolving nature of EV technology, making accurate future predictions challenging. Nonetheless, the proliferation of public charging stations is poised for exponential growth in the forthcoming decade. To address this, the analysis focused on two extreme conditions: the worst-case scenario (85% home charging) and the best-case scenario (90% public charging station). Tables 6 and 7 outline the projected additional peak demand attributed to the transition to electric vehicles for the worst-case and best-case scenarios, respectively.

In 2020, demand across all scenarios remains relatively consistent due to the comparable total vehicle counts. However, peak demand is anticipated to experience substantial growth across the board, as outlined in Tables 6 and 7. By 2040, the GDP5A scenario could introduce over 21,000 MW of additional load if home charging predominates. Conversely, with an extensive adoption of public fast charging stations, this demand could be confined to around 9348 MW.

**Table 6.** Additional peak demand estimation based on the selection of the charging scheme: worst case additional peak demand (MW).

| **Scenarios** | **2020** | **2025** | **2030** | **2035** | **2040** |
|---|---|---|---|---|---|
| BAU | 57 | 266 | 721 | 1468 | 2533 |
| GDP3A | 59 | 768 | 3742 | 9967 | 17,258 |
| GDP3M | 59 | 535 | 2329 | 5560 | 11,613 |
| GDP5A | 62 | 897 | 4537 | 12,265 | 21,368 |
| GDP5M | 62 | 621 | 2817 | 6831 | 14,387 |

**Table 7.** Additional peak demand estimation based on the selection of the charging scheme: best case additional peak demand (MW).

| **Scenarios** | **2020** | **2025** | **2030** | **2035** | **2040** |
|---|---|---|---|---|---|
| BAU | 25 | 116 | 315 | 642 | 1108 |
| GDP3A | 25 | 336 | 1637 | 4360 | 7550 |
| GDP3M | 25 | 234 | 1018 | 2432 | 5081 |
| GDP5A | 27 | 392 | 1985 | 5365 | 9348 |
| GDP5M | 27 | 271 | 1232 | 2988 | 6294 |

### *4.2. Discussion*

In the high-growth scenario, the projected number of vehicles in 2040 is approximately 27-million, whereas it is expected to be limited to around 23-million in a slower economy scenario. However, a previous study [35] projected a higher value for the same year, approximately 14% higher than the estimate in this paper. This difference could be attributed to the consideration of a 20-year retirement period in this study. Conversely, the estimate of 19-million vehicles for 2030 in another study [32] aligns closely with the current projection of 20-million. The Energy Efficiency Plan (EEP) 2015 has set an energy-saving target of 351 TWh for the entire transportation sector by 2036 [27]. The most-aggressive EV promotion scheme can contribute to saving approximately 36 TWh (around 10%) from the LDV segment alone, highlighting the significant potential of EVs in energy efficiency programs.

It is important to note that electrical power demand represents less than one-third of total energy consumption, with demand expected to continue rising beyond 2040. The widespread use of home charging poses challenges for system operators and utilities, highlighting the need for robust fast charging infrastructure. Strategies such as improved charging technology, battery swapping, V2G technology, time-of-use pricing, and real-time tariffs can help address excessive home charging.

PDP2018's official 2037 projections are 367.4 TWh for electrical energy demand, 77.2 TW for installed capacity, and 54 TW for peak load. These projections are based on 1.2-million EVs by 2030, but do not consider a ban on IC vehicles by 2035. The highest EV projection for 2030 is 2.83-million in the GDP5A scenario, requiring 15.6 TWh annually and 4537 MW of extra peak demand in the worst charging configuration. These demands seem manageable within PDP2018's limits until 2030. However, the LDV numbers surge after 2030, leading to significant demand growth in both annual demand and peak load. PDP2018 may not accommodate this growth, suggesting a need for future revisions.

In comparison, unlike [35], this article estimated around 26-million LDVs in 2037, 14% lower, possibly due to varying survival probability profiles. This study assumed a 20-year vehicle lifespan, removing any remaining vehicles after this period. However, Reference [32] projected 19-million LDVs for 2030, closely aligning with our current estimate of 20-million.

The study highlighted TIEB's ability to meet the additional energy and power demand from the EV transition in the medium term. It also emphasized the impact of uncoordinated charging on peak load and suggested that widespread use of public fast charging could help manage peak demand. This information may prompt authorities to accelerate public charging infrastructure development. While the reduction in overall power demand aligns with energy efficiency goals, electricity's share in total energy demand remains below one-third even in the most-favorable scenario.

## 5. Conclusions

In this paper, we presented a scenario-based LEAP model that integrated EV growth potential and penetration rates to forecast future energy demand, fuel composition, and GHG emissions. Thailand served as the case study, and the key findings were as follows:

- Vehicle ownership has steadily increased, albeit subject to the country's future economic performance.

- In almost all scenarios, the overall energy demand will be significantly lower than in the BAU scenario, aligning with energy efficiency policy goals. However, even in the most-favorable scenario, the share of electricity in total energy demand remains below one-third.
- This article also highlighted potential challenges associated with EV introduction into the electrical generation system. Uncoordinated home charging could pose significant issues for the system operator by causing a considerable rise in peak demand. However, widespread use of public fast charging could help mitigate peak demand.
- Despite TIEB only considering a 30% EV penetration rate in 2030, the proposed generation infrastructure could potentially support even the most-aggressive EV transition scenario described in the article in the medium term, especially if fast charging becomes widespread.
- In all scenarios, vehicle exhaust emissions are significantly lower compared to both the BAU scenario and the base-year emission levels.

This article underscored the significance of rapid public charging infrastructure in shaping peak charging demand, emphasizing the need for its prioritized development. Despite various transition scenarios, the share of electricity in the fuel mix remained below one-third due to the presence of older IC vehicles. Future policies aimed at phasing out these IC vehicles before their useful life ends are recommended to enhance emission reduction efforts. It is worth noting that this article did not consider the implementation of stricter emission standards, solely demonstrating the impact of EV adoption on emission reduction. Even without such standards, emissions decreased notably, but introducing new standards could further limit emissions.

Future research will prioritize the development of an optimal coordinated charging scheme and a new power development plan, aligned with the outcomes of the optimized charging scheme featuring increased renewable energy integration. This analysis will yield insights into the net emission reduction resulting from EV promotion, serving as a crucial test of the program's effectiveness in fulfilling climate commitments.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| IC | Internal combustion |
| LDV | Light-duty vehicle |
| LEAP | Low Emission Analysis Platform |
| SoC | State-of-charge |
| ZEV | Zero-emission vehicle |
| TIEB | Thailand Integrated Energy Blueprint |
| PDP | Power Development Plan |
| AEDP | Alternative Energy Development Plan |
| EEP | Energy Efficiency Plan |
| V2G | Vehicle-to-grid |
| ED | Energy demand |
| FE | Fuel economy |
| HEV | Hybrid electric vehicle |
| BEV | Battery electric vehicle |
| VO | Vehicle ownership |
| PCI | Per capita income |
| FP | Fuel price |

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# APPENDIX J Introduction of LEAP and model used

Figure A: LEAP logo

LEAP (Low Emissions Analysis Platform), developed by the Stockholm Environment Institute, is a widely used tool for energy policy analysis and climate change mitigation. Adopted by thousands of organizations across over 190 countries, its users include governments, academics, NGOs, consultants, and utilities. LEAP is utilized for various scales, from local to global, and is becoming a standard for integrated resource planning and GHG mitigation, especially in developing countries. It supports reporting to the UNFCCC, with 32 countries using LEAP for their INDCs, which is crucial for the Paris climate agreement.

LEAP is a comprehensive modeling tool that analyzes energy consumption, production, and resource extraction across all economic sectors. It enables tracking of both energy and non-energy sector GHG emissions and sinks. Beyond GHGs, LEAP also assesses local and regional air pollutants and short-lived climate pollutants (SLCPs), making it ideal for evaluating the climate benefits of reducing local air pollution.

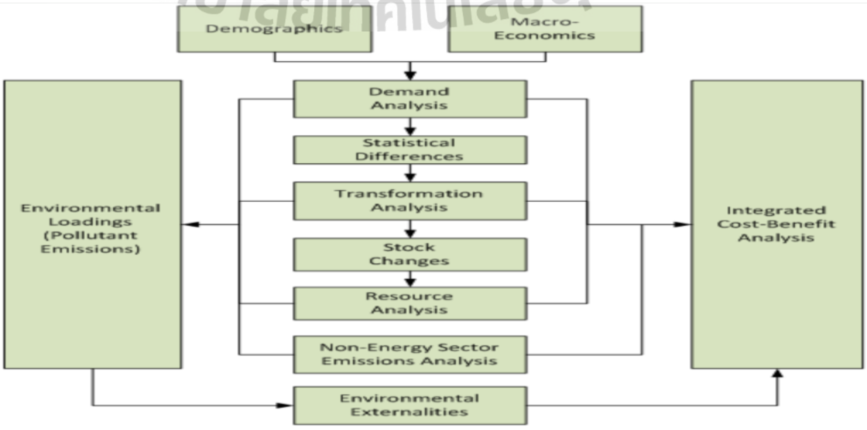
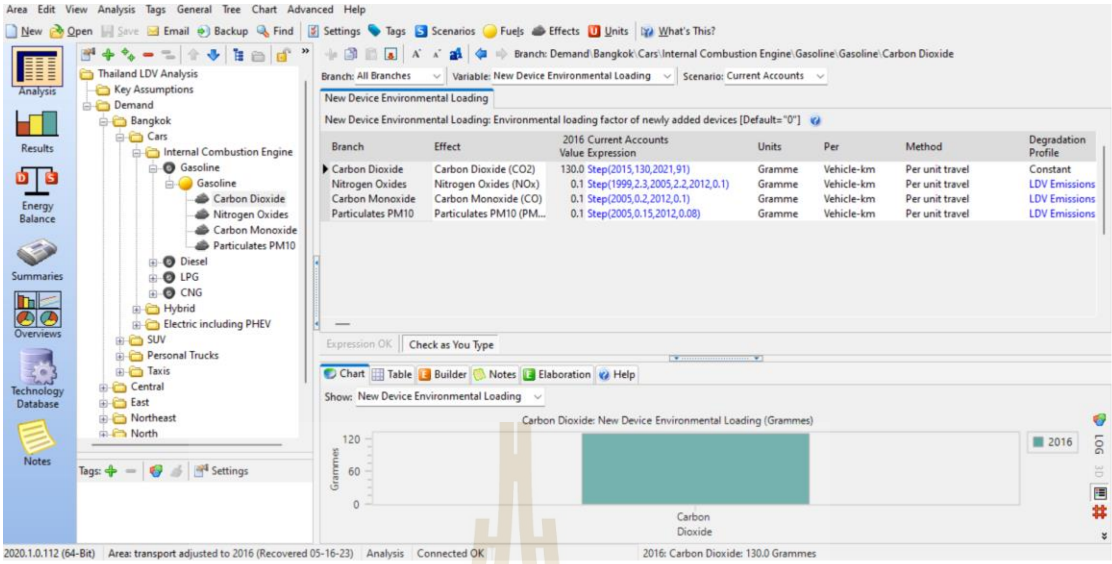


Figure B LEAP architecture in integrated resource planning mode

A model developed in this study is presented below:



Branch: Demand\Bangkok\Cars\Internal Combustion Engine\Gasoline\Gasoline\Carbon Dioxide

Branch: All Branches   Variable: New Device Environmental Loading   Scenario: Current Accounts

New Device Environmental Loading

New Device Environmental Loading: Environmental loading factor of newly added devices [Default="0"]

| Branch | Effect | 2016 Current Accounts Value | Expression | Units | Per | Method | Degradation Profile |
|---|---|---|---|---|---|---|---|
| Carbon Dioxide | Carbon Dioxide (CO2) | 130.0 | Step(2015,130,2021,91) | Gramme | Vehicle-km | Per unit travel | Constant |
| Nitrogen Oxides | Nitrogen Oxides (NOx) | 0.1 | Step(1999,2.3,2005,2.2,2012,0.1) | Gramme | Vehicle-km | Per unit travel | LDV Emissions |
| Carbon Monoxide | Carbon Monoxide (CO) | 0.1 | Step(2005,0.2,2012,0.1) | Gramme | Vehicle-km | Per unit travel | LDV Emissions |
| Particulates PM10 | Particulates PM10 (PM... | 0.1 | Step(2005,0.15,2012,0.08) | Gramme | Vehicle-km | Per unit travel | LDV Emissions |

Show: New Device Environmental Loading

2020.1.0.112 (64-Bit)   Area: transport adjusted to 2016 (Recovered 05-16-23)   Analysis   Connected OK   2016: Carbon Dioxide: 130.0 Grammes

Figure C Tree diagram developed for the study

Steps involved in the model development

1. Get vehicle data of seven regions of Thailand (stock and future growth) **(APPENDIX B, APPENDIX D, section 3.3)**
2. Type of vehicle (car, SUV, trucks and taxis) **(APPENDIX A)**
3. Vehicle by fuels **(APPENDIX C)**
4. Develop a mathematical model about energy demand and GHG emission **(section 3.2)**
5. Develop a tree diagram and enter the necessary data **(Figure C)**
6. Form scenarios (future sales, EV penetration etc.) **(section 4.4.1)**

# BIOGRAPHY

Ashok Paudel earned his B.Eng. degree in Electrical Engineering from Tribhuvan University, Nepal, in 2017. In 2018, he continued his academic journey at Suranaree University of Technology, Nakhon Ratchasima, Thailand, where he obtained a master’s degree in electrical engineering and started his pursuit of a doctoral degree subsequently. His research interests encompass distributed generation, energy trading, electric vehicles, integrated resource planning, energy policy, sustainable energy transition and smart grid technology.