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Review article

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Sustainable plug-in electric vehicle integration into power systems

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Abstract

Integrating plug-in electric vehicles (PEVs) into the power and transport sectors can help to reduce global CO_2 emissions. This synergy can be achieved with advances in battery technology, charging infrastructures, power grids and their interaction with the environment. In this Review, we survey the latest research trends and technologies for sustainable PEV–power system integration. We first provide the rationale behind addressing the requirements for such integration, followed by an overview of strategies for planning PEV charging infrastructures. Next, we introduce smart PEV charging and discharging technologies for cost-efficient and safe power system operations. We then discuss how PEVs can help to promote clean energy adoption and decarbonize the interconnected power and transport systems. Finally, we outline remaining challenges and provide a forward-looking road map for the sustainable integration of PEVs into power systems.

Sections

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Key points

- Coupling plug-in electric vehicles (PEVs) to the power and transport sectors is key to global decarbonization.
- Effective synergy of power and transport systems can be achieved with advances in battery technology, charging infrastructures, power grids and their interaction with the environment.
- Planning PEV charging infrastructures should support the active interaction of PEVs with the power grid and zero-emissions power generation.
- Advanced optimization and control technologies are in need to fully exploit large-scale PEV flexibility in interconnected power and transport.
- Innovative financial incentives are required to leverage the benefits of PEVs while coordinating the interests of different stakeholders.

Introduction

Plug-in electric vehicles (PEVs) can be divided into two major categories: battery PEVs and hybrid PEVs. The former are fully powered by batteries, whereas the latter use a combination of battery and fossil fuel power and can switch power modes on demand. The global PEV market has experienced an explosive growth since 2010 (ref. 1); according to the International Energy Agency[1], 10.5 million new PEVs, 73% of which are battery PEVs, were delivered in 2022 accounting for 13% of global light vehicle sales, an increase of 55% compared with 2021. Promoting the adoption of PEVs, particularly battery PEVs, is key to the decarbonization of the transport system, which contributed 22% to the global energy-related CO_2 emissions in 2022 (ref. 2).

PEV batteries are charged by plugging into the power grid via a charging infrastructure, thereby reducing fossil fuel consumption. As a result, PEVs produce no (for battery PEVs) or less (for hybrid PEVs) direct emissions through the tailpipe, including PM2.5, NO_x, NH_3, volatile organic compounds and CO_2, compared with conventional internal combustion vehicles[3]. These advantages make PEVs suitable for urban areas with high pollution levels. However, battery PEVs might still have indirect emissions if the electricity for charging comes from fossil fuels such as thermal power plants. In regions where the electricity is mainly generated from fossil fuel, the well-to-wheel CO_2 emissions (all CO_2 emissions related to electricity generation, transmission, distribution and use) of PEVs can be higher than those of conventional vehicles[4]. For example, a comprehensive analysis shows that PEVs might have higher CO_2 emissions than conventional vehicles after 2021 when nuclear energy began to be replaced by natural gas power plants in New York State, USA[5].

The power sector, responsible for 40% of global energy-related CO_2 emissions in 2022, is also undergoing decarbonization because of transitioning to zero-emissions wind and solar power generation[2]. Operating power systems requires a real-time balance between electricity supply and demand; however, wind and solar generation are intermittent and variable, which makes the balance challenging. Therefore, future power systems will need balancing resources that can adjust power generation or consumption following system operators' instructions to tackle real-time supply–demand mismatches[6]. Currently, these balancing resources are mainly provided by fossil fuel power plants, which are, however, being phased out with the decarbonization of power systems worldwide. According to the International Energy Agency, if the net zero-emissions targets in the European Union and other 83 countries worldwide are fully realized on time, coal use in the electricity sector will be reduced from 36% in 2021 to 3% in 2050; whereas renewables will rise from 28% in 2021 to 80% by 2050 (ref. 7).

The growing PEV adoption and deployment of charging infrastructures are intertwined with the power and transport sectors (Fig. 1a). For example, PEV charging profiles should match with zero-emissions generation in the power system to reduce indirect CO_2 emissions. Otherwise, PEV charging demands have to be satisfied by other power sources and the corresponding CO_2 emissions can increase despite high penetration of zero-emissions generation[8]. However, PEV charging profiles are flexible in which energy can be pushed back to the power grid from the battery, a concept known as vehicle to grid (V2G). The flexibility of charging and discharging power can provide substantial balancing resources in the power system and further promote the adoption of zero-emissions generation[9] (Fig. 1b).

This Review highlights recent technological advances towards sustainable PEV integration from the perspectives of batteries, charging infrastructure, power grids and their interaction with the environment. It also envisions the pathway, remaining challenges and future research directions from the perspectives of infrastructure planning, technologies for modelling, operation and control, and incentive mechanism design to realize sustainable PEV integration into power systems.

Battery considerations for PEV integration

Batteries have a remarkable impact on PEV key performances such as safety, durability, charging speed, driving mileage and cost. These performances determine the capability and willingness of PEVs to interact with the power grid, and PEV driving experiences. Unfortunately, battery abuses such as collision, overcharge, over-discharge and local overheat of the battery can negatively affect these performances and cause safety hazards[10]. Therefore, battery management technologies are indispensable.

Battery types and structures

Lithium-ion (Li-ion) batteries have been widely used in PEVs owing to their higher power and energy densities, longer cycle life, higher efficiency and lower environmental impact compared with other types of rechargeable battery technologies. Commercial Li-ion battery types for automotive applications vary in terms of their chemistry, design (cell shape) and specifications (Table 1). Although the anodes of existing Li-ion batteries are identical, mainly from graphite, their cathode materials are different, such as lithium iron phosphate (LFP), lithium nickel–manganese–cobalt oxide (NMC) and lithium nickel–cobalt–aluminium oxide (NCA)[11,12]. Compared with LFP batteries, NMC and NCA batteries have a higher energy density and are more prevalent in PEVs, but they are more expensive and have a shorter cycle life, poorer safety and lower thermal stability[12] (Table 1). Battery shapes, including cylindrical, prismatic and pouch cells, can also influence the energy and power densities of the PEV battery pack once the individual cells are scaled up[12,13] (Fig. 2a).

The cell design is fundamentally important for battery performance, including safety, battery degradation, charging speed and driving mileage[13,14]. For example, the all-climate battery structure – where nickel foils serve as the heating components of the battery cells – allows the battery to heat itself up at temperatures as low as −30 °C (ref. 14)

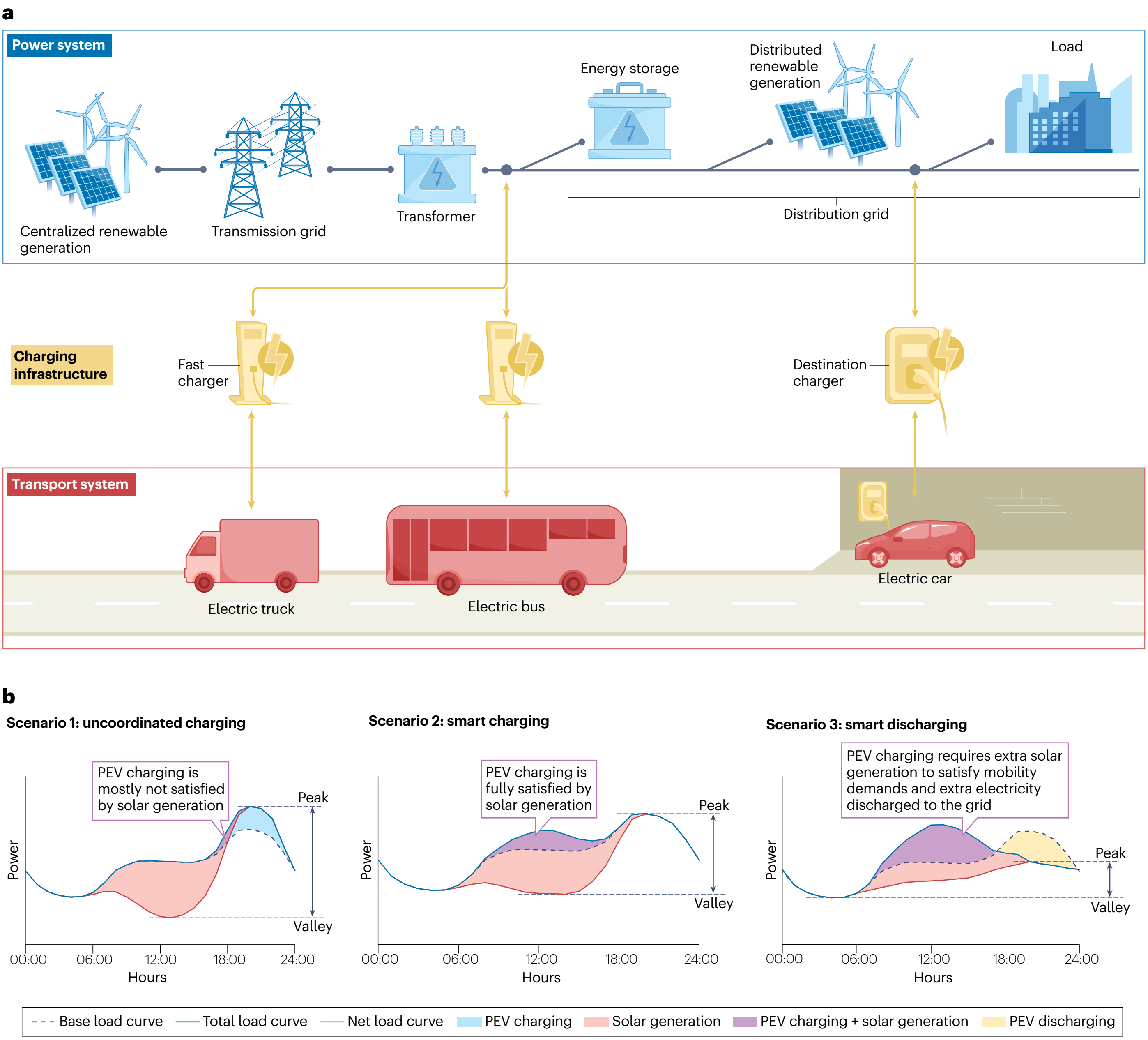


Fig. 1 | A zero-emissions interconnected power and transport system. a, The concept of an interconnected power and transport system. In the power system, most of the energy is generated from zero-emissions renewable sources, mainly wind and solar. This renewable generation is intermittent, variable and might not match demands. Therefore, the power system will need more balancing resources, such as energy storage, to mitigate the mismatch between electricity demands and supplies. In the transport system, plug-in electric vehicles (PEVs) consume electricity instead of fossil fuel. Their flexible charging or discharging power can act as a balancing resource to help to smooth fluctuations of renewable generation and promote decarbonization of the interconnected system. **b**, Example of coordination of PEV charging and discharging with renewable generation (solar as an example). Smart charging allows PEVs to consume more electricity when renewable generation is high. Smart discharging can transfer electricity from time periods with high renewable generation to time periods with low renewable generation, which further flattens the net load profile and promotes renewable generation consumption.

(Fig. 2b). The self-heating process can improve the energy and power capabilities of Li-ion batteries in cold weather. The blade battery technology, proposed by the Chinese manufacturer BYD, makes the LFP cells long and thin, thereby improving the pack energy density and thermal safety[13].

Battery health and safety management

Battery health and safety play vital roles in the charging–discharging management of PEVs. Improper or frequent charging and discharging cycles can accelerate battery degradation, resulting in reduced capacity and heightened resistance. Such degradation can also induce safety

Table 1 | PEV battery technologies

Cell design	Cell chemistry (cathode/anode)	Voltage plateau (V)	Specific power ($W kg^{-1}$)	Specific energy ($Wh kg^{-1}$)	Lifetime (cycle)	Cell use example[a]
Cylindrical	LFP/C1	3.3	2,600	108	>3,000	JAC Yiwei 3 (2023)
	NMC/C1	3.6	1,480[b]	264	300–600	Tesla Model X (2022)
	LTO/C1	2.3	1,673[b]	76	>25,000	Tesla Model S (2015)
	NCA/C	3.6	618[b]	243	500–1,000	Tesla Model 3 (2018)
Prismatic	LFP/C2	3.2	518[b]	129	>2,000	BYD Qin EV (2019)
	NMC/C2	3.7	410[b]	206	1,000–1,200	NIO ES6 (2023)
	LTO/C2	2.3	1,130[b]	62	>25,000	Honda Fit EV (2013)
	NCA–NMC/C[12]	3.7	369[b]	122	600–1,000	BMW i3 (2014)
Pouch	LFP/C3	3.3	2,400	166	>3,000	BYD Han EV (2020)
	NMC/C3	3.7	2,500	180	1,000–1,200	Chevrolet Bolt (2016)
	LTO/C3	2.3	1,068[b]	90	>20,000	–
	LMO–NCA/C[12]	3.7	845[b]	167	600–1,000	Nissan Leaf (2015)

Quantitative values are from cited sources and qualitative evaluations such as safety, cost, low-temperature performance and charging time have been performed according to ref. 157. C, graphite or carbon; LFP, lithium iron phosphate ($LiFePO_4$); LTO, lithium titanate oxide ($Li_4Ti_5O_{12}$); NCA, lithium nickel–cobalt–aluminium oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$); NMC, lithium nickel–manganese–cobalt oxide ($LiNi_{1-x-y}Co_xMn_yO_2$); PEV, plug-in electric vehicle. [a]Year in parentheses indicates when the PEV model was first put on the market. [b]The specific power values that could not be retrieved from the corresponding reference were estimated using typical data such as nominal voltage and maximum continuous discharging current from the battery manual.

issues, for example, thermal runaway — a scenario where exothermic reactions within the battery go out of control.

Ageing mechanism and prognostics. Li-ion batteries inevitably age during operation. Therefore, it is important to understand the ageing mechanisms and influencing factors to inform the use of prognostic methods[15] and develop suitable and accurate models for battery health prognostics[16]. Degradation modes related to the capacity and power decay of Li-ion batteries mainly involve the loss of active materials and the loss of lithium inventory (the quantity of cyclable lithium)[17]. Degradation mechanisms often arise from the side reactions on the anode, cathode and electrolyte. For instance, growth of a passive film, deposition of metal lithium and attenuation of active materials are generally ageing reactions at the anode electrode, which dominate the whole battery ageing process. For the metal oxide cathode, electrode material dissolution, electrode structure destruction and phase transition commonly occur[18]. External usage conditions such as temperature, loading current mode and rate, and depth of discharging strongly influence battery ageing[19]. Ageing mechanism detection can be directly measured based on an electron microscope test and an infrared test, or through modelling methods such as pseudo-2D and molecular dynamics simulation[15]. In practical battery usage, the attenuation of energy and power capacities is of primary concern, which requires accurate battery health prognostics including state of health (SOH) estimation and lifetime prognostics.

The methods for battery health prognostics can be broadly divided into model-based, data-driven and hybrid methods[20]. Model-based methods aim to build an empirical, equivalent circuit or electrochemical model to simulate battery properties and then adopt parameter optimization methods for ageing status prognostics[21]. Data-driven methods are mainly used to map the relationship between the observable features and battery SOH[22]. However, these models have their own limitations. For example, the high computational burden of electrochemical models and the poor generalizability of data-driven methods can hinder their practical applications. One option is to use hybrid methods that combine the strengths of model-based and data-driven methods to provide more accurate and reliable prognostics[15]. For example, a computationally efficient physics-informed multi-output Gaussian process regression method was proposed to simultaneously estimate battery capacity and diagnose its degradation modes using solely limited early-life battery degradation data. This approach improved simulation fidelity by more than 50% compared with the purely data-driven approach[23]. Alternatively, a generative machine learning method that considers physics-based constraints was used to improve purely data-driven SOH diagnostics[24]. In this case, the physical laws and boundary conditions involved in the electrochemical reactions inside the battery were introduced to limit the time-varying model weights or coefficients. Additionally, a battery electrochemical model was developed to generate a set of physics features reflecting battery degradation and these features serve as the inputs of a neural network model for improving the accuracy and generalizability of battery health prognostics[25] (Fig. 2c).

Safety and fault diagnosis. Safety concerns are critical in the large-scale grid integration of PEV batteries. Li-ion batteries are susceptible to various abuse conditions (such as mechanical penetration, external short circuiting and an overheating battery), which increase the risks of safety issues such as thermal runaways[25]. To guarantee the safe operation of batteries, efficient thermal management and online fault diagnosis are indispensable (Fig. 2d). Battery thermal management systems serve to regulate the battery temperature within a range that is favourable to battery operations and safety[26,27]. Their development involves the characterization of heat generation and transfer of batteries, pack-structure design and optimization, and thermal control strategies[26,27]. For fault diagnosis, effective numerical modelling and online fault diagnosis technologies guide the safer operation of batteries[28]. Numerical model-based fault diagnosis can detect the difference between the measured signal and the model-estimated information, but it is difficult to implement large battery packs owing to model uncertainty and inconsistency among cell parameters, such as temperature, state of charge, internal resistance and capacity[29,30]. By contrast, data-driven battery fault diagnosis uses measured data to analyse the anomalies among the battery cells in the pack and flag outliers instead of relying on a predefined model[30]. However, labelled fault categories are required for model training, which are difficult to obtain. Combining model-based and data-driven methods can improve the efficiency of fault diagnosis. For example, fault-related battery parameters and states can be estimated using physical battery models, which can then serve as the inputs of data-driven methods for augmenting interpretability and accuracy.

Battery charging management

Charging speed is one of the key metrics of PEVs. Reducing the charging duration brings PEVs closer to internal combustion engine vehicles in terms of refuelling convenience. However, increasing the charging speed can accelerate battery ageing and reduce PEV economic viability[31]. Therefore, it is crucial to develop health-aware fast charging protocols to boost the charging speed without sacrificing battery health. Given that PEVs are subject to different operating conditions that can affect batteries' charging performance, for instance, environmental temperature, adaptive charging management is also required to guarantee optimal PEV charging under these variable conditions. The trade-offs between charging speed, battery health and temperature adaptability should be carefully considered in a battery management system.

Health-aware fast charging. Fast charging that charges batteries with a high power rate, for instance, charging an empty battery to its 80% capacity in 15 min, can trigger negative side reactions inside the cell. For example, lithium plating on graphite, which is considered the main reason for capacity degradation and safety issues in Li-ion batteries, occurs when the charging rate exceeds the intercalation rate into the graphite crystal structure[32]. Therefore, the trade-off between charging speed and battery degradation should be addressed by optimizing charging current profiles and developing health-aware charging protocols[33,34]. For this purpose, electrochemical–ageing coupled battery models that accurately predict the degradation mechanism during charging should be developed. Moreover, internal electrochemical states can inform electrochemical–ageing coupled models to minimize the side reactions responsible for degradation[31]. An accurate battery lifetime model should be developed based on an historical experimental data set covering various operation conditions including environment temperature, depth of discharge and SOH. PEV fast charging current profiles can be optimized to maximize the battery lifetime according to the battery lifetime model, given the specific battery's degradation patterns and current SOH[32].

Adaptive charging. Owing to the varying operational conditions of PEV batteries, charging protocols might perform differently in terms of charging efficiency, charging speed, temperature stability and degradation across conditions. Therefore, adaptive charging management has an essential role in dealing with operation uncertainties and guaranteeing PEV optimal charging performance adapted to a specific set of conditions. For example, adaptive charging management at extremely low temperatures (for example, below −30 °C) is one of the most critical considerations[35]. PEV charging management in cold places such as Nordic regions is challenging because of the increased battery resistance and accelerated capacity degradation that greatly reduce rechargeability[36]. Adaptive charging management warms up the battery to a favourable temperature range (15–35 °C) through controllable internal preheating or hybrid warm-up technology combining internal and external heating, which boosts the charging speed while reducing battery degradation[36,37].

Infrastructures for PEV integration

The manner in which drivers operate their PEVs, including where and how long they charge, shapes their charging needs and preferences. This, in turn, affects PEV integration into the interconnected power and transport system. In this section, the most important aspects for planning PEV charging infrastructures are discussed.

Charging modes and options

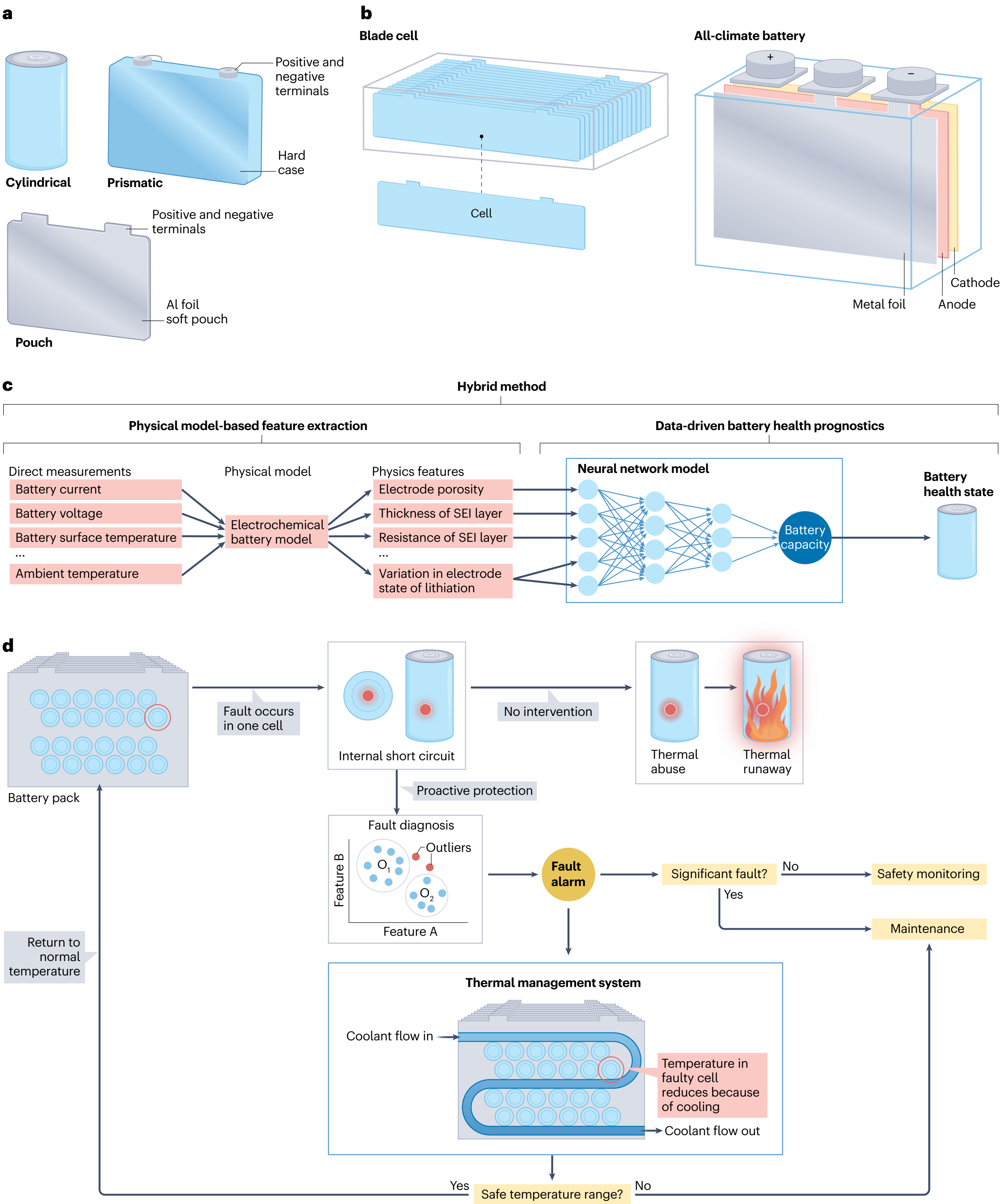
PEVs can be refuelled using different battery charging modes, such as conductive charging, battery swapping, and wireless and mobile charging (Table 2). The selection of each charging technique depends on the needs of PEV users.

Conductive charging. Conductive charging is the most common wired charging technology. Depending on the charging urgency, conductive charging can be further categorized into destination charging and fast charging[38]. Destination charging is used when PEVs are charged at parking lots of trip destinations[39], such as residential and commercial areas. Residential areas usually offer slow charging (a couple of kilowatts), taking up to 10 h for a full charge, whereas commercial areas can charge faster (from a couple of kilowatts to tens of kilowatts), completing from 30 min to a few hours[40]. Destination charging is the most popular option for PEV users because it does not require additional stops[41]. Particularly, residential charging accounts for about 50–80% of all charging events[42]. Furthermore, when a user parks at a destination for a period longer than the time required for the vehicle to completely charge, the vehicle's charging power profile becomes flexible and can be strategically optimized or even discharge electricity to the power grid.

By contrast, fast charging and ultra-fast charging are used during a trip to quickly boost a PEV's range. Whereas common fast charging typically uses power levels around tens of kilowatts[43], ultra-fast charging can go up to 200–350 kW (ref. 44). Fast charging complements destination charging; whereby private PEV users driving for trips that are longer than PEV ranges or commercial PEV users (such as taxis drivers) often opt for fast charging to save time. Given that the primary objective of fast charging is to minimize the charging duration, factors such as deviation time from the original route, potential queuing duration and the inherent charging time predominantly influence the user's determination for modes of charging.

According to a survey by the International Energy Agency[1], the number of public charging stations for PEVs worldwide reached 2.7 million at the end of 2022, more than 0.9 million of which were installed in 2022. The distribution of conductive charging infrastructure varies considerably with countries. As the largest PEV market, China owns more than 1 million slow destination chargers (over half of the global stock) and 0.76 million fast chargers[1]. Because of the dense population in China's urban areas, access to home chargers is limited. Consequently, the share of fast chargers (43%) is substantially higher than in Europe (13%) or the USA (22%)[1].

Nonetheless, promoting the development of charging infrastructure across the world remains challenging. For example, many people in China live in multi-storey apartments, in which private parking spaces


a
Cylindrical
Prismatic
Positive and negative terminals
Hard case
Pouch
Positive and negative terminals
Al foil soft pouch
b
Blade cell
Cell
All-climate battery
+
−
Metal foil
Anode
Cathode
c
Hybrid method
Physical model-based feature extraction
Data-driven battery health prognostics
Direct measurements
Battery current
Battery voltage
Battery surface temperature
...
Ambient temperature
Physical model
Electrochemical battery model
Physics features
Electrode porosity
Thickness of SEI layer
Resistance of SEI layer
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Variation in electrode state of lithiation
Neural network model
Battery capacity
Battery health state
d
Battery pack
Fault occurs in one cell
Internal short circuit
No intervention
Thermal abuse
Thermal runaway
Proactive protection
Fault diagnosis
Outliers
Feature B
Feature A
Fault alarm
Significant fault?
No
Yes
Safety monitoring
Maintenance
Return to normal temperature
Thermal management system
Coolant flow in
Temperature in faulty cell reduces because of cooling
Coolant flow out
Yes
Safe temperature range?
No

Fig. 2 | Battery technologies for PEV integration. a, Different types of battery format. Three types of battery format are commonly used in current plug-in electric vehicle (PEV) applications: cylindrical cells, prismatic cells and pouch cells. The battery format is related to the battery pack assembly, which affects the energy density of the battery pack and, thus, the vehicle driving range. **b**, Novel battery structure designs. The all-climate battery enables the battery to heat itself at low temperatures (as low as −20 °C) by adding nickel foil to the battery cell. The self-warming process improves the ability of lithium-ion (Li-ion) batteries to charge in cold weather while alleviating battery degradation and safety concerns[14]. The blade battery technology makes the lithium iron phosphate (LFP) cell long and thin[13], which can increase the energy density of the battery pack and improve the thermal safety of the battery cell. **c**, Example of battery health prognostics based on the hybrid method. The battery direct measurements are utilized to build an electrochemical model of the battery and simulate the battery's ageing process. Based on the simulation, a set of physics features reflecting battery degradation are extracted as the inputs of a neural network model for battery health prognostics[158]. This neural network learns the nonlinear relationship between battery capacity (output, an explicit indicator reflecting battery degradation process) and these physics features (input). Because these physics features have a closer relationship with battery degradation and stronger physical interpretability compared with the direct measurements, this neural network trained by the hybrid method can have higher estimation accuracy and generalizability than a network trained simply based on the direct measurements. SEI, solid electrolyte interphase. **d**, Illustration of battery thermal management and fault diagnosis. Battery thermal management uses coolant to keep the battery within a safe temperature range. When an internal short circuit fault occurs in one cell, this will cause abnormal heat generation and temperature rise. If no intervention is taken, continuously rising temperatures can lead to battery thermal abuse, triggering thermal runaway when temperatures reach a critical point, which in turn destroys the battery. However, proper online fault diagnosis technology can help to detect the internal short circuit fault in advance and pull the alarm. The thermal management system will then try to further reduce battery temperature by accelerating cooling. This fault will also be continuously monitored, and battery engineers may also manually maintain the battery, that is, replace the cell, when the fault is significant.

and power supplies are too limited to install home chargers. In Europe, some insurance companies are reluctant to provide insurance for buildings with PEV charging stations because of safety concerns. Nevertheless, the strong government support and the rapidly growing PEV numbers continue to generate investment into both destination and fast chargers worldwide. In 2022, some countries such as China, the UK, Germany and Switzerland began to shift their previous subsidies on vehicles to charging infrastructures. For instance, the UK plans to install 300,000 public chargers by 2030 and committed about £1.6 billion in government funding in 2022 (ref. 1).

Battery swapping. Swapping batteries instead of charging them is a more convenient option for PEV users[45]. The entire battery swapping process typically takes less than 5 min, which is similar to how long it takes to refuel a gasoline vehicle[46]. The removed batteries can be charged during the valley-load period (the hours with low base power demands and cheap electricity), which can save PEV electricity consumption costs.

Despite its advantages compared with conductive charging, battery swapping is less common. Battery swapping was briefly commercialized by Better Place in Israel and Denmark, Tesla in the USA and State Grid Cooperation in China, but they all failed[47]. On the one hand, battery swapping stations usually need to maintain sufficient charged batteries to avoid queuing for customers, which increases investment and maintenance costs[48]. On the other hand, the lack of standardization among different battery manufacturers also limits the adoption of battery swapping and causes concerns about the quality of the replaced batteries[49]. Batteries of different PEV models — even from the same manufacturer — often have different performance and characteristics, which limits their exchangeability.

Currently, battery swapping companies either provide services to PEVs that they produce (for example, NIO) or work with manufacturers to design PEV models compatible with their services (Aulton)[1]. NIO now operates the world's largest battery swapping system with more than 1,300 stations providing services for private PEVs around the world[1]. Aulton runs more than 800 battery swapping stations for commercial PEVs (such as electric taxis and buses) in both China and Europe[50]. Presently, the global share of battery swapping PEVs remains low. For example, it accounts for less than 5% of all PEVs in China[47]. The popularization of conductive charging infrastructures and the improvement of fast charging technologies might make battery swapping less attractive in the future. Nevertheless, it could still be appealing for commercial PEVs, such as taxis, which usually prefer a short charging time to enhance vehicle utilization.

Wireless charging. Wireless charging refers to charging a PEV en route through pads buried beneath the road surface[51]. This mode is the most desirable option for PEV users as it almost entirely eliminates the inconvenience of PEV charging. Wireless charging comes in two main forms: inductive and capacitive. The former works through magnetic resonance coupling between transmitting and receiving coils, whereas the latter functions by electric field interaction between coupled capacitors[52]. The currently available wireless charging technology mainly belongs to the inductive type, as it allows power transmission above 10 kW over air gaps reaching several metres. By contrast, capacitive charging is suitable for only a few millimetres in air gap[53]. The main limitation of wireless charging is the investment cost; for example, in the FABRIC EU project, the cost of building wireless charging infrastructures was evaluated at 3 million € per kilometre[54]. In another study conducted in California, the cost was estimated at around US$1 million per kilometre[55].

Mobile charging. Mobile charging refers to a mobile charging station (typically a truck with batteries) to charge PEVs[56]. Compared with other charging options, mobile charging does not need to service PEVs in a fixed spot, enabling it to charge PEVs in arbitrary locations. Mobile charging can serve as a complementary solution before the large-scale deployment of fixed charging infrastructures. Alternatively, it could also address the charging demand in areas with limited power grid capacity[57]. However, mobile charging requires a full-time driver, wastes substantial electricity when moving the batteries and usually has a low utilization level because their customers are often sparsely distributed on the transport network. Hence, it is much more expensive than the other charging options. As a result, it is only used for PEV charging rescue services nowadays. In 2010, Nation-E launched the world's first mobile charging station for providing PEV charging rescue services[58]. In 2021, China's PEV manufacturer NIO announced the deployment of 120 mobile charging stations by 2024 (ref. 59).

Table 2 | PEV charging infrastructures

Charging option	Application scenario	Charging power range (kW)	Charging efficiency (%)	Charging duration[a] (h)
Destination charging (conductive)	Residential	3–7	~95	8–12
	Commercial	10–60	~95	1–6
Fast charging (conductive)	Specialized station	100–500	~95	0.15–0.5[b]
	Public station	30–300	~95	0.25–2
Battery swapping	Private and/or commercial	3–500[c]	~95	0.15–0.25
Wireless charging (inductive)	Public charging stations	3–15	<90	4–8
	On-road charging	3–5	<90	Rely on trip duration
Mobile charging	Emergency charging	15–30	~95[d]	2–4

PEV, plug-in electric vehicle. [a]Charging duration is estimated based on fully charging a 60-kWh battery. [b]The battery capacity of PEVs in specialized fast-charging stations is often large. For a typical capacity of 200 kWh for electric buses, the charging duration is 0.5–2 h. [c]The charging power range in battery swapping stations depends on the type of installed chargers. [d]The extra energy consumption for moving the mobile charger to users has not been counted in calculating the charging efficiency.

Charging infrastructure planning

Building convenient and economical charging facilities is key to improving user satisfaction, reducing charging costs and promoting PEV adoption. The aim of planning charging infrastructures includes maximizing the charging demand coverage, improving service quality and maximizing social welfare[60]. The key constraints considered in the charging infrastructure plan fall into two categories: economy and convenience. The former includes resource limitation such as investment capital, land, optimal charging scheduling and user preference, whereas the latter covers charging demand satisfaction and service quality, for example, queuing duration[61].

For the planning of charging infrastructure, it is imperative to first delineate the distribution of charging demand. For destination charging, the charging demand can be estimated based on statistics of drivers' mobility behaviours (particularly driving destinations). For fast charging or battery swapping stations[62], the charging often happens en route instead of at destinations. As a result, it is difficult to estimate the locations where fast charging demands appear, whereas locations of charging infrastructure can also affect PEV driving behaviours. Hence, modelling the fast charging demand and battery swapping should not only consider PEV mobility demands but also consider charging infrastructure planning's impacts on PEV behaviours[63].

Early research in charging infrastructure planning was largely inspired by classic work on conventional vehicle refuelling facility planning and conducted from the perspective of transport engineering[64]. This approach considers mileage limitation of PEVs[65] and maximizes traffic flow through charging stations, thereby maximizing the demand coverage or minimizing the total cost[66]. Because PEVs have shorter driving range and longer refuelling time than conventional vehicles, modelling PEV charging demands faces new challenges. Traffic simulation[67] and data-driven methods[68] have also been applied to charging infrastructure planning. The former builds agent-based simulation tools to simulate PEV driving and charging behaviours, in which it can validate charging system plans' performance[67]. The latter utilizes historical real-world PEV charging data to estimate future charging demands to guide infrastructure planning[68]. Besides the transport perspective, the siting and sizing of charging facilities in the power distribution network have also been investigated to help to alleviate the adverse effects of PEV charging (for example, overloading) on the power grid or promote renewable generation adoption[69].

In this context, combining transport and power networks in the planning of PEV charging infrastructure can help to account for both the users' mobility demands and power grid constraints[70,71]. For example, a user equilibrium-based framework to deploy a charging infrastructure has been proposed, which considers PEV rational routing and charging decisions to minimize both electricity costs in the power system and driving time costs in the transportation system[72]. When optimal deployment of the charging infrastructure is achieved, the PEVs also reach an equilibrium state, in which no vehicle tends to change its routing and charging decision, and social costs can be minimized. In addition to charging facilities, coordination with renewable energy and energy storage systems can also be integrated into the optimization model to improve the overall decarbonization of the system[73].

Grid considerations of PEV integration

The global rise in PEV adoption has led to increasing charging loads which constitute a substantial fraction of peak power consumption in many regions. For example, PEV charging will account for 10% of the peak load in California by 2030 and 11% of the peak load in Shenzhen, China by 2025 (ref. 74). In this section, we first analyse the impact of PEV charging on the power grid and then introduce charging and discharging technologies that promote seamless and beneficial PEV integration into the power grid (Fig. 3).

Uncoordinated PEV charging

The uncoordinated spatiotemporal charging of PEVs can perturb the normal load profiles of power grids and exert pressure on the operation of power systems. Therefore, smart PEV charging and discharging technologies need to be developed.

Impact on the distribution power grid. PEV charging demands often overlap with other power loads resulting in short-term overloading and exacerbation of peak–valley differences[75]. For example, in some regions of the Pacific Gas & Electric utility network of California, large-scale PEV integration might exceed the feeder current threshold by more than 300% and last for up to 22 h (ref. 76). Such conditions will likely accelerate transformer ageing, cause power outages and risk fire hazards[77]. Thus, utility companies must upgrade distribution grids based on projections of PEV charging load profiles. However, the peak load of uncoordinated PEV charging may only last for a brief period throughout the day, resulting in a low usage rate of the upgraded distribution grid. Therefore, costly upgrades to accommodate uncoordinated PEV charging might be uneconomical[78].

Uncoordinated PEV charging can deteriorate the power quality in distribution grids. For example, the number and charging modes of PEVs being charged in a distribution power grid may change frequently, which, depending on the charger type, may produce different amounts of harmonic content, that is, currents and voltages with frequencies that are integer multiples of the fundamental frequency of the alternating current (AC) power system, causing harmonic pollution and decreased usage efficiency[79]. Moreover, feeder overloading can increase line losses, which might lower electrical bus voltages for end users[80]. Finally, the single-phase slow charging mode allows the charging load to be randomly connected to any phase of the three-phase AC power. This situation might cause an imbalance in the three-phase voltage and current of the distribution grid, leading to temperature rises, drops in efficiency and abnormal operation for equipment requiring three-phase power[81].

Impact on the transmission power grid. The uncoordinated charging of PEVs has a similar impact on the transmission grids by causing congestion in transmission lines, deteriorating power quality and reducing system efficiency[82]. In particular, uncoordinated PEV charging may increase peak–valley differences in load curves of the bulk power system. Therefore, tackling such mismatches between electricity supply and demand requires balancing sources, such as controllable power plants or energy storage systems. For example, extra renewable generation has to be curtailed when the load is low[8].

Smart charging for distribution grids

The average daily usage of PEVs accounts for a small portion (about 4%) of the time in a day[83]. Therefore, PEVs often have sufficient time to connect to the power grid and their charging and discharging profiles are flexible[84]. Smart charging is usually the strategy to manipulate PEV charging and discharging power profiles to match the electricity supply and demand, which could help to mitigate the negative effects on the power grid caused by uncoordinated PEV charging, save charging costs and bring balancing advantages to the power grid.

Smart destination charging. The flexibility of destination charging allows grid operators and users to optimize their charging behaviours[85]. First, based on the time-of-use electricity prices set by utility companies, PEV users can charge more at the 'valley' price and less at the 'peak' price[86], thereby reducing costs[87]. Second, through coordination with other baseloads, grid operators can let PEVs charge when the other baseloads are low (valley-load filling) and stop charging or even discharging when the other baseloads are high (peak-load shaving). As a result, PEVs can help to flatten power loads in distribution grids, reduce overload risks and defer the grid upgrade investment[88].

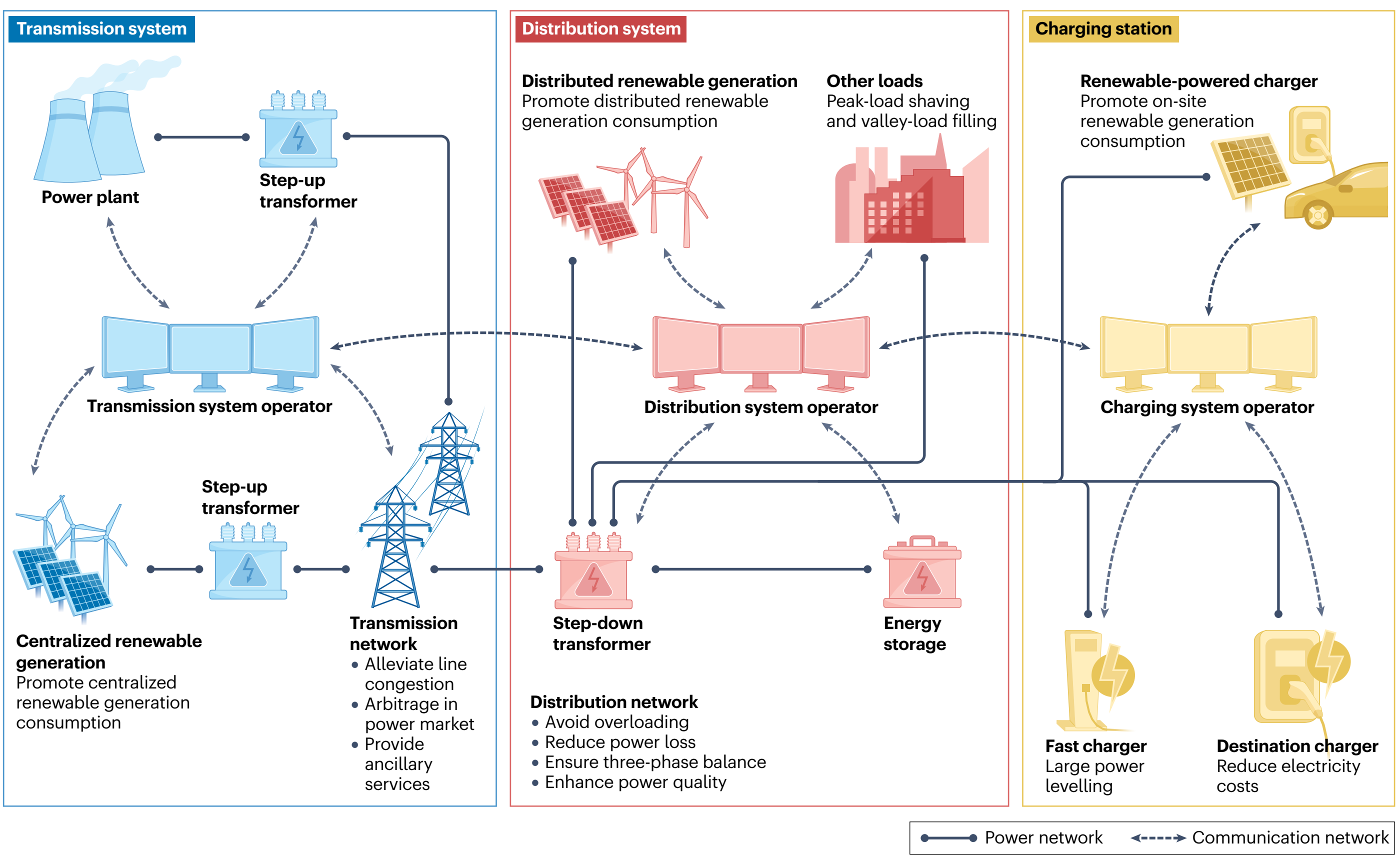

Fig. 3 | The role of smart PEV charging and discharging in the power system. By controlling their charging, discharging and reactive power, plug-in electric vehicles (PEVs) can provide various services to charging stations, distribution systems and transmission systems such as shaving peak load, enhancing power quality, alleviating line congestion and providing ancillary services (for example, frequency regulation). They can also help to promote the consumption of renewables in the power system. Solid lines represent the power network and dashed lines represent the communication network through which the system operators, PEV charging stations and other resources share market prices and control signals and measurement information.

Third, grid operators can also coordinate the charging demand of different voltage phases to avoid the three-phase imbalance problem, which helps to reduce line loss costs and improve power quality[89]. Moreover, PEVs can also work as backup energy storage systems that can help to enhance the power supply reliability in distribution grids[90]. For example, idle PEVs can be assigned to power grids at locations at risk to prepare for outage events facing natural disasters such as hurricanes[91,92]. Many PEV models on the market, including Nissan Leaf and BYD Atto 3, already support discharging to power household appliances. In 2023, General Motors announced that they have planned to equip all its electric cars and trucks with V2G ability to act as backup power supplies during blackouts by 2026 (ref. 93).

Coordinated fast charging. Fast charging power is often high and intermittent, and only lasts for a short period (from a few minutes to 1 h) each time, which strongly impacts the normal operation of the power grid[94]. Because fast-charging stations are mainly used in urgent situations, they are regarded as uncontrollable[95]. However, charging station operators may be able to reduce some PEV charging power to avoid overloading at peak hours[96]. For example, fast-charging stations can install energy storage systems to smooth the fluctuating charging load curves by scheduling their charging and discharging[73]. Moreover, advanced algorithms can be used to coordinate the scheduling of multiple fast-charging stations to adjust the peak charging load[97].

Coordinated reactive power control. In power systems, many power loads are capacitive or inductive and generate or consume reactive power. Although reactive power does not really dissipate energy, the voltage stability will deteriorate if it is imbalanced. Reactive power compensation helps to balance reactive power through the energy exchange between capacitive and inductive power loads in the same circuit to improve power quality[98]. Advanced power electronic devices in PEV chargers, such as voltage source converters, can be used for reactive power compensation[99]. During the charging process, PEVs can participate in reactive power compensation through off-board chargers[100]. This process not only satisfies the charging demand but also adjusts the reactive power flow of the grid. Moreover, this compensation strategy reduces the investment cost of traditional reactive power compensation equipment (such as capacitor banks and synchronous condensers) and does not adversely impact the battery life of PEVs[101].

Smart charging for transmission grids

Aggregating tens to thousands of PEVs can increase the power and energy capacities to reach grid-scale energy storage levels[102]. As a result, PEVs can arbitrage energy and provide ancillary services (such as frequency regulation and operating reserve) in power markets.

Price arbitrage. PEVs can participate in power markets and use their charging and discharging flexibility to arbitrage price differences, that is, buy more electricity when the price is low and buy less or even sell electricity when the price is high[103]. Power markets often have a minimum bidding capacity threshold; for example, for PJM, the largest wholesale electricity market in the USA, the threshold is 1,000 kW, which one PEV whose charging power is commonly only several kilowatts to tens of kilowatts can hardly meet[104]. Therefore, tens or more PEVs need to group together to participate in power markets under the coordination of an aggregator[105]. The aggregator represents these PEVs to bid in power markets and conducts energy arbitrage transactions through day-ahead or intra-day markets to maximize revenue. The aggregator is also responsible for the coordination and control of PEV charging during real-time operations to ensure that the aggregation can meet the market commitment[106]. An investigation by PJM and Bayerische Motoren Werke (BMW) North America on PEV interaction with wholesale electricity pricing signals and vehicle owner battery charging habits revealed that managing PEV charging alleviates power grid operation stress and reduces PEV fuel costs.

Providing ancillary services. Ancillary services mainly provided by the aforementioned balancing resources in power systems assist power system operators in maintaining system reliability. PEV batteries often have a short response time (less than 1 s) – the duration of power consumption adjustment responding to a signal triggered from the power system – to control signals so that aggregation of PEVs can swiftly adjust the charging and discharging power following a power system operator's request[107]. Therefore, PEVs can be used for various ancillary services in power systems such as frequency regulation and operating reserve[108]. Frequency regulation maintains the stability of grid frequency by balancing the power load and demand, and its operating time scale ranges from one second to tens of seconds. Through aggregators, PEVs can improve frequency control performance of the system[109]. Operating reserve service refers to the spare power capacity that can compensate for the generation gap between load demand and power supply within a few to tens of minutes. Idle PEVs can work as energy storage units and improve the flexibility and reliability of grid operation[110]. In a pilot V2G project conducted by PJM and the University of Delaware in 2007, an electric BMW Mini had earned approximately US$100 per month for its services when charged and discharged in response to the PJM frequency regulation signal. From 30 January 2016 to 30 September 2017, a mixed-use 29 PEV demonstration fleet at the US Los Angeles Air Force Base provided a total of 373 MWh of power regulation to the California ISO power market[111].

Environmental aspects of PEV integration

The environmental impact of PEV integration depends on how the PEVs interact with the power system, especially with respect to zero-emissions renewable generation. The higher the penetration of renewables in the power system, the lower well to wheel CO_2 that PEVs will emit[4,5]. However, if PEV charging profiles do not coincide with that of renewable power generation, the peak–valley difference of the net power load, which is the load not satisfied by renewable generation, will increase (Fig. 1b). The mismatch will further decrease the energy efficiency of fossil fuel power plants, increase the demands for balancing resources, reduce renewable power generation and increase CO_2 emissions[8]. Therefore, adopting these PEVs might have a negative effect on the decarbonization of the interconnected power and transport system. Hence, it is necessary to achieve a synergy between PEVs and renewable generation at distribution and transmission levels.

PEVs with distributed renewables

Unlike centralized bulk power plants that are often built in rural areas, renewable generation (for example, solar panels) is mainly distributed and located close to end users. Therefore, PEVs can be directly powered by on-site or nearby distributed renewable generation.

Renewable PEV charging station. Some charging stations are equipped with on-site rooftop solar panels[112] and can be connected to the power grid for backups, or operate in an island mode whereby a battery storage system is installed to manage the mismatch of renewable generation and PEV charging[113]. The intermittent and variable renewable generation is first stored in the battery storage system and then supplied to PEVs when needed. For example, 30 100% solar-powered PEV charging stations have been installed by a US company, Electrify America, in rural California. In 2023, the Republic of Kenya launched its first solar-powered battery charging and battery swapping hub for rural mobility[114]. Renewable-powered PEV charging stations are an important charging solution for rural areas with limited access to power grids.

PEVs and renewables in distribution grids. Integrating a large amount of renewable generation could deteriorate the power quality in distribution power grids, part of which can be alleviated by smart PEV charging and discharging[115]. For example, renewable generation might cause inverse power flow in unidirectional distribution networks, resulting in high nodal power voltages which could damage electric appliances (also known as the 'voltage rise')[115]. Charging PEVs when there is high renewable generation can help to reduce inverse power flow and mitigate the voltage rise problem[116]. Similarly, intermittent and variable wind or solar generation could cause power flow fluctuations in the distribution network, resulting in voltage deviations, three-phase voltage and current imbalance, and harmonic distortion[115].

PEV batteries can swiftly adjust their charging and discharging power and smooth these power flow fluctuations[117]. Although fast charging is often uncontrollable, it can also be used to coordinate with renewable generation through the support of battery storage systems[118]. PEV coordination with renewable generation in distribution power grids must account for stochastic PEV charging behaviours and variable renewable generation as well as power grid operation safety.

Current power grids are mostly AC systems. However, because PEV batteries, solar panels and battery storage systems work with direct current (DC), power grids could also have DC distribution power grids or microgrids[119]. Adopting DC can help to reduce the number of power conversion stages and improve energy efficiency[120]. Furthermore, because there is no reactive power flow in a DC grid, the power quality is easier to regulate[120]. The role of PEVs in a DC power grid is similar to that in an AC power grid; for example, PEVs in destination charging stations can work as flexible loads or batteries to promote renewable generation adoption, whereas fast charging PEVs are often treated as stochastic loads.

Bidirectional DC–DC converters are the key interface connecting PEV batteries and other resources with the DC power grid. These devices adapt PEV batteries' voltages with the power grid and regulate power flow and voltage/current. Various circuit types have been designed to improve the voltage conversion ratio, power density and conversion efficiency of converters[121]. For example, a bidirectional four-port DC–DC converter was designed, which has dual bidirectional ports with only six switches and can support flexible integration of batteries and renewables in a DC microgrid[122]. A series of advanced controlling technologies for DC–DC converters have also been proposed to ensure stable, reliable and efficient operation of DC power grids[123]. For example, uncertainties of renewables or power loads in DC microgrids often cause stability problems and deteriorate the performance of DC–DC converters. By employing a robust controller with disturbance compensation, a DC–DC converter can be more tolerant to these uncertain disturbances[124].

PEVs with grid-scale renewables

Grid integration of large-capacity, centralized renewable generation can cause spatiotemporal supply and demand imbalances in the power system. Aggregated PEVs can synergize with renewable generation to mitigate these fluctuations by trading renewable electricity or mutual spatiotemporal coordination[125].

Trading renewable electricity. Participating in the power market could be an option to coordinate PEVs with grid-scale renewable generation. Because renewable generation consumes no fossil fuel, the generation per kilowatt-hour of renewable electricity is often close to zero during the operation stage. Therefore, renewable power plants often act as price takers offering electricity at very low prices in the power market[126]. Consequently, during the intervals of heightened renewable power generation, the electricity price often declines, potentially reaching negative values[126]. Aggregators of PEVs can then buy this low-priced electricity to reduce costs by manipulating PEV charging and discharging behaviours, which in turn promotes renewable generation adoption (see PJM website for details).

PEV aggregators and renewable energy providers can also collaborate with each other to participate in power markets[127]. For example, PEV charging and discharging flexibilities are used to neutralize fluctuating outputs of renewable generation. This strategy helps to reduce the bidding risks of renewable power plants and increases profitability in power markets. Furthermore, a fleet of PEVs and renewable generation can also form a 'virtual power plant' (VPP) with or without other resources (such as controllable loads and energy storage)[128]. By coordinating PEVs with renewable generation, and other resources, a VPP can function similar to a conventional power plant, in which it bids in the power market and even provides ancillary services[129,130]. For example, eight VPPs participated in a 3-year demonstration project in Australia. These VPPs are constructed of household batteries connected with solar generation from more than 7,150 residential customers and their total battery capacity is more than 31 MW. This project shows that VPPs are highly capable of responding to energy market prices in real time and they can provide more than one service (such as arbitraging electricity prices and providing frequency regulation), at times simultaneously[131].

Spatiotemporal dispatching of PEVs. Being mobile battery storage systems, PEVs can alleviate spatial supply–demand imbalances in power systems. Strategically routing PEVs allows them to get charged with renewable power when and where needed[132]. The resulting price differences are reflected by the locational marginal prices that reflect the spatiotemporal supply–demand relationship in power markets[133]. For example, given that fuel is the major operating cost of PEVs for long heavy-duty freight transport[133], consuming cheaper renewables is economically convenient[134] and environmentally beneficial[135] for them.

Coordinating mobile PEV batteries with renewable generation is even more relevant for autonomous PEVs. For example, centrally operated passenger/driver-free freight transport has fewer time constraints and higher flexibility compared with vehicles with drivers[136,137].

Sustainable PEV integration

To achieve sustainable PEV integration in power systems, supporting infrastructure, technologies for modelling, operating and controlling power grids and batteries, environmental considerations and incentive mechanisms need to be assessed (Table 3). At stage 1, PEV charging is manually planned by the driver without much flexibility. At stage 2, smart PEV charging occurs by advanced remote operation and control technologies. As a result, PEV charging profiles can be optimized to reduce charging costs and generate revenue by providing local grid

Table 3 | Road map of sustainable PEV integration in power systems

Timeline		2010	2020	2025	2030	2035		2040
Stage of PEV integration		**Stage 1: planned charging**	**Stage 2: smart charging**		**Stage 3: V2G smart discharging**			**Stage 4: mobile storage**
		Charger level	**Charger/station level**	**Distribution level**	**Station level**	**Distribution level**	**Transmission level**	**Interconnected power and transport systems**
Description		Unmanaged or manually managed charging	Scheduled charging to reduce electricity costs	Scheduled charging to provide local grid services	Scheduled discharging to provide backup electricity	Scheduled discharging and reactive power control to provide local grid services	Aggregated PEV charging and discharging scheduling to provide bulk power grid services	Autonomous PEVs are spatiotemporally optimized and actively interact with both systems
Infrastructure	Charger	Manual on/off control	Remote on/off or continuous charging power control	Remote continuous charging power control	Remote continuous charging and discharging power control	Remote continuous charging, discharging and reactive power control	Remote continuous charging, discharging and reactive power control	Fully unmanned operation and control
	Information and communication	Local monitoring	Communication with station operator	Communication with station and distribution system operators	Communication with station operator	Communication with station and distribution system operators	Communication with station, distribution and transmission system operators	Communication between PEVs, power system operators and transport operators
Modelling, operation and control	PEV fleet size	Individual	Small	Medium	Small	Medium	Large	Extremely large
	Source of uncertainty	User behaviour	User behaviour, on-site renewable generation	User behaviour, grid operation status, market price	User behaviour, on-site renewable generation	User behaviour, grid operation status, market price	User behaviour, grid operation status, market price	User behaviour, grid operation status, transport operation status, market price
	Operation and control structure	Local	Centralized	Centralized or decentralized	Centralized	Centralized or decentralized	Hierarchical	Hierarchical
Incentive mechanism		Time-of-use electricity price	Time-of-use electricity price, peak-load price	Distribution electricity market, distribution grid service market	Discharge electricity price	Distribution electricity market, distribution grid service market	Bulk electricity market, ancillary service market	Integrated pricing of charging/discharging and mobility services

PEV, plug-in electric vehicle; V2G, vehicle to grid.

services. At stage 3, PEVs can discharge to the power grid, allowing higher flexibility to interact with the power grid. At stage 4, when PEVs and charging infrastructures are fully autonomous, they will function as mobile storage systems to provide spatiotemporal flexibility to power grids.

Supporting infrastructures

Supporting infrastructures including charging, information and communication systems are required for sustainable PEV integration.

Charging infrastructure. Planning PEV charging infrastructures initially focused on satisfying customers' charging demands[65], alleviating PEV charging's adverse impacts on power grids[68] or promoting renewable generation integration[72]. PEV chargers are designed to be used for typically 15–20 years. However, how PEVs interact with the grids, particularly V2G, is often neglected, mostly because the business model of smart PEV charging and discharging is not yet mature. Therefore, most of the chargers currently being installed do not support V2G or even smart charging. Understanding how charging infrastructure can be designed and planned not only to satisfy charging demands but also to maximize the future grid interaction capability of PEVs is thereby essential[138].

Information and communication infrastructures. Information and communication infrastructures are crucial for synergistic and sustainable PEV integration[139]. To promote PEV coordination with renewables, sufficient sensors should be installed to monitor the real-time status of PEVs, chargers, renewable generation and grids[140]. For example, to realize high-frequency PEV controlling for regulation services, the frequency of information collection and communication needs to be in the order of seconds. This data transmission causes extra power loads on communication systems which are often isolated from the public ones[140,141]. Therefore, it is indispensable to design low-cost and efficient information and communication infrastructure. Moreover, the large-scale integration of PEVs might also threaten the cyber-physical security of power systems[142]. This requires the information and communication infrastructure to have strong cyber resilience.

Modelling, operation and control

Modelling of PEVs. Actively discharging electricity to the power grid will accelerate battery degradation and lower the economic benefits of a V2G programme. Therefore, it is necessary to quantify battery degradation for different V2G systems[143]. User behaviours, such as plug-in and plug-out times, determine PEV charging and discharging flexibility. However, these behaviours are highly stochastic and difficult to predict. An advanced forecasting method is therefore required to accurately predict PEV user behaviours for smart PEV charging and discharging. Data-driven artificial intelligence (AI) algorithms are popular approaches to forecast PEV user behaviours (Box 1).

For grid integration, a PEV aggregator might need to represent thousands of PEVs to bid in power markets. Therefore, given that every PEV's detailed constraints are computationally expensive, developing aggregate models of large-scale PEVs is indispensable[144]. Such a model would describe a fleet of PEV behaviours as a whole with simplified aggregate parameters (such as their overall power and energy boundaries) instead of heterogeneous parameters of individual PEVs to reduce model complexity and improve computational efficiency. However, this simplification might limit accuracy and result in operation and control errors. How to balance modelling efficiency and accuracy for large-scale PEVs needs further in-depth research.

Operation and control. Operating and controlling large-scale PEVs to provide grid services or promote renewable generation are difficult. First, an operator must simultaneously coordinate tens to thousands of small-capacity and heterogeneous PEVs and respond to power systems' control signals efficiently. Such computational complexity would be intolerable with a centralized algorithm. Decentralized or distributed algorithms are commonly used, in which the operation or control decisions are not made at the operator level but at the charging station or PEV level based on information shared between the operator and PEVs[145]. These algorithms can considerably reduce the computational burden, but often result in a heavy communication burden and might not achieve optimal solution when the fleet size is too large. A compromise is to adopt a hierarchical framework[146], which is half-centralized and half-decentralized, to balance between computational and communication overloads. Moreover, the operation and control of PEVs

Box 1

Application of AI in modelling, operating and controlling PEVs in power systems

The application of artificial intelligence (AI) technologies for the integration of plug-in electric vehicles (PEVs) into power systems is a hot research area. These AI methods can be divided into three major categories, that is, unsupervised learning, supervised learning and reinforcement learning.

Unsupervised and supervised learning acquire knowledge by leveraging historical data. The difference is that the former works with unlabelled data, as opposed to the latter. With the growing use of PEVs and their supporting information and communications systems, vast amounts of data are collected daily. Data-driven AI methods can use these data to help with integrating PEVs into power systems. Unsupervised learning (such as the *k*-means algorithm) is often used for the pre-processing of PEV charging data. For example, by adopting an unsupervised clustering algorithm, PEV driving and charging profiles can be grouped based on their similarity, which can help in understanding PEV usage patterns[159]. Unsupervised learning could also be used to plan PEV charging systems. By clustering PEV charging demands based on their locations, a planner algorithm can strategically locate their charging systems to satisfy these demands[160,161].

Based on historical data on PEV charging loads, supervised learning can be used to train a neural network model to predict future charging loads[162,163]. This prediction is important for 'ahead-of-time' operation of PEVs, such as bidding in power markets. Supervised learning can also be applied for real-time operation or control decision-making. For example, a system operator can first collect historical PEV charging station operation data under different power grid conditions (such as electricity price, charging demand and local renewable generation). These data can then be used to train a supervised learning model (for example, a neural network) to predict suitable operation decisions under new conditions based on the past experiences[164]. However, historical operation decisions data may be unavailable or of suboptimal quality. To overcome this issue, a PEV charging system operator can first build a model-based operation strategy to generate optimal operation data under different conditions, and then use these generated data to train an AI model[165].

Reinforcement learning does not rely on historical data; instead, it trains an agent by interacting with the environment through a 'trial and error' process. During the training, if the agent makes a good decision, which contributes positively to the operation objective (for example, reducing electricity consumption costs), it gets rewarded; otherwise, it is penalized. After taking sufficient iterations, the agent learns how to make good decisions even in new situations. Moreover, as the agent is continuously trained online, it can adapt to a changing environment. Various reinforcement learning algorithms have been used to solve the operation and control problems of PEVs in power systems[151]. For example, a constrained reinforcement learning algorithm[166] and a soft actor-critic deep reinforcement learning algorithm[167] have been used to schedule PEV charging power in distribution systems to respond to time-varying electricity prices while including uncertain PEV parking and charging behaviours. Reinforcement learning has also been applied to solve complex decision-making challenges for coupling power and transport system. Similarly, a multi-agent deep reinforcement learning algorithm has been developed to study PEV charging stations' pricing strategies for autonomous mobility on-demand systems in cities[168].

are exposed to inevitable uncertainties, including user behaviours, renewable generation and market prices[147]. These uncertainties are commonly addressed by stochastic programming, robust optimization, chance-constrained programming[148] and model predictive control[149]. However, these methods often require large historical samples for uncertainty modelling, which may be unavailable, or have limitations in over-conservativeness (for instance, underestimating PEV regulation capacity). Finally, PEV operation and control face demands and constraints from both the power grid and the transport network[150].

Notably, data-driven AI algorithms have shown great promise for overcoming the limitations of existing operation and control models (Box 1).

Incentive mechanism

Multiple stakeholders are involved in PEV integration, such as automobile companies, users, charging service providers and power grids. Effective incentive mechanisms will therefore need to address the interests of all stakeholders.

Business models. PEVs are already integrated into the power market, such as time-of-use electricity prices, energy and ancillary service markets, in which PEVs can make revenue by smart charging and discharging. However, only smart charging has been applied so far whereas discharging is still a proof of concept[151]. Because active discharging may lead to battery degradation, cost and user compensation are hard to evaluate[152]. Furthermore, this active discharging might also influence vehicle warranty. Currently, V2G is only occasionally used, for example, during camping when there is no access to the power grid, by most customers in the current markets. In contrast, when PEVs are used intensively to provide power grid services in the future, the amount of battery degradation will be comparable with driving, which might raise battery warranty concerns. To fully leverage PEV potential, a business model which can solve this issue is urgently required. One solution could be warranting battery charging cycles instead of driving mileages[153], which would better reflect V2G usage.

New power markets. Existing power markets are mostly designed at the transmission level for traditional power consumers and generators. Policymakers need to redesign current power markets to encourage new players such as PEV aggregators or VPPs. These new power markets should allow PEV-like distributed small-capacity resources from different locations to jointly bid in them. Furthermore, power markets at the distribution level also need to be designed; these new distributed markets should provide a lucrative environment for PEVs to provide distribution grid services and accommodate nearby renewable generation[154].

Power and transport coordination. Traditionally, the power and transport sectors have always operated independently, a status which has now changed with the emergence of PEVs. Failing to coordinate between these two sectors might lead to energy inefficiencies, higher carbon emissions and malfunctions. For example, in Shenzhen on 19 May 2018, a scheduled power outage forced up to 2,700 taxis (10% of the total) out of service because they could not be charged on time[155]. Furthermore, it is essential to appropriately price PEV charging services. Prices should not only encapsulate the electricity supply costs but also account for traffic congestion costs. This pricing approach can bolster the integration of renewable generation, modulate traffic flow and augment transportation efficiency[156].

Outlook

In the future, anticipated advancements in battery technology include reduced costs, augmented energy densities, accelerated charging rates, extended durability and enhanced safety. An increase in energy density allows a PEV to achieve equivalent range with a more compact and lightweight battery, thereby optimizing space utilization and augmenting fuel efficiency. Should a PEV reduce its charging duration for reaching 80% capacity from the present standard of approximately 30 min to a mere 10 min or less, its charging experience could parallel the refuelling time frames of traditional vehicles. There are two main future research directions. One is to design new types of batteries. For example, since 2020, solid-state batteries have attracted interest owing to their superior energy density, charging rate and safety when compared with Li-ion batteries. The other direction is to further exploit the potential of existing batteries with more advanced battery management. For example, techniques such as data-driven predictive operations and maintenance — which combine battery health estimation, fault diagnosis and safety alerts — are expected to markedly improve the durability and safety of battery systems.

A well-designed charging infrastructure is the key to alleviating range anxiety and promoting adoption of PEVs. The future planners should take the objectives and constraints of both the transport and power sectors into consideration when designing the infrastructure. Apart from passively satisfying the charging demands of PEVs, a more forward-looking infrastructure plan that supports the upcoming PEV integration paradigms, such as smart charging and even discharging, is needed. Different charging options are suitable for different application scenarios, and they complement each other. Future infrastructure planning should also address this complementarity. In addition, an affordable, efficient, reliable and secure information and communication infrastructure is essential to support the large-scale integration of PEVs. This requires systematic innovations in data collection, perception and communication.

With adequate operation and control, smart PEV charging and discharging power can increase the operational flexibility of the power grid and synergize with renewable generation to promote the decarbonization of the interconnected power and transport system. However, it is still a challenge to effectively model, operate and control large-scale, small-capacity and heterogeneous PEVs. Uncertainty is one of the crucial problems. Compared with stationary energy storage systems, the combined power and energy capacity of a fleet of PEVs fluctuates and is uncertain due to the variable driving and charging behaviours. Another substantial challenge lies in scalability. For system operators managing thousands of PEVs, executing optimal operational decisions and meticulously controlling each vehicle's power become arduous. As the global adoption of PEVs grows, there will be a surge in real-world data related to their driving and charging patterns. Merging conventional physical model-based modelling, operation and control approaches with cutting-edge AI-assisted data-driven technologies offers a promising avenue for future research.

Moreover, innovative financial incentives are required. Currently, no mature business model or market mechanism exists that maximizes the flexibility of PEVs while also effectively coordinating the interests of various stakeholders. This challenge calls for joint innovations involving power system operators, charging service providers and automobile manufacturers. As the costs of grid-scale energy storage systems continue to decline, the comparative advantage of V2G may diminish. After all, leveraging numerous small-capacity PEVs demands more efforts than utilizing a singular, large grid-scale storage. Hence, how to economically utilize the V2G capacity of each individual PEV for providing power grid services remains a pivotal question. However, despite these considerations, V2G holds promise in bolstering the resilience of power systems, especially in scenarios where cost is not the primary concern.

Autonomous driving is a disruptive technology set to revolutionize the landscape of PEV grid integration. Acting as driverless mobile storage systems, autonomous PEVs will possess capabilities to interact with the power grid and promote system decarbonization. For instance, an autonomous PEV fleet can be dispatched to locations with abundant renewables to harness zero-emissions electricity or to regions experiencing power outages, offering emergency power supply without disturbing any driver or passenger. Yet, relevant studies are still nascent and necessitate sustained interdisciplinary collaboration.

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