Cylinder: Jurnal Ilmiah Teknik Mesin
Volume 10, Nomor 02 Oktober 2024
ISSN 2252-925X (Online)

Integration of Electric Drive Systems in ICE to EV Conversion: A GT-Suite Approach

Yosua Setiawan[1], Mohd Farid[2]
[1] Department of Mechanical Engineering, Atma Jaya Catholic University of Indonesia
[2] Automotive Development Centre, Universiti Teknologi Malaysia
E-mail: yosua.setiawan@atmajaya.ac.id

ABSTRAK

Penelitian ini berfokus pada konversi kendaraan mesin pembakaran internal (ICE) menjadi kendaraan listrik (EV) menggunakan simulasi GT-Suite, dengan fokus pada integrasi sistem penggerak listrik. Dengan meningkatnya emisi CO_2 global, banyak negara berupaya mencapai netralitas karbon, sehingga peralihan ke elektrifikasi menjadi sangat penting. Meskipun kendaraan listrik baterai (BEV) baru menghasilkan emisi gas rumah kaca (GHG) yang lebih rendah, biaya produksi EV yang tinggi masih menjadi penghalang adopsi secara luas. Oleh karena itu, mengonversi kendaraan ICE yang ada menjadi EV muncul sebagai strategi yang lebih hemat biaya dan ramah lingkungan. Penelitian ini menggunakan Toyota Avanza sebagai model dasar, menggantikan mesin ICE dengan motor AC Sinkron dan baterai LiFePO4. Hasil simulasi menunjukkan kinerja yang kompetitif dengan waktu akselerasi 0-100 km/jam dalam 14 detik, kecepatan maksimum 190 km/jam, dan perkiraan jarak tempuh 310 km. Penelitian ini menunjukkan bahwa konversi ICE ke EV dapat mempercepat transisi ke transportasi berkelanjutan.

Kata kunci : Konversi; Kendaraan Listrik; Simulasi; GT-Suite

ABSTRACT

This study was focus on converting internal combustion engine (ICE) vehicles to electric vehicles (EVs) using GT-Suite simulations, focusing on the integration of electric drive system. With increasing global CO_2 emissions, many nations aim to achieve carbon neutrality, making the shift to electrification crucial. While new battery electric vehicles (BEVs) produce significantly lower greenhouse gas (GHG) emissions, the high costs associated with new EV production remain a barrier to widespread adoption. Thus, converting existing ICE vehicles into EVs emerges as a more cost-effective and environmentally beneficial strategy. Using Toyota Avanza as a base model, replacing the ICE with a Synchronous AC motor and a LiFePO4 battery pack. Simulation results indicate competitive performance, with a 0-100 km/h acceleration time of 14 seconds, a top speed of 190 km/h, and an estimated driving range of 310 km. This study demonstrates that ICE-to-EV conversions can accelerate the transition to sustainable transportation.

Keywords *: Conversion; Electric Vehicle; GT-Suite; Simulation;*

1. **Introduction**

With increasing of global economic power, it has been reported that the greenhouse gases have been increasing as well. Therefore, nations agree to reduce their CO_2 emissions to limit the global average temperature to 1.5°C above pre-industrial levels [1]. Many automotive companies have already implemented a target to be carbon neutral in 2030 by electrification (producing more hybrid and electric vehicles). Because, electric vehicles produce 17-30% lower greenhouse gases (GHG) emissions compare to petrol and diesel car [2].

This is in line with the increase in sales of electric vehicles in the world, for example sales of electric vehicle in the first half of 2021 was increased 160% higher than last year [3]. Not only in major countries, increasing sales of electric vehicles (EV's) also happened in developing countries like Thailand, Malaysia, and Indonesia [4]. In Thailand, it was predicted that in 20 years electric vehicles sales in Thailand will increase from 0.23 to 2.1 million vehicles [4]. This trend also shown in China with increasing of battery demand every year from 2011 to 2016 as shown in [5].

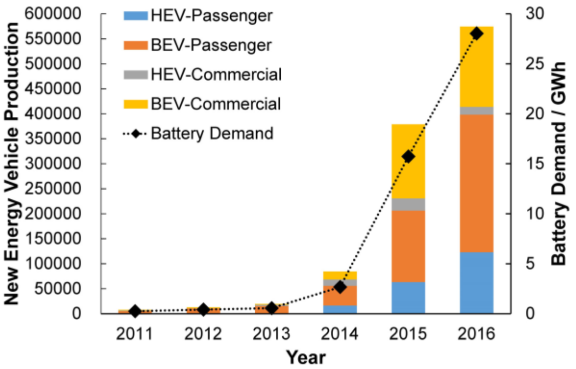

Figure 1. Battery demand in China from 2011 to 2016 [5].

Increase in EV's sales reportedly still grow even during pandemic in 2020, study by Lieven and Huegler [6] shown that EV's sales still growing because of environmental awareness and subsidies by government [7,8]. Figure 2, shown that in 2020 total vehicles sales in the world was decreased compared to their 2020 forecast and total sales in 2019. Meanwhile, EV's sales alone have exceeded the forecast sales in 2020 by 500 thousand cars even during pandemic. Even though EV's sales increased, Asia Pacific and rest of the world are still lagging behind compared to United States and European Countries [9].

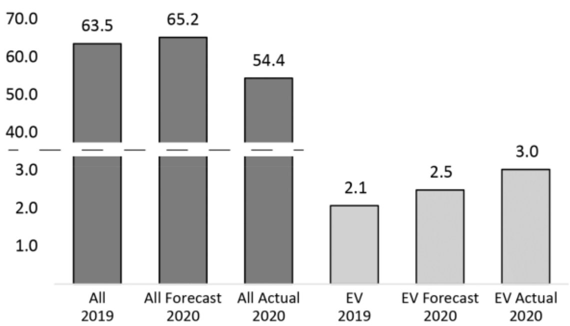

Figure 2. Sales forecasts and actual sales for all vehicles versus only EVs 2019-2020 (in million cars) [6].

Based on research done by Verma, et al. [10] in India, it was shown that battery electric vehicles (BEVs) have the lowest life-cycle GHG emissions. With the current situation of India source of electricity, BEVs have lower GHG emissions by 19-34% compared to average new gasoline cars. Meanwhile, hybrid electric vehicles (HEVs) only reduce the life-cycle GHG emissions by 20%.

Study by Qiao, et al. [11] shown that in China, to produce one medium size passanger car, it produce 15,005 kg CO_2eq for a BEV with an NMC battery and 15,174 kg CO_2eq for an EV with an LFP battery. This means, to produce BEV, it requires around 50% more CO_2eq compared to ICE car which is around 9985 kg CO_2eq. Most of the additional CO_2eq came from battery production.

Although newly developed Battery Electric Vehicles (BEVs) have demonstrated a significant reduction in CO2 emissions, the most feasible and immediate approach to addressing the emissions from the road transport sector is to increase BEV production and adoption. However, the high costs associated with manufacturing brand new BEVs present a considerable barrier to widespread adoption. Compared to traditional Internal Combustion Engine (ICE) vehicles, BEVs are still considered to be relatively expensive, making them less accessible to a large segment of consumers. Additionally, the development process for new BEV models is costly and time-consuming, requiring substantial investment in research, infrastructure, and production technologies.

Given these challenges, an alternative solution that has gained traction is the conversion of existing ICE vehicles into BEVs. This method involves retrofitting traditional vehicles with electric powertrains, which is proving to be a more cost-effective and resource-efficient approach. By repurposing ICE vehicles instead of developing new BEVs from the ground up, manufacturers and vehicle owners can significantly reduce the overall expenses associated with electrification. Converting ICE vehicles to BEVs not only extends the lifespan of current automobiles but also offers a faster pathway to reducing emissions from the current fleet of road transport vehicles. This strategy, therefore, represents a reasonable and economically viable solution for accelerating the transition to a lower-emission transportation system [12] .That is why, converting from internal combustion engine (ICE) to EV is interesting because it could reduce overall life-cycle of GHG emissions for that car.

Energy storage, particularly in the form of battery systems, is widely recognized as one of the most crucial and sensitive components in the development of Battery Electric Vehicles (BEVs). The role of batteries in BEVs extends beyond merely storing and supplying power; they also significantly influence the vehicle's safety, efficiency, and overall performance. However, one of the inherent challenges associated with battery systems is their propensity to generate excessive heat during both charging and discharging cycles. This heat buildup, if left unchecked, can lead to safety hazards such as thermal runaway—an uncontrollable reaction within the battery that can result in overheating, fires, or even explosions.

Ferrero, *et al*. [13] highlighted that the fundamental challenge for electric vehicle batteries lies in ensuring that they can support high mileage, rapid charging, and efficient energy utilization. Among the various battery types available, Lithium-ion batteries are widely regarded as the most suitable option for electric vehicles due to their high energy density and reliability. However, despite their advantages, Lithium-ion batteries still produce significant heat during operation, necessitating an effective thermal management strategy. According to research [14], the optimal operating temperature for these batteries ranges from 15°C to 35°C. If the battery temperature falls outside this range—either too low or too high—adverse effects on performance and longevity are observed. For instance, charging at low temperatures can result in reduced driving range, while sustained high temperatures accelerate battery degradation, shortening its usable life. Figure 1 illustrates the optimal operating conditions for Lithium-ion batteries, emphasizing the importance of temperature regulation.

Moreover, battery temperature management is directly linked to the overall life cycle of the battery pack. As demonstrated in a study conducted by Tete, et al. [15], the life cycle of a standard Lithium-ion battery was measured to be approximately 3,323 cycles at 45°C but dropped dramatically to just 1,037 cycles when the operating temperature increased to 60°C. This stark difference highlights the detrimental impact of elevated temperatures on battery durability. Nonetheless, it is noteworthy that some advanced battery chemistries, such as Lithium Iron Phosphate (LiFePO4), offer greater thermal stability. Cao, et al. [16] found that LiFePO4 batteries, although experiencing a higher initial degradation rate when exposed to 55°C, demonstrated a slower degradation rate over time compared to standard Lithium-ion cells at 25°C after 600 cycles shown in **Figure 3**. This behavior makes LiFePO4 batteries a favorable option for automotive applications, where high temperatures are often encountered, and durability is a key concern.

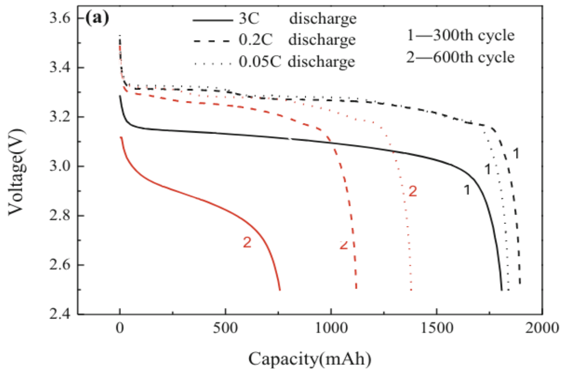

Figure 3. Battery degradation of LiFePo4 at 25°C [16].

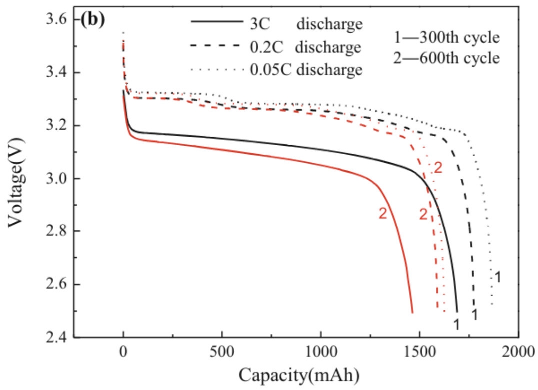

Figure 4. Battery degradation of LiFePo4 at 55°C [16].

Figure 4 further illustrates this phenomenon, showing that while LiFePO4 batteries degrade more rapidly at 55°C during the first 300 cycles, their performance stabilizes afterward, indicating better high-temperature tolerance than conventional Lithium-ion chemistries. Such characteristics make LiFePO4 batteries an attractive choice for automotive use, particularly in scenarios requiring high power output and extended cycle life. Consequently, selecting the appropriate battery type, along with implementing an effective thermal management system, is crucial for optimizing the performance and safety of BEVs.

2. RESEARCH METHODOLOGY

The author selected the Toyota Avanza as the base vehicle for conversion from an internal combustion engine (ICE) to an electric vehicle (EV) due to its widespread popularity and availability in Indonesia. The chosen vehicle was a 1.3-liter variant equipped with a manual transmission, originally producing 93 horsepower and 120 Nm of torque. To match the original vehicle's performance, it was essential to identify an electric motor with comparable specifications. For the EV conversion, a Synchronous AC motor was used, delivering a maximum power of 60 kW and a rated power of 33 kW with efficiency rated at 95%. The motor provides 220 Nm of torque and is capable of reaching a maximum rotational speed of 12,000 rpm. **Table 1** presents the specifications of the converted vehicle, detailing both the electric motor and the battery pack configuration.

Table 1. Converted toyota avanza specification

Vehicle Parameter	Values	Unit
Vehicle Gross Weight	1250	kg
Aerodynamic drag coefficient	0.3	
Frontal Area	2.23	m^2
Final Drive Gear Ratio	5.125	
Transmission Gear Ratio	1.376	
Motor Voltage	260-410	V
Max Torque	220	Nm
Peak Power	60	kW
Battery Pack Rated Voltage	268.8	V
Battery Pack Capacity	40.32	kWh

Based on the specifications outlined in Table 1, a detailed model was developed using GT-Suite. The resulting vehicle model is shown in **Figure 5**. The simulation was conducted utilizing the electric vehicle template available in GT-Suite. Although the template provided a solid foundation, several parameters had to be modified to achieve accurate simulation results that aligned with the specifications of the converted vehicle. For instance, the final drive ratio was adjusted to reflect the use of the stock differential from the original car. The transmission system of the converted EV retained the vehicle's stock 5-speed manual gearbox, with the third gear being selected for the simulation as it offered an optimal balance between acceleration and top speed. Transmission efficiency typically ranges from 85% to 90% depending on the condition of the gearbox and the operational mode. Mechanical losses in the transmission occur due to friction between moving parts, and this needs to be accounted for in the simulation to ensure realistic energy consumption.

In GT-Suite, transmission losses can be modeled by defining efficiency maps for each gear. These maps indicate the percentage of mechanical energy lost during power transfer from the motor to the wheels. In this simulation, losses in the final drive gear ratio and differential were also considered to accurately predict the vehicle’s powertrain efficiency under different load conditions. Efficiency was used at 90% for this simulations. Even though the clutch plays a less significant role in electric vehicles than in ICE vehicles, it is still considered in the simulation when modeling the transition between gears. The clutch efficiency refers to how effectively power is transferred without excessive slipping. GT-Suite provides models for clutch behavior, and efficiency losses during engagement and disengagement can be simulated. These losses typically range from 2% to 5%, depending on the system's design and condition.

Regarding the battery pack configuration, the author opted for a LiFePO4 chemistry due to its suitability for a wide range of temperature conditions. The battery pack consists of 84 cells, each with a capacity of 105 Ah, resulting in a total battery capacity of 40.32 kWh for the converted EV.

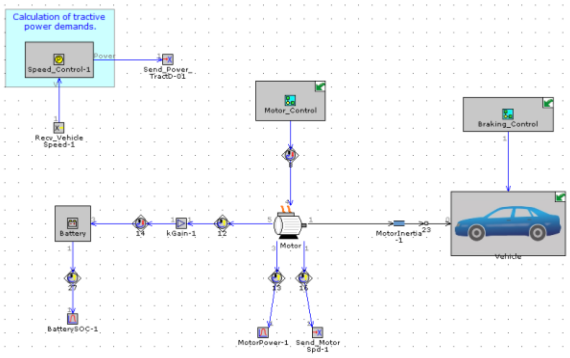

Figure 5. GT-Suite main model map for Toyota Avanza.

The simulation in GT-Suite follows a modular approach where various vehicle components are modelled independently and then integrated into the overall system. The electric drive system consists of the motor, battery pack, transmission, and braking systems, all of which are dynamically modelled.

1. **Vehicle Model Setup**: The Toyota Avanza's specifications, such as vehicle mass, aerodynamic drag coefficient, frontal area, and gear ratios, were input into the simulation. GT-Suite offers a pre-built template for electric vehicles, but customizations were made to accurately reflect the vehicle's mechanical systems, such as the use of the stock 5-speed transmission.

2. **Motor and Battery Parameters**: A synchronous AC motor was chosen for its high torque at low speeds and consistent power delivery across a wide range of RPMs. The motor provides a peak power of 60 kW with a torque output of 220 Nm. The **battery pack**, composed of LiFePO4 cells, was modeled with a capacity of 40.32 kWh and a nominal voltage of 268.8 V. GT-Suite's battery model allows for dynamic analysis of charge and discharge cycles, temperature effects, and power output.

3. **Dynamic Simulations**: The vehicle was simulated under the **New European Driving Cycle (NEDC)** to evaluate performance metrics such as acceleration, top speed, and range. During the simulation, GT-Suite calculates power demand from the motor, energy draw from the battery, and losses due to mechanical inefficiencies in the transmission and other components. For instance, during acceleration, the system considers the instantaneous torque from the motor, as well as transmission losses, to predict the vehicle's speed and battery consumption.

4. **Regenerative Braking**: While not detailed in the document, regenerative braking could be incorporated into the simulation. This would involve modeling the braking system to capture energy during deceleration, feeding it back into the battery, which reduces overall energy consumption and extends the driving range.

3. RESULTS AND DISCUSSION

3.1 Acceleration and Top Speed Test

Electric vehicles (EVs) typically exhibit superior acceleration compared to conventional internal combustion engine (ICE) vehicles. This advantage is primarily attributed to the unique characteristics of electric motors, which provide linear acceleration and instantaneous torque delivery.**Figure 6** illustrates the acceleration performance of the converted EV based on simulation results, showing that the vehicle achieved 0 to 100 km/h in approximately 14 seconds. As observed in the graph, the acceleration profile is linear throughout the 0 to 100 km/h range.

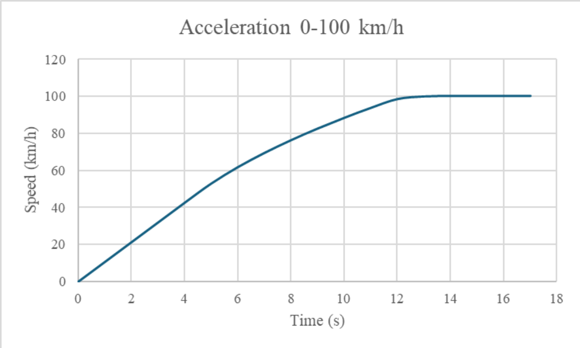

Figure 6. Acceleration 0-100 km/h on converted EV.

In terms of top speed, the converted Toyota Avanza reached a maximum speed of 190 km/h, as depicted in **Figure 7**. The simulation indicated that the acceleration from 0 to 190 km/h took approximately 43 seconds. At this top speed, the motor operated at 11,850 rpm, which is near its maximum allowable rotational speed. Additionally, the motor's efficiency was recorded at 83% when traveling at 190 km/h. When operating at 100 km/h—the maximum legal speed limit in Indonesia—the motor's efficiency was slightly lower, at 78%.

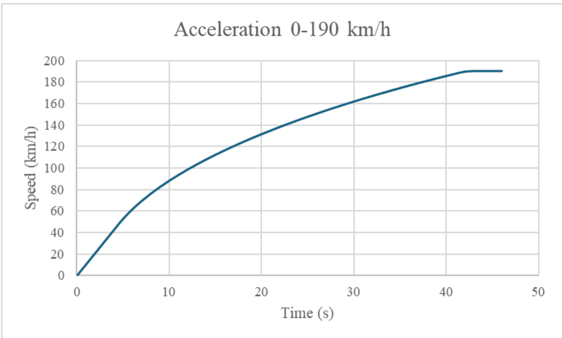

Figure 7. Acceleration 0-190 km/h on converted EV.

3.2 Range of the Electric Vehicle

One of the most famous and common driving cycle for automobile testing is new European driving cycle. The New European Driving Cycle (NEDC) test procedure allows a vehicle to achieve a maximum speed of up to 120 km/h during its operation. In terms of duration, the complete NEDC test cycle spans a total of 1180 seconds, providing a comprehensive evaluation of the vehicle's performance across various speed and load conditions. This cycle was used to test how far the vehicle can run from fully charge until the battery completely flat. In this study, the car was run from 100% State of Charge (SoC) to 50% SoC as shown in **Figure 8**.

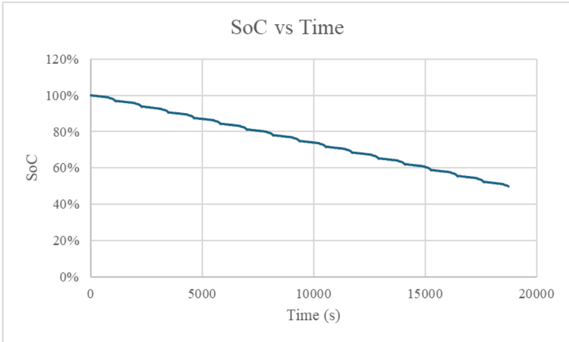

Figure 8. SoC vs Time from 100% to 50%.

When the vehicle was simulated operating from a 100% State of Charge (SoC) to 50% SoC, the measured distance covered was 172.8 km, as depicted in **Figure 9**. Extrapolating from this data, the total estimated driving range of the converted electric vehicle (EV) from 100% to 0% SoC would be approximately 345.6 km (or around 345 km). As outlined in the methodology, the total battery pack capacity for this converted EV is 40.32 kWh. By dividing the driving range by the battery capacity, the energy consumption rate for this EV was calculated to be 8.55 km per kWh.

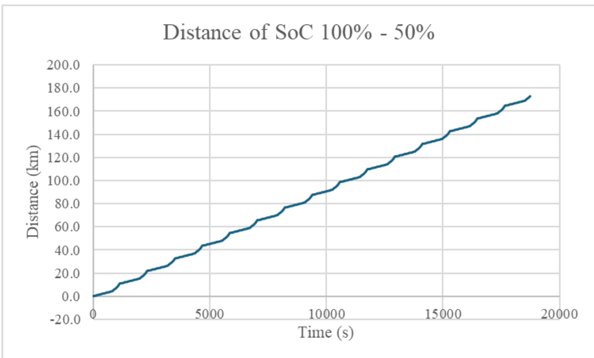

Figure 9. Distance from 100% SoC to 50% SoC.

However, in practical applications, the entire battery capacity cannot be utilized fully from 100% to 0% SoC due to the need to maintain battery health and longevity.

Manufacturers typically limit the SoC range to a minimum of 10% to prevent over-discharge and to extend the battery's lifecycle. This means only 90% of the battery's capacity is usable, which equates to approximately 36.3 kWh. When multiplied by the vehicle's efficiency, the actual usable driving range for this converted EV is estimated to be around 310 km under real-world conditions.

CONCLUSION

The research successfully demonstrated the feasibility of converting a conventional internal combustion engine (ICE) vehicle into an electric vehicle (EV) using the Toyota Avanza as a base model. The conversion was performed using a Synchronous AC motor with a peak power of 60 kW and a LiFePO4 battery pack with a total capacity of 40.32 kWh. The resulting converted EV exhibited competitive performance metrics, achieving a 0 to 100 km/h acceleration time of 14 seconds and a top speed of 190 km/h, indicating its suitability for urban and highway driving conditions.

The energy consumption of the converted EV was found to be 8.55 km per kWh based on simulations conducted under the New European Driving Cycle (NEDC) test procedure. From a 100% to 50% State of Charge (SoC), the vehicle covered a distance of 172.8 km, translating to an estimated total range of approximately 345 km from a fully charged battery. However, due to practical limitations and to ensure battery longevity, only 90% of the battery’s capacity can be utilized, resulting in a more realistic driving range of around 310 km.

However, several factors could further optimize the efficiency and performance of the converted vehicle:

1. **Transmission Efficiency**: Although the stock manual transmission was retained, an optimized transmission system tailored for electric vehicles, such as a single-speed reduction gear, could reduce mechanical losses and improve efficiency. Future work could explore the impact of transmission optimization on energy consumption and vehicle dynamics.
2. **Regenerative Braking**: The incorporation of regenerative braking was not thoroughly examined in this study. Adding this feature could enhance energy recovery during braking, leading to increased range. Simulating different regenerative braking strategies in GT-Suite could provide insights into how much energy can realistically be recaptured.
3. **Battery Thermal Management**: While LiFePO4 batteries offer improved thermal stability, they still experience degradation at high temperatures. A detailed study into the implementation of battery thermal management systems (BTMS), including liquid cooling and phase change materials, could prevent overheating, extend battery life, and improve performance under heavy load conditions.

By addressing these factors, future ICE-to-EV conversions can achieve even higher performance levels and efficiency, contributing to the broader goal of promoting sustainable transportation.

REFERENCES

[1] G. Liobikienė and M. Butkus, "The European Union possibilities to achieve targets of Europe 2020 and Paris agreement climate policy," *Renewable Energy*, Article vol. 106, pp. 298-309, 2017, doi:10.1016/j.renene.2017.01.036.
[2] E. E. Agency. "Electric vehicles." https://www.eea.europa.eu/en/topics/

in-depth/electric-vehicles (accessed 25 October, 2023).

[3] S. Mallick and D. Gayen, "Thermal behaviour and thermal runaway propagation in lithium-ion battery systems – A critical review," *Journal of Energy Storage*, vol. 62, p. 106894, 2023/06/01/2023, doi:https://doi.org/10.1016/j.est.2023.106894.

[4] T. Chinda, "Long-term trend of electric vehicle sales in Thailand," *Engineering Management in Production and Services*, Article vol. 14, no. 1, pp. 13-25, 2022, doi: 10.2478/emj-2022-0002.

[5] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He, "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review," *Energy Storage Materials*, vol. 10, pp. 246-267,2018/01/01/2018, doi:https://doi.org/10.1016/j.ensm.2017.05.013.

[6] T. Lieven and B. Huegler, "Did Electric Vehicle Sales Skyrocket Due to Increased Environmental Awareness While Total Vehicle Sales Declined during COVID-19?," *Sustainability*, vol. 13, no. 24, Dec 2021, Art no.13839, doi:10.3390/su132413839.

[7] J. F. Guo, X. M. Zhang, F. Gu, H. Q. Zhang, and Y. Fan, "Does air pollution stimulate electric vehicle sales? Empirical evidence from twenty major cities in China," *Journal of Cleaner Production*, vol. 249, Mar 2020, Art no. 119372, doi: 10.1016/j.jclepro.2019.119372.

[8] Z. X. Liu, "Impact of vehicle purchase tax exemption on electric vehicle sales: Evidence from China's automotive industry," *Energy Strategy Reviews*, vol. 49, Sep 2023, Art no. 101148, doi: 10.1016/j.esr.2023.101148.

[9] Z. Skidmore. "Electric vehicle sales surge in 2021. Available online : https://www.power-technology.com/news/electric-vehicle-sales-surge-in-2021/

[10] S. Verma, G. Dwivedi, A. Zare, and P. Verma, "Life Cycle Assessment of Greenhouse Gas Emissions of Electric and Internal Combustion Engine Vehicles in India," in *SAE Technical Papers*, 2022, doi: 10.4271/2022-01-0749. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85135112879&doi=10.4271%2f2022-01-0749&partnerID=40&md5=a29e26ea0d41d75d2b7528ef4315de6c

[11] Q. Qiao, F. Zhao, Z. Liu, S. Jiang, and H. Hao, "Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China," *Applied Energy*, vol. 204, pp. 1399-1411, 2017/10/15/ 2017, doi:https://doi.org/10.1016/j.apenery.2017.05.041.

[12] D. Pedrosa, V. Monteiro, H. Goncalves, J. S. Martins, and J. L. Afonso, "A Case Study on the Conversion of an Internal Combustion Engine Vehicle into an Electric Vehicle," in *2014 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 27-30 Oct. 2014 2014, pp. 1-5, doi:10.1109/VPPC.2014.7006994.

[13] E. Ferrero, S. Alessandrini, and A. Balanzino, "Impact of the electric vehicles on the air pollution from a highway," *Applied Energy*, vol. 169, pp. 450-459, 2016/05/01/ 2016, doi:https://doi.org/10.1016/j.apenergy.2016.01.098.

[14] L. Ianniciello, P. H. Biwolé, and P. Achard, "Electric vehicles batteries thermal management systems employing phase change materials," *Journal of Power Sources*, vol. 378, pp. 383-403, 2018/02/28/ 2018, doi:https://doi.org/10.1016/j.jpowsour.2017.12.071.

[15] P. R. Tete, M. M. Gupta, and S. S. Joshi, "Developments in battery

thermal management systems for electric vehicles: A technical review," *Journal of Energy Storage*, vol. 35, p. 102255, 2021/03/01/ 2021, doi:https://doi.org/10.1016/j.est.2021.102255.

[16] W. Cao, J. Li, and Z. Wu, "Cycle-life and degradation mechanism of LiFePO4-based lithium-ion batteries at room and elevated temperatures," *Ionics*, Article vol. 22, no. 10, pp. 1791-1799. doi:10.1007/s11581-016-1703-4.