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Review Article

A Review of Malaysia's Current State and Future in Electric Vehicles

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ABSTRACT

The global surge in the electric vehicle market shows a growing commitment to sustainable transportation. However, Malaysia's progress in electric vehicle development has been slow. This article presents the challenges to electric vehicle adoption in Malaysia. The study identifies critical issues such as inadequate charging infrastructure, uneven distribution of charging stations, high costs of ownership, and low consumer awareness, acceptance, and safety. These challenges collectively impact the adoption rate of electric vehicles in the Malaysian market. The study also suggests potential solutions, such as expanding the charging infrastructure, developing cost-effective strategies, implementing fast charging with renewable integration, enforcing safety protocols and standards, and establishing a battery recycling industry. By addressing these key areas, the research highlights a feasible path to boost electric vehicle adoption in Malaysia that aligns with international trends and promotes a greener future.

KEYWORDS

Electric vehicle, EV in Malaysia, Electric vehicle growth, EV adoption in Malaysia, Battery recycling.

INTRODUCTION

Electric Vehicles (EVs) have emerged as a focal point in the global transportation landscape, driven by a pressing need to reduce greenhouse gas emissions and reliance on fossil fuels [1]. The rapid adoption of EVs worldwide is attributed to environmental sustainability, energy efficiency, and alignment with international commitments to combat climate change [2]. Governments, automotive industries, and consumers increasingly embrace EVs, recognizing the potential to revolutionize transportation by offering a cleaner and more economically viable alternative to conventional Internal Combustion Engine (ICE) vehicles [3].

The global EV market has shown solid growth during the past few years. Recent reports indicate EV sales may hit 33.5 million by 2025 [4]. This surge is fueled by substantial investments in charging infrastructure, governmental incentives, and a rising public awareness of the environmental benefits of EVs. Major automotive companies have led the charge, frequently unveiling new models offering better range, quicker charging times, and more affordable price tags [5]. This worldwide momentum in the EV sector exemplifies the synergistic impact of policy, industry innovation, and consumer demand in stimulating a sustainable transportation ecosystem [6], [7], [8].

Despite the global shift towards EVs, Malaysia's progress in this domain remains slow [9], [10]. Several factors contribute to this slow growth, with the most notable being insufficient charging infrastructure, especially in vital locations like highways. This limited charging infrastructure makes EVs less practical and less attractive to potential users. The limited selection of EV models and a widespread lack of consumer knowledge exacerbate this challenge, decreasing enthusiasm for electric mobility in Malaysia [11]. The significant price gap between the Nissan Almera and the Nissan Leaf shows the financial challenges of switching to an EV [12]. The uneven distribution of charging points across Malaysia, especially on interstate routes, worsens this problem. The developing phase of EV adoption in the nation raises safety concerns due to the lack of maintenance guidelines and safety protocols and a general lack of awareness about potential electrical risks. Moreover, Malaysia lacks a battery recycling industry, which is an important factor to consider for future EV growth.

This review article comprehensively examines the challenges affecting EV adoption in Malaysia. The article focuses on the EV charging infrastructure, the uneven distribution of charging stations, high ownership costs, and consumer knowledge, acceptance, and safety issues. Additionally, the potential of EVs in Malaysia and practical solutions and strategies to overcome the existing challenges are discussed. Numerous studies have explored the challenges related to charging infrastructure in Malaysia, yet there's a gap in the literature regarding the recent advancements within the Malaysian EV market. This article addresses this gap by delivering the latest EV situation in Malaysia. The significance of this research is highlighted by the ability to guide policymakers, industry stakeholders, and consumers in making informed decisions and implementing strategic interventions to accelerate EV adoption in the country. This study promotes regional sustainability by developing an eco-friendly transportation strategy that fits well with local conditions.

METHODS

This section presents the methods used to review the study, detailing the search protocol employed for data collection and outlining the study framework utilized in the review. This article first discusses global EV growth, then examines the challenges in the EV industry in Malaysia, and presents potential solutions that can be integrated into the industry to enhance EV adoption in the country.

Search Protocol

This review utilized Google Scholar, Scopus, and ScienceDirect databases for relevant research papers. Figure 1 presents the search protocol. This search protocol used the keywords "Electric Vehicles", "growth", and "Malaysia" from the past decade. The preliminary search on Google Scholar using these keywords produced a notable collection of 16,900 documents, selected based on keyword relevance, title precision, and thematic alignment. Additionally, initial searches on Scopus and ScienceDirect yielded 2,737 and 3,165 documents, respectively.

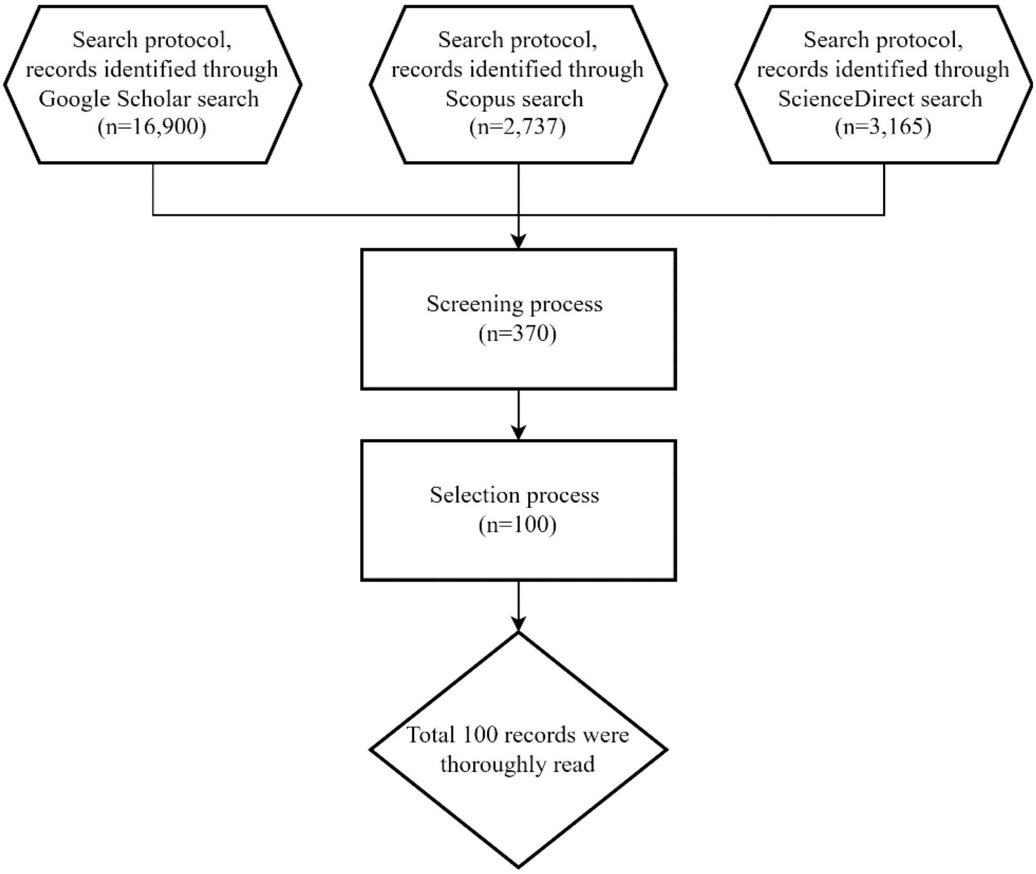

Figure 1. Search protocol

A secondary filtering step was employed to refine the initial selection, aiming to streamline the review process and to ensure the inclusion of only relevant documents. This filtering step considered evaluating factors, including the impact factor of the journals publishing the papers, the recognition and relevance of the conferences presenting these works, and the frequency of citations attributed to these publications. Consequently, this screening process resulted in a more focused selection of 370 papers. Finally, a more rigorous selection process yielded 100 research papers identified as most relevant and influential to this study. More than 60 papers have been published within the last five years.

Study Framework

Initially, the study focused on the worldwide EV market, pinpointing growth catalysts in developed countries. This global perspective laid the groundwork for a deeper insight into the Malaysian market. After this extensive analysis, the research highlighted Malaysia's EV market, delving into charging infrastructure and identifying potential growth avenues, all set against the distinct backdrop of the Malaysian scenario. With a clear understanding of these challenges, the study presented possible solutions, considering global best practices and Malaysia's particular needs and characteristics. **Figure 2** depicts the various stages of the study, creating a clear pathway from the initial investigation to the final recommendations. The data on EV charging stations was collected by Agmo Studio Sdn Bhd **[13]**.

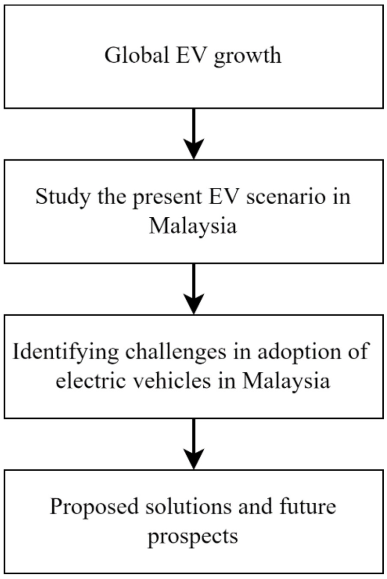

Figure 2. Various stages to conduct the study

GLOBAL ELECTRIC VEHICLE GROWTH

In 2022, the EV sector saw a significant surge, with 10.5 million new vehicles, including Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), hitting the market as illustrated in **Figure 3**. This upswing marks a 55% increase compared to the previous year.

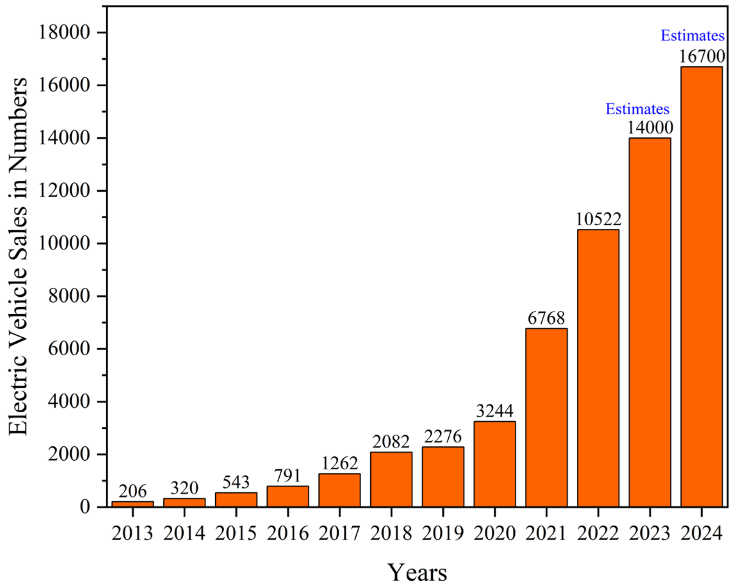

Figure 3. Global EV growth from 2013 to 2022 [14]

Despite the volume growth, a shift occurred in the PHEV market share, which receded to 27% in 2022 from 29% in 2021. The cause of this shift lies in reductions in governmental incentives and the increased attractiveness of BEV options [15]. Moreover, the growth rates were diverse across different EV categories, with BEVs growing by 59%, PHEVs by 46%, non-rechargeable Full Hybrids by 15%, and Mild Hybrids by just 1% year-over-year. 2022 marked a significant achievement in the automotive industry as BEV sales surpassed non-chargeable Full Hybrids' sales. Meanwhile, sales of traditional ICE-only vehicles declined by 7% [16]. On the other hand, Fuel Cell Electric Vehicles (FCEVs) continued to occupy a small niche, with sales stagnant at 18,892 units in 2022, representing a negligible portion of the global market. Increased uptake of EVs, especially in underperforming automotive sectors, has boosted market shares [17]. The global percentage reached 13% in 2022, a significant increase from 8.3% in the previous year. Various countries displayed market shares, with major growth in Indonesia, India, and New Zealand [18], [19], [20].

In 2023, the global market for EVs maintained strong momentum, with sales reaching 3.7 million units in the third quarter and an expected total of 14 million units for the year [21]. This marks a substantial increase of approximately 3.5 million vehicles compared to 2022. The upward trend in EV sales in 2023 hints at a continued rise in the coming years, with projections indicating sales of 16.7 million EVs in 2024 [22]. However, the growth rate may decelerate in 2024 due to regulatory changes in Europe, market saturation in China, and higher interest rates affecting U.S. consumers.

Focusing on specific regions, China's passenger EV market received a 27% increase in the third quarter, year-over-year, with sales surpassing 2.2 million units. The total sales in China are expected to reach 8.1 million in 2023. However, 2024 forecasts a modest 18% increase due to regulatory obstacles, market saturation, and economic factors. EV sales grew by 31% in Europe in the third quarter to nearly 800,000 units. The region is on track to meet its 2023 target of 3.3 million units. Despite this, changes in subsidies and less stringent fuel-economy targets in countries like France and Germany are likely to result in a more subdued growth in 2024, with sales anticipated to hit 3.6 million units.

In North America, EV sales increased by 54% in the third quarter of 2023. The forecast for passenger EV sales in North America is set at 1.6 million for 2023, with 1.4 million expected in the U.S. alone, marking a 47% increase from 2022. The 2024 outlook is optimistic, with a projected 32% increase, totaling 1.9 million units in the U.S. and 230,000 in Canada. This growth in the U.S. will be partly driven by the availability of EV tax credits at the point of sale starting in 2024. However, achieving these numbers will require significant efforts from major automakers like General Motors (GM), Ford, and Stellantis.

Overall, the EV industry is witnessing a significant transformation, underscored by a substantial increase in sales and changing market dynamics. The year 2023 continued this upward trajectory, with regional variations in growth and shifting preferences towards BEVs over PHEVs. Looking forward, the industry faces challenges such as regulatory changes and market saturation, but the consistent rise in EV adoption and technological advancements promise a dynamic and evolving landscape for EVs globally.

EXAMINING THE ELECTRIC VEHICLE SITUATION IN MALAYSIA

With the significant surge in EV adoption worldwide, Malaysia has also seen significant improvements in its EV market over the past few years. **Figure 4** shows the EV sales in Malaysia from 2013 to 2024, highlighting that the growth of EVs was extremely slow from 2013 to 2020 compared to the global trend. While global EV sales saw a significant and steady increase during this period, EV sales in Malaysia fluctuated below 100 units annually. However, in 2021, EV sales in Malaysia surged by 267.14%, while global EV sales increased by 108.63%. This trend continued with exponential growth in 2022 and 2023, where Malaysian EV sales increased by 1115.95% and 324.51%, respectively, marking a strong improvement compared to global sales. The minimal improvements in EV sales from 2013 to 2020 in Malaysia were due to high ownership costs, limited availability of EV models, and low consumer awareness and acceptance.

Additionally, the lack of government incentives and support further hampered market growth. However, starting in 2021, introducing tax exemptions and subsidies significantly boosted EV adoption. The surge in EV sales from 2021 onwards is attributed to increased consumer awareness and recognition of the importance of EVs. Given the previously low adoption rates from 2013 to 2020, Malaysia has substantial potential for continued EV growth. The EV sales in Malaysia are expected to reach 20,000 units by 2024, representing a 50.76% increase compared to 2023. Despite the increase in EV sales since 2021, the overall adoption of EVs in Malaysia is still slow compared to global EV sales trends since 2013.

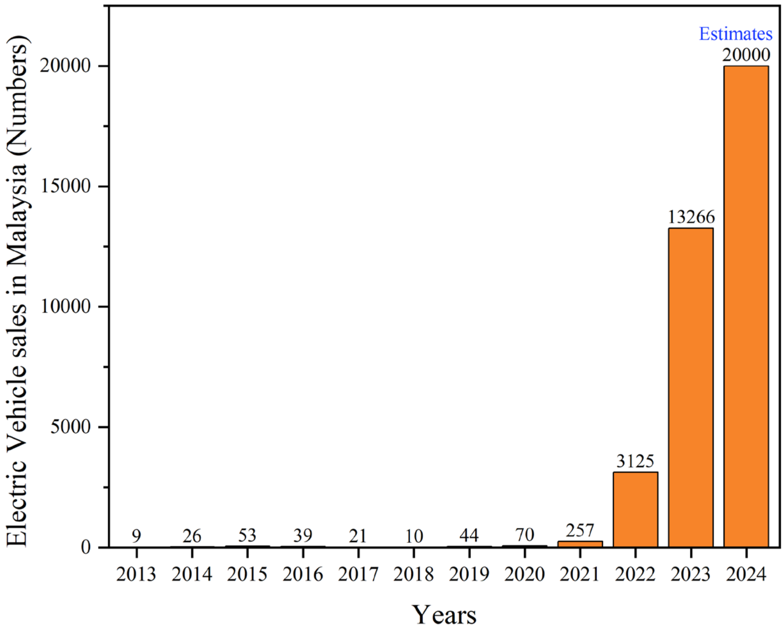

Figure 4. Global EV growth from 2013 to 2022 [14]

The interest in EVs is also low in Southeast Asia despite the overall surge in EV adoption [23], [24], [25], [26]. Several factors, including current consumer preferences, cause this slower adoption [27]. A Deloitte survey reveals that while EV enthusiasm in Southeast Asia might be slower, there is a rising interest in HEVs instead of BEVs [28]. According to the survey, based on a sample size of 910, 58% of Malaysian consumers lean toward ICE for their next vehicle purchase. In contrast, only 4% are considering BEVs.

Meanwhile, hybrid vehicles seem to be gaining traction, with 23% of consumers expressing interest in HEV and 14% in PHEVs as shown in Figure 5. It has been noted that consumers in Southeast Asian countries generally favor ICE, except Singapore, where a preference for EVs is emerging. The dominant preference for ICE in Malaysia, over 50%, shows that consumers still see it as the top choice for future vehicles.

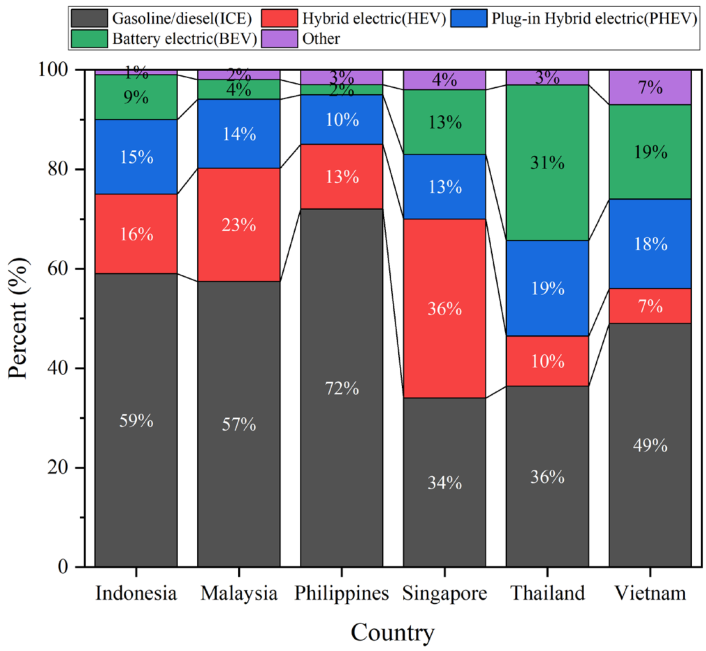

Figure 5. Consumer interest in electric vehicles in Southeast Asia

The slow EV adoption trend in Malaysia is evidenced by the 1,500 charging stations across Malaysia, which are read across public and commercial locations, as per the data until December 31, 2023 [13]. As shown in Figure 6, 36.7% of these charging stations are in Selangor, and 24.5% are in Kuala Lumpur. The distribution of these charging stations aligns with the specific needs of different states. As the business hub with the highest population density, Kuala Lumpur requires strategically placing charging stations in the region.

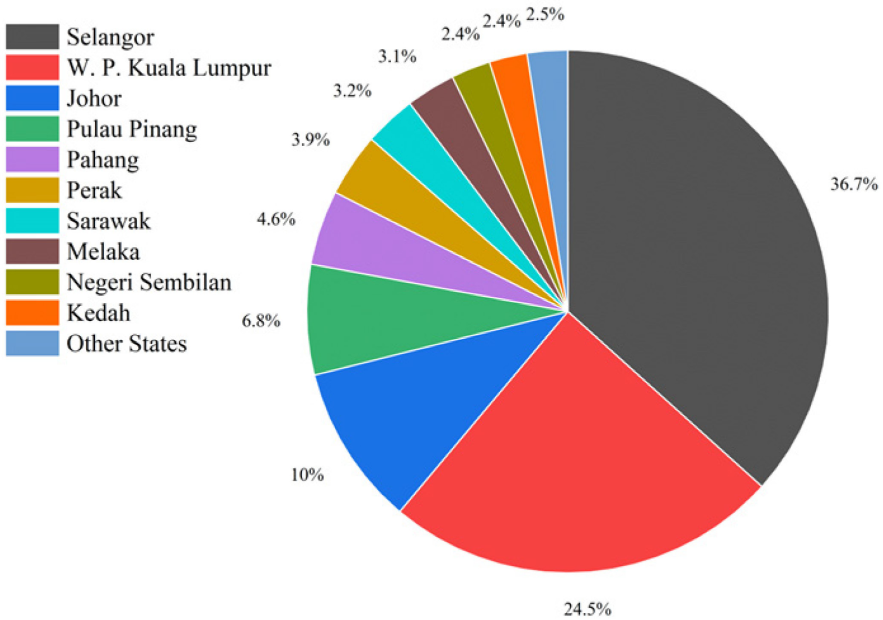

Figure 6. Allocation of EV charging stations in different states of Malaysia

A detailed examination of the sockets and ports in Malaysia's chargers reveals that 62.8% are of the Alternating Current (AC) Type 2 socket variety. In comparison, just 16.9% are Combined Charging System (CCS) Type 2 ports, and a 2.4% belong to the CHArge de MOve (CHAdeMO) port. This distribution indicates a constraint in the country's availability of Direct Current (DC) chargers. Table 1 lists the details of available charge point operators in Malaysia, including the AC and DC chargers, showing that 31% of the overall charging plugs are self-operated, and 20.4% are associated with JomCharge. Regarding power output, most chargers fall within the 8 kW to 29 kW range, accounting for 57.7% of the total.

Conversely, 19.1% of chargers operate from 2 kW to 7 kW. This data leads to the conclusion that over 70% of charging stations in Malaysia are categorized under 29 kW in power until December 31, 2023. Further observation shows that the JomCharge and ChargeSini operators comprise 16.5% and 11.8% of overall charging stations in Malaysia and have primarily focused on installing chargers in the Selangor and Kuala Lumpur regions. Additionally, it has been noted that the highest power output available in the country is 400 W, supplied by chargeEV, with JomCharge and Setel following closely, offering a maximum of 350 W.

It's important to note that over 3000 EVs have been registered in Malaysia [29]. While this number is relatively low compared to top countries in the EV market, like China and the United States of America, it seems pretty modest when weighed against the number of charging stations in Malaysia, population, and geographical area. As per the data from the Malaysian Automotive Association (MAA), the total cars registered for 2023 was 799,731 units, with 719,160 passenger vehicles and 80,571 commercial vehicles, which is an increase of 10.97% from the previous year [30]. This growth in car sales in Malaysia indicates the potential for EV market.

Table 1. Details of available charge point operators in Malaysia as of December 31, 2023

Charge Point Operator	**Total Plugs**	**Total Stations**	**AC Plugs [Type2]**	**AC Plugs [3&5pin]**	**DC Plugs**	**Min Power [W]**	**Max Power [W]**
Self Operate	1,388	496	612	716	60	2	180
JomCharge	915	248	548	0	367	4	350
ChargeSini	765	177	613	3	149	2	82
Charge	612	274	471	0	141	0	400
ParkEasy	189	92	172	0	17	4	180
Setel	80	40	25	0	55	7	350
JusEV	52	11	52	0	0	7	120
Tesla	51	5	19	0	32	250	250
Go-To-U	45	20	15	0	30	11	100
Flexi Parking	41	11	39	0	2	7	22
Carput	34	12	27	0	8	7	120
Plugit Cloud	33	8	33	0	0	7	22
REXcharge	27	11	12	0	15	7	180
EVPower MY	26	8	21	0	5	11	60
Plugit Cloud	33	8	33	0	0	7	22
REXcharge	27	11	12	0	15	7	180
EVPower MY	26	8	21	0	5	11	60
ChargeCore	19	3	17	0	2	7	120
CEE4EV	14	8	2	12	0	-	-
Nichom	14	5	10	0	4	7	60
EVlution	13	7	13	0	0	-	-
1U app / One Card	8	3	8	0	0	11	11
EVGuru Charge	8	4	8	0	0	22	22
Autel Charge	7	2	5	0	2	22	60
EV Wave	7	4	4	0	3	22	180
ChargeNGo	5	3	5	0	0	7	22
Pluginfinite	3	2	3	0	0	22	22
RISE app	2	2	2	0	0	-	-
EVGuru Charge	8	4	8	0	0	22	22
Autel Charge	7	2	5	0	2	22	60
EV Wave	7	4	4	0	3	22	180
ChargeNGo	5	3	5	0	0	7	22
Pluginfinite	3	2	3	0	0	22	22
RISE app	2	2	2	0	0	-	-

Despite the expansion of EV charging infrastructure in Malaysia, **Figure 7** illustrates the overall development of charging stations throughout the second, third, and fourth quarters of 2023. The growth remained consistent in the second and third quarters, but a significant increase was evident in the last quarter of 2023. Specifically, the count of charging stations in October 2023 reached 68, marking a 74.36% rise from September 2023. This upward trend continued through November and December 2023, with 61 and 68 charging stations, respectively. In the last quarter of 2023, the total count of charging stations reached 197, marking a substantial increase of 58.87% from the third quarter. On the other hand, the total number of charging stations for January 2024 and February 2024 were 56 and 23, respectively. March 2023 will determine the overall number of charging stations for the first quarter of 2024, but based on the rising trend of development in the EV sector, the charging stations are expected to show a positive trend. The significant growth in the final quarter of 2023 highlights the rapid expansion of the EV sector and demonstrates Malaysia's continued dedication to this industry into 2024.

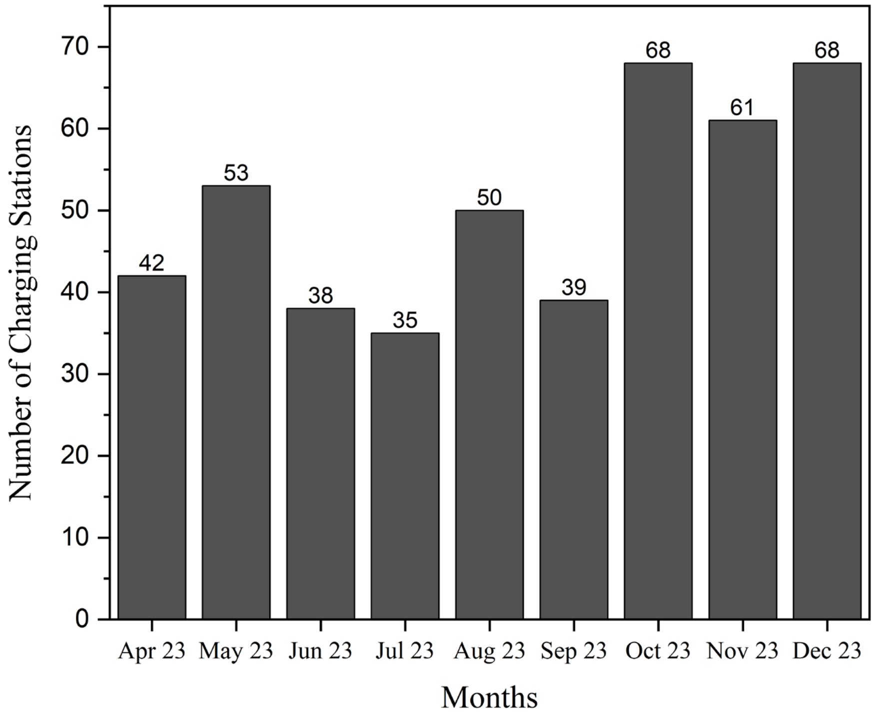

Figure 7. Charging infrastructure growth in Malaysia in 2023

These factors underline the critical importance of developing a robust charging station infrastructure to support the emerging EV market in Malaysia. However, progress toward this essential development remains slow, and the EV growth rate in 2023 has not met expectations. The situation underscores the need for increased efforts to facilitate charging station growth to align with the country's anticipated rise in EV usage.

CHALLENGES IN THE ADOPTION OF ELECTRIC VEHICLES IN MALAYSIA

This section presents the challenges in the Malaysian EV market and discusses the charging infrastructure, uneven distribution of charging stations, high cost of ownership, and consumer awareness, acceptance, and safety.

Limited Charging Infrastructure

Several factors are driving the global increase in EVs, but Malaysia faces challenges in the evolving EV market **[31]**, **[32]**, **[33]**. In Malaysia, the limited charging infrastructure is a significant challenge that affects the adoption of EVs. As of December 31, 2023, Malaysia has only 1,500 charging stations, primarily concentrated in Selangor and Kuala Lumpur. This lack of charging facilities influences the decision to own an EV. **Figure 8** shows a heat map of Malaysia, highlighting a significant discrepancy in the availability of charging stations. Most of these stations are located in Selangor, Kuala Lumpur, and Johor Bahru, whereas the eastern regions of West Malaysia suffer from a substantial lack of such facilities. Additionally, East Malaysia has an insufficient number of charging stations. This imbalanced charging infrastructure distribution poses a considerable challenge for prospective EV owners considering long-distance travel **[34]**.

To address these issues, a strategic expansion plan is necessary to develop multiple additional charging stations, focusing on highways and rural areas. Currently, DC fast chargers constitute only 16.9% of the total, and increasing this proportion to 50%, with a minimum power output of 50 kWh, is important for implementing a robust fast charging infrastructure. This expansion will significantly improve accessibility, reduce range anxiety, make long-distance travel more feasible, and encourage consumers to adopt EVs.

Figure 8. Heat map of EV charging stations in West Malaysia

Consider the journey between Johor Bahru and Kota Bahru, a 688 km route that exceeds the maximum driving range of most EVs in Malaysia. A driver attempting to travel this distance from south to north using an EV may experience anxiety due to the limited driving range and the limited number of charging stations available on this route. This anxiety is further supported by the impact of elevation on the EV driving range [35]. Malaysia has a maximum elevation of 3432 m with an average elevation of 80 m. The high elevation requires additional EV energy during driving, reducing the driving range. The energy required can be calculated by:

$$E = m \times g \times h \tag{1}$$

where m is the mass of the vehicle, g is the acceleration due to gravity (g= 9.81 m/s^2), and h is the elevation gain. A vehicle with a mass of 1,500 kg and a battery capacity of 60 kWh driving at an elevation of 1,000 m may consume approximately 4.08 kWh of energy, which is 6.8% of the electric vehicle's battery capacity. The use of regenerative braking systems in EVs can help recover energy and extend the driving range [36]. Based on Malaysia's topography, the elevation may further affect the EV driving range, which requires careful planning and additional infrastructure support.

These limitations could prompt the driver to abandon the idea of using an EV, leading them to choose a conventional fuel-powered vehicle. Furthermore, **Figure 9** highlights that the absence of adequate charging infrastructure is a significant challenge, with 61% of respondents identifying it as a primary challenge to adopting EVs in Malaysia. The data also suggests that the charging duration is a concern, reflecting the efficiency and distribution of charging stations throughout various locations in Malaysia [37], [38], [39].

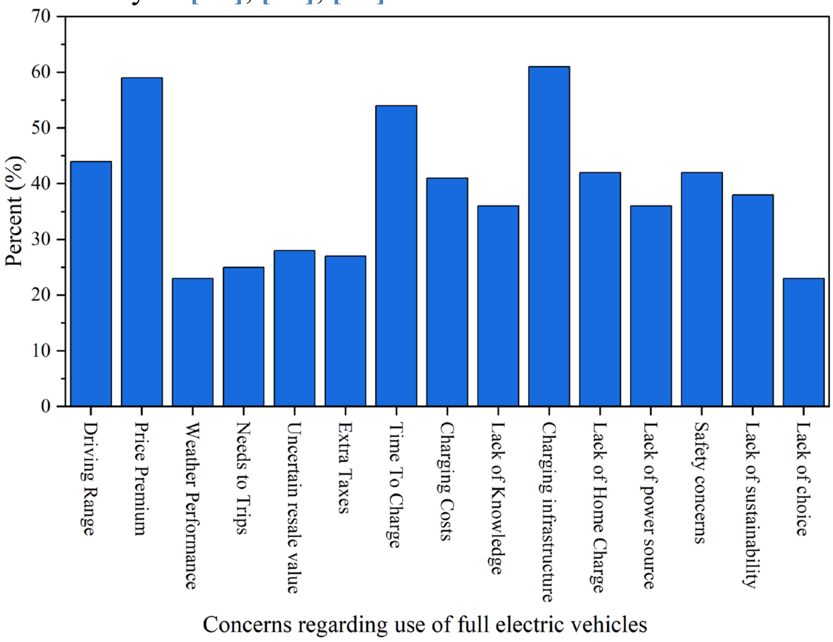

Figure 9. Concerns regarding the use of electric vehicles in Malaysia

Table 2 presents the existing battery sizes for EVs in Malaysia, indicating that the most extended driving range is 715 km and is only available in high-priced models beyond the means of more budget-minded consumers [40]. This divergence between the requirement for an extensive charging network and the current availability highlights a key obstacle in Malaysia's journey towards environmentally friendly transportation [41], [42]. It emphasizes the pressing need for a joint effort by policymakers, industry professionals, and researchers to forge solutions to close this gap.

Table 2. Available EVs in Malaysia with an extended driving range as of December 31, 2023

EV Models	Battery Capacity [kWh]	Battery Type	Range [km]
Nissan Leaf	40	Lithium-ion	270
BMW i3s	42.2	Lithium-ion	260
Porsche Taycan	93.4	Lithium-ion	523
ORA Good Cat	47.788 - 63.139	Lithium-ion	400 – 500
Hyundai Kona Electric	39.200 - 64.000	Lithium-ion	305 – 484
Kia EV6	77.4	Lithium-ion	506
Mercedes-Benz EQS	107.8	Ternary Lithium	782
Hyundai Ioniq 5	58 - 72.6	Lithium-ion Polymer	384 - 430
Mercedes-Benz EQA	66.5	Lithium-ion	402 - 429
BYD ATTO 3	49.92 - 60.48	Lithium-ion	410 - 480
Mercedes-Benz EQE	90.56	Lithium-ion	669
BMW i4	83.9	Lithium-ion	510 – 590
Volvo XC40	78	Lithium-ion	418
BMW iX	-	Lithium-ion	630
Mini 3 Door Electric	28.9	Lithium-ion	232
Jaguar I-PACE	90	Lithium-ion	470
BMW iX3	73.8	Lithium-ion	461
Kia Niro	65	Lithium-Ion Traction Battery	407
Tesla Model 3	-	-	713
Tesla Model Y	60-80.5	Lithium iron phosphate Ternary lithium battery Ternary lithium battery 80.5-kWh lithium-ion battery pack	430-533
BMW iX1	66.5	Lithium-ion	438
BMW i7	102	Lithium-ion	715
Neta V	38.54	Lithium-ion	384
Hyundai Ioniq 6	77.4	Lithium Polymer Traction	614
Peogeot e-2008	50	Lithium-ion	403

Uneven Distribution of Charging Stations

Another challenge within the Malaysian EV landscape is the uneven distribution of charging stations, as shown by the map in Figure 10a. The distribution of petrol stations in Malaysia is shown in Figure 10b. These maps highlight Malaysia's situation, revealing a concentration of EV charging stations in urban areas. This pattern shows limited charging station availability along highways, a significant issue that needs attention. Research indicates that many Malaysians travel across states during holidays to reunite with their families or for various business activities [43]. Additionally, most of these travelers favor using personal vehicles as their primary mode of transportation [44].

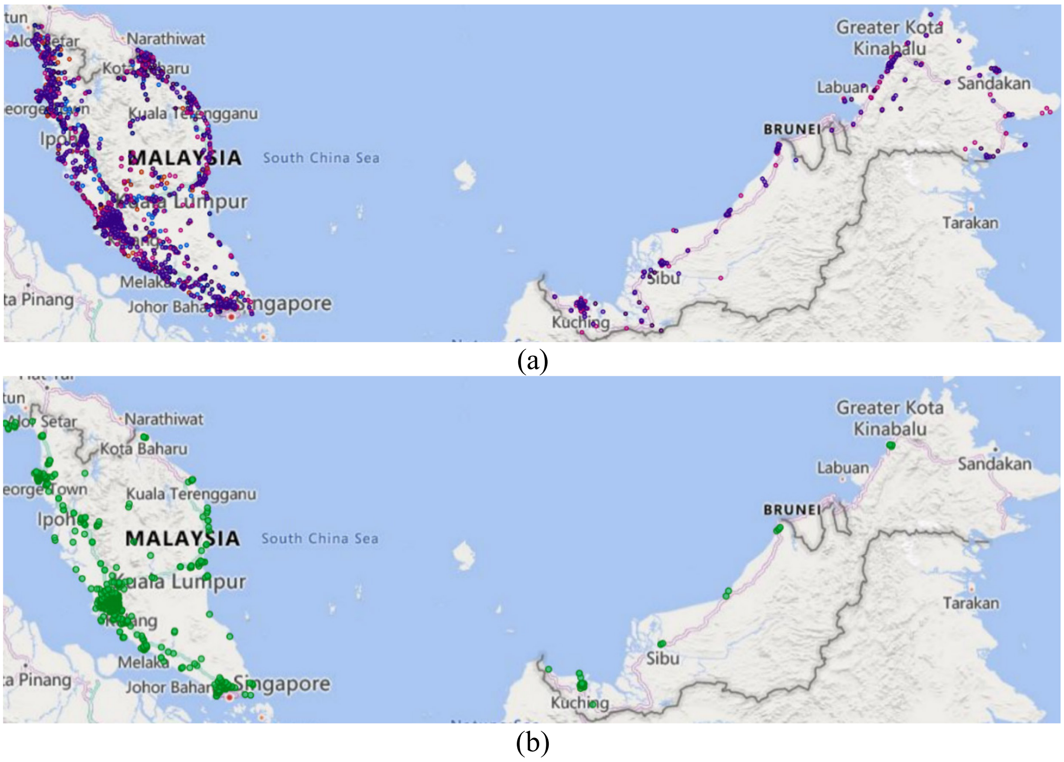

Figure 10. Distribution of vehicle stations in Malaysia: Petrol stations (a); and EV charging stations (b)

Highways are crucial links between the states of Malaysia, and the limited driving range of EVs, combined with inadequate charging infrastructure, generates real concerns regarding inter-state travel [45], [46].

This problem is further exacerbated by the location of charging stations in areas that are not strategically important. Figure 11 demonstrates that shopping malls, residential areas, and car dealerships account for 16.4%, 14%, and 11.9% of charging facilities, respectively. This distribution means that around 42% of charging stations are situated in locations that fail to address urgent needs. Such a mismatch between charging infrastructure and the real-world demands of EV operation has placed challenges for potential EV owners, influencing the willingness to transition from traditional vehicles [47], [48]. Nevertheless, significant research and development efforts are ongoing to enhance the charging station infrastructure in Malaysia.

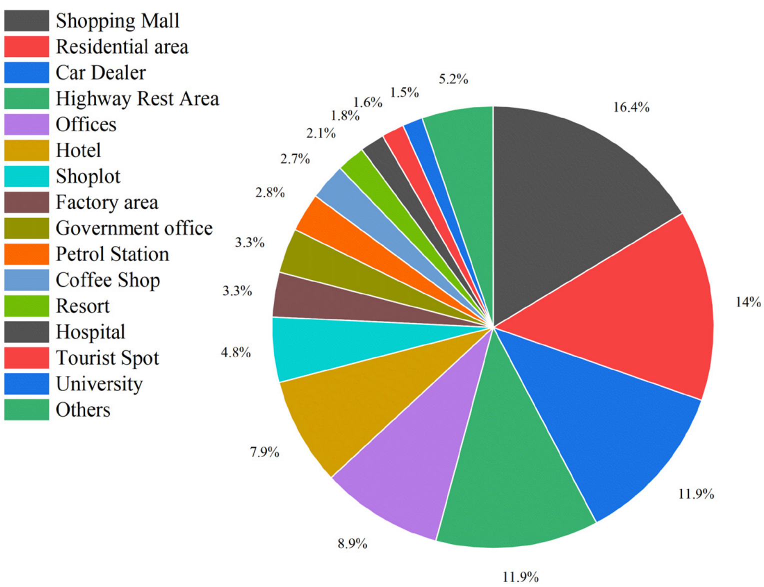

Figure 11. Distribution of charging stations in Malaysia in different facilities

Furthermore, the disproportion in the types of chargers available signifies an overarching limitation in the availability of DC chargers in the country. The present allocation of charging stations, where Selangor holds 36.7% and Kuala Lumpur 24.5%, highlights the need for a distribution that better reflects the unique needs of different states. This approach could consider population density and economic activity to develop a more adaptive and efficient EV charging network across Malaysia.

High Cost of Ownership

Another challenge to the broader adoption of EVs in Malaysia is the substantial cost of ownership compared to conventional gasoline-powered vehicles [49]. This challenge is significant, with examples such as the Nissan Almera being more than 40% cheaper than the Nissan Leaf's electric counterpart [12]. The relatively high price tag on EVs has dampened buyer interest, as the immediate cost-saving benefits are not apparent.

The high cost of EVs is further exacerbated by the nascent stage of the EV market in Malaysia, where the availability of second-hand EV options is limited [27], [49]. This scarcity is of particular concern for budget-conscious consumers who typically consider purchasing used vehicles. Table 3 compares different models of petrol-based cars and EVs in Malaysia, which provides a detailed overview of this price disparity.

Table 3. Prices for conventional and electric vehicles in Malaysia

Vehicle Category	Car Model	Retail Price [RM]
Electric	Hyundai Kona Electric e-Max	RM199,888.00
	BYD ATTO 3 Extended Range	RM167,800.00
	BYD Dolphin Premium Extended	RM124,900.00
	Mazda MX-30	RM199,000.00
Conventional	Perodua Myvi 1.5 AV	RM59,900.00
	Perodua Axia 1.0 AV	RM49,500.00
	Proton Saga 1.3 Premium AT	RM41,800.00
	Proton X70 SE	RM123,800.00

Beyond the vehicle's upfront cost, the EV battery's expense significantly influences the overall price [50], [51], [52]. The manufacturing process for EVs, particularly battery components, is more costly than that of conventional vehicles, reflected in the final cost to consumers. The battery's cathode, an essential element for storing and releasing charge, incurs significant costs. Consequently, extensive research has been undertaken to find ways to reduce battery costs to optimize the overall price of an EV [53], [54], [55], [56].

Another factor contributing to the high cost of EV ownership in Malaysia is the limited selection of models available in the Malaysian automotive market. The restricted variety can lead to a lack of competitive pricing, further driving up costs. The battery's cost, being a primary factor affecting the overall price of an EV, symbolizes a broader challenge in making electric transportation more affordable. A concerted effort involving research, market expansion, and potential subsidies may be necessary to make EVs more accessible and attractive to Malaysian consumers.

Consumer Awareness, Acceptance, and Safety

Consumer awareness and acceptance are pivotal factors in the booming market penetration of any new technology [57], [58]. This is particularly evident in Malaysia's EV market, which has witnessed slower growth despite advantages [57], [59]. One of the significant impediments in this trajectory is undeniably the challenges related to consumer awareness and acceptance. The benefits of EVs, both environmental and economic, often go unnoticed or are poorly communicated [60]. Traditional vehicles significantly contribute to urban pollution with emissions [61].

In contrast, with zero tailpipe emissions, EVs promise a cleaner and more sustainable future. Economically, while the upfront cost of an EV might be higher, long-term ownership can be more economical [62]. Savings are accrued from fuel costs, reduced maintenance due to fewer moving parts, and the decreasing cost of batteries.

However, the landscape is riddled with misconceptions and myths about EVs that discourage potential consumers. These misconceptions often stem from early EV models and include concerns about limited driving ranges, long charging times, and perceived low vehicle performance [63]. Another prevalent myth is the rapid degradation of EV batteries, assuming frequent and costly replacements, even though modern EV batteries have shown longevity and have extended warranties [64]. The restricted exposure of potential consumers to EVs amplifies limited awareness. Malaysia has seen a limited variety of EV models, reducing the choices available to consumers. Test drives are important for deciding on a vehicle purchase and are hard to come by when dealerships have fewer EVs. Moreover, uncertainty about charging infrastructure causes worry. While developing this infrastructure is crucial, the slow pace is holding back consumer acceptance.

From a societal perspective, cultural and behavioral factors play a non-trivial role. In many societies, the vehicle type carries cultural implications or is a status symbol [65], [66], [67]. Moving from well-known conventional vehicles to newer alternatives demands a substantial change in mindset and perspective. Furthermore, there's an underlying hesitancy among consumers who prefer to wait for the technology to mature further, apprehensive about the risk of the current technology becoming obsolete. While the Malaysian government has made efforts to introduce EV incentives, a more aggressive stance in promotional campaigns, subsidies, and widespread awareness campaigns might be the catalyst to bolster consumer acceptance.

Safety Protocols and Standards. The growth and acceptance of EVs in the market are substantially shaped by safety considerations, significantly affecting consumer perceptions [68]. In Malaysia, the absence of robust safety protocols and a deficit in targeted awareness campaigns have instilled apprehension among potential EV consumers [12], [69]. Intricate designs characterize EVs that operate on high-density batteries and complex electric circuits. Such a design necessitates unwavering safety protocols, emphasizing risks like direct contact with electrical parts, the overheating of batteries, and strategic placement within the vehicle for optimal collision safety [12]. For all-encompassing protection, it's essential to set thorough standards for consumers, power grid suppliers, and charging equipment manufacturers. These standards should span the entirety of the EV landscape, from the charging apparatus to the vehicle's internal mechanics.

The Energy Commission (EC)'s Guide on Electric Vehicle Charging System (EVCS) is tailored to be an all-encompassing manual for professionals in the field [70]. It presents the criticality of technical proficiency for individuals engaged in electrical installations for EVs and mandates prior approval from the commission to introduce any charging-related equipment. The document also highlights four distinct modes of EV charging, each with the technical specifications as per the International Electrotechnical Commission (IEC) 61851. Moreover, Mode 1 charging is prohibited in Malaysia due to inherent design flaws; it cannot automatically halt charging once the battery is fully charged and fails to meet essential safety criteria. In contrast, Modes 2 and 3 employ the Type 2 connector in the charging system owing to the integrated locking mechanism, which enhances safety and versatility in supporting single- and three-phase charging. The Type 1 connector, deficient in a locking feature and limited to single-phase capacity, is consequently not approved. For Mode 4 charging, the CCS Type 2 and CHAdeMO connectors are deemed suitable and permissible for use within the charging system.

The path to boosting EV growth in Malaysia is comprehensively addressing these safety protocols and standards. The ongoing efforts by the government and associated bodies reflect a forward-thinking approach that, if implemented effectively, can reshape the trajectory of EV adoption in Malaysia.

Vehicle Maintenance. Proper maintenance of EVs requires skilled technicians equipped with specialized knowledge and training [71]. The emerging nature of the EV industry in Malaysia has led to a shortage of experienced professionals. This lack can cause apprehension among consumers concerned about properly treating and maintaining vehicles' complex electrical and mechanical parts [72], [73]. Regular check-ups and adherence to standard maintenance protocols are imperative for the safe operation of EVs [74]. The tools to maintain EVs should be adequately insulated, and technicians must be trained to use all necessary safety gear.

POTENTIAL SOLUTION

To accelerate the development of Malaysia's EV sector, addressing the identified challenges and promoting sustainable growth is crucial. An analysis of the existing situation uncovers various techniques that could significantly enhance the proliferation of EVs in the region, thereby aiding in creating a robust and eco-friendly industry. This section presents potential solutions to improve EV adoption in Malaysia by expanding the charging infrastructure, implementing cost-effective strategies, enforcing safety protocols and standards, and integrating fast charging within the infrastructure. The significance of the battery recycling industry and its impact on the Malaysian economy are also highlighted.

Expanding charging infrastructure

The limited charging infrastructure is a major challenge to the uptake of EVs in Malaysia, necessitating an immediate and comprehensive strategy to tackle this issue. The solution might begin with an aggressive and strategic expansion of charging stations nationwide. A particular focus should be on highways and critical inter-state routes, the lifeblood of long-distance travel in the region [75]. Developing charging stations along these vital routes at regular intervals will alleviate potential EV users' range anxiety, thus promoting greater EV adoption [76], [77].

Mathematical calculation. To effectively plan and implement the expansion of charging infrastructure, a few mathematical equations can be employed. Charging Station Demand (CSD) can be calculated by using:

$$\text{Charging Station Demand (CSD)} = \frac{N_{\text{ev}} \times E_{\text{avg}} \times D_{\text{avg}}}{C_{\text{cs}} \times U_{\text{cs}}} \tag{2}$$

where N_{ev} is the number of electric vehicles, E_{avg} is the average energy consumption per kilometer, D_{avg} is the average distance driven per day by each EV in km/day, C_{cs} is the capacity of a charging station in kWh/day and U_{cs} is the utilization rate of a charging station. The charging station demand is critical to ensure that there is enough charging stations to meet the needs of current and future EV users [78]. This helps prevent situations where users cannot find available charging points, which can deter EV adoption. Moreover, the CSD helps avoid installing too many charging stations, which could lead to underutilization and wasted resources. The calculation of required charging stations also helps allocate resources more efficiently.

On the other hand, the Station Placement (SP) is determined by considering the distance from the charging station to the nearest highway and the area's population density. SP is essential for ensuring that the expansion of EV charging infrastructure is efficient, effective, and meets the needs of EV users. The placement of charging stations at optimal locations helps EV users to plan their trips better, knowing that charging is available. SP can be measured using:

$$\text{Station Placement (SP)} = \arg\min \sum_{i=1}^{n} (\alpha D_i \times \beta P_i) \tag{3}$$

where D_i is the distance from the charging station to the nearest highway, and P_i is the population density of that area. α and β are weighting factors reflecting the importance of distance and population density.

The calculation of the Accessibility Index (AI) is also important for improving the effectiveness and convenience of EV charging infrastructure. AI provides insights into how accessible charging stations are for users, which directly impacts the adoption and usage of EVs [79]. The UAI measures how easily users can access charging stations from their locations. Higher accessibility means users are more likely to use and rely on the charging infrastructure. By calculating AI, planners can identify areas with low accessibility, highlighting regions needing additional charging stations or better placement to improve access. AI can be calculated by using:

$$\text{Accessibility Index (AI)} = \frac{\sum_{i=1}^{n} U_i \times C_i}{T} \quad (4)$$

where U_i is the number of users in region i, C_i is the number of charging stations, and T is the total number of users.

Such an expansion may not only increase in numbers; it may be a thoughtful distribution catering to different charging needs. This expansion should reduce charger types and power output disparities, ensuring compatibility with various EV models and creating a seamless charging experience. Universal standards across all charging stations may facilitate accessibility [80].

The establishment of this enhanced network requires strategic planning. It utilizes a detailed analysis of current and potential EV usage patterns, highway traffic, population density, significant elevation changes, and commercial dynamics across different regions of Malaysia. Such insights would then inform the implementation of a zoning approach where charging stations are allocated hierarchically according to critical needs, ranging from highways and inter-state connectors to urban centers and residential zones.

Consumer preferences and home charging solutions. A study reveals users' preferences for EV charging locations [28]. The data shows that 60% of users in Malaysia prefer home charging, while 29% prefer street or public charging stations, as shown in **Figure 12**. Similar trends are observed in Thailand, Singapore, Indonesia, the Philippines, and Vietnam, where most users favor home-based charging solutions. This inclination towards home charging will likely influence the EV market's growth. Industry professionals and experts may consider focusing on home charging solutions for users since the increase in home charging will likely increase the adoption of EVs [81], [82]. The study also found limited interest in workplace charging for EVs.

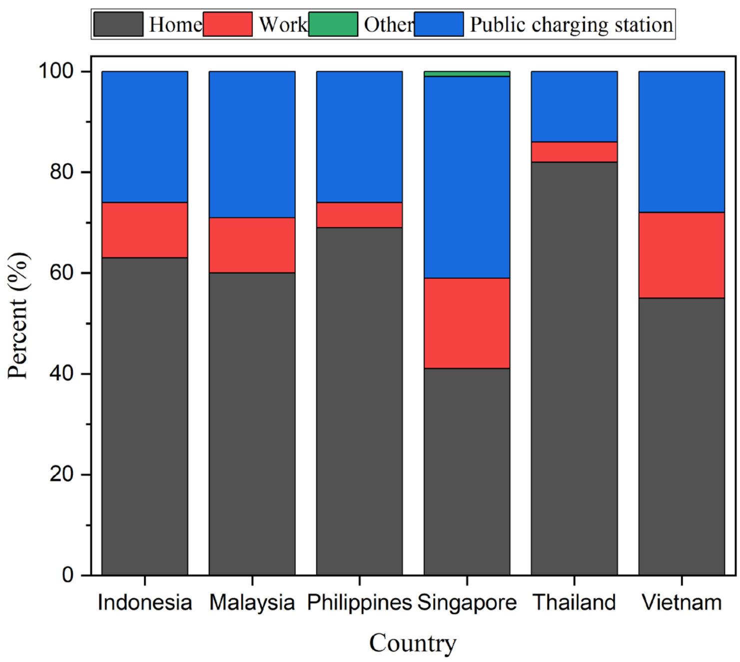

Figure 12. Charging preferences for consumers in Southeast Asia

Additionally, the data reveals that only 15.8% of consumers in Malaysia are not interested in installing home EV chargers, possibly due to safety concerns or other preferences, as shown in **Figure 13**. However, this relatively low percentage suggests a growing opportunity for the home charger market in Malaysia. Enhancing home charging options could boost consumer interest and alleviate range anxiety, a significant barrier to EV adoption in Malaysia. Moreover, 30.7% of consumers are uncertain about how to set up home chargers. This data indicates strong demand and willingness for home-based charging solutions but lacks information on implementation. Therefore, increasing educational initiatives could be a pivotal solution to accelerate EV growth [83]. If the Malaysian government and industry experts initiate academic training activities, it can accelerate the widespread acceptance and adoption of EVs.

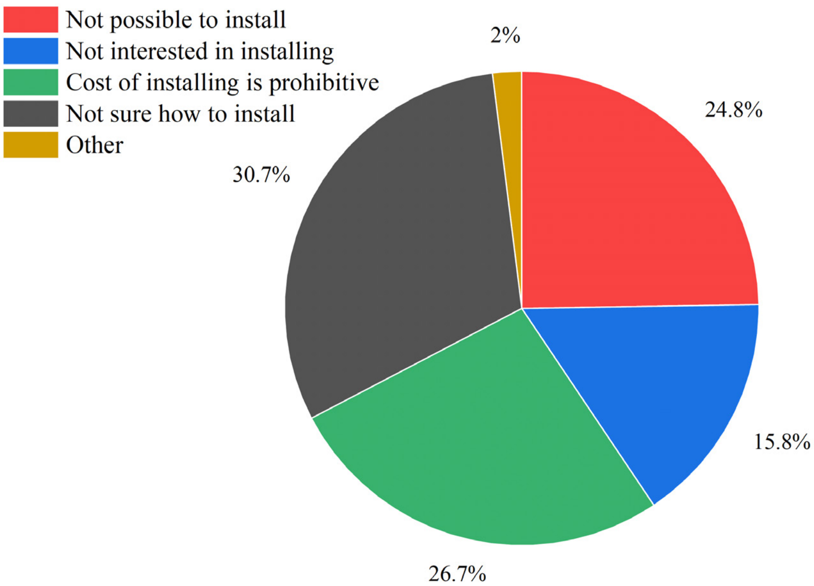

Figure 13. Consumer preferences for installation of home chargers in Malaysia

Collaboration and financial incentives. The collaboration of the private sector and industry stakeholders is crucial in driving EV growth [84], [85], [86]. Encouraging the manufacture or import of EVs with longer driving ranges at affordable prices will appeal to a wider customer base, addressing the needs of long-distance travelers. A united front comprising the government, industry leaders, researchers, and private sectors can merge resources, knowledge, and skills to cater to the unique needs of different regions.

Financial incentives also hold significant weight. The government can balance supply and demand by incentivizing businesses to establish charging stations and giving subsidies to consumers buying EVs with more extended driving capabilities. Such collective actions will accelerate EV adoption in Malaysia and align with the nation's overarching sustainability and environmental protection objectives [87], [88].

Cost-Effective Strategies

A primary avenue to make EVs more accessible is by promoting the establishment of local battery cell manufacturing units [89]. By producing critical components such as lithium, cobalt, and graphite within the country, Malaysia can significantly reduce the costs linked to imports, taxes, and shipping delays [90], [91]. Local manufacturing ensures cost savings and enhances the nation's self-reliance and sustainability in the EV sector.

The economic impact of establishing local battery cell manufacturing units can be seen by:

$$\Delta C = (C_{\text{import}} - C_{\text{local}}) \times N_{\text{battery}} \tag{5}$$

where ΔC is the total cost reduction, C_{import} is the cost of importing battery cells, and C_{local} is the cost of locally manufactured battery cells, and N_{battery} is the number of battery cells. The above equation shows that the increase in the number of local manufacturing batteries can reduce the total cost of batteries, reducing the total cost of EVs.

The evolving landscape of EV production has shown notable improvements over the years. To further capitalize on this, Malaysia may streamline and refine the processes of extracting and producing raw materials for batteries and other EV components. Addressing cost issues, component shortages, and production delays may ensure a more robust and consistent supply chain for EV battery packs [92]. The impact of supply chain optimization is determined by using the Supply Time Ratio (STR):

$$\text{Supply Time Ratio (STR)} = \frac{t_{\text{optimized}}}{t_{\text{current}}} \tag{6}$$

where $t_{\text{optimized}}$ is the optimized time for the supply chain process and the t_{current} is the current time for supply chain process. Assuming that the optimized time after addressing the issues of component shortages and production delays is 35 days while the current time is 45 days. Then STR will be 0.67, indicating a 33% improvement in supply efficiency and a reduction in the time from 45 to 30 days.

Impact of Research and Development on Malaysia's EV Sector. Promoting a solid Research and Development (R&D) foundation in the EV sector also impacts EV growth [93], [94]. By directing funds into consistent research, Malaysia may significantly reduce EVs' direct and indirect expenses, enhancing the appeal to potential buyers. Simultaneously, partnerships between renowned original equipment manufacturers (OEMs) and emerging EV startups are pivotal. Such alliances may result in the creation of tailored, efficient EVs, removing unnecessary parts and optimizing battery capacity. This approach sets the stage for vehicles with extended driving ranges and reduces production costs.

Malaysia derives inspiration and strategic insights from global EV trends, underscoring the importance of R&D. China and Europe have witnessed significant EV growth due to socio-economic advantages and environmental consciousness [95], [96]. The nation motivates local consumers and producers by tailoring these success narratives to a Malaysian context. Moreover, by nurturing a diverse and competitive EV market with vehicles that differ in prices, features, and specialties, Malaysia can ensure that consumers have ample choice, further driving down costs.

The advancement of EVs in Malaysia largely depends on ongoing innovation, particularly in the field of battery technology, which depends on R&D. By creating an environment that supports technological progress through robust R&D initiatives, the country can make sure that new developments are scalable and adaptable for future improvements. Furthermore, Malaysia can position itself as a key player and cooperative ally in the worldwide EV movement by emphasizing collaborations with emerging economies and acknowledging their growth possibilities.

By integrating R&D across these strategic areas, Malaysia can build a sustainable and forward-thinking EV industry. Continued investment in research and development will be essential for maintaining momentum, driving innovation, and ensuring that the country's EV sector remains resilient and competitive on the global stage.

Implementing Safety Protocols and Standards

The Malaysian market requires a comprehensive strategy to elevate safety standards and protocols for EVs. Firstly, stakeholders may run extensive educational campaigns to strengthen awareness and acceptance of EVs. These educational campaigns may focus on underlining the benefits and safety of EVs and encouraging the emergence of a pre-owned EV market.

Further, rigorous safety protocols may be established and implemented. These safety protocols include formulating guidelines on battery positioning, insulation, charging durations, and measures to limit damage during accidents [97]. Addressing concerns like battery overheating and potential fire hazards can alleviate public apprehension. Additionally, maintaining EVs necessitates specific training and standardized procedures [98], [99]. Initiatives for training technicians and setting guidelines for the optimal care and handling of EV components are paramount to ensuring safety. Tools must also be appropriately insulated, and the proper safety gear must be employed [98]. It is imperative to design, consolidate, and enforce unified safety standards for all EV-related operations. This manual should be readily available for every stakeholder and supported by regulatory oversight for compliance.

The strategy of instituting safety protocols and standards in the EV market has the potential to boost the rate of EV adoption in Malaysia. Safety concerns have been a significant challenge for many consumers when considering EVs as the primary mode of transportation. Enhancing consumer awareness, fostering acceptance, and setting clear safety guidelines may bolster consumer trust and set the stage for Malaysia's transition to a greener, electric-driven transportation landscape. **Table 4** presents the safety standards adopted in China. Malaysia's EV industry could also apply these standards to improve safety procedures.

Table 4. Safety standards for EV owners and power grid

Category	Testing Items	Reference Standard
User	Impulse current	GB/T 18487.1-2015 9.7
	Overcurrent protection	GB/T 18487.3-2001 10.3
	Overvoltage protection	GB/T 18487.3-2001 10.3
	Temperature requirement	GB/T 18487.1-2015 13
	Charing cable overload protection	GB/T 18487.1-2015 11.6
	Charing cable short circuit protection	GB/T 18487.1-2015 12.2
	Noncontact electric shock protection	GB/T 18487.1-2015 12.3
	Electrical interlocking inspection	GB/T 18487.3-2001 9.1
Power grid provider	Voltage deviation	GB/T 18487.1-2015 10.5
	Unbalanced three-phase voltage	GB/T 12325.1-2008
	Total harmonic distortion	GB/T 15543-2008
	Voltage flicker	GB/T 14549-93
	Voltage sag and short supply interruption	GB/T 30137-2013
Charging equipment	Contact protection	GB/T 18487.1-2015 7.2
	Capacitor discharge	GB/T 18487.1-2015 7.3
	Protective earthing conductor	GB/T 18487.1-2015 7.4
	Contact Current	GB/T 18487.1-2015 11.2
	Insulation resistance	GB/T 18487.1-2015 11.3
	Dielectric strength	GB/T 18487.1-2015 11.4
	Impulse withstand voltage	GB/T 18487.1-2015 11.5
	Lightning protection	GB/T 18487.1-2015 11.7
	Electrical clearance and creepage distance	GB/T 18487.1-2015 10.4
	IP protection level	GB/T 18487.1-2015 10.5

Fast Charging with Renewable Integration

Implementing fast charging technology can significantly boost the EV industry, and integrating these solutions with renewable energy can significantly increase the adoption of EVs in Malaysia. By implementing this approach, the EV sector in Malaysia can address concerns about range anxiety while simultaneously easing the grid's pressure by integrating renewable energy sources. Choosing renewable energy instead of conventional grid power promotes efficient use of energy and supports a more sustainable and eco-friendly method of energy consumption in the EV industry [100]. This strategic combination can help accelerate the process of increasing the use of EVs.

Addressing Range Anxiety Using DC Charging. Concern about the battery depleting before arriving at a charging point is a significant barrier for many potential EV buyers. **Table 5** showcases the charging durations of EVs across four charging modes as per IEC 61851-1 standards **[101]**. Notably, mode 1 offers a maximum current of 16 A, taking 14 hours for a full charge of 50 kWh battery. Mode 2 provides up to 32 A of current, reducing the charge time to between 2 and 7 hours. However, mode 3 outperforms with a peak current of 63 A, enabling a charge time of 1 to 2 hours. This variable charging duration contributes to the concerns of EV owners, particularly for planning long trips. For instance, if Malaysians are on a journey and a vehicle runs out of power on the highway, a considerable wait might ensue. This prolonged charging time is among the foremost challenges facing the EV sector. Nevertheless, research shows that DC charging can refuel an EV in 15 minutes **[102]**. Implementing fast-charging infrastructure can significantly curtail charging durations, making long-distance travel more viable and alleviating concerns linked to EV usage.

Table 5. The charging durations of electric vehicles across four charging modes as per IEC 61851-1 standards **[103]**.

Charging Mode	Charging Type	Max. Current	Charging Time for 50 kWh
Mode 1	Slow	16 A, AC	14 h
Mode 2	Fast	32 A, AC	2-7 h
Mode 3	Rapid	62 A, AC	1-2 h
Mode 4	Ultra-Rapid	400A, DC	15 min

Utilizing Renewable Energy. Malaysia receives ample solar irradiation and holds potential for wind energy due to its geographical location **[104]**. Malaysia can develop an eco-friendly charging network fueled by photovoltaic (PV) panels and wind power systems by tapping into its renewable resources. This strategy could align well with Malaysia's objectives for sustainable energy. It may significantly reduce the country's carbon footprint, aligning with findings emphasizing the technical viability of integrating PV and wind energy conversion systems with the power grid.

However, the variable nature of renewable energy sources, especially solar and wind, necessitates implementing Energy Storage Systems (ESS), as shown in **Figure 14**. These systems can stabilize the grid during low renewable power generation **[105]**. Notably, fast-charging stations equipped with such ESS can serve a dual purpose in Malaysia: firstly, by offering rapid charging solutions to EV users, reducing range anxiety, and promoting EV adoption; and secondly, by acting as buffer storage units during low renewable generation and high consumption periods.

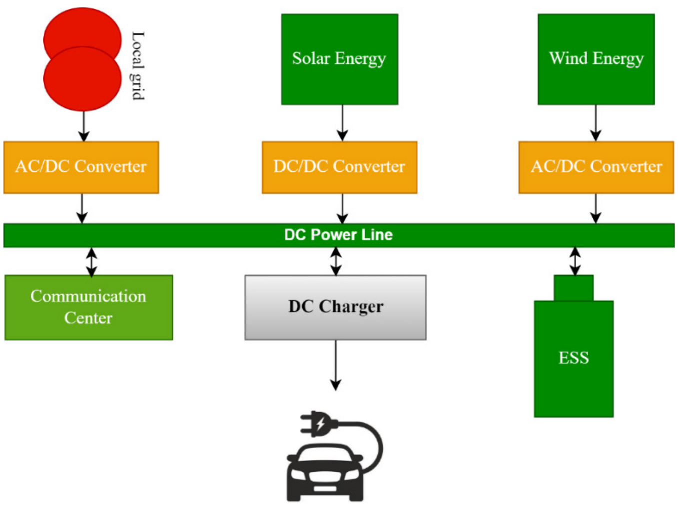

Figure 14. Renewable energy integration with the fast-charging station

Solar-powered batteries can facilitate EV adoption in Malaysia to cater to fluctuating grid demands [106]. Advanced battery technologies, including lithium-ion and flow batteries, are apt for this purpose due to rapid charge-discharge cycles and high energy densities. Including an efficient central controller ensures that excess power from the PV arrays is stored, further optimizing the solar energy generation process with the help of Maximum Power Point Tracking (MPPT) and Pulse Width Modulation (PWM) technologies. Based on a survey with 97 participants, 12.1% of respondents prefer alternative energy sources over the conventional power grid. Interestingly, 49.5% chose a combination of the power grid and alternative sources, as shown in **Figure 15**. These findings suggest a growing inclination among Malaysians towards harnessing alternative energy sources in conjunction with the traditional grid. This trend can be leveraged to promote the use of renewable energy for EV charging, potentially boosting the demand for EVs in Malaysia.

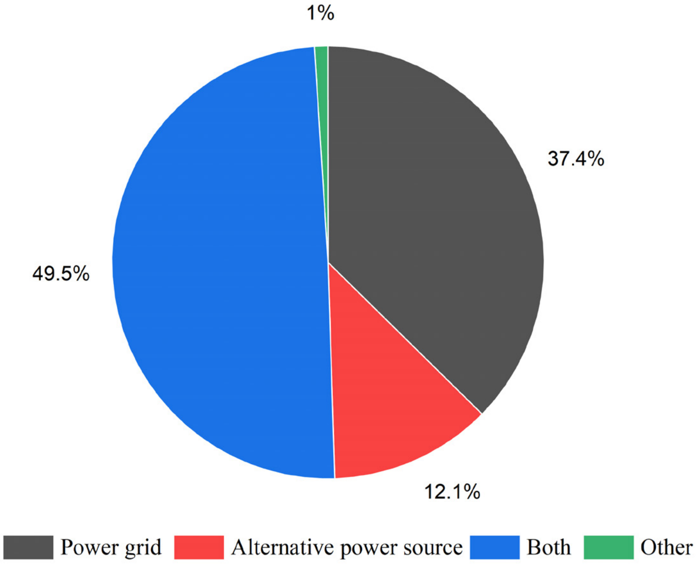

Figure 15. Consumer preference on the use of power sources for electric vehicles

Moreover, converters play a critical role in this system. For the Malaysian EV market, AC/DC converters facilitate the efficient transformation of power from renewable energy sources to be compatible with EV charging requirements [106]. Advanced converter technologies such as string inverters, micro-inverters, and power optimizers ensure consistent and efficient power conversion, adjusting loads in real-time for optimal performance.

The synergy between renewable energy sources, energy storage solutions, and advanced conversion technologies offers a comprehensive approach to fostering EV adoption in Malaysia. By utilizing rich renewable energy potential, Malaysia can address EV charging infrastructure challenges and stride confidently towards a more sustainable and environmentally friendly future.

Reducing Grid Pressure. The introduction of fast charging in the EV sector has brought revolutionary benefits and significantly stresses the traditional power grid [107]. During peak charging times, there's potential for overloads, voltage instability, and service disruptions, possibly hastening the wear and tear of the grid infrastructure [105]. Integrating renewable energy sources with fast charging also reduces the grid stress, as this approach generates a sizable amount of required power locally, reducing the load on the primary grid [108]. This decentralized energy system also acts as a backup during grid failures, offering uninterrupted fast charging and reducing energy losses from long-distance transmission, presenting economic and environmental advantages [109]. Integrating renewable energy with fast charging is crucial for addressing immediate grid challenges and aligns with global sustainability goals.

Moreover, using renewable energy in fast charging stations directly correlates with reducing the carbon footprint associated with EV charging. By drawing power from solar and wind, these stations can operate more sustainably than those relying on conventional fossil-fuel-based electricity. This shift benefits the environment by cutting greenhouse gas emissions and enhances the public perception of EVs as truly green alternatives to traditional vehicles. However, the intermittent nature of renewable energy sources poses a challenge, necessitating advanced energy storage solutions and smart grid technologies to ensure a reliable and consistent power supply for fast-charging [110].

Another significant aspect of integrating renewable energy with fast-charging infrastructure is the potential for innovation in energy management and storage systems [111]. Smart grid technologies, such as demand response and battery storage systems, can help balance the load on the grid, especially during peak charging times. These technologies enable the storage of excess renewable energy, which can then be used during high-demand periods or when renewable sources are less productive [112]. Moreover, by using advanced analytics and AI-driven predictive models, it is possible to optimize the operation of fast charging stations, thereby increasing efficiency and reducing operational costs [113]. This harmonious integration of renewable energy and cutting-edge technology fortifies the EV infrastructure and paves the way for a more resilient and sustainable energy ecosystem.

Battery Recycling Industry in Malaysia

A critical element in preparing Malaysia for the ongoing EV implementation is the development of a robust battery recycling sector [114]. As the adoption of EVs increases, the demand for effective battery recycling solutions becomes important. Proper management and recycling of used batteries are essential for mitigating environmental impacts, conserving resources, and ensuring the sustainability of the EV industry [115].

Currently, Malaysia's battery recycling infrastructure is still developing. There is a need for more comprehensive policies and facilities dedicated to the recycling of lithium-ion batteries, which are commonly used in EVs. According to the Malaysian Investment Development Authority (MIDA), several initiatives have been launched to promote electronic waste recycling, including batteries [116]. Still, these efforts are insufficient to meet the anticipated surge in EV battery waste.

Improper disposal of EV batteries can lead to significant environmental hazards due to toxic materials, such as heavy metals and electrolytes. An efficient recycling system can prevent soil and water contamination, thereby reducing the ecological footprint of EVs. Furthermore, recycling batteries allow for the recovery of valuable materials such as lithium, cobalt, and nickel, which can be reused in producing new batteries, thus reducing the need for virgin material extraction and minimizing the environmental impact of mining activities [117]. Creating a battery recycling industry offers substantial economic benefits by generating new economic opportunities. This sector can attract investments and foster the growth of related industries, contributing to the country's overall economic development. In collaboration with industry stakeholders, achieving this requires the Malaysian government to establish clear regulations and standards for battery recycling. Incentives for companies investing in recycling technologies and infrastructure will be crucial, and partnerships between battery manufacturers, automotive companies, and recycling firms can drive innovation and efficiency in the recycling process.

Figure 16 presents the role of a robust recycling industry in the Malaysian market. The cycle starts with mining the materials for essential elements like cobalt, lithium, manganese, and nickel. These materials are used to produce new batteries that are used in EVs. Once these batteries are depleted, they may be collected and sorted at collection centers. These batteries can be classified into three classes at the collection centers.

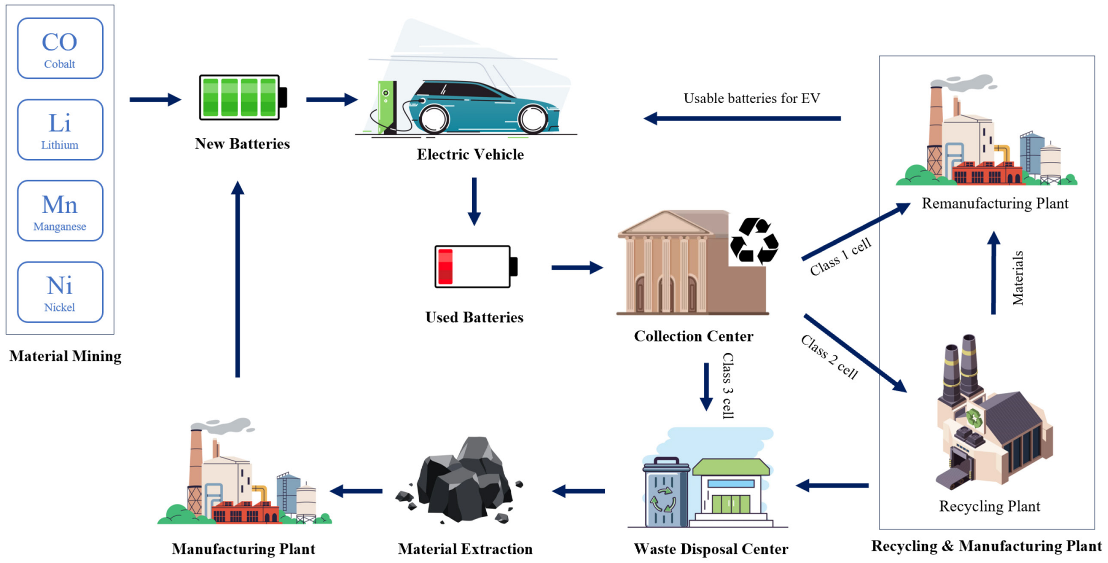

Figure 16. Electric vehicle recycling network

- Class 1 – capacity is higher than 70% of initial capacity
- Class 2 – capacity is in between 50% and 70% of initial capacity.
- Class 3 – capacity is lower than 50%.

Class 1 batteries are sent to the remanufacturing plant for refurbishing into usable batteries. In comparison, class 2 batteries are sent to the recycling plant, where the batteries are processed and sent to the remanufacturing plant for refurbishing. On the other hand, class 3 batteries are directly sent to the waste disposal center.

Studies from countries with advanced battery recycling programs, such as Japan and Germany, demonstrate the effectiveness of stringent regulations and robust recycling infrastructures [118]. These countries have implemented comprehensive recycling systems that manage waste efficiently and contribute to the circular economy by reintroducing recycled materials into the supply chain. Incorporating battery recycling into Malaysia's EV strategy may enhance the sector's sustainability, minimize environmental hazards, conserve resources, create economic opportunities, and support the sustainable growth of the EV industry in Malaysia.

Impact on the Malaysian Economy

The expansion of EVs in Malaysia may significantly impact the nation's economy, fostering local manufacturing, enhancing supply chain efficiencies, encouraging innovation, and implementing strategic infrastructure development. Figure 17 presents the primary and secondary benefits of EV growth in Malaysia, leading to economic growth. The EV growth will lead to new industries and services, including battery manufacturing, EV production facilities, charging infrastructure development, and maintenance services, creating job opportunities across various skill levels [119]. Increased employment will boost consumer spending and generate higher tax revenues, fueling economic growth. Additionally, local production of EV components, such as batteries, will reduce import dependency, lowering costs associated with tariffs, shipping, and import taxes [120]. These savings can be reinvested into further R&D, infrastructure expansion, and subsidies for EV adoption, creating a positive feedback loop that accelerates sector growth and makes EVs more affordable for consumers.

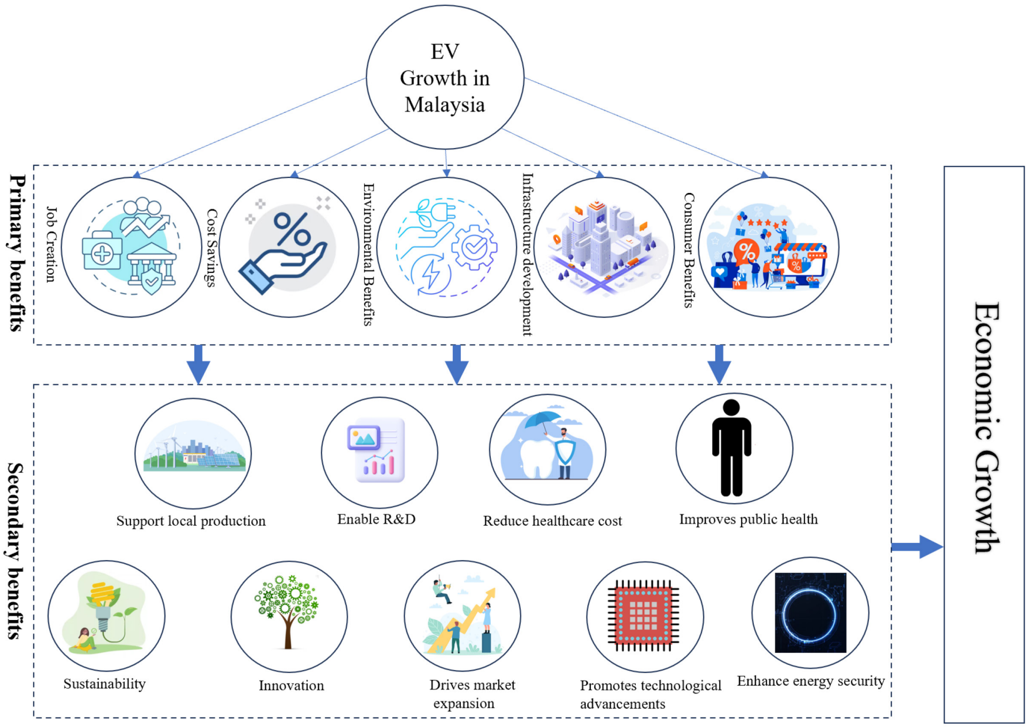

Figure 17. Impact of electric vehicle growth in Malaysian economy

Investments in R&D and innovation will enable Malaysia to develop advanced EV technologies and solutions, enhancing its competitiveness in the global market [121]. This increased competitiveness can open up export opportunities, boost national revenue, and establish Malaysia as a key player in the global EV industry. The expansion of EV charging infrastructure with optimal placement and accessibility indices will spur development in related sectors such as construction, energy, and technology. This infrastructure development will support the EV sector and the broader economy by enhancing connectivity, reducing transportation costs, and improving energy efficiency. The widespread adoption of EVs will substantially reduce greenhouse gas emissions and air pollutants, improving public health by decreasing the incidence of respiratory and cardiovascular diseases and lowering healthcare costs [122]. By shifting from traditional internal combustion engine vehicles to EVs, Malaysia can significantly cut emissions of CO_2, NO_x, and particulate matter, contributing to a cleaner environment. Improved air quality will also enhance the overall quality of life and productivity of the population, contributing positively to the economy.

Integrating renewable energy sources with EV charging infrastructure will enhance Malaysia's energy security and sustainability, reduce reliance on fossil fuels, mitigate the impact of global energy price fluctuations, and help Malaysia meet its international environmental commitments. A more sustainable energy strategy will provide long-term economic stability and resilience. Promoting a robust R&D environment may drive technological advancements and innovation in the EV sector, attracting foreign investment, encouraging the growth of local startups, and creating a dynamic innovation ecosystem. As the cost of EVs decreases and charging infrastructure becomes more accessible, more consumers will be able to afford and maintain EVs, driving higher adoption rates and expanding the market for EVs. This larger market will attract more manufacturers and service providers, further driving competition, innovation, and cost reductions. By investing in local manufacturing, infrastructure development, and technological innovation, Malaysia can build a sustainable and resilient economy that benefits from the global shift towards electric mobility, transforming the transportation landscape and driving broader economic growth and sustainability, positioning Malaysia as a leader in the new energy economy.

LIMITATIONS AND FUTURE PROSPECT

The review primarily relied on Google Scholar, Scopus, and ScienceDirect databases to source relevant research papers. Although efficient, this approach may overlook potentially important research articles available in other databases, limiting the breadth of the sources—moreover, the search protocol focused on papers published within the last ten years. Consequently, any significant studies or data predating this timeline were excluded, potentially overlooking historical contexts or foundational research in Malaysia's EV domain.

The secondary filtering step was based on factors like the impact factor of journals and the frequency of citations. This may have inadvertently excluded significant studies from lesser-known but valid sources or newer publications with limited citations. Additionally, the information regarding charging stations for EV chargers was collected by Agmo Studio Sdn Bhd. The study may not account for unforeseen external factors like sudden policy changes, technological breakthroughs, or economic shifts that could influence the growth and adoption of EVs in Malaysia. Researchers and readers may consider these limitations when interpreting the insights of this study. Nevertheless, the methodology provides a strong foundation for understanding the current landscape of EVs in Malaysia.

The outlook for EVs in Malaysia is positive. With strong measures in place to tackle current challenges and align with worldwide trends towards sustainable transportation, Malaysia is well-positioned to lead the adoption of EVs. The government is working closely with key industry players, paying close attention to what consumers want, to shape a revival in EVs carefully. The foundation of this journey is built on comprehensive research, innovative breakthroughs, strategic improvements in infrastructure, and continuous education. The key recommendations and areas for future work are discussed below:

- Crucial Role of Power Management: Efficient power management is integral for the smooth operation of EVs in Malaysia, offering a pivotal role in advancing EV technology [123], [124]. By leveraging rule-based and optimization-focused controls, there's substantial potential to enhance the efficiency and longevity of EVs significantly. Given the surge in power demand due to increased EV adoption, strategic planning and action are imperative.
- Evaluating Grid Impacts: The large-scale adoption of EVs has the potential to put considerable stress on Malaysia's electricity grid. It's crucial to assess the ramifications of widespread EV use on the country's power generation capabilities, focusing on areas with grid constraints to secure against potential disruptions and to ensure stability and sustainability in power distribution.
- Leveraging Innovative Solutions: Incorporating innovative frameworks like Vehicle-to-Grid (V2G) technology and embracing renewable energy sources can provide resilient solutions to possible grid stresses. Further, the development of technologies supporting Vehicle-to-Home (V2H) and Vehicle-to-Vehicle (V2V) interactions opens up exciting avenues for reshaping power distribution paradigms [125], [126].
- Maintaining Adaptive Approach: Transitioning to greener transport necessitates flexibility and adaptability. An iterative and responsive approach is essential, characterized by regular evaluations, international benchmarking, and swift recalibrations. This transformative journey represents more than just a shift in transportation; it underscores Malaysia's steadfast commitment to ecological preservation and sustainable development.
- Data Modeling and Simulation: The data from charging stations can be used to predict EV adoption trends and infrastructure needs. This involves detailed algorithms to analyze the real-time data on usage patterns, charging durations, and energy consumption. Additionally, the integration of renewable energy sources with fast-charging stations can also be modeled to evaluate their impact on grid stability and environmental sustainability. Implementing advanced data analytics and machine learning techniques can optimize the placement and number of charging stations, ensuring they meet the growing demand

effectively. Furthermore, developing predictive maintenance systems using IoT data from charging stations can enhance reliability and reduce downtime.

CONCLUSION

In conclusion, Malaysia's EV landscape is poised for significant growth but needs to overcome specific challenges. While the global EV market is expanding rapidly, Malaysia's adoption rate is slowed by limited charging infrastructure, high costs, safety concerns, and low consumer awareness. The country's charging infrastructure is still developing, focusing on expanding and evenly distributing charging stations, particularly along highways and in rural areas. This would address range anxiety among potential EV users. The high cost of EVs compared to traditional vehicles is another major challenge. Strategies such as local manufacturing of EV components, including batteries, could help reduce costs. Promoting a competitive EV market with various options could further lower prices.

Safety standards and consumer awareness are also essential. Implementing strong safety protocols and educating consumers about the benefits and safety of EVs could improve public perception and acceptance. This requires a joint effort from government bodies, industry players, and educational institutions. Additionally, integrating renewable energy sources with fast-charging infrastructure could reduce grid pressure and environmental impact. Solar and wind energy, along with advanced energy storage solutions, can create a sustainable and efficient charging network, aligning with global sustainability goals and enhancing the green image of EVs. As EV growth increases in the future, there will be a need for battery recycling in the country, which may positively affect economic growth.

Overall, a comprehensive approach that includes building efficient charging infrastructure, lowering vehicle costs, improving safety, and educating consumers is key to boosting the EV market in Malaysia. By adopting these strategies, Malaysia can fully realize the benefits of EVs, leading to a more environmentally friendly and sustainable transport system.

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STATEMENTS & DECLARATION

During the preparation of this work, the author(s) used GPT-4 to improve the readability of the content. After using this tool, the author(s) reviewed and edited the content as needed. The work is written and prepared by the authors, who take full responsibility for its content.

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