Transition to Electric Mobility in India: Barriers Exploration and Pathways to Powertrain Shift through MCDM Approach

B. Ashok 1,2 · C. Kannan 1 · Kaisan Muhammad Usman 2 · R. Vignesh 1 · Chirag Deepak 1 · Rathan Ramesh 1 · Tharun M. V. Narendhra 1 · C. Kavitha 3

Abstract The ever-increasing environmental concern necessitates the implementation of electric vehicles (EVs) in the public fleet in a larger proportion. While developed countries have accomplished this objective through unique ways, developing and underdeveloped countries are still lagging. Deficiencies in technological readiness and supportive infrastructure are major concerns for them. To support their future endeavours in the field of electric vehicles, a review article that encompasses the present status, barriers for EVs adoption and operation in developing countries proves highly critical. A critical analysis of EV adoption barrier information is used to develop appropriate technology to tackle these barriers and provide necessary plans for policymakers to effectively implement electric vehicles. Furthermore, this article comprehensively analyses barriers to EV implementation and adopts the multi-criteria decision making (MCDM) model to rank the evaluation criteria based on expert opinions. From the results for developing countries such as India, the model placed battery-operated electric vehicles at 5th position on the hierarchy ranking. This is because the existing infrastructure and technology will not currently support the imminent shift to electric mobility. The identification of a possible alternative propulsion system that bridges the gap between necessity and feasibility is essential. For this purpose, the article also explores the prospects and critically analyses hybrid electric vehicles as an intermediary propulsion system that smoothens the transition to EV. The outcomes of the literature review, expert opinions and author findings suggest that hybrid technology uses powertrain components that are chiefly similar to those found in conventional vehicles, yielding vehicle manufacturers with a smoother changeover to Electric Vehicle technology, which may otherwise lead to an immense failure in technology transition.

Keywords Future mobility · EV barriers review · Electric vehicles · Hybrid electric vehicles · MCDM

Abbreviations

MCDM Multi-criteria decision making
PROMETHEE Preference ranking organization method for the enrichment evaluation
EV Electric vehicle
ICE Internal combustion engine
CV Conventional vehicle
HEV Hybrid electric vehicle
LCA Life cycle assessment
ANOVA Analysis of variance
AHP Analytic hierarchy process
EPC Electric powered car
EU European Union
LCV Light commercial vehicle
RES Renewable energy sources
BMS Battery management system
FCEV Fuel cell electric vehicle
SOC State of charge
AC Alternating current
DC Direct current

© The Institution of Engineers (India) 2022
Unless the required attributes for EVs are balanced in the power grids that are linked to charging infrastructure. EVs into the market is the reaction on global and national factor often disregarded to the considerable penetration of criterion that induces the public to lose interest in EVs. A progress convincingly. Range anxiety is an important cri-

mment support. At this time, charging infrastructure is power grid management, consumer mindset and govern-

ance dependent. However, the shift from conventional to fully electric propulsion will require immense developments in vehicle powetrain architecture, charging infrastructure, power grid management, consumer mindset and government support. At this time, charging infrastructure is inadequate, insufficiently distributed and requires time to progress convincingly. Range anxiety is an important cri-

terion that induces the public to lose interest in EVs. A factor often disregarded to the considerable penetration of EVs into the market is the reaction on global and national power grids that are linked to charging infrastructure. Unless the required attributes for EVs are balanced in the right proportion, the transition becomes significantly difficult. Even a small disturbance or irregular transition from ICE-powered vehicles to EVs will produce a negative impact on the economic growth and overall performance of the automotive sector.

To establish the target areas of research for this paper, an analysis of the lapses/gaps found in the existing literature is performed and summarised in Table 1. The electrification of vehicles becomes a prominent subject in the field of automotive technology, various assessment studies on the large-scale electrification of vehicles and its barriers are adequately explored by the researchers. The impact evaluation of an extended transition for the transportation sector within a country/region mandates an analytical study that focuses on the influence of the entire vehicle population. Various research studies are investigating the overall environmental impacts of EVs throughout their lifetime of operation. These studies have often presented and compared comprehensive quantitative information for the emissions/fuel efficiency standards of conventional vehi-

cles (CV), EVs and HEVs. A life cycle assessment (LCA) is the analysis tool prevalent used for such studies; however, this methodology neglects the qualitative effect of EV usage on factors such as the quality of power required and stress of heightened energy demand on power grids. A majority of research work highlights the importance of implementation of EVs and HEVs over CVs although most of them refrain from going into detail on comparing the two based on factors ranging from performance to infrastructure. Additionally, some papers consider the barriers to EV adoption although these barriers are often limited to performance/technological factors and abstain from considering infrastructural or governmental parameters. Furthermore, research work falling under the above categories neither consider the potential of other propulsion systems nor compare the overall characteristics of EVs to fossil liquid fuel vehicle, gaseous fuel vehicle, hybrid vehicle, plug-in hybrid vehicle, fuel-cell vehicle and alternative fuel vehicles. An untouched comparative research perspective of this kind is essential to explore factors assisting automotive manufacturers in developing sustainable vehicle propulsion technology along with ease of transition. Studies on transportation systems that are based on expert opinions make use of numerous methods of data accumulation and analysis as seen in Table 2. Numerous studies implement the analysis of variance (ANOVA) methodology in tandem with an analytic hierarchy process (AHP). In such a system, decision-making comparisons via AHP is used to set initial weights per criterion following which an ANOVA study is conducted for correlation between various groups. The Q-method (Q-

sort) is another common methodology used in similar studies. In such studies, factor ranking is conducted via

| EVGI | Electric vehicle grid integration |
| THD | Total harmonic distortion |
| BSS | Battery swapping station |
| LFV | Liquid fuel vehicle |
| GFV | Gaseous fuel vehicle |
| AFV | Alternative fuel vehicle |
| BEV | Battery electric vehicle |
| ZEV | Zero emission vehicle |
| PHEV | Plug-in hybrid electric vehicle |
| TFO | Total cost of ownership |
| RBS | Regenerative braking system |
| PaHEV | Parallel HEV |
| SHEV | Series HEV |
| SPaHEV | Series–parallel HEV |
| WTW | Well-to-wheel |

Introduction

As of 2017, there exist approximately 197 registered vehicles per every thousandth of the human population in India [1]. As the nation looks to improve its standard of mobility, an exponential increase in this trend is anticipated in the coming years. With a sharp increment in the total number of vehicles on road, a substantial escalation of greenhouse gases, depletion of fossil fuels and damage to the health of the environment and its inhabitants will develop. Owing to these drawbacks, future mobility will move towards eco-friendly and carbon–neutral alternatives. In recent years, electric vehicles (EVs) have gained extensive attention as sustainable and eco-friendly alternatives to conventional internal combustion engine (ICE) based vehicles. Forecasts show a tremendous increase in the national fleet of EVs in the future and this can be attributed to characteristics of reduced emissions and noise whilst realising the potential for improved vehicle crash structures. Furthermore, EVs exhibit considerable promise in revolutionising the two-wheeler and public transport sectors where India’s automotive industry is predominantly dependent. However, the shift from conventional to fully electric propulsion will require immense developments in vehicle powetrain architecture, charging infrastructure, power grid management, consumer mindset and government support. At this time, charging infrastructure is inadequate, insufficiently distributed and requires time to progress convincingly. Range anxiety is an important cri-

terion that induces the public to lose interest in EVs. A factor often disregarded to the considerable penetration of EVs into the market is the reaction on global and national power grids that are linked to charging infrastructure. Unless the required attributes for EVs are balanced in the right proportion, the transition becomes significantly difficult. Even a small disturbance or irregular transition from ICE-powered vehicles to EVs will produce a negative impact on the economic growth and overall performance of the automotive sector.

To establish the target areas of research for this paper, an analysis of the lapses/gaps found in the existing literature is performed and summarised in Table 1. The electrification of vehicles becomes a prominent subject in the field of automotive technology, various assessment studies on the large-scale electrification of vehicles and its barriers are adequately explored by the researchers. The impact evaluation of an extended transition for the transportation sector within a country/region mandates an analytical study that focuses on the influence of the entire vehicle population. Various research studies are investigating the overall environmental impacts of EVs throughout their lifetime of operation. These studies have often presented and compared comprehensive quantitative information for the emissions/fuel efficiency standards of conventional vehicles (CV), EVs and HEVs. A life cycle assessment (LCA) is the analysis tool prevalent used for such studies; however, this methodology neglects the qualitative effect of EV usage on factors such as the quality of power required and stress of heightened energy demand on power grids. A majority of research work highlights the importance of implementation of EVs and HEVs over CVs although most of them refrain from going into detail on comparing the two based on factors ranging from performance to infrastructure. Additionally, some papers consider the barriers to EV adoption although these barriers are often limited to performance/technological factors and abstain from considering infrastructural or governmental parameters. Furthermore, research work falling under the above categories neither consider the potential of other propulsion systems nor compare the overall characteristics of EVs to fossil liquid fuel vehicle, gaseous fuel vehicle, hybrid vehicle, plug-in hybrid vehicle, fuel-cell vehicle and alternative fuel vehicles. An untouched comparative research perspective of this kind is essential to explore factors assisting automotive manufacturers in developing sustainable vehicle propulsion technology along with ease of transition. Studies on transportation systems that are based on expert opinions make use of numerous methods of data accumulation and analysis as seen in Table 2. Numerous studies implement the analysis of variance (ANOVA) methodology in tandem with an analytic hierarchy process (AHP). In such a system, decision-making comparisons via AHP is used to set initial weights per criterion following which an ANOVA study is conducted for correlation between various groups. The Q-method (Q-

sort) is another common methodology used in similar studies. In such studies, factor ranking is conducted via
Q sorts after which Q method is implemented to observe the diversity within opinions of various experts. Often, such studies compare varying opinions of both the general public as well as industry experts. A majority of studies however limit their survey criteria to vehicle safety, handling and security due to which predominantly concentrated around intelligent cyber-physical vehicles. Multi-criteria decision making (MCDM) is made use of to solve the complex decisions that are produced when numerous criteria are considered. This method allows for opinion-based decision-making, consideration of alternatives as well as the effects produced by each alternative. The preference ranking organization method for enrichment evaluation (PROMETHEE), an MCDM tool has been adopted in this study due to its appropriate ranking capability for criteria based on additional deviation information from the evaluation of alternatives within the same criterion.

Motivation and Objective

A review of automotive research works published in the last decade discloses the nature of mobility transition towards eco friendliness and sustainability. EVs present themselves as the most compelling yet viable solution for future mobility. However, the monumental essential requirements to be fulfilled for EV operation impede the path of quicker transition from conventional internal combustion vehicles. This review article is focused on the motivation of elucidating the status of EVs with a detailed examination of the significant barriers to their adoption and operation in the context of developing countries. The thorough articulation of EV barrier information will be useful to discover the relationship within economical, technological, infrastructural, societal and environmental barriers and it will be supportive holistic material for manufacturers, policymakers in strategic planning and devising suitable measures in controlling the barriers. Included with the review status for an objective of identifying the possible alternative propulsion for the passenger vehicle segment, a quantitative examination method is proposed in the successive sections of the paper. To the best of the author’s knowledge, there are no review papers that deal with a plan for an efficient propulsion system transition pathway. Moreover, the existence of enormous barriers for imminent EV transition necessitates a decisive solution with the perspective of an intermediate propulsion system that is capable of utilizing the existing industrial and infrastructural facilities. To accomplish this objective, an expert perception ranking method is utilized in discerning and justifying the mindset of respective experts on EVs and other propulsion types. The preference ranking organization method for enrichment evaluation (PROMETHEE) decision-making tool is employed, the hierarchy order is extracted in form of variable criteria and equivalent criteria weight.

Electric Vehicle Transportation Status Around the Globe

To interpret the overall impact of EV penetration on a global scale, the current state of EVs must be visualised and analysed [15, 16]. The present status of EV sales, stocks, as well as forecasted figures, are used as focal points for this analysis. To condense the analysis, global EV leaders such as Europe, China and USA are considered along with developing nations such as India and Brazil.

Global Scenario on EV Sales

In 2020, Europe overshadowed China for the first time since 2015 and ascended to the top of the global EV sales ranking. Nevertheless, China holds the majority of electric-powered cars (EPCs), about 45% as compared to 24% for Europe as seen in Fig. 1 [17]. Developing nations such as India and Brazil have shown significant growth in the EV sector although their sales volumes are incomparable with the top three entities within this market [18]. EV markets in these countries thrive off of the steep demand for two-wheelers and for commercial vehicles aiming for propulsion based on alternative sources [19, 20].

Global Scenario EV Stock

Throughout the last decade, Europe and China exhibited the most significant growth in EVs and accounted for a combined contribution of more than 50% in global EV stocks as seen in Fig. 2 [21]. This can be attributed to the various stringent emission norms, incentive schemes and policies placed by the respective governments. The regulation targets officiated by the European Union (EU) for 2021 mandate CO2 emissions of new cars and light commercial vehicles (LCVs) should fall under 95 g/km and 147 g/km respectively [22]. As existing conventional powertrain architectures are unable to match these regulations, automakers are perpetually looking for a technology shift towards EVs. As a consequence, the plug-in car segment in Europe has grown in size even during the decline of the automotive sector due to the COVID-19 pandemic. In China, there exist adequate public charging points and hence the demand for EVs is less subservient to government policies as consumers face fewer issues with range anxiety and EV recharge. India has shown significant growth in the EV sector owing to policies such as the
950 million subsidies for EVs as issued by the Ministry of New and Renewable Energy [23].

**EV Status in India**

At present, EVs hold 1% of the Indian automotive market out of which, 95% is two-wheelers. The market has seen steep development in two-wheeler technology due to the support of both government and private entities, as demonstrated in Fig. 3. Future projections show the exponential increase in the BEV segment which peak at 42 million units by 2030 [25]. The gradual increase in projected sales of CVs till 2025 is ascribed to vehicle manufacturers’ intention of improving their existent powertrains before the transition to EVs is completed. Additionally, manufacturers are conducting R&D on hybrid powertrain technology to maximise their efficiencies before a complete shift to an electric-based architecture. A target sale of 30–40 million EV units by 2030 is set by the Indian government, one-third of which is expected to be EV cars. The primary scheme proposed by the government is the faster adoption and manufacturing of hybrid and electric vehicles (FAME) [26]. Despite various initiatives taken by the Indian government, certain barriers limit the production and sales of EVs in India such as charging infrastructure, battery technology, consumer behaviour and overall government support which are elaborated in detail in the subsequent section.

### Practical Challenges in Implementing EVs for Mass Transport

EVs are garnering attention worldwide for their environmental benefits with many countries starting to implement policies to promote them to replace CVs [27]. However, a complete shift towards EVs could not be possible without

---

**Table 1** Literature survey of analogous research papers

| References | Objectives of work | Categorization (EV/HEV/CPS) | Geographic context | Inferences | Identified gaps |
|------------|--------------------|-----------------------------|--------------------|------------|-----------------|
| [2]        | Life cycle assessment (LCA) of mass usage of EVs | EV              | China             | CO₂ impact due to life cycle emissions of EVs is defined using a time-dependent model | Considered the factors that are only related to emission reductions and fuel savings |
| [3]        | Life cycle analysis for transition to EVs | EV/HEV          | Australia         | Highest overall carbon footprint for EVs then ICVs and finally HEVs. Renewable energy sources required to reduce EV carbon footprint | Life cycle emissions considered for tank-to-wheel and well-to-tank but not well-to-wheel |
| [4]        | CO₂ emission targets for passenger vehicles | EV/HEV          | Europe            | CO₂ targets post 2020 need to be carefully considered and possibly reduced in order to drive increase in EV market share | Defines importance of EVs/HEVs in reducing CO₂ emissions but does not compare the two in detail |
| [5]        | Planning for Smart Grid and V2G technology integration | EV              | India             | Maximum possible number of EVs that can fit within a grid while balancing cost of energy generation and fuel emission is found | The paper does not explain in detail about the fluctuation of grid power with respect to harmonics and method of EV charging |
| [6]        | Carbon footprint control for EVs/HEVs | EV/HEV          | Global            | PHEVs achieve greater fuel economy while benefits of EVs are dependent on time and extent of use | The paper accurately compares carbon emissions of EVs to PHEVs but does not compare other technological/infrastructure parameters |
| [7]        | Barriers to adoption of EVs | EV/CPS         | India             | EV cost is less concern to buyers in comparison to lack of infrastructural/government support | The paper defines and compares barriers to EV adoption but does not look upon the use of HEV as a potential solution |
| [8]        | Barriers to adoption of EVs | EV/CPS         | India             | To strengthen the EV market, a multitude of barriers need to be considered and researched | The paper does not consider barriers related to government support and grid power quality fluctuation |
| [9]        | Challenges faced by EV usage in India | EV              | India             | HEVs/PHEVs/EVs prove to be able to increase fuel economy at the compromise of costing | The paper defines benefits of EVs and HEVs but does not compare the two |

---

[23] J. Inst. Eng. India Ser. C (October 2022) 103(5):1251–1277

---
the obstacles shown in Fig. 4. This is depicted by the current market’s penetration. The acceptance of EVs and their initial diffusion into the market largely depend on consumer perception and attitude towards EVs [28]. The mindset of consumers plays a crucial role in EV adoption. Similarly, charging infrastructure, driving range, charging time, government support, total cost and awareness among consumers are crucial factors limiting EV adoption rates [29]. The present battery technology is a significant barrier that affects the overall cost, driving range and charging time of EVs [30]. Indeed, the policymakers and authorities have decreased the barrier effects by formulating appropriate policies and incentives, benefitting both consumers and manufacturers. These could have helped EV introduction into the market, although not ensuring their sustainability [31]. Therefore, a thorough understanding and analysis of existing barriers are necessary to improve EV diffusion further.

**Technology Difficulties**

Limited range, packaging, safety, component standards and energy generation are the most important factors hindering the adoption of EVs as shown in Fig. 5. Battery capacity, vehicle weight and aerodynamic drag dominantly influence EV range [32]. EV propulsion necessitates a large number of batteries to match the range of CVs due to the smaller size and low voltage capacity of batteries [33]. A lack of a sufficient number of charging stations also influences the EV range. The weight of an EV is an important parameter that determines its performance and ultimately its success in the market. EV weight is proportional to the expenditure on energy storage thus increasing cost and ultimately reducing customer demand. To improve driving range, the use of lightweight materials, high energy density batteries and battery charging with renewable energy sources (RES) should be employed [34]. This latter technology presents additional challenges such as increased installation and repair costs, inconsistent charging due to its diurnal nature and reduced battery life in the case of standalone photovoltaic cell based EVs. [35]. Although the idea of new batteries seems to have a good prospect, much like fossil fuels, battery production materials are sourced from finite elements such as Li, Ni, Mn. Safety is another important criterion affecting the acceptance and success of EVs. Current EV batteries pose threats in terms of overheating, fire safety, thermal runaway and high energy storage [36]. EVs also pose the threat of cyber security issues within the communication aspect of battery management systems (BMS) [37]. However, the most concerning factors are the disposal of used batteries and the associated environmental impairment. Minimal technological developments in the field of battery recycling are not promising enough to support the claims of a greener future. Lack of standards during EV manufacturing immensely impacts manufacturing cost. The choice of propulsion motor types, viz. induction motor, permanent magnet motor, permanent magnet assisted synchronous motor available to EV manufacturers further affect standardization [38]. Even though placed under the clean vehicle category, fuel cell electric vehicles (FCEVs) powered by H₂ exhibit notable CO₂ emissions, produced during the process of H₂ extraction from methane. The process of hydrogen extraction from water requires large amounts of electricity and can be produced with the help of RES such as wind, tidal, hydro, solar, although these have not been adopted for large-scale electricity production. Furthermore, the presence of H₂ in FCEV raises safety concerns due to its unstable nature.

| References | Objectives of work | Geographic context | Inferences |
|------------|--------------------|--------------------|------------|
| [10]       | Comparison of advantages and disadvantages of cyber-physical vehicles | Global | Importance of vehicle safety, driving and parking improvement show high admission for EPS implemented through AHP and ANOVA methodology |
| [11]       | Policy development for reduction of carbon footprint due to transportation sector | Global/Turkey | Fuzzy Cognitive Map (FCM) methodology used to determine the significance of expert based opinions |
| [12]       | Identifying potential markets for EVs in Europe | Europe | Interquartile range values used to allocate weights for each criteria of the EPS |
| [13]       | Impact of accessibility due to automated vehicles | Global | Q-method used to interpret the various viewpoints for each survey topic. Three separate viewpoints used for factor assignment |
| [14]       | National climate-based transportation policy evaluation | India | Weights assigned according to extent of support/opposition of expert opinions. Analytic Hierarchy Process (AHP) implemented to evaluate various policies |
Before envisioning the EV concept for a specific automotive market, a robust yet sustainable charging infrastructure must exist within the region. Figure 6 explains the main barriers related to EV infrastructure. Range anxiety is the most substantial roadblock to the EV acquisition. It is induced due to the scarcity of adequate on-road battery charging infrastructure in most regions of EVs usage [39]. To overcome this issue, regions with a significant EV population must invest in a cohesive network of numerous interconnected battery charging/swapping stations. Specifications and safety standards to be adopted in charging stations are other parameters to scrutinise while addressing the inadequacy of charging infrastructure [40]. Charging units with high voltage power cables in the circulation require substantial power flow control systems that disconnect current flow in case of loose connections. ‘Inductive Charging’ allows the user/EV to be shielded from the physical charging circuitry as they are allocated below the road surface. However, the charging efficiency for this technology is highly dependent on the separation distance of the EV from the charging emitter, limiting it to a maximum charging efficiency of 85%. Additionally, peak
charging distances of only 250 mm can be accommodated after which charge efficiency diminishes immensely [41–44]. ‘Fast Charge’ circuitry capable of charging an EV under 10 min requires additional installation of safety circuits and components to function effectively either in a charging station or at the home [45–47]. Global EV charging standards administer appropriate regulations for different charging, viz. Level 1 (Opportunity Charging), Level 2 (Primary Charging) and Level 3 (Fast Charging) to ensure safe and efficient charging [48]. Level 1 technology (8–16 h) uses standard 120 V outlets/connectors, without the need for supplementary installations. The size of cabling and thermal constraints imposes limitations on current rating and charging time. Level 2 technology (4–8 h) adopts 240 V with specified connectors/adaptors due to rated voltage and power management requirements. Level 3 technology (10–15 min for 80% SOC) uses 480 V and is limited to on-road charging terminals [49, 50]. This technology however encounters an expensive technological disparity for household application. It requires 3 phase alternating current (AC)/direct current (DC) connections exceeding 22 kW and a minimum current of 32 Amps and 3225 Amps for AC and DC, respectively. Ratings of this magnitude pose safety hazards for a household and require expensive thicker insulated cabling with shortened charger-vehicle cables. Furthermore, various protocols and complex BMS are mandatory to reduce battery degradation and to safeguard the consumer [51]. Consequential effects of power transmission and storage due to EV charging need to be considered both at the consumer end and the producer end. The impact of electric vehicle grid integration (EVGI) is of utmost relevance when it comes to power grid management for the government. EV charging has been found to intensify grid loading thereby causing voltage instability and producing heightened peak load demands. Its

Fig. 3 Past, present and future status of EV in India [18]

Lithium is a non-renewable source of energy. Alternative fuels like Ethanol, Hydrogen, etc. could compete healthily.

Inadequacy of charging grids and outlets present in India

Large and high capacity batteries poses a threat to the safety of passengers

Government policies are not encouraging enough for drastic shift from ICEVs to EVs.

Due to larger batteries, charging times are higher for EVs than HEVs

Price of EVs are much higher than HEVs and ICEVs

Customers are unsure about the reliability of the range of EVs

As it’s 100% electrically driven, the battery packs are large and heavy

Fig. 4 Various barriers for EV implementation
consequence is a depreciation in power reserve margins and power quality issues due to the nonlinear loading properties of EV charging. Furthermore, distribution transformers experience decreased lifetime due to increased hot spot temperatures [52]. Future projections reveal that for an EV population of 42 million, surplus power demand could rise to 92%, accentuating the importance of power management systems. The principal contributing factor for this is the existing uncoordinated charging systems for EVs which cause disorderly peak load demand and more importantly, harmonics within the system. Harmonic distortions (20%—45%) deteriorate the power quality of the grid and impact the durability of components such as transformers [53]. It is found that Level 3 charging technology derives the highest level of harmonic distortion. To maintain power quality, total harmonic distortion (THD) must be less than 5% for a 69 kV network although EV charging often causes THD greater than 10% [54, 55]. With larger EV penetration, normal rate charging may also be subjected to significant power quality deviations. To overcome the inadequacy of charging infrastructure, committees around the world are introducing concepts such as swappable battery packs [56]. This infrastructure is positioned based on storage capabilities rather than technological charging standards. However, immense capital investment, cost incurred during EV layout redesign and land area requirements prove to be deterrents. Moreover, the homogeneity of batteries is required in a market unlike for existing EVs in the market [57—60]. Similar to charging infrastructure, complications of congestion exist due to uncoordinated charging within the battery swapping station (BSS) system [61—63]. Shortly, the countries must focus on coordinated EV battery charging/swapping and power management systems to provide sustainable charging systems that possess favourable power quality.

**Battery Difficulties**

The requirement of sophisticated battery technology is one of the main factors that prevent the mass emergence of EVs into the current market as shown in Fig. 7. The effectiveness of EV batteries is determined by their range, cost, charging time and safety, working temperature range, materials used, recycling prospectus and disposal capabilities. Lithium-ion batteries currently dominate the market due to high energy density, high power density, low weight, cost-effectiveness, non-toxicity and acceptance for fast charging [63, 64]. The main drawback of Li-ion batteries is their high threat of causing fire hazards. The high potential of these batteries for thermal runaway causes temperatures to reach extremities thereby posing an explosive threat [40, 65, 66]. Li-ion batteries pose flammable risks in case of overcharging and place a threat to passengers’ safety if not properly insulated. Furthermore, a major drawback associated with any battery technology is its capacity, the most influential factor for EV range. Heavier, high voltage batteries are being utilized to improve the range but the increased mass takes up more space as compared to a fuel tank in a CV counterpart [67, 68], ultimately affecting the vehicle handling and performance. Likewise, the charging time of these batteries is much higher than the refuelling time of CVs, even considering fast charging technology [50], a significant barrier to EV adoption. A crucial issue being faced by battery manufacturers is maintaining battery temperature...
within the optimal window irrespective of climatic and regional changes. This necessitates battery thermal management systems, increasing system complexity. Materials and manufacturing issues associated with batteries also restrict large-scale EV emergence. Battery materials dictate the operational efficiency and quality of the battery. LiCoO₂, LiMn₂O₄ and LiFePO₄ are materials currently used for cathodes in EVs, while graphite is used for anodes. Drawbacks such as higher cost, complexity, toxicity, poor conductivity and low safety of these materials urge battery producers to develop and incorporate novel materials [69]. The processing of these materials leads to large volume changes which can be avoided with the use of composite materials such as micro-scaled or nano-scaled particles [70]. Large-scale production of Li-ion batteries for EV applications will use up large volumes of industrial fossil fuels. A less disclosed challenge is the limitation of lithium reserves to meet the annual EV demand of 100 million of 40 kWh Li-based batteries. This will also make the cost reduction in Li-ion batteries a challenging task in the future [71]. As EV batteries reach their end-of-life, they emerge as a waste management challenge due to their high volume, complexity and material variance [72, 73]. One probable solution to this issue is the process of recycling, reducing the amount of toxic waste generated and the cost involved in management [74–77]. However, battery recycling involves numerous tasks that collectively increase the cost of disposals such as collection, transportation, storage, disassembly, residual energy, echelon reuse and pollution [73]. When these costs are added to manufacturing, logistics, raw material and material processing, EV batteries become more expensive. A shift towards novel battery materials implementation would result in soaring costs, further hindering the acceptance of EVs.

**Purchasing Capability/Consumer Behaviour for EV**

Attitudes, perception, experience and societal influence are primary psychological factors influencing consumer behaviour [78] as shown in Fig. 8. Statistical data show that majority of EV users are well-educated with medium to high income, using their vehicles for private purposes and charging them at home at night [35]. The young and middle-aged populations, especially those working in technical fields normally prefer to use EVs [79–82]. However, certain barriers limit the acceptance of EVs. Range, charging issues and high capital cost of EVs substantially influence consumer behaviour [83–85]. Media that offers attention to EV fire accidents, increases awareness among the public regarding the safety of EVs. This is contrary to results from studies that imply that EVs do not bear higher flammability risks than CVs [86]. Lack of awareness amongst the public on the environmental benefits of EV also hinders EV purchase [87]. Consumers often give preference to EV performance over their environmental benefits [29]. Total battery life is a major factor that stimulates consumer behaviour towards EV purchase [88]. The current EV market does not encourage potential...

---

**Fig. 6** Infrastructural barriers for EV Implementation

- **Inferences**
  - Large number of batteries must be prepared, requiring high investment cost and area.
  - All EVs should run on similar battery types.
  - Level 2 and 3 chargers require dedicated installation units.
  - Household current demand and cost increases by 25% atleast for Level 2 charging
  - Charging devices require high energy density and charge/discharge within 20 minutes.
  - Multi-stage charging protocols and thick cabling insulation required.
  - Voltage instability due to EVGi causes unpredictable load increase.
  - Decreases power reserves, harmonic distortion (level 3 chargers) and power quality issues.
  - EV chargers exhibit non-linear charging characteristics.
  - This causes unpredictable voltage drops and distorted voltage waveforms.

- **Infrastructural Barriers of EV**
  - EV Charging Standards [61]
  - In-House Charging [62–65]
  - Battery Swapping [71–73]
  - Power Smoothing [69–71]
  - Grid Stability [66–68]

- **Suggestions**
  - Real time demand based framework required for efficient mass battery swapping
  - SMS required for diverse batteries.
  - Variation in charging method induces difficulty in load forecasting.
  - Power networks require RES support to contain impacts of high EV grid penetration.
  - Standard connectors for EV charging devices need to be enforced.
  - Redesign of charging cables to support auxiliary cooling for usage under high load.
  - EV charging must be controlled in a scheduled manner.
  - Periodic examination of operation of each charging station merged with power grid.
  - Satisfactory power quality must be achieved.
  - For this, Total Harmonic Distortion (THD) for a 69 kV network must be less than 5%.
buyers due to a lack of variants. Thus, variety in EV range, style, appearance and functionality can attract more consumers [89, 90]. Moreover, government policies and incentives offering monetary benefits have a significant influence on EV purchases. Financial subsidies, tax rebates, free parking, etc. should be initiated to drive consumers towards EV purchase [91–94]. Monetary incentives will aid in the initial penetration of EVs into the market although they will not sustain in the long run. The understanding of consumer mindsets and their varying attitudes will help in implementing better policies to promote EV diffusion into the market [31].

**Government Support**

Government support is vital during the promotional stage of an EV market as it motivates consumers to adopt EVs as depicted in Fig. 9. Existing government policies include financial subsidies, a decrease in taxes, free parking and driving privileges [78] and these policies have been shown to influence customers to adopt EVs [95, 96]. Increased EV penetration could be possible if more beneficial policies are implemented in the future. Monetary incentives unrestricted to sales, tax waiving, income tax credit, subsidies for vehicle purchase and construction of charging stations are expected from the government to promote the EV market. A helping hand from the government in signage standardisation for the identification and increased accessibility of charging stations is also mandated in many areas [86]. Governments should also work on creating awareness among the public on the environmental friendliness of EVs which not only aids in EV market promotion but also in reducing pollution and carbon footprint. EV penetration can be further promoted if governments levied heavy taxes and restrictions on vehicle carbon emissions. A practical implementation of this scheme is already available in Norway, wherein CVs are heavily taxed whilst BEVs and FCEVs are completely exempted from import and value-added taxes [82]. The provision of substantial funds and encouragement towards the development and implementation of alternative fuels will help in the long run. All governments should increase EV market penetration by procuring large-scale fleets of EVs for public transport which, if implemented, can increase the motivation for EV adoption [97] for large companies. Consequently, the number of charging stations available in the community will increase. Indirect usage incentives such as free parking, free usage of tolled roads, free charging at municipal stations are also expected from the government, often even more so than monetary incentives to encourage consumers to adopt EVs [98–101].

**Fig. 7** Battery barriers and their effect on powertrain electrification

Suggestions

- Design of efficient battery packs is a necessity.
- Integration of high energy into compact and densely packed cells.
- High energy density electrodes, synthesis and processing methods.
- Safer and more ecological battery pack/case materials.
- High voltage battery pack with large format cells for thermal management and control.
- Increased discharge rates reduces overall lifespan.
- Analysis of overcharging and damage caused due to voltage fluctuations.
- Cohesion of Automotive and Power Utilities industry.

Inferences

- High voltage batteries are sizable and heavy, affecting handling of an EV.
- Heavy batteries prone to safety hazards, vibrational damage and thermal runaway.
- Organic electrolytes cause instability of high-voltage cathodes.
- Toxicity of such materials is of immense concern, CNT exhibits high potential for usage in batteries.
- In V2G operation mode, batteries should operate at higher SOC.
- Smoothening of battery voltage fluctuations will further improve lifespan.
- Standardisation of technical and organisational issues for development of EVs.
- Multiple sectors of industry must collaborate to this goal.

Power Electronics [103–105]

- Dynamic load behaviour crucial for power electronics.
- Identification of features/options for integration must be conducted at system level.

Battery Standards [101–102]

- By 2040, annual EV battery waste flow of 340,000 metric tons projected.
- Utilisation of retired batteries for Echelon implementable.
- Manufacturers must target overall cell management system cost less than 1% of battery pack cost.
- This system decides the ease of use for consumer.

Battery Recycling/Disposal [99–100]

- Reduction of batteries cost is necessary.
- Research on electrode material, processing and durability.

Charging Characteristics [86–89]

- Charging mechanism must be user friendly.
- Substantial growth required in EV battery power electronics infrastructure and cost reduction.

Battery Materials [90–91]

- Health concerns arise due to exposure to RF waves.
- As per global commissions, production costs of EV batteries high.
- This is expected to decrease.

Battery Economics [92–94]

- This by 2040, annual EV battery waste flow of 340,000 metric tons projected.
- Utilisation of retired batteries for Echelon implementable.
- Manufacturers must target overall cell management system cost less than 1% of battery pack cost.
- This system decides the ease of use for consumer.

Battery Life [95–96]

- Standard frameworks/methodology for battery recycling must be formulated.
- Battery disassembly and reuse becomes uncomplicated and cost efficient.

Battery Recycling/Disposal [99–100]
Experts Perception towards Pathway of Vehicle Power Train Shift through MCDM Tool

With the increasing pressure from the public and government to recognize a convenient and effective vehicle power train from the existing one, the MCDM tool is employed in this research work. Based on the expert’s perception towards desired evaluation criterion, the pathway of passenger vehicle segment propulsion system transition hierarchy is recommended.

PROMETHEE Approach

The preference ranking organization method for enrichment evaluation (PROMETHEE) is a popular multi-criteria statistical decision tool. In comparison to other methods, PROMETHEE tends to overcome deficiencies of dominance relation by considering additional information of deviation within the included criteria. In PROMETHEE, dominance is mainly identified based on the pairwise comparisons i.e. the deviation between the evaluations of two alternatives for the same criterion. The preference function translates a particular criterion deviation based on Preference (P) and Indifference (I) thresholds into a certain degree of preference. Typically, six different types of preference functions exist to estimate quantitative criteria. If the deviation is smaller than the indifference threshold, no preference rate is considered. If the deviation is larger than the preference threshold, the maximum preference rate has opted. If it is in between threshold limits respective to the choice preference function, an intermediate rate is awarded. In this study, a level type preference function is selected similar to that in Fig. 10 which is better suited to the qualitative scaling of criteria. The 5 points qualitative scale shown in Table 3 is selected for providing expert perception. Twenty experts are approached for this study based on academic publication records and industrial years of experience. The 10 subject matter expertise decision-makers are finally categorized as 5 from academic backgrounds and 5 from industrial backgrounds. All the experts are provided with a complete research background and motivation for this study. Additionally, experts are suggested to give their opinions on concurrent situations such as the consequent impact of the employment of a particular propulsion system.

The successful selection of vehicle propulsion is significantly difficult due to the existence of numerous barriers and with each propulsion type encompassing favourable and unfavourable features. Thus, framing the evaluation criterion is a critical step to assess the propulsion system uniformly. In such aspects, the main criteria: Economic, Behavioural, Infrastructure, Society and Environment are identified as the dominant decision-making variables in vehicle propulsion selection. Furthermore, an associated sub-criterion is structured to recognize the real tendency of the main criterion. Therefore, internal relationships among the selected criteria are the focal point of decision making. Table 4 summarizes significant criteria for the evaluation and selection along with providing associated preference characters. As far as alternatives are concerned, a total of 7 different propulsion systems are selected based on the mode of energy generation. The obtained expert’s individual perception data matrices are loaded into the visual PROMETHEE software for recognizing superior

![Fig. 8 Barriers associated with consumer behaviour on EV acceptance](image)
alternatives. During the analysis, two techniques of decision-making processes are carried out. In the first case, intermediate main criteria weights are varied from 0.25 to 1 with increments of 0.25. The balance weights are equally allotted to the other three main criteria (i.e. if Economic is 0.50, then Behavioural, Infrastructure, Society and Environment criteria carry 0.17). Through this, the entire hierarchy order respective to the change in the level of importance of criterion is validated. In the subsequent phases, equal criterion weights are allotted to understand the exhaustive characteristics of a vehicle power train. As the preference of consumers may vary individually, the most favourable propulsion in all aspects potentially promotes wider acceptance.

Criteria Wise Alternatives: Best to Worst

Through the support of visual PROMETHEE software, intermediate criteria weights are varied and the associated results are organized in the direction of best to worst in Table 5. By inducing changes in economic criteria weights while keeping all other criteria weights identical, liquid fuel vehicles (LFVs) are spotted as the best propulsion system for the present scenario of this economic phase. In the subsequent position, HEVs up to 0.50 weight are suggested after which gaseous fuel vehicles (GFVs) replace this position. This could be potentially due to the major barrier of higher capital cost. In the central zone, PHEVs and alternative fuel vehicles (AFVs) occupy positions. On the lowest side, BEV and FCEVs take up positions due to their technologies still being in the emerging stages, with their manufacturing not proving cost-effective. For behavioural criteria, up to the weight of 0.50, LFVs is considered as the best choice while above this weight, PHEVs take up the position. Notably, LFVs move to the lower zone as the entire weight is provided to the behavioural criteria, while BEVs top this position because of higher energy conversion efficiency levels. AFVs show the worst behavioural nature in all forms of weights level except 0.25. This could be due to the properties of biofuel in comparison to that of fossil fuels. In terms of infrastructure, irrespective of weights, the rank order does not show any alteration. This proves that each propulsion system requires a specific kind of primary mandatory infrastructure even at minimum weight, without which the accomplishment of a particular propulsion system is problematic.

LFVs are shown as the best alternative due to well-established existing infrastructure for their utilization and development. HEVs are positioned at second as the infrastructure required is similar to that of LFVs. For GFVs, slight changes are required in refuelling stations, and therefore they rank third. PHEV, BEV, AFV, and FCEV vehicles are ranked in subsequent positions as a significant change in charging infrastructure is required to make them functional. From the societal and environmental aspects, the best alternatives are BEVs in...
comparison to HEVs as corresponding weights increase. At
the second rank, LFVs swap with HEVs at higher weights.
This shows that less polluting vehicles are preferred as
better alternatives. Interestingly, FCEVs rank in the lower
category. This is potentially due to inadequate vehicle
response under varying weather conditions and the lack of
a skilled workforce. From this criteria weight alteration
study, it is understood that focusing on a particular attri-
bute will affect various other aspects. Each vehicle pow-
ertrain has particular advantages and disadvantages.
Therefore, the selection of vehicles should optimally sat-
ify all criteria. This type of weight assessing approach will
be an appropriate preceding step while looking for the
evolution from conventional power trains.

Characteristics and Probable Pathway
of Powertrain Shift Hierarchy

The aim is to determine the best powertrain system for the
present scenario without any significant changes in the
automotive industry from the chain of production to con-
sumer usage. The PROMETHEE analysis is further pro-
ceeded as per the first phase of decision, and equivalent
weights are employed for economic, behavioural, infra-
structure, society, and environment-based criteria. Figure 11
shows the significant positive and negative characteristics
of a powertrain based on expert opinion. LFVs have strong
infrastructure administration, while this criterion is satis-
fy at the top level for HEVs and GFVs. This could be due
to similar infrastructural requirements for the three
propulsion systems. However, this measurement will be
comparatively lower for LFVs. For PHEVs, HEVs, and
FCEVs, infrastructure is shown as a major barrier as its
energizing technology is entirely different from conven-
tional LFVs and is not yet developed in India. The beha-
vioural attribute is only present in the negative side of
LFVs and GFVs and in the region of BEVs and FCEVs, it
is positioned at the peak. This shows that it has a higher
level of efficiency and satisfactory operational tendency.
As for PHEVs and BEVs, both have similar kinds of
attributes and although the level of scoring for the criteria
is different, PHEVs are ranked higher than BEVs. The
main reason is the infrastructural requirements and its
ability to run only on ICEs, which push BEVs further
below. FCEVs and AFVs possess only one positive feature
differently. FCEVs satisfy the behavioural criterion due to
higher energy efficiency and smooth operation, although
contrastingly, they have poor features in all other criteria.
Similarly, in the economic aspect alone, AFVs secured
their best position. As the power development operation is
quite identical to LFVs and the only difference is the fuel
utilization, they scored more in the sub-criterion of capital
cost and resale value. Among all alternatives, HEVs
encompass all the criteria in the positive sector. They have
a greater score in infrastructural, behavioural, social,
environmental, and economic criteria. Although they pos-
sess electric motors, they do not pose many infrastructural
barriers as the battery is recharged by the running of ICE.
Additionally, the presence of switchable powering modes
satisfies the behavioural criterion. Concerning demanded
equipment operation, effective energy management strategies
prefer appropriate powering modes. Furthermore, the
presence of dual powering mode provides environmental
benefits as the electric motor drives the vehicle at idle and
low speed, improving fuel efficiency and correspondingly
reducing CO2 emissions. Despite possessing such superior
qualities, HEVs received the lowest score due to the major
factor of the economic aspect for a consumer. However, in
comparison to BEVs, FCEVs, and PHEVs, they provide
better economic benefits. Finally, for clear and concise
visualization of the pathway for a vehicle powertrain shift,
the PROMETHEE diamond plot is shown in Fig. 12. Based
on the present scenario, the existing LFV is the most
advantageous in all desired criteria. The second position is
held HEVs followed by PHEVs, GFEVs, BEVs, FCEVs, and
AFVs. This ranking order displays that for the present

Fig. 10 Representation of a Level type preference function

Table 3 Qualitative scale for rating alternatives

| Label     | Level |
|-----------|-------|
| Very low  | 1     |
| Low       | 2     |
| Moderate  | 3     |
| High      | 4     |
| Very high | 5     |
scenario, the alternative for a conventional LFV is the HEV, which should be the next phase of powertrain technology rather than BEVs, which might instead lead to a failure in technology transition. Since BEVs require the evolution of automotive, industrial and infrastructural technology, this would take longer to achieve, especially for developing countries. This analysis does not conclude that BEVs have inferior features; instead, it derives that considering the BEV as an alternative powertrain solution to conventional LFVs is not feasible for the present scenario. The proposed recommendation is statistically identified via academician and industry expertise perception.

### Hybrid Electric Vehicle Status

There has been a considerable increase in the sales of HEV and PHEVs since the last decade [102]. With 276,000 units of PHEVs as of 2017, China persisted in the top position, followed by countries like Japan, the UK, France, and Norway [103]. However, in 2018, Japan took the top spot with a total of 7.51 million HEVs on road, accounting for nearly 20% of the total number of vehicles on road in the country [104]. This was followed by the USA with cumulative sales of 5.4 million units as of December 2019 [105], closely followed by Europe with around 550,000 units being sold in 2019 alone and cumulative sales of 3 million units of HEVs as of July 2020 [106]. From Fig. 13, it is observed that the market share of PHEVs has seen a significant increase in the UK, Canada, Norway and Sweden along with other developing countries. A steady increase in the market share of PHEVs can be observed in France, Korea and the USA, with Europe displaying a similar trend. From Fig. 14, of the HEV categories, Full Hybrid vehicles are further categorized as Series Hybrids, Parallel Hybrids, Mild Parallel Hybrids, Micro-Parallel Hybrids, Plug-In Parallel Hybrids and Series–Parallel Hybrids. Sales of HEVs in the US began to decline following the financial crisis of 2007–08, and after a short recovery, began to decline again in 2014 due to low gasoline prices, when CVs dominated the market and later had a rebound in 2019 to 2.4% of the market share, along with PHEVs jumping to 0.5% of the market share [107]. In the transit buses category in the USA, hybrid buses are the fastest-growing category as they have increased more than

### Table 4 Evaluation criteria for vehicle power train hierarchy

| Main criteria | Sub-criteria | Preference |
|---------------|--------------|------------|
| Economic      | Capital cost | Minimum    |
|               | Operational cost | Minimum    |
|               | Maintenance cost | Minimum    |
|               | Resale value | Maximum    |
| Behavioural   | Durability | Maximum    |
|               | Endurance | Maximum    |
|               | Drive range | Maximum    |
|               | Safety and reliability | Maximum    |
|               | Efficiency | Maximum    |
|               | Emissions | Minimum    |
|               | Vibration and Noise | Minimum    |
|               | Drivability and comfort | Maximum    |
| Infrastructure| Fuel/charging stations | Maximum    |
|               | Maintenance and service stations | Maximum    |
|               | Manufacturing facility | Maximum    |
|               | Supply chain | Maximum    |
|               | R&D | Maximum    |
| Society and environment | Wastage and recycling | Minimum    |
|               | Sustainability of energy source | Maximum    |
|               | Health risks | Minimum    |
|               | Skilled workforce | Maximum    |
|               | Incentive schemes | Maximum    |
|               | Purchase Awareness | Maximum    |
|               | Adaptability to weather | Maximum    |

### Table 5 Report of hierarchy variation with different criteria weights

| Alternatives | Economic | Behavioural | Infrastructure | Society and environment |
|--------------|----------|-------------|----------------|-------------------------|
| Weights level between the main criteria | Best to worst | .25 | .50 | .75 | 1 | .25 | .50 | .75 | 1 | .25 | .50 | .75 | 1 |
| A1 A2 A3 A4 A5 | A1 A1 A1 A1 A4 | A1 A1 A1 A1 A1 | A3 A3 A3 A3 A3 | A1 A1 A1 A1 A1 | A3 A3 A3 A3 A3 |
| A6 A7 A8 A9 A10 | A2 A2 A2 A2 A2 | A2 A2 A2 A2 A2 | A4 A4 A4 A4 A4 | A4 A4 A4 A4 A4 | A2 A2 A2 A2 A2 |

A1, Liquid fuel vehicle; A2, Gaseous fuel vehicle; A3, Hybrid vehicle; A4, Plug-in hybrid vehicle; A5, Battery electric vehicle; A6, Fuel cell electric vehicle; A7, Alternative fuel vehicle
eight times from 2007 to 2018. Figure 15 depicts the number of transit buses in use in the USA, categorized by fuel type, from 2007 to 2018. In California, the zero-emission vehicle (ZEV) regulation was devised to achieve emission reduction goals by mandating auto manufacturers to offer specific numbers of vehicles powered by clean fuels involving BEVs, FCEVs, and PHEVs for sale as shown in Fig. 16. Since 2010, more than 550,000 ZEVs and PHEVs have been registered in California [108]. In general, mild HEVs are most preferred among HEV categories due to various advantages [109, 110]. Under the FAME II scheme launched in 2019 in India, a maximum of 20,000 Strong HEVs were supported, with total allotted funding of Rs. 26 crores by the Department of Heavy Industry [111]. Additionally, from Fig. 2, it can infer that the annual growth of sales of HEVs and PHEVs is much higher than that of EVs. Customers are looking for a midway trade-off between the range assurance & safety of CVs and the environmental benefits of newer and cleaner EVs. This dilemma enhances the prospect of HEVs as the frontrunner in the market in the coming years before the arrival of EVs. This point is further supported by the fact that the sales of more than 15 million HEVs worldwide have resulted in savings of more than 120 million tonnes of CO₂ [106].

Advantages of Hybridizing the existing ICE Infrastructure

CVs are dominant in the current market, however; harmful tailpipe emissions, low fuel efficiency, and increasing fuel prices force customers to look for alternatives. Hybrid technology is one such alternative solution to alleviate the above concerns. Hybridizing CVs with an electric power train improves fuel economy, reduces emissions, and helps reduce the environmental impact. These also help reduce total ownership cost (TCO) by providing improved savings during its lifetime usage, as shown in Fig. 17. Finally, HEVs also help smoothen the transition to EVs from both the consumer’s and the manufacturer’s point of view.

Fuel Economy

CVs provide good performance and long operating range but bear the disadvantages of poor fuel economy and environmental pollution. The main reason for poor fuel economy is the mismatch between engine fuel efficiency characteristics with that of fundamental operational requirements. Other reasons include kinetic energy dissipation during braking and low transmission efficiency during stop-and-go driving patterns. HEVs help to overcome these disadvantages by using two power sources. This is possible as HEVs use engines that operate only in the most efficient torque and speed region while providing excess power to recharge the battery/meet the motor’s remaining power needs [114, 115]. The electric motor compensates for all other regions and provides the vehicle with the dynamic power needed for transient power demands and low power operations. HEVs also incorporate a regenerative braking system (RBS), thus conserving the kinetic energy during braking and being used for charging the batteries [116]. All these factors give HEVs better fuel efficiency, especially in stop-and-go conditions and low-speed conditions [115–119]. The fuel economy of various hybrid architectures depends on various driving characteristics and traffic scenarios. Parallel HEVs (PaHEVs) performed better on highways, Series HEVs’ (SHEVs) on city roads [120–122] and ‘Series–Parallel HEVs’ (SPaHEVs) exhibit good fuel economies on both highways and city roads [123–125]. Finally, data analysis of various

Fig. 11 Identification of vehicle positive and negative attributes based on Expert’s opinion
HEVs currently available in the market showed their superiority to CVs in fuel economy [126–128].

**Reduction in Emissions**

EVs are known for their zero emissions and pollution reduction, but to truly understand EV environmental impact, well-to-wheel (WTW) emissions must be considered. WTW emissions include emissions caused by vehicle production and operation, energy production and distribution required to power the vehicle and the end-of-life phase [129]. EVs have very high WTW emissions, potentially more than CV emissions under certain driving conditions [130, 131]. Another significant contributor to EV emission is the manufacture of large batteries required for their operation [132]. This is where HEVs stand out, as they have lower life cycle emissions than EVs and lower tailpipe emissions than CVs. HEVs use smaller batteries and are recharged mainly by the engine. Ironically, fossil fuels account for most of the electricity generated to power EVs [133–135]. Furthermore, due to higher efficiency, reduced fuel consumption and RBS, HEVs have lower emissions throughout their lifetime compared to CVs [136]. Hence, HEVs are more eco-friendly than CVs and EVs at least until a significant development in battery production and technology or electricity generation occurs through RES [137–139].

**Total Cost of Ownership (TCO)**

TCO accounts for a vehicle’s purchase price, fuel costs, and non-operating (maintenance and repair) costs during its lifetime. It can also include societal and environmental costs such as upstream vehicle emissions, tailpipe emissions, and upstream energy production emissions costs [140, 141]. HEVs have lower TCO than CVs due to higher fuel economy, higher engine efficiency, and rising fuel fossil fuel prices. The higher initial purchase price of an HEV is compensated with a lower operating cost even without tax benefits [142, 143]. In many EU countries, governments are imposing taxes on vehicles based on their tailpipe carbon emissions which are higher for CVs than HEVs [144]. This further increase cost of CVs while significantly decreasing HEVs cost. Additionally, incentives and subsidies offered by some governments also decrease the initial price of HEVs, further reducing TCO. HEVs have lower TCO than EVs due to lower manufacturing costs, improved fuel efficiency, and government incentives [83]. EVs also get incentives from governments, but their TCO is higher than HEVs mainly because EVs have a high manufacturing cost, especially for their large batteries [145]. The upstream emissions costs for energy production are very high for EVs as electricity generation is mainly from fossil fuels, further increasing its TCO [146–148]. Hence, HEVs are superior and have clear advantages over CVs and EVs in terms of the TCO.

**Driving Range**

Consumer range anxiety is one of the most significant factors preventing the adoption and further penetration of EVs in the market [149–151]. Range anxiety is either due to the lack of fast charging infrastructure or the limited driving range of EVs. In terms of driving range, HEVs and PHEVs have an intrinsic advantage over EVs with the aid of their ICE. HEVs have two power sources, i.e. the battery and the ICE, with the batteries being recharged either through the ICE or from RBS [114]. The HEV engine also operates in its optimal condition, thereby improving its fuel economy and hence having a higher range than its CV counterparts and EVs. PHEVs also can recharge their batteries externally and provide a higher all-electric range than HEVs due to their larger capacity batteries [152]. Even though the all-electric range of PHEVs is less than EVs, they act as regular HEVs when the battery depletes, giving them a high driving range.

**Ease of Transition to EV Manufacturability**

The EV market is yet to develop in most countries, and there is a lack of EV manufacturers to support its
penetration into the market [153, 154]. Significant resources and time are needed to develop and bring about the required production technology and maintain a proper supply chain for components [155]. This is where HEVs help to smoothen the transition and pave the way for EVs. HEV components are produced in-house by existing automobile companies and OEMs as the basic structure of CVs and HEVs are similar. With an increase in HEV sales, HEV component production increases. Subsequently, production technology will improve when the market sees a significant enhancement in automotive electronic component development [156]. This makes it easier for the OEMs to manufacture EV components in the future as HEVs and EVs have very similar powertrain components [157, 158], especially in PHEVs. By the time EV technology develops and matures to penetrate the market further, EV manufacturers can easily access various components with optimized supply chains.

### Resale Value

With the advent of EVs, future used-car markets are bound to change; however, CVs are still dominant in this market. At present, electric-powered cars depreciate faster than CVs, and in that caveat, BEVs lose resale value quicker than HEVs [159]. This is associated with two main reasons: lack of infrastructure and rapid EV technology developments [160]. Lack of infrastructure includes lack of
network coverage of charging stations and also the unavailability of spare parts. On the other hand, with rapid battery improvements, the driving range increases, and EV’s cost significantly decreases, leading the consumers with old EVs to have no place in the used-car market. This rapid depreciation of EVs is said to cause resale anxiety [161] among consumers and hence is a potential barrier to the adoption of EVs [162]. HEVs on the other hand have a steady depreciation rate and show a similar ratio of resale value to initial price as that of CVs [163]. This can be attributed to an HEV’s high fuel efficiency, improvements in battery costs and performance, and increasing fuel costs [147]. With rising fuel prices over the years and in the coming future, consumers start to look for other viable options [164, 165], and therefore, HEV sales are bound to increase. Hence, HEVs show the highest potential in the resale market in the coming years.

Techno-economic Analysis for Transition to Electric Mobility

The techno-economic analysis on electric mobility transition requires several factors, viz. capital, fuel for electricity production, operation and maintenance costs to be considered. The data for the same are summarised and presented in Fig. 18. A report from the ‘International Council of Clean Transportation’ [166] exhibited a declining trend in the cost of electric vehicle battery packs in USD/kWh from 2020 to 2030 through a multitude of research studies. This is attributed to the advancement in battery pack technologies, specifically in materials science. The primary components for typical electric vehicles such as inverters, high voltage cables and onboard chargers also show a decrease in unit cost from 2017 to 2025 of an average of 9.5%, Whilst the indirect costs for electric vehicles such as
research and development or administration expenses are said to reduce by about 70% in the same period. A study that highlights the predicted decrease in the capital cost for the purchase/installation of charging infrastructure for EVs from 2014 to 2035 is available in the literature [167]. In the same period, it is anticipated that the cost for at-home and public level 2 charging units would decrease by about 73% while the decrease in the cost of rapid charging units is about 70%.

During the transition to electric mobility, there is a possibility of diesel being replaced by biodiesel and hence the impact of such replacement should be analysed in terms of cost. The primary fuel and environmental cost comparison between diesel and biodiesel is depicted in Table 6. In general, biodiesel is more expensive than conventional diesel in terms of production and environmental costs [172, 173]. However, while considering the life cycle of the vehicle, the environmental costs for biodiesel are relatively less, and the production cost of biodiesel can further be reduced depending on the production process and the type of feedstock used [173]. The bio fuelled HEVs follow a trend of lower brake power and torque, and higher brake specific consumption when compared to fossil fuel HEVs which necessitates the tuning of the engine operating parameters, thereby increasing cost [174, 175]. Additionally, it is found that with an increase in the biofuel level in the mixture with fossil fuels, there is higher NOx emissions and more CO2 production due to more complete combustion [176–179]. To reduce the same, it is needed the catalytic converters, ultimately increasing the cost of installation and overall weight of the vehicle. Also, the use of biofuels in engines results in a higher heat release rate and in-cylinder pressure [180]. This mandates a better engine design and thus increasing the cost. Furthermore, it is found that out of all the biodiesel mixtures with fossil fuels, it is found that only B20 and B50 are suitable for automotive applications [181]. For the production of these variants of biodiesel, special manufacturing equipment, processes, skilled professionals and production techniques have to be adopted, which are different from the existing and known standards. As a result, all these factors together contribute to the increased cost of utilizing biofuel HEVs in place of fossil fuel HEVs.

Other Advantages

Other advantages of HEVs include but are not limited to RBS, reduced noise emissions and acceptance of EVs in the future. RBS helps in conserving the kinetic energy during braking, usually lost as heat in CVs. As braking in urban conditions leads to the consumption of almost half of the energy from prime movers, RBS becomes significant in improving the efficiency of HEVs. RBS helps the conversion of kinetic energy into electrical energy during braking and using it to charge the battery. This can be used to meet the vehicle’s power requirements at a later stage [184, 185]. HEVs also help to reduce noise pollution in urban areas, mainly when driven in all-electric mode in PaHEVs and PHEVs [116]. In this mode, only the electric motor is used to drive the vehicle and the noise produced is insignificant [186]. PHEVs in all-electric mode exhibit noiseless driving similar to BEVs, albeit for a shorter
PHEVs in all-electric mode help transition to BEVs smoother by providing BEV style driving experience [148]. Studies have shown that first-hand experience at driving BEVs has a positive impact on EV adoption [187] and PHEVs provide this experience to consumers, making it easier to transition to EVs by providing the right mindset thus improving consumer perception of EVs [188, 189].

![Fig. 18 Techno-Economic analysis for transition to electric mobility [166–171]](image)

**Table 6** Cost comparison between diesel and biodiesel

| References | Parameter                                      | Diesel (USD) | Biodiesel (USD) |
|------------|-----------------------------------------------|--------------|-----------------|
| [182]      | Fuel price (per gasoline gallon equivalent)   | 2.35         | 3.68            |
| [172, 173] | Production cost of fuel (per gallon)          | 1.77         | 2.5–3.35        |
| [183]      | Total environmental cost                      | 80,443       | 83,867          |
| [183]      | Life cycle based total environmental cost     | 183,243      | 181,923         |
Concluding Remarks

The extensive review of the literature related to electric mobility demonstrates the large gap to be bridged for the complete diffusion of EVs to the market in developing countries. Numerous technical and socio-economic factors, viz. purchasing cost, driving range, range anxiety, consumer perception and lack of charging infrastructure play a significant role in impeding the transition. The majority of the technical barriers and purchase costs could be reduced with corresponding development in battery technology and increased density of charging infrastructure. Governments of developing and underdeveloped countries should consider these barriers during the creation and implementation of new policies to maximize the EV transition. As this transition is also largely reliant upon consumer mindset, awareness improvement programs on EV policies and environmental benefits could motivate the consumers to switch to EVs. A larger scale of such programs should be conducted either by government bodies or forums of public interest.

An expert perception survey conducted at the end of the review revealed the potential of HEVs as the best alternative propulsion system for India. For this purpose, the categorized barriers with their sub-categories for different propulsion systems are shared with the academicians and industrialists to obtain their opinions. The criteria and sub-criteria analysis of barriers for alternative propulsive systems are carried out with their impact on deployment. The data obtained from experts are processed with MCDM based PROMETHEE approach through which appropriate weights to each criterion are assigned and the ranking of alternatives are accomplished. The prevailing transportation scenario in India places LFV first place due to its widespread acceptance and development which then followed HEVs. This transportation performs better in all criteria as compared to other alternatives. The lack of OEMs and production units in India only placed them in the second position. PHEVs and EVs are further below in ranking mainly due to their infrastructure deficiency. Thus, the hierarchy report, which is the main outcome of the expert perception survey concluded HEVs as the most viable option for India, considering the existing technology and infrastructure. The ample use of HEVs in India will help in reducing emissions and path transition to EVs.

Literature review on the advantages of HEVs portrays its capability to ease EV transition. Adopting HEVs by auto-makers helps them get familiar with the production of EV components as HEVs and EVs have similar power train components. With increased HEV sales, production technology for electric-drive components increases and the supply chain for these components undergoes significant development. Furthermore, the introduction of PHEVs also helps to smooth the transition to EVs. It helps to develop the charging infrastructure gradually and gives the consumers an experience of all-electric drive, thus helping EV adoption rates. At present, other advantages of HEVs over EVs include lower TCO, higher driving range, higher resale value and reduced life emissions. HEVs also have a significant advantage over CVs with improved fuel economy, reduced lifetime cost and emissions, especially in India with the increasing fuel price and stricter emission norms. Future research studies can be oriented to enhance the evaluation of sub-criteria datasets and thus the accuracy of the developed model. This study offers the flexibility of extending to other countries to find an optimal alternative propulsive system depending on various barriers and sub-criteria as applicable to them.

Acknowledgements The authors would like to thank the Management of Vellore Institute of Technology, Vellore for the facilities provided during the execution of this work. This research is supported by funding from the Royal Academy of Engineering, United Kingdom under the scheme of Transforming Systems through Partnership (Grant No: RAE TSP - T21/100100).

Declarations

Competing interests The authors have not disclosed any competing interests.

References

1. https://www.statista.com/statistics/665071/number-of-registered-motor-vehicles-india-by-population/. Accessed 25 Feb 2021
2. S. Xiong, Y. Wang, B. Bai, X. Ma, A hybrid life cycle assessment of the large-scale application of electric vehicles. Energy 216, 119314 (2021). https://doi.org/10.1016/j.energy.2020.119314
3. P. Wolfram, T. Wiedmann, Electrifying Australian transport: hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. Appl. Energy 206, 531–540 (2017). https://doi.org/10.1016/j.apenergy.2017.08.219
4. R.T. Smokers, M. Verbeek, S. Van Zyl, EVs and post 2020 CO2 targets for passenger cars, in 2013 World Electric Vehicle Symposium and Exhibition (EVS27) (IEEE, 2013), pp. 1–11. https://doi.org/10.1109/EVS2013.6915006
5. M.S. Ahmad, S. Sivasubramani, Optimal solution of plug in hybrid electric vehicles to minimize cost and emission in a Smart Grid-a developing country view, in 2015 IEEE Power & Energy Society General Meeting (IEEE, 2015), pp. 1–5. https://doi.org/10.1109/PESGM.2015.7286422
6. J. Zhao, X. Xi, Q. Na, S. Wang, S.N. Kadry, P.M. Kumar, The technological innovation of hybrid and plug-in electric vehicles for environment carbon pollution control. Environ. Impact Assess. Rev. 86, 106506 (2021). https://doi.org/10.1016/j.eiar.2020.106506
7. P. Goel, N. Sharma, K. Mathiyazhagan, K.E.K. Vimal, Government is trying but consumers are not buying: a barrier analysis for electric vehicle sales in India. Sustain. Prod. Consum. 28, 71–90 (2021). https://doi.org/10.1016/j.spc.2021.03.029
20. K. Gesevicius, M. Catalo˜n-Lopes, P.M. Carvalho, The impact of
21. https://auto.economictimes.indiatimes.com/news/industry/
22. https://www.citivelocity.com/citigps/electric-vehicle-transition/.
23. https://www.iea.org/reports/global-ev-outlook-2020. Accessed
24. M.K. Kim, J.H. Park, J. Oh, W.S. Lee, D. Chung, Identifying
25. N. Abhyankar, A.R. Gopal, C. Sheppard, W.Y. Park, A.A.
26. S. Rokadiya, A. Bandivadekar, Hybrid and electric vehicles in
27. O. Egblue, S. Long, Barriers to widespread adoption of electric
28. M. Rejje, M. Abou-Zeid, I. Kaysi, Consumer preferences for
29. X. He, W. Zhan, Y. Hu, Consumer purchase intention of electric
30. M.A. Hannan, F.A. Azidin, A. Mohamed, Hybrid electric
31. J.H. Langbroek, J.P. Franklin, Y.O. Susilo, The effect of policy
32. M. Mruzek, I. Gajda´cˇ, L’ Kucˇera, D. Barta, Analysis of param-
33. J. Zhang, L. Zhang, F. Sun, Z. Wang, An overview on thermal
34. R. Farrington, J. Rugh, Impact of Vehicle Air-Conditioning on
35. A.M. Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, V.
36. J. Zhang, L. Zhang, F. Sun, Z. Wang, An overview on thermal
37. H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion
38. A. Báltıatanu, L.M. Florea, Comparison of electric motors used
39. R. Farrington, J. Rugh, Impact of Vehicle Air-Conditioning on
40. H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion
41. R. Farrington, J. Rugh, Impact of Vehicle Air-Conditioning on
42. T. Franke, I. Neumann, F. Bühler, P. Cocron, J.F. Krems,

8. P.K. Tarei, P. Chand, H. Gupta, Barriers to the adoption of electric
9. S. Goel, R. Sharma, A.K. Rathore, A review on barrier and
10. S.S. Raghavan, G. Tal, Plug-in hybrid electric vehicle observed
11. F. Ülengin, M. İşık, ŞÖ. Ekici, Ö. Özaydın, Ö. Kabak, Y.İ
12. A. Zabaryeva, C. Thiel, E. Barbone, A. Mercier, Assessing
13. D. Milakis, M. Kroesen, B. van Wee, Implications of automated
14. V. Dutta, P. Dasgupta, N. Hultman, G. Gadag, Evaluating expert
15. M.A. Hannan, M.M. Hoque, A. Hussain, Y. Yusof, P.J. Ker,
16. C.C. Chan, Y.S. Wong, Electric vehicles charge forward. IEEE
17. https://www.spglobal.com/platts/en/market-insights/latest-news/coal/012021-europe-overtakes-china-in-ev-sales-growth-in-2020. Accessed 11 April 2021
18. F. Cantiz, P. Alpkokin, S.T. Kiremitci, Sustainable urban
19. https://auto.economictimes.indiatimes.com/news/industry/despite-slowdown-in-ly20-ev-industry-posts-20-growth-in-domestic-sales/75247103. Accessed 11 April 2021
20. K. Gesevicius, M. Catalo˜n-Lopes, P.M. Carvalho, The impact of
electric vehicles’ market expansion on wholesale electricity
21. https://www.spglobal.com/platts/en/market-insights/latest-news/coal/012021-europe-overtakes-china-in-ev-sales-growth-in-2020. Accessed 11 April 2021
22. https://www.citivelocity.com/citigps/electric-vehicle-transition/.
23. https://www.iea.org/reports/global-ev-outlook-2020. Accessed 11 April 2021
24. M.K. Kim, J.H. Park, J. Oh, W.S. Lee, D. Chung, Identifying
25. N. Abhyankar, A.R. Gopal, C. Sheppard, W.Y. Park, A.A.
26. S. Rokadiya, A. Bandivadekar, Hybrid and electric vehicles in
27. O. Egblue, S. Long, Barriers to widespread adoption of electric
28. M. Rejje, M. Abou-Zeid, I. Kaysi, Consumer preferences for
29. X. He, W. Zhan, Y. Hu, Consumer purchase intention of electric
30. M.A. Hannan, F.A. Azidin, A. Mohamed, Hybrid electric
31. J.H. Langbroek, J.P. Franklin, Y.O. Susilo, The effect of policy
32. M. Mruzek, I. Gajda´cˇ, L’ Kucˇera, D. Barta, Analysis of param-
33. J. Zhang, L. Zhang, F. Sun, Z. Wang, An overview on thermal
34. R. Farrington, J. Rugh, Impact of Vehicle Air-Conditioning on
35. A.M. Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, V.
36. J. Zhang, L. Zhang, F. Sun, Z. Wang, An overview on thermal
37. H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion
38. A. Báltıatanu, L.M. Florea, Comparison of electric motors used
39. R. Farrington, J. Rugh, Impact of Vehicle Air-Conditioning on
40. H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion
41. R. Farrington, J. Rugh, Impact of Vehicle Air-Conditioning on
42. T. Franke, I. Neumann, F. Bühler, P. Cocron, J.F. Krems,
psychological barriers. Appl. Psychol. 61(3), 368–391 (2012). https://doi.org/10.1111/j.1464-0597.2011.00474.x

43. X. Yuan, L. Li, H. Gou, T. Dong, Energy and environmental impact of battery electric vehicle range in China. Appl. Energy 157, 75–84 (2015). https://doi.org/10.1016/j.apenergy.2015.08.001

44. S. Chopra, P. Bauer, Driving range extension of EV with on-road contactless power transfer—a case study. IEEE Trans. Ind. Electron. 60(1), 329–338 (2011). https://doi.org/10.1109/TIE.2011.2182015

45. Z. Lin, Optimizing and diversifying electric vehicle driving range for US drivers. Transp. Sci. 48(4), 635–650 (2014). https://doi.org/10.1287/trsc.2013.0516

46. R. German, S. Shili, A. Desreux, A. Sari, P. Venet, A. Bouscayrol, Dynamical coupling of a battery electro-thermal model and the traction model of an EV for driving range simulation. IEEE Trans. Veh. Technol. 69(1), 328–337 (2019). https://doi.org/10.1109/TVT.2019.2955856

47. H.H. Wu, A. Gilchrist, K. Sealy, P. Israelseth, J. Muhs, A review on inductive charging for electric vehicles, in 2011 IEEE International Electric Machines & Drives Conference (IEMDC) (IEEE, 2011), pp. 143–147. https://doi.org/10.1109/IEMDC.2011.5994820

48. I. Rahman, P.M. Vasant, B.S.M. Singh, M. Abdullah-Al-Wadud, N. Adnan, Review of recent trends in optimization techniques for plug-in hybrid, and electric vehicle charging infrastructures. Renew. Sustain. Energy Rev. 58, 1039–1047 (2016). https://doi.org/10.1016/j.rser.2015.12.353

49. F.M. Eltoumi, M. Becherif, A. Djerdjir, H.S. Ramadan, The key issues of electric vehicle charging via hybrid power sources: techno-economic viability, analysis, and recommendations. Renew. Sustain. Energy Rev. (2020). https://doi.org/10.1016/j.rser.2020.110534

50. H. Shareef, M.M. Islam, A. Mohamed, A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles. Renew. Sustain. Energy Rev. 64, 403–420 (2016). https://doi.org/10.1016/j.rser.2016.06.033

51. M.C. Falvo, D. Scordone, I.S. Bayram, M. Devetsikiotis, EV charging stations and modes: International standards, in 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (IEEE, 2014), pp. 1134–1139. https://doi.org/10.1109/SPEEDAM.2014.6872107

52. S. Deb, K. Kalita, P. Mahanta, December. Impact of electric vehicle charging stations on reliability of distribution network, in 2017 International Conference on Technological Advances in Power and Energy (TAP Energy) (IEEE, 2017), pp. 1–6. https://doi.org/10.1109/TAPENERGY.2017.8397272

53. H. Xiao, Y. Huimeij, W. Chen, L. Hongsun, A survey of influence of electric vehicles charging on power grid, in 2014 9th IEEE Conference on Industrial Electronics and Applications (IEEE, 2014), pp. 121–126. https://doi.org/10.1109/ICIEA.2014.6931143

54. A.K. Karmarkar, S. Roy, M.R. Ahmed, Analysis of the impact of electric vehicle charging station on power quality issues, in 2019 International Conference on Electrical, Computer and Communication Engineering (ECCE) (IEEE, 2019), pp. 1–6. https://doi.org/10.1109/ECACE.2019.8679164

55. P.S. Moses, S. Delami, A.S. Masoum, M.A. Masoum, Power quality of smart grids with plug-in electric vehicles considering battery charging profile, in 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe) (IEEE, 2010), pp. 1–7. https://doi.org/10.1109/ISGTEUROPE.2010.5638983

56. https://Cordis.Europa.Eu/Project/id/265684/Reporting. Accepted 11 April 2021

57. M. Di Paolo, Analysis of harmonic impact of electric vehicle charging on the electric power grid, based on smart grid regional demonstration project—Los Angeles, in 2017 IEEE Green Energy and Smart Systems Conference (GESSC) (IEEE, 2017), pp. 1–5. https://doi.org/10.1109/IGESC.2017.8283460

58. W. Zhang, K. Spence, R. Shao, L. Chang, Grid power-smoothing performance improvement for pv and electric vehicle (ev) systems, in 2018 IEEE Energy Conversion Congress and Exposition (ECCE) (IEEE, 2018), pp. 1051–1057. https://doi.org/10.1109/ECCE.2018.8557954

59. M. Singh, I. Kar, P. Kumar, Influence of EV on grid power quality and optimizing the charging schedule to mitigate voltage imbalance and reduce power loss, in Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010 (IEEE, 2010), p. T2-196. https://doi.org/10.1109/epepemc.2010.5606657

60. S. Yang, J. Yao, T. Kang, X. Zhu, Dynamic operation model of the battery swapping station for EV (electric vehicle) in electricity market. Energy 65, 544–549 (2014). https://doi.org/10.1016/j.energy.2013.11.010

61. M. Zeng, Y. Pan, D. Zhang, Z. Lu, Y. Li, Data-driven location selection for battery swapping stations. IEEE Access 7, 133760–133771 (2019). https://doi.org/10.1109/access.2019.2941901

62. G. Wang, F. Zhang, H. Sun, Y. Wang, D. Zhang, Understanding the long-term evolution of electric taxi networks: a longitudinal measurement study on mobility and charging patterns. ACM Trans. Intell. Syst. Technol. (TIST) 11(4), 1–27 (2020). https://doi.org/10.1145/3393671

63. L. Johannesson, B. Egardt, A novel algorithm for predictive control of parallel hybrid powertrains based on dynamic programming. IFAC Proc. Vol. 40(10), 343–350 (2007)

64. Y. Tian, J. Liu, Q. Yao, K. Liu, Optimal control strategy for parallel plug-in hybrid electric vehicles based on dynamic programming. World Electr Veh. J. 12(2), 85 (2021)

65. M. De Gennaro, E. Paffumi, G. Martinii, A. Gaillardon, S. Pedroso, A. Loiselle-Lapointe, A case study to predict the capacity fade of the battery of electrified vehicles in real-world use conditions. Case Stud. Transp. Policy 8(2), 517–534 (2020)

66. I. López, E. Ibarra, A. Matallana, J. Andreu, I. Kortabarria, Next generation electric drives for HEV/EV propulsion systems: technology, trends and challenges. Renew. Sustain. Energy Rev. 114, 109336 (2019). https://doi.org/10.1016/j.rser.2019.109336

67. E. Kamal, L. Adouane, R. Abdrakhmanov, N. Ouddah, Hierarchical and adaptive neuro-fuzzy control for intelligent energy management in hybrid electric vehicles. IFAC-PapersOnLine 50(1), 3014–3021 (2017). https://doi.org/10.1016/j.ifacol.2017.08.669

68. S.K. Mohammadian, Y. Zhang, Thermal management optimization of an air-cooled Li-ion battery module using pin-fin heat sinks for hybrid electric vehicles. J. Power Sources 273, 431–439 (2015). https://doi.org/10.1016/j.jpowsour.2014.09.110

69. M.R. Hanipah, R. Mikalsen, A.P. Roskily, Recent commercial free-piston engine developments for automotive applications. Appl. Therm. Eng. 75, 493–503 (2015). https://doi.org/10.1016/j.applthermaleng.2014.09.039

70. A. Manthiram, Materials challenges and opportunities of lithium ion batteries. J. Phys. Chem. Lett. 2(3), 176–184 (2011). https://doi.org/10.1021/jz1015422

71. J. Li, C. Daniel, D. Wood, Materials processing for lithium-ion batteries. J. Power Sources 196(5), 2452–2460 (2011). https://doi.org/10.1016/j.jpowsour.2011.09.011

72. D. Deng, Li-ion batteries: basics, progress, and challenges. Energy Sci. Eng. 3(5), 385–418 (2015). https://doi.org/10.1002/esse.201511464
environmental analysis. Energy Policy 61, 441–447 (2013). https://doi.org/10.1016/j.enpol.2013.06.026

142. R. Sharma, C. Manzie, M. Bessedé, M.J. Brear, R.H. Crawford. Conventional, hybrid and electric vehicles for Australian driving conditions—part 1: technical and financial analysis. Transp. Res. Part C Emerg. Technol. 25, 238–249 (2012). https://doi.org/10.1016/j.trc.2012.06.003

143. J. Lee, Y. Kwon. Analyzing factors of hybrid electric vehicle adoption using total cost of ownership. J. Soc. Sci. Res. 6(5), 606–614 (2020). https://doi.org/10.32861/jssr.606.614

144. P. Letmathe, M. Suares. A consumer-oriented total cost of ownership model for different vehicle types in Germany. Transp. Res. Part D: Transp. Environ. 57, 314–335 (2017). https://doi.org/10.1016/j.trd.2017.09.007

145. M. Redelbach, B. Propfe, H.E. Friedrich. Competitive cost analysis of alternative powertrain technologies, in Conference Programme IAMEF 2012 (2012)

146. W. Xiong, Z. Wu, C. Yin, L. Chen. Economical comparison of three hybrid electric car solutions, in 2008 IEEE Vehicle Power and Propulsion Conference (IEEE, 2008), pp. 1–6. https://doi.org/10.1109/VPPC.2008.4677402

147. P. Cicconi, M. Germani, D. Landi, M. Mengarelli. Life cycle cost from consumer side: A comparison between traditional and ecological vehicles, in 2014 IEEE International Energy Conference (ENERGYCON) (IEEE, 2014), pp. 1440–1445. https://doi.org/10.1109/ENERGYCON.2014.6850612

148. E.A. Gilmore, L.B. Lave. Comparing resale prices and total cost of ownership for gasoline, hybrid and diesel passenger cars and trucks. Transp. Policy 27, 200–208 (2013). https://doi.org/10.1016/j.tranpol.2012.12.007

149. A. Rusich, R. Danielis. Total cost of ownership, social lifecycle cost and energy consumption of various automotive technologies in Italy. Res. Transp. Econ. 50, 3–16 (2015). https://doi.org/10.1016/j.retrec.2015.06.002

150. T. Markel, A. Simpson. Cost-benefit analysis of plug-in hybrid electric vehicle technology. World Electr. Veh. J. 1(1), 294–301 (2007). https://doi.org/10.3390/wev101010294

151. M. Redelbach, H.E. Friedrich, F. Le Berr, A. Rousseau, F. Badin, N. Kim, A. Da Costa, D. Santini. Comparison of Energy consumption and costs of different HEVs and PHEVs in European and American context (2012)

152. X. Hao, Z. Lin, H. Wang, S. Ou, M. Ouyang. Range cost-effectiveness of plug-in electric vehicle for heterogeneous consumers: an expanded total ownership cost approach. Appl. Energy 275, 115394 (2020). https://doi.org/10.1016/j.apenergy.2020.115394

153. R.R. Heffner, K.S. Kurani, T.S. Turrentine. Driving plug-in hybrid electric vehicles: reports from US drivers of hybrid electric vehicles converted to plug-in hybrid vehicles. Transp. Res. Rec. 2139(1), 38–45 (2009). https://doi.org/10.3141/2139-05

154. S. Sair, N. Rao, S. Mishra, A. Patil. India’s charging infrastructure—biggest single point impediment in EV adoption in India, in 2017 IEEE transportation electrification conference (ITEC-India) (IEEE, 2017), pp. 1–6. https://doi.org/10.1109/ITEC-India.2017.8333884

155. S. Steinhilber, P. Wells, S. Thankappan. Socio-technical inertia: understanding the barriers to electric vehicles. Energy Policy 60, 531–539 (2013). https://doi.org/10.1016/j.enpol.2013.04.076

156. A.K. Digalwar, G. Giridhar. Interpretive structural modeling approach for development of electric vehicle market in India. Procedia Cirp 26, 40–45 (2015). https://doi.org/10.1016/j.procir.2014.07.125

157. https://ir.cit.com/nrwvZSxQnlSldMVhs5kSx1SpV% 2BOMeUBDwmoY12pU5R2ldpUE9Wgqsd tRyku7xQ6uVd8%3D. Accessed 30 March 2021

158. https://www.autocarindia.com/car-news/why-maruti-is-betting-on-hybrids-cng-instead-of-evs-420242. Accessed 30 March 2021

159. B. Propfe, M. Redelbach, D.J. Santini, H. Friedrich. Cost analysis of plug-in hybrid electric vehicles including maintenance & repair costs and resale values. World Electr. Veh. J. 5(4), 886–895 (2012). https://doi.org/10.3390/wev5040886

160. B. Schoettle, M. Sivak. Resale values of electric and conventional vehicles: recent trends and influence on the decision to purchase a new vehicle (2018)

161. F. Kleiner, H.E. Friedrich. Maintenance and repair cost calculation and assessment of resale value for different alternative commercial vehicle powertrain technologies (2017)

162. M.K. Lim, H.Y. Mak, Y. Rong. Toward mass adoption of electric vehicles: impact of the range and resale anxieties. Manuf. Serv. Oper. Manag. 17(1), 101–119 (2015). https://doi.org/10.1287/msom.2014.0504

163. X. Zhang, C. Zhao. Resale value guaranteed strategy, information sharing and electric vehicles adoption. Ann. Oper. Res. (2021). https://doi.org/10.1007/s10479-020-03901-4

164. H.L. Breetz, D. Salon. Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 US cities. Energy Policy 120, 238–249 (2018). https://doi.org/10.1016/j.enpol.2018.05.038

165. G. Mattioli, I. Philips, J. Anable, T. Chatterton. Vulnerability to motor fuel price increases: socio-spatial patterns in England. J. Transp. Geogr. 78, 98–114 (2019). https://doi.org/10.1016/j.jtrangeo.2019.05.009

166. N. Lutsey, M. Nicholas. Update on electric vehicle costs in the United States through 2030. Int. Council Clean Transp. 2 (2019)

167. J. Riesz, C. Sotiriadis, D. Ambach, S. Donovan. Quantifying the costs of a rapid transition to electric vehicles. Appl. Energy 180, 287–300 (2016)

168. P. Kumar, S. Chakrabarty. Total cost of ownership analysis of the impact of vehicle usage on the economic viability of electric vehicles in India. Transp. Res. Rec. 2674(11), 563–572 (2020)

169. D.L. Wood, J.D. Quass, J. Li, S. Ahmed, D. Ventola, C. Daniel. Technical and economic analysis of solvent-based lithium-ion electrode drying with water and NMP. Drying Technol. 36(2), 234–244 (2018)

170. C. Le Quéré, R.M. Andrew, P. Friedlingstein, S. Sitch, J. Hauck, J. Pongratz, P.A. Pickers, J.I. Korsbakken, G.P. Peters, J.G. Canadell, A. Arneth. Global carbon budget 2018. Earth Syst. Sci. Data 10(4), 2141–2194 (2018)

171. G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke, J. Van Mierlo. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. Energies 10(9), 1314 (2017)

172. https://voltacoil.com/what-makes-up-retail-price-for-gasoline/. Accessed 25 Feb 2022

173. https://www.tnstate.edu/extension/documents/Biodies elEconomics.pdf. Accessed 25 Feb 2022

174. A.R. Shirneshan, M. Almasi, B. Ghobadian, G.H. Najafi. Investigating the effects of biodiesel from waste cooking oil and engine operating conditions on the diesel engine performance by response surface methodology. Iran. J. Sci. Technol. Trans. Mech. Eng. 38(2), 289 (2014)

175. A. Shirneshan, B.H. Samani, B. Ghobadian. Optimization of biodiesel percentage in fuel mixture and engine operating conditions for diesel engine performance and emission characteristics by Artificial Bees Colony Algorithm. Fuel 15(184), 518–526 (2016)

176. B. Hosseinizadeh Samani, M. Ansari Samani, A. Shirneshan, E. Fayyazi, G. Najafi, S. Rostami. Evaluation of an enhanced ultrasonic-assisted biodiesel synthesized using safflower oil in a diesel power generator. Biofuels 11(4), 523–532 (2020)
177. A. Hojati, A. Shirneshan, Effect of compression ratio variation and waste cooking oil methyl ester on the combustion and emission characteristics of an engine. Energy Environ. 31(7), 1257–1280 (2020)

178. A. Shirneshan, M. Almassi, B. Ghobadian, G. Najafi, Modeling the effects of biodiesel-diesel fuel blends on CO₂ emission of a diesel engine by response surface methodology. Casp. J. Environ. Sci. 14(3), 227–238 (2016)

179. M. Gharibian, B. Hosseinzadeh Samani, A. Shirneshan, S. Rostami, Investigation and ranking of the effect of biodiesel produced from safflower oil by the hydrodynamic method in diesel generator engine using TOPSIS method. J. Renew. Energy Environ. (2021)

180. A. Shirneshan, M. Almassi, B. Ghobadian, A.M. Borghei, G. Najafi, Response surface methodology (RSM) based optimization of biodiesel-diesel blends and investigation of their effects on diesel engine operating conditions and emission characteristics. Environ. Eng. Manag. J. (EEMJ), 15(12) (2016)

181. A. Nedayali, A. Shirneshan, Experimental study of the effects of biodiesel on the performance of a diesel power generator. Energy Environ. 27(5), 553–565 (2016)

182. https://atb.nrel.gov/transportation/2020/diesel_fuel. Accessed 25 Feb 2022

183. I. Yildiz, E. Açıkalp, H. Caliskan, K. Mori, Environmental pollution cost analyses of biodiesel and diesel fuels for a diesel engine. J. Environ. Manag. 1(243), 218–226 (2019)

184. M. Palinski, A comparison of electric vehicles and conventional automobiles: costs and quality perspective (2017)

185. D. Ouyang, S. Zhou, X. Ou, The total cost of electric vehicle ownership: a consumer-oriented study of China’s post-subsidy era. Energy Policy 149, 112023 (2021). https://doi.org/10.1016/j.enpol.2020.112023

186. Y. Gao, M. Ehsani, Electronic braking system of EV And HEV—integration of regenerative braking, automatic braking force control and ABS. SAE Trans. 110, 576–582 (2001)

187. A. Ajanovic, The future of electric vehicles: prospects and impediments. Wiley Interdiscip. Rev. Energy Environ. 4(6), 521–536 (2015). https://doi.org/10.1002/wene.160

188. S.C. Mukherjee, L. Ryan, Factors influencing early battery electric vehicle adoption in Ireland. Renew. Sustain. Energy Rev. 118, 109504 (2020). https://doi.org/10.1016/j.rser.2019.109504

189. O. Egbue, S. Long, V.A. Samaranayake, Mass deployment of sustainable transportation: evaluation of factors that influence electric vehicle adoption. Clean Technol. Environ. Policy 19(7), 1927–1939 (2017). https://doi.org/10.1007/s10098-017-1375-4

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.