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Advancements and Challenges in Load Modeling for Plug-In Electric Vehicles: A Comprehensive Review

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Abstract
This review provides a comprehensive examination of Plug-in Electric Vehicles (PEVs), focusing on their current market status, technological advancements, and the challenges associated with their integration into the power grid. With increasing global emphasis on sustainable energy and carbon emission reduction, PEVs are emerging as pivotal in the transition toward cleaner transportation. This paper explores various load modelling techniques that predict and manage the electricity demand resulting from PEV adoption, highlighting their role in grid management and strategic energy planning. Key topics include uncontrolled charging, smart charging strategies, and Vehicle-to-Grid (V2G) systems, alongside their respective impacts on grid stability and renewable energy integration. The review identifies research gaps and underscores the importance of innovative load modelling methods to address the dynamic and scalable nature of PEV usage, ultimately contributing to a more sustainable energy future.

Keywords: Plug-in Electric Vehicles (PEVs), Load Modelling Techniques, Smart Grid, Charging Strategies, Vehicle-to-Grid (V2G).

Introduction

The rapid depletion of fossil fuels and growing environmental concerns have led to an urgent need for sustainable alternatives in the transportation sector. Among the various solutions, Plug-in Electric Vehicles (PEVs) have gained significant attention due to their potential to reduce greenhouse gas emissions, decrease dependency on non-renewable resources, and enhance energy efficiency. As governments and industries around the world aim to combat climate change, PEVs are playing a critical role in this transition toward a cleaner and more sustainable future. The adoption of PEVs is steadily increasing, supported by advancements in battery technology, charging infrastructure, and government policies promoting electric mobility. However, the widespread integration of PEVs into the existing energy system presents several challenges, particularly in managing the increased demand for electricity [1]. This increased load can create stress on the power grid, necessitating the development of effective load modelling techniques to predict and manage PEV-related electricity demand. Electric vehicles (EVs) present several advantages over traditional vehicles. One of their most significant benefits is zero emissions, as these vehicles neither emit tailpipe pollutants such as CO2 nor nitrogen dioxide (NO2).

Additionally, their manufacturing processes are generally more environmentally friendly, though the production of batteries does negatively impact the carbon footprint. EVs also exhibit simplicity, with fewer engine components leading to much cheaper maintenance. Their engines are compact, do not require cooling circuits, and eliminate the need for gearshifts, clutches, or noise-reducing elements. This simplicity contributes to their reliability, as fewer and less complex components result in fewer breakdowns. Furthermore, EVs do not experience the wear and tear caused by engine explosions, vibrations, or fuel corrosion. Cost is another notable advantage, as the maintenance expenses and electricity costs for EVs are significantly lower than the upkeep and fuel costs for traditional vehicles. The energy cost per kilometre is also much lower in EVs. EVs also enhance comfort due to the absence of vibrations and engine noise [2]. In terms of efficiency, they outperform traditional vehicles, although their overall well-to-wheel (WTW) efficiency depends on the power plant efficiency. For example, gasoline vehicles have a WTW efficiency ranging from 11% to 27%, while diesel vehicles range from 25% to 37% [3].

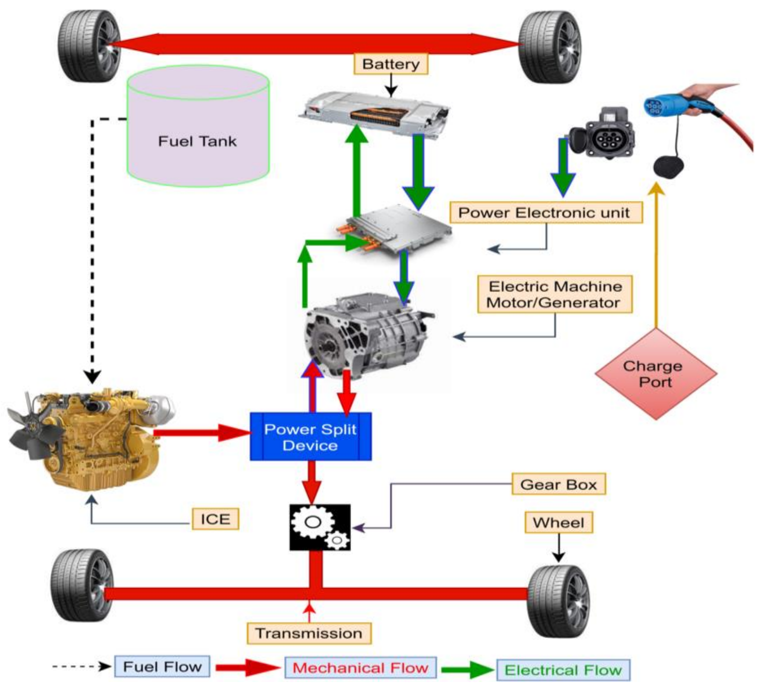

Figure 1 Block diagram of plug-in electric vehicle

In contrast, EVs powered by natural gas plants achieve efficiencies between 13% and 31%, and those powered by renewable energy can reach up to 70%. EVs also provide better accessibility, allowing access to urban areas restricted to traditional combustion vehicles, such as low-emission zones. They are not subject to the same traffic restrictions in large cities during periods of high pollution. However, recent studies, such as one by the OECD, suggest that in terms of particulate matter (PM) emissions, EVs may not significantly improve air quality [4]. Despite these advantages, EVs face challenges related to their batteries. Driving range remains a limitation, typically between 200 and 350 km per full charge, although advancements are ongoing. For instance, the Nissan Leaf offers a maximum driving range of 364 km, while the Tesla Model S exceeds 500 km [6, 7]. Charging time is another concern, as fully charging the battery pack can take 4 to 8 hours, and even a "fast charge" to 80% capacity can take 30 minutes. Tesla's superchargers, for example, can charge the Model S to 50% in just 20 minutes or 80% in half an hour [7]. Additionally, the excessive cost of large battery packs continues to pose a significant barrier to adoption.

This review aims to provide an overview of PEV technology, discuss the current status of their adoption globally, and examine the various load modelling methods that have been proposed to address the challenges associated with integrating PEVs into the power grid. By exploring these aspects, the paper highlights the importance of efficient grid management and strategic planning to ensure the smooth integration of PEVs, contributing to a sustainable energy future.

2. PEV Charging Technology

The integration of Plug-in Electric Vehicles (PEVs) into the power grid presents a critical challenge in terms of managing the increased electricity demand. In order to address this, various charging strategies have been developed to optimise the charging process, balance the load on the grid, and improve overall energy efficiency. These strategies can be broadly categorised into three types: uncontrolled charging, controlled (or smart) charging, and vehicle-to-grid (V2G) systems.

2.1 Uncontrolled Charging

Uncontrolled charging refers to the most basic and straightforward method of charging Plug-in Electric Vehicles (PEVs). In this approach, vehicle owners plug in their PEVs as soon as they arrive home or reach a charging station without any scheduling or coordination with the power grid. The vehicle begins charging immediately and continues until the battery is fully charged. While simple and convenient for users, uncontrolled charging poses significant challenges for the electric grid.

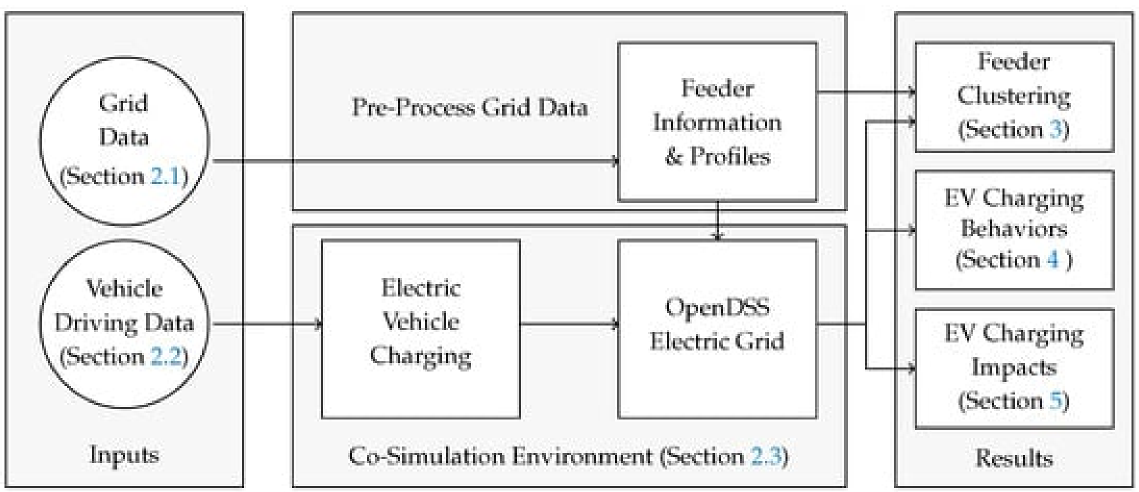

Figure 2 Uncontrolled charging

2.1.1 Characteristics of Uncontrolled Charging

Immediate and uncoordinated charging processes characterise the uncontrolled charging of Plug-in Electric Vehicles (PEVs). When a PEV is connected to a charger, the charging begins instantly. It proceeds at a constant rate until the battery is fully charged, without considering the time of day or the conditions of the power grid. This approach lacks synchronisation with the grid, as there is no coordination to align charging times with periods of lower demand or when surplus power is available. Instead, charging is driven solely by user convenience, which can result in inefficiencies and increased strain on the power grid.

2.1.2 Impact on the Power Grid

Uncontrolled charging of Plug-in Electric Vehicles (PEVs) has a significant impact on the power grid, primarily due to increased electricity demand during peak hours. Many PEV owners charge their vehicles immediately after returning home from work, typically between 5 p.m. and 8 p.m., a period already characterised by high electricity consumption for household activities such as lighting, heating, and cooking. This uncoordinated demand creates spikes in consumption, known as "peak loads," which place stress on the power grid and may lead to overloads or outages. Additionally, uncontrolled charging results in inefficient use of power resources, as it fails to utilise renewable energy sources like solar or wind, which are often more abundant during off-peak hours. Instead, it increases reliance on non-renewable energy during peak times, leading to suboptimal energy utilisation. The additional demand also necessitates costly upgrades to the power grid infrastructure, including power generation capacity, transformers, and distribution lines, increasing expenses for utility companies and consumers alike. Moreover, the heightened demand during peak periods drives up electricity prices for consumers, as the costs of generating and distributing electricity are higher during these times.

2.1.3 Challenges of Uncontrolled Charging

Uncontrolled charging of Plug-in Electric Vehicles (PEVs) poses several challenges that can affect the power grid and the environment. One significant issue is grid stability, as large numbers of PEVs charging at the same time can destabilise the grid, particularly in regions with high PEV adoption rates. Without effective load management, this can lead to voltage fluctuations, outages, or even rolling blackouts during periods of peak demand. Another challenge is the environmental impact. Uncontrolled charging often forces utilities to rely on fossil fuel-based "peaking power plants" to meet sudden spikes in electricity demand. These plants are typically less efficient and more polluting than baseload power plants, which undermines the environmental benefits of PEV adoption.

Additionally, uncontrolled charging misses opportunities to leverage renewable energy sources fully. Since it is not synchronised with periods of high renewable energy generation, such as midday solar or nighttime wind, the potential to maximise the use of clean energy is often lost. While uncontrolled charging offers simplicity and convenience for PEV owners, it introduces several challenges for the power grid. The lack of coordination between charging times and grid conditions can cause increased peak demand, grid stress, higher electricity prices, and inefficiencies in energy usage. As the number of PEVs grows, addressing these issues through smarter, more controlled charging strategies will be essential to ensure a stable, efficient, and sustainable integration of electric vehicles into the energy ecosystem.

2.2 Controlled (Smart) Charging

Controlled or "smart" charging refers to the use of advanced technology and communication systems to optimise the charging of Plug-in Electric Vehicles (PEVs). Unlike uncontrolled charging, where vehicles begin charging as soon as they are plugged in, smart charging coordinates the charging process based on several factors, such as electricity demand, grid conditions, renewable energy availability, and pricing signals. The goal of controlled charging is to reduce grid stress, improve energy efficiency, and maximise the use of renewable energy while still meeting the needs of PEV owners.

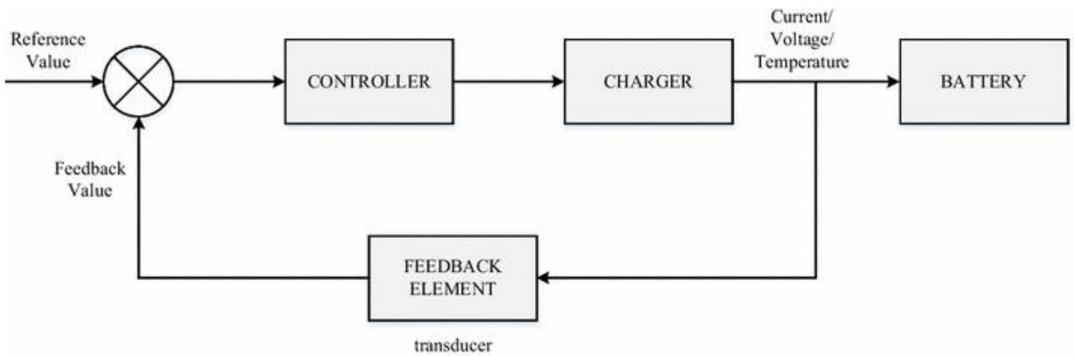

Figure 3: Block diagram of Controlled charging

2.2.1 Characteristics of Smart Charging

Smart charging of Plug-in Electric Vehicles (PEVs) is characterised by advanced features designed to optimise energy use and support grid stability. One key feature is optimised charging schedules, where charging does not begin immediately upon plugging in the vehicle. Instead, it is strategically scheduled based on real-time data about grid capacity and electricity demand. Algorithms or intelligent systems determine the best times to charge, typically during off-peak hours when demand and electricity prices are lower. Another feature is two-way communication between the PEV, charging infrastructure, and grid operators. This enables the grid to send signals to adjust the charging process—delaying, accelerating, or slowing it down based on current grid conditions, such as changes in demand or renewable energy availability. Smart charging systems often work with time-of-use (TOU) pricing models, where electricity prices fluctuate throughout the day based on demand. Consumers benefit by charging their vehicles during low-cost, off-peak hours, which also reduces strain on the grid. Additionally, smart charging supports grid-friendly load management by dynamically distributing the charging load over time. This approach prevents sudden spikes in electricity demand, flattens the load curve, and enhances grid stability, ensuring a more efficient and reliable energy system.

2.2.2 Benefits of Smart Charging

Smart charging of Plug-in Electric Vehicles (PEVs) offers numerous benefits for both consumers and the energy grid. One major advantage is reduced grid stress, as smart charging shifts vehicle charging to off-peak hours, alleviating pressure on the grid during peak demand periods. This prevents overloads, reduces the risk of power surges, and minimises the need for costly infrastructure upgrades. Additionally, smart charging provides cost savings for consumers by enabling vehicle charging during off-peak times when electricity prices are lower. It also facilitates participation in demand response programs, where utilities offer financial incentives for users to adjust their electricity consumption during peak periods. Another key benefit is the integration of renewable energy. Smart charging systems can synchronise charging schedules with periods of high renewable energy generation, such as midday solar or nighttime wind. This reduces reliance on fossil fuels, lowers carbon emissions, and supports a cleaner, more sustainable energy system.

Moreover, smart charging improves grid resilience by dynamically adjusting charging rates in response to sudden changes in grid conditions, such as energy supply fluctuations or demand surges. This enhances grid flexibility and ensures a stable power system, even during periods of high demand or unexpected disruptions. Lastly, smart charging promotes the broader adoption of electric vehicles by addressing grid overload concerns. By ensuring that increased PEV use does not negatively impact the existing energy infrastructure, smart charging supports the electrification of transportation while maintaining a reliable and efficient energy system.

2.2.3 Types of Smart Charging

There are several types of smart charging, each offering varying levels of flexibility and efficiency in managing the charging process. The simplest form is scheduled charging, where users set a preferred time for charging, typically during off-peak hours. This helps reduce costs and alleviate grid stress by ensuring that the vehicle charges when electricity demand is lower. A more advanced option is dynamic charging, which adjusts in real time based on grid conditions. In this case, charging speeds may fluctuate, or charging may pause altogether during peak demand periods and resume when grid conditions are more favourable, such as during off-peak hours. Load balancing is another type of smart charging that involves distributing the available charging power among multiple vehicles to prevent any single charger from overloading the system. This is particularly beneficial in public charging stations or other shared charging environments, where several PEVs may be charging simultaneously. By evenly distributing the load, load balancing ensures that the grid remains stable and that the charging process is as efficient as possible.

2.2.4 Challenges of Smart Charging

Smart charging offers many advantages, but it also comes with several challenges that need to be addressed. One of the primary challenges is infrastructure costs. Implementing smart charging requires significant investment in new infrastructure, including smart meters, communication systems, and upgraded charging stations capable of two-way communication with the grid. While these costs can be substantial, they are often offset by the long-term savings achieved in grid management and the reduced need for costly infrastructure upgrades in the future. Another challenge is consumer participation. Successful smart charging systems rely on active engagement from PEV owners, who need to understand the benefits and actively participate in load-shifting programs. Educating consumers about the advantages of smart charging, such as cost savings and environmental benefits, is essential. Incentives like time-of-use pricing and demand response programs are key to encouraging consumer involvement and ensuring the success of smart charging initiatives. Lastly, there are concerns about privacy and security. The two-way communication involved in smart charging systems requires secure data transmission to protect users' personal information and to safeguard against potential cyber-attacks on the power grid.

Ensuring the privacy and security of these systems is critical to their widespread adoption and reliability. Smart charging is a powerful tool for managing the integration of PEVs into the power grid, offering numerous benefits such as grid stability, cost savings, and enhanced use of renewable energy. By coordinating charging times and speeds based on real-time data, smart charging helps prevent grid overloads, reduces peak demand, and supports a cleaner, more efficient energy system. While there are challenges in terms of infrastructure and consumer engagement, the long-term advantages of smart charging make it a vital strategy for the future of electric vehicle adoption and grid management.

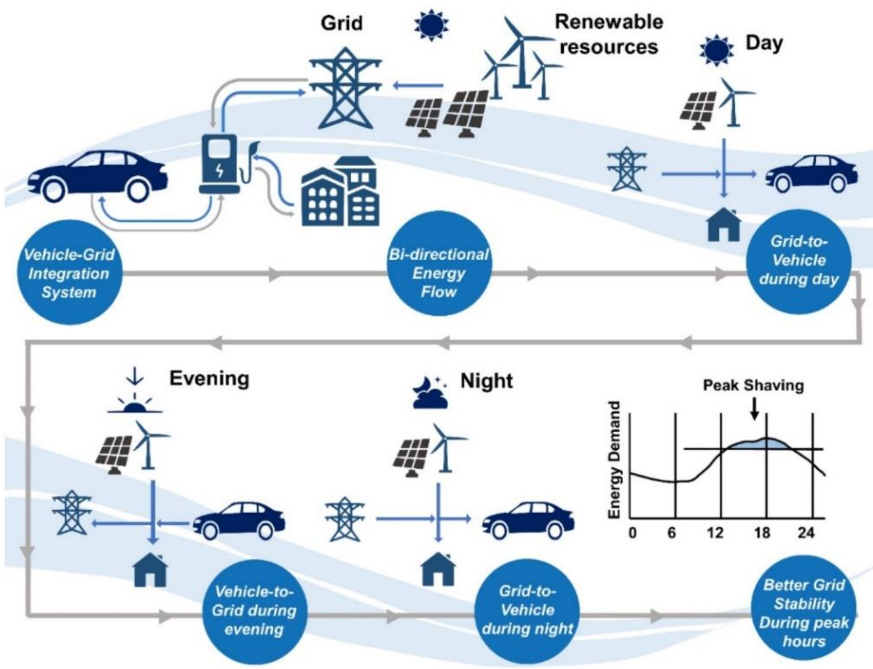

Figure 4 Block diagram of vehicle-to-grid charging technology.

2.3 Vehicle-to-Grid (V2G) Systems

Vehicle-to-grid (V2G) is an advanced technology that allows Plug-in Electric Vehicles (PEVs) to interact bidirectionally with the power grid. In a V2G system, PEVs not only consume electricity for charging but can also supply stored energy back to the grid when needed. This transforms PEVs into mobile energy storage units, which helps to stabilise the grid, especially during periods of high demand or supply shortages. V2G systems play a crucial role in enhancing grid resilience, improving energy efficiency, and integrating renewable energy into the power system.

2.3.1 Key Features of V2G Systems

Vehicle-to-grid (V2G) systems have several key features that enable them to integrate electric vehicles with the power grid in a bidirectional manner. The first key feature is bidirectional power flow, which allows two-way energy transfer between Plug-in Electric Vehicles (PEVs) and the grid. This means the vehicle can draw electricity from the grid to charge its battery, and when needed, it can also feed power back into the grid, supporting grid stability. The second feature is communication between the PEV and the grid. V2G systems rely on advanced communication networks that connect vehicles, charging stations, and grid operators. This communication enables the grid to monitor energy demand and send signals to vehicles, instructing them to either charge or discharge electricity based on real-time grid requirements. The third feature is smart charging infrastructure. V2G systems require specialised infrastructure, including bidirectional chargers and inverters, to manage the flow of electricity to and from the vehicle. In addition, the system is equipped with smart meters and control software that coordinates the vehicle's participation in grid services, ensuring seamless and efficient operation. These technologies allow V2G systems to provide valuable grid support while maintaining the optimal function of both the vehicle and the grid.

2.3.2 working of V2G.

Vehicle-to-grid (V2G) systems operate in two primary modes: charging and discharging, each playing a crucial role in balancing grid demand and supporting energy systems. In charging mode, the Plug-in Electric Vehicle (PEV) functions like a typical electric vehicle, drawing electricity from the grid to recharge its battery. Charging typically occurs during off-peak times when electricity demand is lower, and prices are more affordable, helping reduce grid strain during peak hours. In discharging mode (also called energy export), the PEV supplies electricity back to the grid. This mode is activated during peak demand periods or in situations of power shortages, such as during an emergency or power outage. The energy stored in the vehicle's battery is discharged into the grid, providing essential power support to help balance supply and demand. The V2G systems can also offer several grid services, including frequency regulation, which helps maintain grid frequency stability. Demand response, where electricity use is reduced or shifted during peak periods, and voltage regulation, which ensures proper voltage levels are maintained on the grid. These services enhance grid reliability and flexibility, making V2G systems an important asset for future energy networks.

2.3.3 Benefits of V2G Systems

V2G (Vehicle-to-Grid) systems offer several benefits that enhance grid stability, support renewable energy integration, and provide financial incentives for vehicle owners. First, V2G systems help stabilise the grid by providing flexible, decentralised energy storage. By discharging energy during peak demand or emergencies, V2G-equipped vehicles reduce the reliance on fossil-fuel-based peaking power plants, which are both costly and environmentally harmful. These systems also offer ancillary services, such as frequency and voltage regulation, which improve the overall reliability and resilience of the grid. Another significant advantage of V2G systems is their ability to aid in the integration of renewable energy sources like solar and wind power. These energy sources are intermittent, and their generation depends on weather conditions. V2G systems can store excess renewable energy when generation is high, such as during sunny or windy days, and feed it back into the grid when demand is high or renewable generation is low. This helps smooth out fluctuations in renewable energy supply and maximises the use of clean energy, contributing to a more sustainable and efficient energy system. V2G also offers financial incentives for PEV (Plug-in Electric Vehicle) owners. By selling surplus electricity back to the grid during peak demand, vehicle owners can take advantage of higher electricity prices.

Additionally, utilities may offer incentives, such as payments for providing grid support services like frequency regulation or demand response, making V2G a financially rewarding opportunity for PEV owners. Furthermore, V2G helps reduce overall energy costs by lowering the need for expensive peak power generation and minimising the construction of additional power plants. The stored energy in PEVs can be used to offset peak demand, benefiting the entire energy system by reducing costs and increasing efficiency. Lastly, in the event of a grid outage or emergency, V2G-capable vehicles can act as backup power sources, providing electricity to homes or critical infrastructure. This enhances grid resilience, reduces the risk of widespread blackouts, and improves energy security, especially during natural disasters or other grid-disrupting events.

2.3.4 Challenges of V2G Systems

V2G (Vehicle-to-Grid) systems present several challenges that need to be addressed for widespread adoption. One of the primary concerns is battery degradation. Frequent charging and discharging cycles required for V2G operation can potentially accelerate wear on vehicle batteries. While modern batteries are designed to withstand these cycles, the additional stress from V2G participation could slightly reduce their lifespan. However, advances in battery technology and the development of V2G-specific battery management systems can help mitigate these effects, reducing the impact on battery longevity. Another challenge is the infrastructure cost. V2G requires specialised infrastructure, such as bidirectional chargers, communication systems, and software to manage energy flows between the vehicle and the grid. The initial investment in this infrastructure can be a barrier to the widespread adoption of V2G systems. Despite these upfront costs, the long-term benefits, including grid services and potential financial incentives, can offset the initial investment, making V2G a cost-effective solution over time. Regulatory and market barriers also pose a challenge. The successful implementation of V2G systems depends on supportive regulatory frameworks that allow plug-in electric vehicles (PEVs) to participate in energy markets. In many regions, regulatory obstacles and a lack of market incentives hinder the widespread adoption of V2G technology. To overcome these barriers, policies that encourage the grid integration of PEVs and reward their participation in grid services are essential for the growth of V2G systems. Finally, consumer participation and awareness are crucial for V2G systems to be effective.

PEV owners need to be educated about the benefits and potential financial incentives associated with V2G. Ensuring that participation in V2G programs is simple, convenient, and rewarding is key to increasing consumer engagement. Without sufficient consumer interest and understanding, V2G systems will struggle to reach their full potential. Vehicle-to-grid (V2G) technology is a meaningful change in the integration of electric vehicles into the power grid, offering numerous benefits for both PEV owners and the grid. By allowing bidirectional power flow, V2G helps stabilise the grid, improves the integration of renewable energy, and provides financial incentives for PEV owners. Despite challenges such as infrastructure costs and battery wear, the long-term advantages of V2G systems make them an essential component of future energy systems. As the adoption of electric vehicles continues to rise, V2G will play a critical role in creating a more sustainable, resilient, and efficient power grid. Effective PEV charging strategies are essential for ensuring the smooth integration of electric vehicles into the power grid. Uncontrolled charging can lead to significant challenges, such as grid overload and higher electricity costs, while controlled charging and V2G systems offer more sustainable solutions [8]. These advanced strategies enable better load management, improved energy efficiency, and the potential for PEVs to contribute to grid stability. As the adoption of PEVs continues to rise, the implementation of smart charging and V2G technologies will play a crucial role in shaping a sustainable and resilient energy future.

3. Related Work

In the last decade, there has been considerable progress in several aspects related to the production of electric vehicles, the use of modern technologies, and sales. Similarly, research efforts have also increased, which has caused a significant increase in new jobs and proposals that are related to electric vehicles. Within this section, a short compilation of the most relevant topics related to EVs, which previously available works in the literature have addressed, are introduced. In addition, the more notable differences between this survey and the other are highlighted. Some of the studies published to date deal with general aspects, such as the evolution of electric vehicles throughout history, give diverse classifications according to the manner in which they have been designed and the characteristics of their engines or analyse their impact on the electrical infrastructure. For instance, Yong et al. [9] review the history of EVs from their creation in the middle of the nineteenth century until the present.

Additionally, they carry out a classification of the vehicles according to their powertrain settings. Finally, their work analyses the impact of charging electric vehicles on the electric grid. Likewise, Richardson [10] studies the effects that EVs can produce on the required productivity, efficiency, and capacity of the electric grid. Furthermore, he reviews the economic and environmental impact of electric vehicles. Habib et al. [11] present a review of charging methods for electric vehicles and analyse their impact on power distribution systems.

Additionally, the authors carry out an analysis of coordinated and non-coordinated charging methods, delayed loading, and intelligent planning of charges. Finally, they study the economic benefits of vehicle-to-grid (V2G) technology using charging methods. Another aspect that has also been dealt with in diverse works is the use of renewable energy sources (i.e., wind power, solar, and biomass) and their incorporation in the electric vehicles field. Liu et al. [12] present a general vision of electric vehicles and renewable energy sources. They specifically focus on solar and wind power and categorise the related works into three groups: first, studies that explore the interaction between EVs and renewable energy sources to reduce energy costs; second, works aimed at improving energy efficiency; and third, proposals primarily focused on reducing emissions.

On the other hand, Hawkins et al. [13] analyse the existing studies about the environmental impact of the Hybrid Electric Vehicles (HEVs) and the Battery Electric Vehicles (BEVs). For that purpose, they present a study of fifty-one environmental evaluations during the life span of the two kinds of vehicles (i.e., BEVs and HEVs). In their work, the authors take aspects such as greenhouse gas emissions, the production, transmission, and distribution of electricity, as well as the production of vehicles, batteries, and their life span, into account. Vasant et al. [14] analyse the daily usage of PHEVs and state that the appropriate deployment of daytime charging stations, along with suitable charging control and management of this infrastructure, can lead to a wider deployment of PHEVs. Unlike the previous works, Shuai et al. [15] provide a general vision of the new economic model that is present in electric vehicles, bearing in mind the unidirectional and bidirectional flows of energy (in which the EVs themselves are capable of providing energy to the electric grid). To do this, they analyse different charging facilities for EVs, as well as different methods for unidirectional charging and bidirectional energy commercialisation. Finally, they study the use of these vehicles as a feasible storage for the energy that is generated from renewable sources. Other authors have focused on the different strategies that have been proposed for charging EVs. Tan et al. [16] revise the benefits and challenges of vehicle technology to the grid (V2G) in both the unidirectional and bidirectional charging. Besides advantages, they analyse the challenges, such as battery deterioration and the high investment cost. Lastly, they complete a compilation of strategies for optimising V2G by grouping them according to the technique employed (e.g., genetic algorithms (GAs) and Particle Swarm Optimisation (PSO)), as well as according to the objectives of operation costs, carbon dioxide emissions, profit, support for renewable energy generation, load curve, and power loss. Similar to the previous work, Hu et al. [17] present a revision and classification of methods for the intelligent charging of electric vehicles but, in this case, focused on the fleet operators. In particular, they present works regarding battery modelling, charging and communications standards, and driving patterns. Lastly, they showcase a set of different control strategies to manage EV fleets, as well as mathematical algorithms for its modelling. Rahman et al. [18] present a set of employed methods for solving different problems that are related to the charging infrastructure of PHEVs and BEVs.

Additionally, they assess the different charging systems in different environments, such as domestic garages, apartment complexes, and shopping centres. Because the massive EV deployment will introduce negative impacts on the existing power grid, some works review the different issues and the potential opportunities that EV integration in the smart grid can bring. Yong et al. [9] study the impact of EV deployment from the perspective of vehicle-to-grid technology, especially for mitigating the intermittency of renewable energies. Mahmud et al. [19] discuss all of the aspects related to EV charging, energy transfer, and grid integration with distributed energy resources on the Internet of Energy (IoE). More recently, Das et al. [20] presented an evaluation of how future-connected EVs and autonomous driving would affect EV charging and grid integration. Other important EV charging issues are those that are related to battery management, as well as battery health and lifetime estimations since they are key factors in increasing the battery lifetime. Li et al. [21] review recent advancements in Big Data analytics to allow for data-driven battery health estimation. More specifically, they classify them in terms of feasibility and cost-effectiveness and discuss their advantages and limitations. Liu et al. [22] go one step further and propose a machine learning-enabled system that is based on Gaussian process regression (GPR) to predict lithium-ion battery ageing. Finally, other approaches instead explore advanced fault diagnosis techniques since battery faults can potentially cause performance degradation [23]. As previously shown, in general, most of the studies that deal with EVs have focused on the impact of EV charging on the electric demand, the use of renewable energy sources in the charging process, and the proposal of new methods for optimising the charge of electric vehicles, including grid solutions. However, in this paper, we present the current situation of the electric vehicle market, the main characteristics of batteries, their technologies, and charging processes. In particular, besides carrying out a comparison between the different standards, we display the different charging methods that are defined by these standards, as well as the connectors used by each of them. Finally, we also discuss the challenges that EVs have to face and the research lines that we consider are left to explore.

Research Gaps

Despite significant advancements in Plug-in Electric Vehicles (PEVs) and their integration into energy systems, several key research gaps remain. Current load modelling predominantly relies on static data, which limits the ability to capture dynamic and temporal variations in charging patterns influenced by user behaviour, grid conditions, and renewable energy generation. Addressing this requires the development of real-time load modelling frameworks that incorporate dynamic charging data, leveraging technologies such as smart metering and the Internet of Things (IoT) for improved prediction accuracy. Additionally, many studies fail to consider scalability and regional infrastructure variability. Regions with high renewable energy penetration or limited grid infrastructure face unique challenges, and region-specific models that address variations in grid capacity, user adoption rates, and renewable energy availability are necessary to enhance the global applicability of load modelling techniques.

Controlled and Vehicle-to-Grid (V2G) charging systems, while promising for improving grid stability and energy optimisation, remain underexplored in terms of their cost-effectiveness and long-term impacts on grid performance. For instance, the effects of bidirectional charging on battery life and infrastructure costs require further investigation, with potential solutions including advanced battery management algorithms and consumer incentive programs for adopting V2G-enabled vehicles. Similarly, integrating PEV charging with renewable energy sources such as solar and wind remains suboptimal due to their intermittent nature. Research should focus on aligning charging schedules with peak renewable generation using predictive algorithms and machine learning optimisation. Pilot projects that integrate PEV charging stations with renewable microgrids could provide valuable insights.

Another significant barrier is the lack of high-quality, comprehensive data on PEV usage patterns and their impacts on energy systems. Establishing standardised data collection protocols and creating large-scale datasets capturing charging habits, vehicle types, and geographic factors could significantly improve predictive model accuracy. Furthermore, few studies examine the cumulative, long-term effects of PEV adoption on grid infrastructure, such as transformer degradation, distribution line stress, and necessary upgrades. Simulation-based studies assessing infrastructure resilience under varying levels of PEV penetration and renewable integration would be instrumental in planning sustainable grid expansions.

Finally, consumer behaviour and participation are critical to the effective integration of PEVs. Limited research exists on user behaviour, preferences, and barriers to adopting controlled and V2G charging systems. Behavioural studies, coupled with the design of effective incentives, could foster higher participation and reduce resistance to these technologies. Addressing these gaps through innovative modelling techniques, interdisciplinary research, and collaboration among academia, industry, and policymakers will be crucial for ensuring the seamless integration of PEVs into the energy ecosystem.

4. Load Modelling Methods

Load modelling methods are essential tools used to predict and analyse electricity consumption patterns, particularly in the context of integrating Plug-in Electric Vehicles (PEVs) into power grids. These methods help utilities, grid operators, and researchers understand how PEV charging affects overall energy demand, enabling better planning, management, and optimisation of the electrical grid. Several primary load modelling methods are commonly employed in the context of Plug-in Electric Vehicles (PEVs) to predict and analyse electricity demand. Statistical load modelling is one such technique that utilises historical data and statistical methods to identify patterns and relationships within load data, enabling utilities and grid operators to forecast electricity consumption accurately. This is particularly important in the case of PEVs, where understanding charging behaviour is essential for managing the increased demand on the electrical grid. Another method is simulation-based load modelling, which involves simulating the behaviour of electrical loads over time. This advanced approach allows for the consideration of complex interactions and uncertainties, providing greater flexibility in assessing the impact of various variables on electricity demand compared to traditional statistical methods. Bottom-up load modelling is a detailed approach that estimates electricity demand by aggregating the individual contributions of appliances, devices, and loads within a system, contrasting with the macro-level perspective of top-down load modelling. The bottom-up approach is useful in understanding the specific impact of PEVs on electricity demand by considering the contributions of different load types.

Table 2 Comparison of different load modelling methods

Method	Description	Advantages	Limitations
Statistical Load Modelling	Uses historical data and statistical techniques to forecast future electricity demand.	Simple to implement, effective for long-term forecasts, and relies on readily available data.	It may not capture non-linear relationships, depending on the quality and completeness of historical data.

Simulation-Based Load Modelling	Creates a simulated environment to study the behaviour of loads and their interactions.	Captures complex interactions, is flexible in modelling various scenarios, and can incorporate uncertainty.	Computationally intensive, requires detailed knowledge of system behaviour, and is more complex to implement.
Bottom-Up Load Modelling	Builds models by aggregating individual load profiles and characteristics of specific appliances.	Provides high granularity, delivers detailed insights into specific loads, and is more accurate for small areas.	Data-intensive, time-consuming to gather detailed data, and may not accurately reflect aggregate trends.
Top-Down Load Modelling	Aggregate data is used to estimate electricity demand across sectors or regions.	Simpler and faster to implement, useful for macro-level insights, and good for large-scale projections.	Lacks granularity, assumes homogeneity in consumer behaviour, and is less accurate for smaller regions.
Hybrid Load Modelling	Combines both top-down and bottom-up approaches for more comprehensive load forecasting.	Provides a holistic view, balances accuracy and simplicity, and can offer detailed and broad insights.	More complex to develop and implement requires significant data for both top-down and bottom-up inputs.
Machine Learning/AI-Based Models	Uses algorithms to analyse patterns in data and predict future load based on those patterns.	High accuracy, adapts to changing patterns, handles large datasets effectively, and improves over time.	Data quality and availability are crucial, can be complex and difficult to interpret, and require advanced expertise.

In contrast, top-down load modelling uses aggregate data such as historical consumption patterns, economic indicators, and demographic data to estimate overall electricity demand across larger regions or sectors. This method is useful for utilities and policymakers to manage resources and infrastructure. Hybrid load modelling combines both top-down and bottom-up techniques, offering a more comprehensive and accurate forecast by integrating detailed insights from the bottom-up approach with broader trends captured in top-down modelling. This is particularly valuable when analysing complex systems like PEV integration and renewable energy. Lastly, machine learning and artificial intelligence (AI)-based models have become increasingly prevalent in load forecasting, as they leverage large datasets and sophisticated algorithms to uncover patterns and trends that traditional methods may overlook, significantly improving the accuracy and efficiency of electricity demand predictions. Load modelling methods are critical for understanding and managing the impact of Plug-in Electric Vehicles on electrical grids. Each method has its advantages and limitations, and the choice of a specific modelling approach depends on the objectives of the study, the availability of data, and the complexity of the system being analysed. A combination of these methods may be necessary to develop comprehensive load models that can effectively inform grid operators and policymakers in their decision-making processes related to PEV integration.

5. Conclusion

The transition to Plug-in Electric Vehicles (PEVs) represents a pivotal shift in the transportation sector, driven by the imperative for sustainable energy solutions and the reduction of greenhouse gas emissions. This review has explored the current state of PEV adoption, examined various charging strategies, and analysed diverse load modelling techniques to assess their impact on electricity demand. As the adoption of PEVs continues to accelerate, it introduces both opportunities and challenges for energy systems, requiring strategic interventions to ensure their seamless integration.

Controlled charging strategies, such as smart charging and Vehicle-to-Grid (V2G) systems, offer significant potential to mitigate grid stress, integrate renewable energy, and enhance grid reliability. However, addressing challenges like the scalability of these systems, their impact on battery life, and the associated infrastructure costs is essential. Uncontrolled charging, on the other hand, risks exacerbating peak load issues, underlining the need for policy-driven incentives to encourage the adoption of smarter charging practices.

Several actionable recommendations emerge from this review. First, future research should focus on developing dynamic, real-time load modelling techniques that incorporate dynamic charging patterns, renewable energy variability, and regional infrastructure differences. Second, pilot projects integrating PEV charging stations with renewable microgrids could provide valuable insights into optimising renewable energy usage while minimising grid stress. Third, enhanced consumer engagement strategies, including education campaigns and financial incentives, are critical to driving participation in controlled charging and V2G programs. Lastly, collaboration between policymakers, utilities, and researchers is imperative to establish standardised data collection protocols, improve infrastructure resilience, and design regulatory frameworks that support innovative charging solutions.

In conclusion, leveraging advanced load modelling methods and strategic planning will be critical in addressing the complexities of PEV integration. By fostering interdisciplinary collaboration and adopting innovative charging technologies, stakeholders can enhance grid management, optimise energy utilisation, and contribute to a sustainable and resilient energy future. The insights and recommendations presented in this review aim to guide researchers, policymakers, and industry leaders in shaping the next phase of electric vehicle adoption and energy ecosystem transformation.

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