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Interoperability of the Electric Vehicle Charging Ecosystem

Ravi T. Vedula, PhD

ABSTRACT

Reduced pricing, range extension, quiet and luxurious ride experience, sleek designs, and most importantly 'zero emission' are some of the promotional features electric vehicle (EV) sellers use to entice potential buyers. But one thing these sellers cannot yet convince the shoppers is about the EV charging access and convenience. As the EV market share continues to grow, a common goal of all the regulatory entities, it is critical to understand the status of the charging infrastructure. This article depicts the latest status of EV charging infrastructure as of the year 2023–2024 and the potential needs for expanding the same using data-driven calculations and various global targets set for 2030 and beyond. It takes a fresh look at the reality of the existing charging stations and identifies the key areas of improvement to address common EV user concerns. Using a holistic approach of well-to-wheels investigation, the potential improvements discussed here benefit a range of stakeholders within the e-mobility ecosystem, rather than concentrating on just the charging station. With the intent of making the discussion more resourceful for both investors and technologists, data is presented using various public sector sources apart from the overviews on advanced technology concepts that can enhance e-mobility adoption.

Keywords: EV, Charging infrastructure, Well-to-wheels, Vehicle-to-grid, Renewable, Consumer concerns

Introduction

Electromobility (abbreviated as e-mobility) in the passenger car segment keeps persistently growing at a rapid pace. A recent report from the International Energy Agency reveals that electric vehicle (EV) sales accounted for 18% of global car sales in 2023.¹ This represents a striking ninefold increase in the EV sales' share within the previous 5 years. The EV in the context of this article represents a combined population of both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). The data also shows that the EV sales are predominant with BEVs compared to PHEVs. China, Europe, and the US account for nearly 95% of the global EV sales combined. As shown in Figure 1, China leads the race, with EV sales' share reaching nearly 40% of the new car sales and nearly 60% of the global sales.¹ Among these EVs, larger vehicles (larger cars, sports utility vehicles or SUVs, and pickup trucks) constitute two-thirds of the sales' stock. The extra comfort and advanced passenger safety, especially for the younger ones, offered by SUVs make them the primary choice for potential buyers, nuclear families, or new parents. Overall, such an impressive uptake on EV adoption can be attributed

to numerous factors ranging from climate change to financial incentives, geopolitical conflicts to e-motor's instant torque, and original equipment manufacturer (OEM) announcements on conventional vehicle bans. BEVs carry a typical battery capacity of 40 kWh, with larger EVs carrying above 100 kWh batteries. PHEVs are equipped with smaller batteries of about 10 kWh capacity.

Depending on the power output, an EV charger can be categorized into a Level 1, a Level 2, or a direct current fast charger (DCFC).² DCFC is referred to as Level 3 in some places. Level 1 is the slowest charger which can recharge a BEV from empty in 40–50 hrs. These chargers are installed via the common residential alternating current (AC) outlets. Level 2 can recharge a BEV from empty at a 10× faster rate compared to Level 1. These can be seen at the workplace, public charging, or home. The DCFC is the fastest charger which can recharge a BEV from empty to 80% state of charge at a 100× faster rate compared to Level 1 and at a 10× faster rate compared to Level 2. DCFCs are located along the highway corridors, shopping malls, and other public charging stations.

Depending on usage and accessibility, charging stations can be majorly classified into public charging and private charging stations. Public charging stations, as mentioned earlier, are equipped with Level 2 and fast chargers. Private charging stations may include Level 2 (e.g., workplace) but predominantly Level 1 (residential). At the end of 2023, there are over 0.63 million public charging points across the EU, whereas the cumulative stock of rechargeable battery cars in this region is over 10 million.^{3,4} Also, PHEVs account for an almost equal share as the BEV with a cumulative stock of about 10 million.⁵ Using this data, we find that there is one public charging point for every 16 BEVs in the EU. In retrospect, there are over 111000 petrol stations located across the EU, while the passenger car market in this region exceeds 255 million vehicles.^{4,6} Assuming an average of four fuel pumps per petrol station and with the EV segment excluded, there is roughly one fuel pump for every 530 non-EV cars in the EU. This number is arrived at using the following division for the internal combustion engine vehicle (ICEV) population:

$$\frac{[255 \text{ million} - 10 \text{ million EVs} - 10 \text{ million PHEVs}]}{[4 \text{ pumps} \times 111000 \text{ fuel stations}]}$$

Therefore, the likelihood of finding a vacant 'refuelling' spot for a BEV is approximately 35 times (530 non-EVs/16 EVs) greater than that for a non-EV. It should be noted that this ratio of 35:1 is derived assuming that all 255 million passenger cars consist

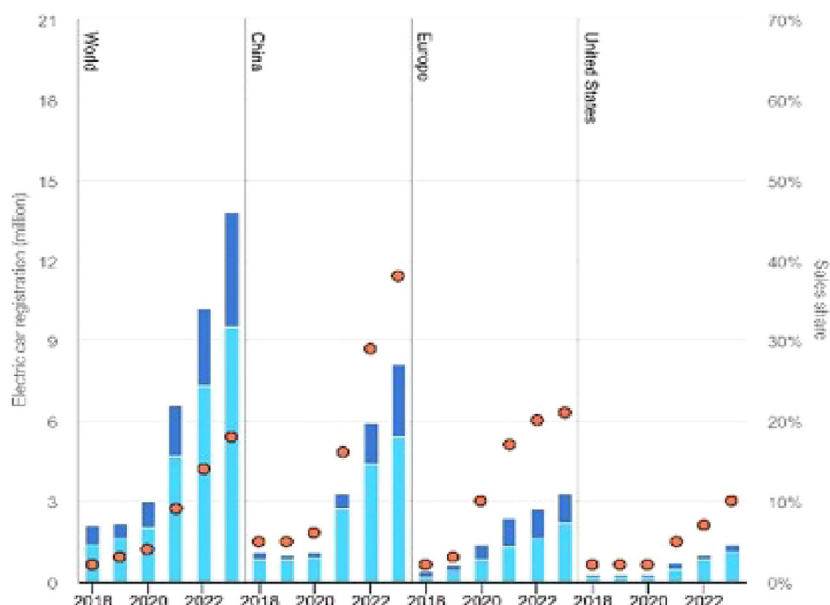


Fig 1 | Electric vehicle sales – Global and the major markets.¹ [Light blue: BEVs, Dark blue: PHEVs, Orange bubbles: EV sales percent of total sales in specified regions]

of petrol engine cars, PHEVs, and BEVs. This may not be accurate as there are some countries in the EU-27 which are predominant with diesel or liquified petroleum gas (LPG)-powered cars apart from petrol.

Nevertheless, petrol engine cars are the key market players in the EU. Also, petrol, diesel, and LPG usually share the same fuel station. Therefore, these assumptions are believed to be satisfactory, and the resulting disparity in the EV infrastructure compared to petrol stations can be considered for further discussion. This disparity brings us to an expected question: *Aren't the existing charging points enough to meet the needs of the current EV population?* Though this analysis is conducted using data from the EU, it can be applied to many other global markets where the non-EVs remain to be the market leaders in the passenger car segment. Hence, the question raised here can be applicable to other global markets as well.

Let us put together some factors to address the above-mentioned question. A Level 2 charger and a fast charger take 4 and 0.4 hrs, respectively, to charge a BEV. In retrospect, we can fill the petrol tank of a car in under 3 minutes (0.04 hrs) at a petrol station. Therefore, the ideal number of cars a petrol pump can serve daily is 600 ($=24 \text{ hrs}/0.04 \text{ hrs}$), whereas the number of BEVs a public charging point can serve daily is 6–60 depending on the charger type. These revised calculations made on a per-day basis clear out the ambiguity and shed light on the reality of EV charging stations.

The previous comparison between the EV and non-EV infrastructures can now be restated as follows: The likelihood of finding a vacant 'refuelling' spot for an EV in a day is 0.35–3.5 times greater than for a non-EV. In the case of the EU and the US, Level 3 fast chargers account for only 20%–30% of the public charging points.¹ This implies that the Level 2 chargers are in the majority, and Level 2 charges slower than

Level 3. Hence, finding a vacant 'refuelling' spot for a BEV in a day is 0.35 times greater or nearly 3 times less than for a non-EV. Compounding this issue, there are constant complaints from the EV owners about poor connectivity, non-functional charging points, freezing screens, payment issues, and short cables that make the corresponding charging points ineffective.⁷ Another white paper on Electrification 2030 identifies the two most common reasons for EV charging inaccessibility in America to be (a) poor connectivity of the charging station with the network and (b) the charging point faults/out-of-order signs.^{7,8} Similar woes on inefficiency and deficiency in the charging infrastructure as well as range anxiety were expressed by other consumer markets as well.^{9–11} Furthermore, social behaviour such as hogging or ICEing can create usage barriers to some extent.^{12–14} Figure 2 depicts the current situation faced by EV users to recharge their vehicles at a public station.

EV users are expected to rely more on public chargers in the coming years. In today's demographics, people tend to limit their EV usage for city driving whereas take out their ICEVs for long-distance trips. However, with the uptake of both EV sales and the charging infrastructure, this behaviour is expected to change. People may opt for public charging stations for their long-distance trips and even for daily commute as these stations will become the Level 3 fast charging hubs offering relatively quick 'check in-and-check out' type of charging activity. Therefore, public charging interoperability and seamless integration of the EV charging station with the vehicles (of different types, sizes, and on-board power inlets or sockets) and the grid are key to enabling the adoption of EVs as a mainstream passenger mobility. To achieve this goal, a joint strategy with innovative and well-defined protocols is essential among several stakeholders and shall ideally be overseen by the regulatory entities. The major stakeholders from the supply side in the e-mobility ecosystem are the (i) vehicle OEMs, (ii) electricity power plants, (iii) electricity grid operators, (iv) charge point operators connecting the charging sites to the grid network, and (v) e-mobility service providers. Vehicle OEMs are responsible for charger connector types and communication software, apart from producing the vehicle equipped with extended range battery management system and grid-compatible hardware. Charge point operators and e-mobility service providers directly interact with the EV users via station locator apps, payment transactions, and memberships. Charging infrastructure topics discussed in the current study include all these stakeholders.

An EV can be accurately labelled as a 'net zero-emission' vehicle after auditing all the emissions incurred along the transfer path of the electricity. This path is similar to the fossil fuel path which is commonly referred to in the literature as 'well to wheels' or 'well to tank and tank to wheels'.¹⁵ Figure 3 displays the complete transfer path from well to wheels. It includes a complicated network of power plants, transmission and distribution power lines, power substations, and

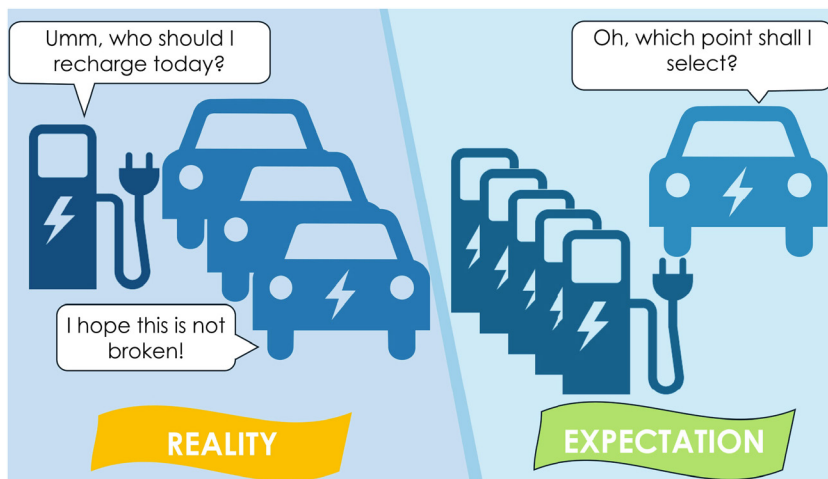


Fig 2 | A clipart depicting the reality on insufficient charging points and the EV user's anxiety

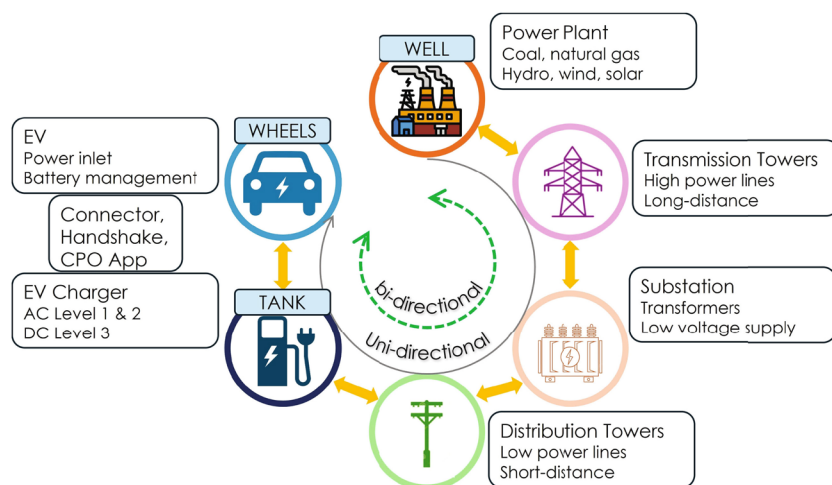


Fig 3 | E-mobility ecosystem from well to wheels

eventually the end users, such as residential buildings, workplaces, and EV charging stations. Nodes (circle) and links (arrow) of this transfer path represent each of the key stakeholders in the e-mobility ecosystem. Also, the electric grid is described as the combination of all nodes and links starting from the well to the tank (excluded). There are two types of grid operations: uni-directional charging where the electricity flows from the power plant to the EV and bi-directional where the electricity can also return from the EV to the power plant via the original transfer path in reverse direction.

This article presents a holistic approach of

- sharing the global status of EV charging infrastructure for the described transfer path.
- extracting data from official sources to identify the most authentic and updated information available on the selected topics.
- discussing various studies conducted on vehicle-to-grid (V2G), smart charging, wireless charging, charging payments, and connectors to achieve high market penetration of EVs.

- identifying synergistic solutions that are important to the supply side, EV users, and regulatory targets.

The remainder of the paper is organized as follows. The section 'Governance In-Charge' gives an overview of the global targets set for the expansion of the EV charging infrastructure. The section 'Charging E-volution' presents a detailed status of global power plants and the evolutions needed in the charging stations and shares the customer concerns on the charging infrastructure. The section 'Consumer's Voice and Choice' outlines the cost-effectiveness of EVs with existing incentive policies and introduces a set of vehicle cost calculators (VCCs) aiming to improve the awareness on ownership costs and range sufficiency.

The section 'Outlook' provides an ensemble data-driven perspective on improving the productivity of existing and new infrastructures in different dimensions. In addition, a brief overview on EV charging cost and potential acceptance factors is discussed. The section 'Concluding Remarks' includes concluding remarks.

Governance In-Charge

The sales growth of EVs along with the issues described on deficiency and inefficiency of current charging points exacerbates the immediate need for more fully functional charging stations. To this effect, various regulators are proactively implementing definitive actions to reach extremely ambitious goals. Until recently, purchasing incentives and subsidies were offered for the EV. Now, the strategy has shifted to investing these funds in the expansion and support of the electric vehicle supply equipment (EVSE). The EV infrastructure plans of various market players as set by their regulatory agencies are tabulated in Table 1.

Notably, a sheer increase in the number of charging points by duplicating existing designs will not likely solve the problem. The issues described so far on the current charging infrastructure are directly applicable to future additions as well if the existing problems are not addressed in tandem. A combination of charging points' expansion as well as sustainable and smart approaches is a more productive strategy to address these issues. This is precisely what all regulators are collaborating with various technology stakeholders and the EV users as well in the case of residential charging. China has been working on pilot demonstrations of sustainable charging behaviour, with the aim that 80% of EV private charging occurs off-peak by 2025.²⁵ According to the UK's regulation on smart charging points, all new private charging points shall include smart functionality, electricity supplier interoperability, uninterrupted connection to network, smart meters, and cyber security.²⁶ Norway and the EU separately announced the 'right to charge' in multi-dwelling residential constructions wherein the parking spaces shall incorporate private/shareable charging sites for residents/owners.^{27,28} India's Model Building Bye-Laws also mandate that a residential

Table 1 | Electric Vehicle Charging Infrastructure Targets of Global Markets

Region	Current Status	EVSE Projects
China ^{1,16}	2.2 million (stations)	To build stations sufficient for 20 million EVs by 2025
EU ^{3,17}	0.6+ million (chargers)	3.5 million public chargers by 2030 At least one public charger every 60 km along the Trans-European Transport Network
United States ¹	180000+ (chargers)	500000 public chargers by 2030
UK ¹	53600+ (chargers)	300000 public chargers by 2030
Canada ^{1,18}	27000+ (chargers)	33500 public chargers by 2026
New Zealand ^{1,19,20}	1200+ (chargers)	10000 public chargers by 2030 One charging station every 150–200 km on main highways At least 600 charging stations in rural areas by 2028
India ^{21–23}	12000+ (stations)	46000+ public charging stations At least one charging station within a 3 km × 3 km grid. One charging station at every 25 km on both sides of highways
Norway ²⁴	22000+ (chargers)	No clear information was available on public charger targets. The country, however, targets to transform to all zero-emission vehicles from 2025 and beyond

building shall have a provision for at least one Level 1 charger. Commercial buildings shall include at least one Level 1 charger and a Level 3 fast charger.²² These initiatives on the private charging expansion and support are expected to increase the consumer's confidence on buying an EV.

Charging E-Volution Well RE-volution

An EV can be accurately labelled as a 'net zero-emission' vehicle after accounting for all emissions along the transfer path of the electricity from well to wheels. The electricity power plant represents the 'well' in the electricity transfer path. Power generation is a critical source of greenhouse gas emissions (GHGs) in the e-mobility ecosystem.²⁹ Generating power with fossil fuels releases GHGs that can trap sun's heat, causing undesired hot weathers.³⁰ Renewable energy (RE) sources tagged with zero emissions can address this issue if the consequences such as supply irregularities and high fluctuations in the grid are controlled. The progress and practical implications of RE have been discussed extensively in the literature.^{31–33} The National Renewable Energy Laboratory (NREL) analysed the impact of BEV and PHEV charging on electricity power plant emissions. A model was employed to simulate different charging scenarios based on hourly grid profiles, range of carbon intensities emitted during electricity production, regular/off-peak charging hours, and charger types (Level 1 and Level 2). It was interesting to note that a BEV charged during off-peak hours from a high-carbon electricity grid showed almost zero emission reduction benefits compared to an ICEV. In contrast, a BEV charged at a workplace (unrestricted start time) from a low carbon grid showed the greatest emission reduction benefits.³⁴ This study highlights the necessity to build low-carbon intensity grids in parallel to the charging infrastructure expansions to achieve the global decarbonization targets.

Data show that electricity is far from being generated entirely by low carbon or clean energy. The

US produced 60% of their annual electricity using fossil fuels in 2023.³⁵ RE source made up 21%. In the EU, about 39% of the electricity was generated using fossil fuels.³⁶ About one-third of the EU member states, however, generated more than 50% of their electricity using fossil fuels. Fossil fuels in this context include gas, coal, oil, and others. Surprisingly, wind and hydro-based fuel types were the leading RE sources and solar type took the third place in the list.

Luxembourg is the leading driver of green energy, with renewables sharing a whopping 93% of electricity supply, followed by Denmark with close to 80%.³⁶ Norway generated 98.5% of its electricity primarily with its hydro RE resource.³⁷ In the UK, nearly half of the electricity was produced using RE sources, whereas fossil fuels accounted for a record low of ≈37% in 2023.³⁸ China's fuel share of the electric supply in 2023 was slightly less than 60% of coal. Notably, this is the first time China has produced electricity with less than 60% of coal.³⁹ On the flip side, China holds more than two-thirds of the world's new coal-fired power plants with further additions each year.⁴⁰ While the new coal-fired plants are environmentally better replacements to the retirements, it is not a RE source and burning coal continues to release GHGs. Figure 4 shows the status of high-carbon fossil fuel usage for energy generation in various developed and developing economies. India, with a boom in solar panel installations in residential and commercial places, showed higher solar energy share than those from hydro and wind. The net share of fossil fuels is comparable to the US and China.⁴¹ We can see that some of the leading market players in the EV sales are still dependent on high-carbon fossil fuels to generate more than 50% of their net electricity annually. Europe, however, demonstrated an impactful transformation in the energy sector, with fossil fuels making up <50% of the annual electricity and RE powering up the continent.⁴² It should be noted that data in Figure 4 includes only percentages related to electricity generation. Additional electricity imports

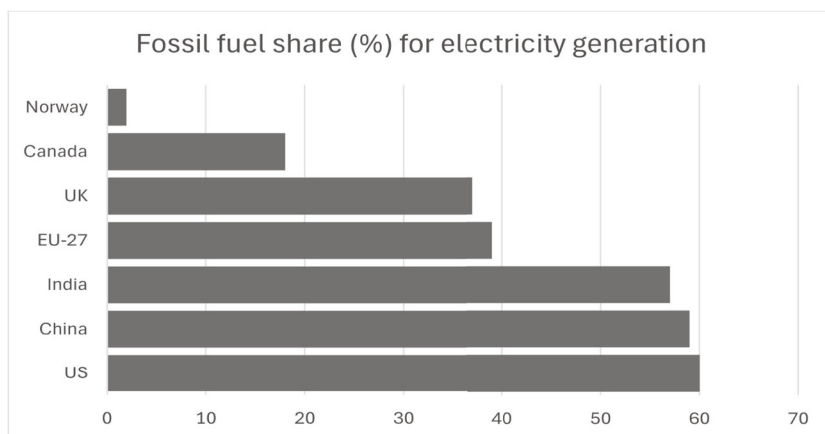


Fig 4 | Percentage of electricity generated using high-carbon intensity fuels

that some countries receive to meet their energy demands are not included.

Tank E-volution

This is the heart of e-mobility as it interacts with both the transfer paths having 'well' on the one end and the 'wheels' on the other end. The proper framework of this segment of the EV charging ecosystem plays a pivotal role in the enhancement of the charging infrastructure, convenience to the EV users, and a rapid adoption of e-mobility. Similar to the multiverse functionalities of a human heart, the 'tank' segment consists of various functionalities and multidisciplinary groups. These groups adopt different technologies such as the vehicle-to-charger (V2G), smart charging, dynamic pricing aggregators/bidders, wireless charging, vehicle-to-charger (charge point operators and e-mobility service providers), and charging station locators.

V2G and Smart Charging

V2G technology can offer several potential ancillary services, such as frequency and voltage regulation, peak shaving, load levelling, spinning reserve, congestion mitigation, RE storage, and reduction of intermittence and curtailment.⁴³ In the V2G interface, the EV can discharge power back to the grid using a 'bi-directional' charger type. This charger type allows the EV to get charged from the charging station and give back to the grid when not in use or for peak shaving. A bi-directional charger, however, is attributed to lower battery life, higher cost, and a complex installation process with an intertwined communication setup. Additionally, unmanaged charging increases peak loads, thereby causing higher power losses, instabilities, and even the transformer degradation due to sudden overloads and overheating.⁴⁴

Incorporating smart charging features into the V2G can counter such issues. Smart charging can be advantageous to both grid operators (to control power fluctuations and protect electrical devices) and the EV users. A smart charger can control the start time of charging and the charging rate, thereby extracting

more renewable-sourced power, say, during day times with solar power or avoiding/moderating peak times' usage. EV users can benefit from reduced charging costs in a dynamic pricing landscape.⁴⁴⁻⁴⁶ Smart meters are believed to put an end to incorrect bills, and back billing, which are currently a significant concern for consumers.⁴⁷ EV aggregator is an approach to smartly integrate the EV population into the grid.⁴⁸ In this business model, the EV aggregator uses smart meters to collect information of EV usage such as how much and at what times is the charging demanded. In addition, the aggregator also carries information of the electricity price and charging stations' locations. EV owners can select their preferred aggregator among the many aggregators available in the market. The aggregator for their EV client predicts the charging power demand for the next day and builds a buy/sell scenario with the grid operators. The grid operators assess the proposed price for the predicted demand and proceed accordingly. This is a business opportunity in the electricity market wherein the EV's storage capacity and its ability to discharge to the grid determine the market progress. Smart charging has also proved to be effective in reducing peak loads in several case studies.⁴⁹⁻⁵²

A persistent concern with using RE for grid supply is the irregularities inherent in their sources, e.g., the popular 'duck-curve' trend observed in a day.⁵³ Such irregularities can be controlled using smart charging applications, such as load scheduling and augmented power discharged from the stationed vehicle to the grid.⁵⁴ Smart grid or smart charging in the eyes of an end user might have a different perspective depending on the working patterns, financial resources, and access to charging stations.⁵⁵⁻⁵⁷ While this is a complicated subject, incorporating the EV user's perspectives in the smart charging strategies is a key enabler for high EV penetration. For instance, a residential charger is prone to remain plugged in even after charging completion during overnight schedule.⁵⁸ Restricting charging to off-peak hours may result in higher 'well' emissions, a result that seems counterintuitive to some of the smart charging methods. The key here is the type of energy source used for power generation. If the grid utilizes a high-carbon (fossil) fuel during off-peak hours, then restricted charging schedules would result in high emissions, same as during peak times.³⁰ Understanding the charging behaviours of regional EV users from extensive data collection on vehicle type, charging requirements, and usage surveys can lead to a successful smart-enabled V2G framework. Participation of administrative groups in these campaign initiatives alleviates user anxiety expressed on data privacy and security.

Wireless Charging

Wireless or inductive charging is an EV charging mechanism where the vehicle is charged by installing an induction coil on the ground. Charging happens via the electromagnetic induction principle wherein the electrical current is transmitted from the charger to the coil and from the coil to the on-board battery system.

Wireless charging system requirements are delegated in several technical standards.⁵⁹ The SAE J2954 is one of the early publications setting stage for both ground assembly and the vehicle assembly requirements of wireless charging.⁶⁰ A magnetic resonance field is created between the transmitting pad on the ground (wired to the grid) and the receiving pad fitted on the underside of the vehicle. This resonance field crosses the air gap present between the two pads, thereby converting AC power into DC power to charge the vehicle batteries. System interoperability was tested and proven using different ground clearances, power levels, vehicle parking positions, as well as different manufacturers of the ground/vehicle pad assemblies.

Wireless charging overcomes the common concerns on incompatible connectors, short/torn cables, and 'handshake' communications issues expressed by the EV users while using a charging point.⁶¹⁻⁶⁴ As with any novel technology, wireless charging also entails certain challenges. The high voltage and current levels included in the wireless charging can potentially cause electrical shock if not handled with care or due to ageing. Such high-power installations at the residential places can create a safety hazard tension among the residents and the community landlords. Cold weather conditions can worsen the situation due to limited vision and accessibility. To address this issue, the SAE J2954 taskforce decided to implement the differential inductive positioning system (DIPS) alignment method to properly position the vehicle underneath the ground assembly.^{65,66} DIPS makes use of an automatic positioning approach wherein the magnetic field generated at the ground assembly is detected by the vehicle assembly on-board.

Depending on the field strength changes, steering and braking instructions are given to the vehicle to reach the spot and start charging. This alignment method was tested under cold and debris presence conditions and is believed to uptake both EV and self-driving cars.

Charger Payment and Accessibility

Perhaps, one of the most common concerns expressed by public fast charge users is the payment acceptance failure and troublesome payment gateway at a charging station. This is ironical because in this situation, the customer is willing to spend more for a hassle-free transaction, but the seller does not offer one. Payments at a charging station can be made in the form of credit card, radio frequency identification (RFID), dedicated mobile apps, plug and charge, or through a toll-free number.⁶⁷ RFID is a charging network membership card with its unique identifier shared with the EVSE. The RFID mode of payment includes contactless scanning of the card at an RFID reader which then reads the account details and bills the amount contingent up on the availability of funds. Paying through apps can be done through a subscription which further offers two options: get a discounted price per kWh with a monthly fee or a higher price on a pay-per-use basis without a monthly fee. These apps would in turn allow

us to make payments using cards or net banking (similar to Google Pay, Apple Pay, etc.). Mobile app-based payments are more prone to failures due to mobile connectivity issues. A study on 'payment anxiety' revealed that 61% of the users surveyed left the charging points due to unacceptable payment options.⁶⁸ As all the contactless modes of payments heavily rely on network connectivity, focusing/fixing this issue will automatically solve all the corresponding problems. The charging station should ensure to have strong network connectivity.

Several issues with network connectivity have been identified, and potential solutions have been recently shared by the NREL and the Idaho National Laboratory.⁶⁷ Placement of an external antenna, using redundant SIM card, enabling wired connection to the router with an Ethernet cable, and providing Wi-Fi hotspots to customers are some of the measures recommended for charging stations, especially for new stations.

Artificial intelligence (AI) can be a powerful tool to optimize the location of charging stations. The locations predicted by such algorithms shall be favourable to robust cellular network area, reduced range anxiety of the EV user, and minimize infrastructure cost and are situated near renewable-energized grids. There are several case studies which deployed AI algorithms to identify the most suitable location in the selected region. A random embedding Bayesian optimization was applied in the metropolitan area of Atlanta to identify the optimal location and capacity of a multi-type (Level 2 and Level 3 public chargers) charging infrastructure.⁶⁹ This agent-based charging station placement model incorporated stochastic charging demand simulations and identified the optimal location with just 2% of the runtime compared to benchmark models. A cost minimization model combined with a demand coefficient using a genetic algorithm was used to determine the optimal (spatial) distribution of charging stations across five transportation hubs of Ireland.⁷⁰ The concentration of charging stations was high in those regions with large urban scale, large population, convenient transportation, and developed economy.

Addition of more EVSE systems in the grid can create network losses and voltage fluctuations. Such adverse effects were controlled using an arithmetic optimization algorithm which identified a suitable bus system.⁷¹ At such an early adoption, AI tools are showing promising results in solving one of the complex problems of decision-making on charging location, with more optimizations foreseen in the coming years.

Wheel Power

Wheel power remains a primary responsibility of the vehicle OEMs and their Tier-1 suppliers in the e-mobility ecosystem. Addressing some of the challenges improves the existing EV capabilities, which in turn affects the charging infrastructure locality and user satisfaction and minimizes capital costs. Among them, the charging connector universality, EV-to-CS

communication, and the repeated concern of limited battery capacity can be immediate flags to boost confidence in buying an EV.

On-Board Charging Inlet

Unlike the traditional fuel pumps at a fuel station, the EV chargers come with different charging systems, power levels, user interfaces, and even plug outlet designs.¹⁰ This latter issue of connector not matching with the plug is believed to have been addressed permanently in the US. There, the car makers made commitments to switch and implement the SAE J3400 (North American Charging System [NACS]) charging connector starting from 2025. This connector type was developed by Tesla and has been predominantly used in the Tesla models until now.⁷² In contrast, Tesla switched to a combined charging system (CCS) in its Model 3 and Model Y sold in the UK. The next-generation fast chargers in the UK are being deployed more with the CCS or the Japanese-based CHAdeMO connectors.⁷³ Likewise, the EU's alternative fuel infrastructure directive ensures interoperability of charging points with all EVs via mandatory installations of Type 2 inlets and CCS/Combo 2 connectors.⁷⁴

Communication Protocols

The charging station communicates with the EV using either a controller area network or a power-line communication (PLC) protocol. Since the latter protocol is also employed in power grid communication, PLC (vehicle) is easier to integrate into the grid, making it the preferred choice of communication protocol for EVs. Similar to charging connectors, global markets employ dedicated charging and communication standards to meet their regional requirements. Communication between the EV and the charger determines the longevity of the EV hardware components such as the battery, charger, and the connectors, apart from providing a smooth and efficient charging operation. IEC

61851-25 provides the earthing safety requirements of DC EV supply equipment and the communication requirements between the EVSE and the EV.⁷⁵ ISO 15118-20 provides communication requirements on secure authentication of the vehicle immediately after the charging cable is plugged into the socket.⁷⁶

Battery

Another critical design feature for car makers is to equip their vehicles with robust batteries. Range anxiety remains on the list of top concerns expressed by EV users and new car buyers.⁹ Literature shows that battery performance and thus range extension can be improved by optimizing the battery management system altogether instead of a specific hardware, such as batteries. Lithium-ion battery is expected to remain as the standard battery for EVs for now.^{77,78} Research is underway on finding alternatives that can achieve range extension or avoid other technical problems, such as thermal runaway or battery degradation due to uncontrolled temperatures.⁷⁹⁻⁸¹ Developing a technology takes time. With the immediate need to ramp up the EV ecosystem to remain proactive on the upcoming EV boom, it is important to find synergistic solutions rather than component-level improvements. Range extension can be achieved when several members of the e-mobility ecosystem collaborate on data-sharing, which is discussed later in this article.

Consumer's Voice and Choice

EV Acceptance Status

Wicki et al⁸² performed a meta-analysis on 94 studies to identify the determinants of EV acceptance in the automotive consumer market.⁸² The main determinant factors along with their acceptance criteria are listed in Table 2. The outcomes represent various areas of the EV ecosystem covering the vehicle design, the charging infrastructure, different costs, and the consumer's personal attitude. In line with most of the literature and

Table 2 | Determinants for EV Acceptance

Determinant Type	Factors	Acceptance Criteria
Vehicle specifications	Motor power Driving range Charging time Reliability	More power, more driving range, less charging time
EV ecosystem	Model variety, charging accessibility Environmental impact Policy and incentives	More varieties, very high charging accessibility, awareness campaigns with proven facts on EV eco-benefits, more policies (e.g., access to high occupancy lanes, parking spaces, and unrestricted license plates)
Cost	Purchase cost Operational cost Fuel efficiency Resale	Lower price especially for small cars, low operating costs (energy and maintenance)
Demographics	Income Education Gender Age	No specific criteria as the analysis gave mixed results
Personal attributes	Travel demand, vehicles per household Technology affinity and familiarity Environmental conscience	Low travel demand, more cars per household can decrease range anxiety, knowledge-sharing on technology, and eco-friendliness, prior experience on EVs

consumer surveys, EV charging availability was identified as the predominant factor for EV acceptance. Effects of demographics such as income, gender, and age on acceptance criteria were inconclusive as some interviewees were in favour of EV adoption, while others were not ready to switch from conventional vehicles to EVs. Interestingly, a key enabler for the EV uptake is the rise in knowledge levels on EV cost of ownership, technology usage, and eco-friendliness.^{82,83}

Several studies have analysed the cost of ownership for an EV and compared the same with an ICEV. A comprehensive framework for total cost of ownership estimated that future EV sales can be stimulated by imposing tax policies and price hikes on ICEV, as bringing down the EV price is not plausible.⁸⁴ In another study, the return on investment was not achieved for an e-SUV compared to an equivalent ICEV even after six years of operation.⁸⁵ Data analysis on ten years of EV operation showed that the EV ownership cost can become competitive with ICEV under certain scenarios: uninterrupted incentives offered for larger luxurious vehicles with longer commute distances.⁸⁶ According to several studies, the total cost of ownership gets even with that of ICEV by the eighth year after an EV purchase with certain subsidy applied in the form of tax rebates, parking fee waiver, or the vehicle purchase incentives.^{87,88} A major maintenance cost for an EV happens only after the eighth year due to battery replacement which can be recouped by the 11th year and become competitive with ICEV.⁸⁹ Depending

on the financial savings offered in the regional markets such as the manufacturer's retail price (MRP) reduction and government incentives, the EV owner cost can breakeven with ICEV in four years.⁸⁹

EV Operating Cost – By Choice

The total cost of ownership constitutes acquisition cost, operating cost, depreciation, and insurance. The operating cost of an EV depends on multiple variables, such as electricity cost, driving range, distance travelled, per cent city driving, and place of residence. Fossil fuelling cost depends on mandated factors such as the geographical location, tax rates, and distribution costs, all of which are beyond the customer's choice. In contrast, the electricity charging cost depends on two unique variables, namely the time of charging and the charger type, apart from the geographical location. These additional but critical factors fortunately are within the customer's choice, i.e., one can choose when to charge and whether to charge with a Level 1 home charger or a Level 3 fast charger. The electricity supply chain faces schedules of peak hours and off-peak hours. Off-peak hours are usually from late night to early morning and hours outside this duration are peak hours. The electricity cost is higher during peak hours because of the extra power generated to meet the excess demand during this duration. Using a web search for relevant data, Figure 5 shows the electricity rebate percentages (inside the parenthesis of Y-axis labels) offered in different countries during

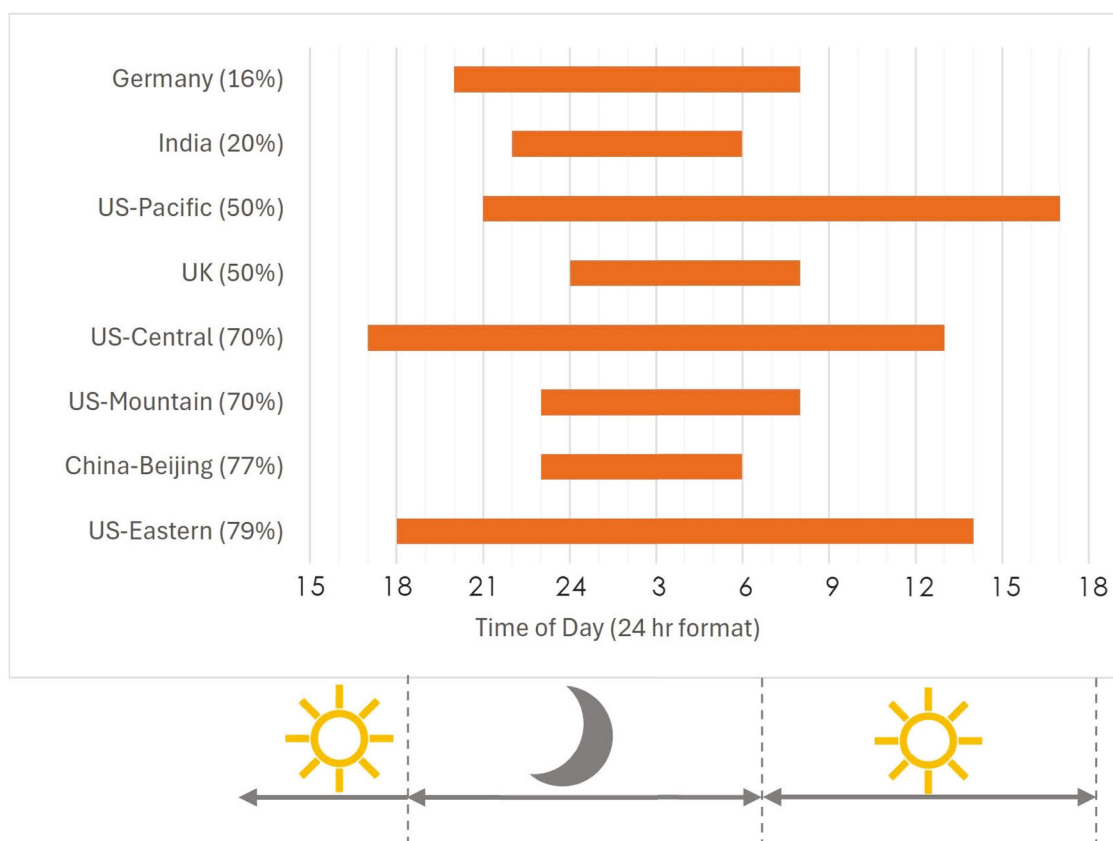


Fig 5 | Off-peak hours and electricity rebates as a percent of peak hour costs

off-peak hours compared to rates charged during peak hours.⁹⁰⁻⁹⁷ India offers a 20% rebate of normal rate of energy charges during off-peak hours (10 pm–6 am). The US-Pacific zone and the UK offer a 50% rebate, whereas China and the remaining parts of the US offer an enticing rebate of 70%–80% if the power is consumed during off-peak hours. In addition, the UK plans to offer £3 per kWh as a part of the increasing uptake of Economy 7 meters and off-peak hours' utilization.⁹⁸ The nominal off-peak duration across the world is 7–12 hrs, while the US assigns an exceptional duration of 20 hrs in many parts of the nation.

The energy cost utilized for power generation can have a greater impact on the electricity cost when compared to crude oil cost on fossil fuel pricing. According to the US Energy Information Administration, crude oil makes up 52.6% of the regular gasoline price, whereas the electricity generation cost attributes to about 61.6% of the electricity pricing.^{99,100} So, energy source which in turn depends on the geographical location plays a key role in pricing electricity. The top 10 countries with the highest electricity cost per kWh are all located in Europe. Denmark, Germany, and the UK carry the highest costs in USD of 50 ± 3 cents/kWh.¹⁰¹ This data should not be surprising given that the European countries invest more on alternative fuels for power generation, which is relatively expensive compared to coal (Figure 4). Given the high energy costs, European EV residents can take significant advantage of overnight Level 1 charging as countries in this region offer up to 50% rebate during off-peak hours. Canada and Norway are tagged with low electric costs due to the abundance of hydroelectric power plants. China and India enjoy the leverage of cheaper coal-based power generation, and conjunction of this source with additional subsidies to retailers leads to some of the least electricity prices in the world (less than 10 cents/kWh). The US is a premium user of fossil fuels for power generation. Nevertheless, the electricity cost there is 18 cents/kWh, which is less than half of the price seen in the top 10 countries (Europe). This is partially attributed to the absence of electricity tax rates in the US unlike in Europe. These findings highlight the importance of other external factors, such as policies and legislation on electricity pricing apart from the energy source. Such regional policies can also modulate the high battery costs which remain as a major part of EV cost, thereby attracting more new car buyers to purchase EV.¹⁰² Notably, some of these policies which offered EV purchase incentives at the time are being removed by governments, and instead, the monetary funds are assigned to the charging infrastructure and decarbonized power generation. In Beijing, a different non-economic policy is applied, resembling to some extent the lottery system seen in the US for work permit visa. According to the 'license plate control' policy amended in 2015, an annual quota of 60000 EV license plates and 40000 gasoline vehicle (GV) license plates were reserved in 2019.¹⁰³ Any potential car buyer can apply for the license of their choice (EV or GV) and a license plate is provided from a pool of applicants using the

lottery system. This strategy had a significant impact on EV uptake in China because the probability of winning a GV license is one in 41 years, whereas it is one in nine years for an EV according to the number of registrants in 2019.

The limited annual license plates available in the city made some buyers to opt for EVs for a quicker vehicle acquisition.¹⁰³

VCCs

An effective means to enhance the understanding of EV operating and acquisition costs is the use of VCCs. VCCs are open-access sources with a certain level of user customization in-built in several tools. The US Department of Transportation (USDOT) centre tested the effectiveness and common public reception levels of 10 VCCs using a survey executed with potential car buyers, EV owners, and EV enthusiasts.¹⁰⁴ The survey results indicated that the 'BeFrugal' calculator was rated highest in terms of accuracy and features availed to the interviewees, whereas the 'PlugStar' was rated highest in user engagement owing to its superior aesthetics and graphical user interface. A common issue reported for these top-rated platforms is that the poor and often overestimated EV maintenance cost. Table 3 lists some of the essential features (extracted from the USDOT report) that are useful for potential car buyers/lease planners in making informed decisions towards picking an EV that suits their needs.¹⁰⁴ Features which are included in a particular VCC are marked with letter 'C' indicating that the corresponding features are 'covered', whereas those which do not have these features are marked with 'NC', which means 'not covered'. Some entries with a 'C' are superscripted with numbers and these are further explained in the footnotes of Table 3. Overall, BeFrugal is rated highest (8 out of 14) followed by PG&E's EV Savings, PlugStar, and WattPlan, each sharing a score of 7 out of 14.

BeFrugal is taken as an example, and an illustration is made to supposedly enhance the presentation for potential stakeholders. The first step of using this calculator is to select a state in the US (BeFrugal is based in the US). In addition, the target driving profile can be created using the number of miles per day, per cent split between city and highway driving, weekend driving miles, long-distance trips, and fuel and electricity costs. For the current exercise, all the default values are retained without any modifications. In step 2, two vehicles to compare are selected. In the current example, a BEV (2022 Hyundai Ionic 5) and an ICEV (2022 Hyundai Tucson) vehicle are selected. The calculator has a provision to modify the fuel economy separately for city and highway miles per gallon, battery range and capacity (kWh for full charge), and the annual maintenance cost. Again, all default values are used for the current example. In step 3, different acquisition methods are listed for the user to pick from: purchase outright, lease with user-selectable term duration, and purchase with financing. Upon selecting the purchase outright option, the calculator autogenerates the vehicle price and a 'one-time tax credit' of \$7500 for EVs.

Table 3 | VCCs and Features Relevant to EV Ownership Cost

	AFLEET	BeFrugal	EV Explorer	PG&E	Fuel economy. gov	Oncor	PlugStar	SMUD	VCC (DOE)	Watt Plan
Fuel, maintenance, insurance	NC	C	NC	NC	NC	NC	C	NC	C	NC
Modifiable fuel price	NC	C	C	NC	NC	NC	NC	NC	NC	NC
Vehicle customization inputs	NC	C	C	NC	NC	NC	NC	NC	C	NC
Depreciation	NC	NC	NC	NC	NC	NC	C	NC	NC	NC
Time to breakeven cost with ICEV	NC	C	NC	NC	C	NC	NC	NC	C	C
Potential financial savings with EV	NC	NC	NC	C	C	C	C	C	NC	C
Public parking percent	NC	NC	C	C	NC	NC	NC	NC	NC	C
Percent driving on electricity	NC	NC	NC	NC	C	NC	C	NC	NC	NC
Fuel consumption	C	C	NC	C	C	NC	NC	NC	C	NC
CO ₂ emission levels	C	C ^a	NC	C	C	C	C	NC	C	C
Number of trees vs. CO ₂ correlation	NC	C	NC	NC	NC	NC	NC	NC	NC	C
CO ₂ savings with EV compared to ICEV	NC	NC	NC	C	NC	C	NC	C	NC	C
Verification of selected EV's driving range	NC	C ^b	C	C ^c	NC	NC	C ^c	NC	NC	C ^d
Ease of switching to a different car	NC	NC	NC	C ^e	NC	NC	C ^e	NC	NC	NC

^a BeFrugal estimates CO₂ emissions at the tailpipe as well as along the transfer path from well to wheels.

^b BeFrugal includes a confirmation footnote stating whether the selected EV can cover the planned travel distance.

^c PG&E and PlugStar provide recommendations to pick a suitable EV that can cover the planned travel distance-useful for car rental scenarios.

^d WattPlan displays a geographical map of a user-defined route with the selected EV along with nearby charging stations.

^e PG&E and PlugStar are non-linear tools in that the data filled for the current vehicle gets carried over to the next vehicle upon selecting a different vehicle later.

Results:

Yearly Costs:		
Annual Fuel & Maintenance Costs	Hyundai 2022 Ioniq 5	Hyundai 2022 Tucson
Gas/Diesel Cost	\$3.01	\$1,285.92
Electricity Cost	\$547.23	\$0.00
Maintenance	\$361.80	\$600.00
Total Annual Cost	\$912.04	\$1,885.92
Cost Equivalent MPG³	68	29
Annual Environmental Costs	Hyundai 2022 Ioniq 5	Hyundai 2022 Tucson
Gas/Diesel used per year (gal)	1	410
Electricity used per year (kWh)	4190	0
Tailpipe CO ₂ (in tons) ⁴	0.0	3.6
Upstream CO ₂ (in tons) ⁵	0.7	0.9
Total CO₂ Emissions (in tons)	0.7	4.5
Equivalent in trees⁶	19	116

Fig 6 | Cost comparison table populated by BeFrugal for a BEV and an ICEV¹⁰⁵

The 'calculate' button located under the window of step 3 is pressed to get the results which are shown in Figure 6. The annual cost for the BEV sums to less than half of the ICEV. The number of trees required to tackle the CO₂ emissions is at about 1:6 ratio for BEV compared to ICEV. The time taken for EV owner-

ship to breakeven with ICEV is 11.5 years (Figure 7a). By changing the annual maintenance cost of BEV from the default value of \$362-\$100, the breakeven time comes down to nine years (Figure 7b). Furthermore, if the one-time tax credit is doubled to \$15000, then the breakeven time is reduced to an attractive 3.75 years (Figure 7c). This value almost matches the reduced duration of four years as estimated with the additional MRP reduction along with tax rebates.⁸⁹ Therefore, such VCCs can be utilized by policymakers and vehicle manufacturers along with EV users to incorporate various scenarios towards making informed decisions on improving EV uptake.

Outlook

A Google Trends search for topics related to charging infrastructure improvements reveals that the 'V2G' happens to be the oldest topic among all (see Figure 8). The Y-axis on this graph indicates the popularity scale of the typed keyword. We can see that the vehicle to grid keyword carries a higher popularity scale among others starting from 2010, perhaps with the inception of Nissan Leaf which was also seen in the sub-queries. This popularity is also owed to the inclusion of grid as a separate word in the query because Google Trends did not yield relevant results when explored with hyphenated keywords (e.g., vehicle-to-grid). After 2019, EV smart charging, communication, and policies started gaining ground. After 2021, EV policies took the lead and charging payments started to appear more. This quick exercise indicates two important observations. The first observation is that the EV policies are being sought after by the world more than ever before. This can be understood in two ways. The

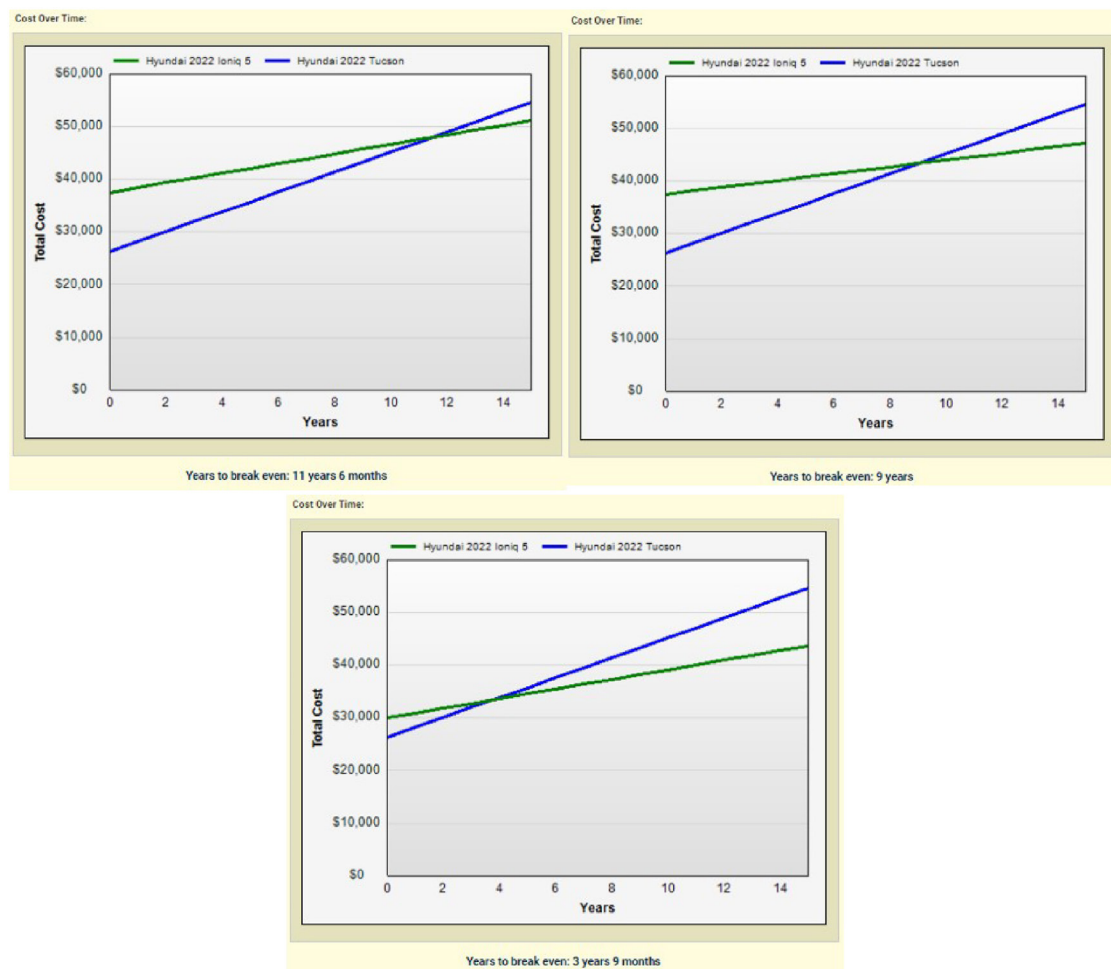


Fig 7 | Clockwise from top-left – (a) Cost breakeven time with default settings, (b) cost breakeven time with modified EV maintenance cost, (c) cost breakeven time with modified tax credit¹⁰⁵

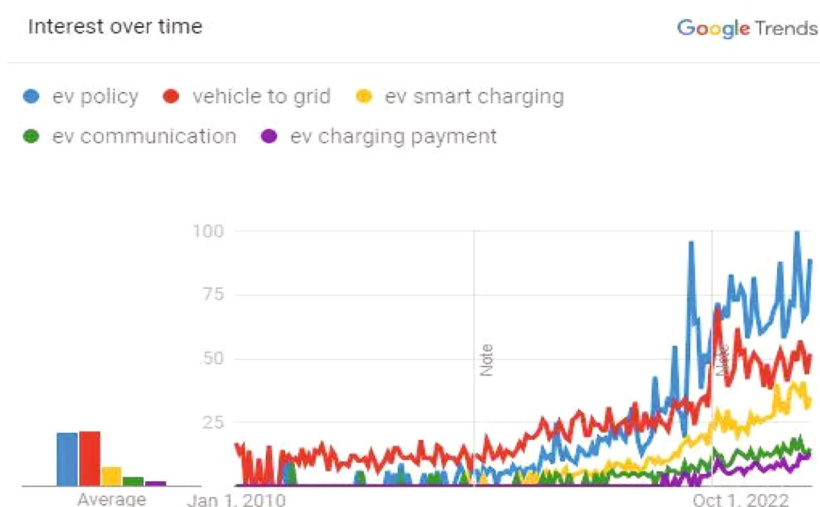


Fig 8 | Time-based graph for popularity of queries on EV charging infrastructure-related topics

queries might be on existing policies that people want to learn and apply. Or the queries might refer to certain concerns raised out of individual experiences for which EV policies may not currently exist. The latter

possibility is a great opportunity for policymakers and charge point operators to streamline the usage of EVs in time (charging schedule, duration, etc.) and space (hogging, charging locator, etc.). The second observation is that the EV smart charging queries have been rapidly growing in the last few years. Figure 9 reveals the regions that are most interested in each of these topics. For instance, Myanmar queried solely on EV policies, whereas Ireland was the one most interested in smart charging. While these observations might seem superficial with further scrutiny recommended, the takeaway here is to learn the needs of the EV users. One such example is the limited uptake of smart tariffs in the Ireland household community where 89% of the smart meter owners did not sign up for the smart tariffs due to a potential lack of understanding on the benefits reaped by signing one.¹⁰⁶ Apparently, Ireland was the region with the most queries made on smart charging as shown in Figure 9, compared to other parts of the world that used this query.

Smart meters can be advantageous to power plants as well because they can augment in higher penetration of RE. Policymakers should come up with regional mandates on employment of smart meters in every

household with certain incentive schemes on installation of solar panels. The smart meter penetration rate stands at over 80% in 13 member states of the EU, 62% in the UK, and 72% in the US.^{107–109} From another perspective, EVs can also be life changers if properly integrated into the grid with a bi-directional charging architecture. During a blackout in Victoria state in Australia, government agencies discharged power from their own EV fleet located in Canberra, which is 500 km away from Victoria. This was believed to be a first-of-its-kind attempt where the national electricity grid made use of stored energy from the EV batteries in an emergency.¹¹⁰ It was mentioned that more vehicles should be integrated with the V2G technology while addressing the faster battery discharge as claimed for a vehicle equipped with V2G. Such emergency situations require the electricity stations to be proactive. In 2022, China suffered from power disruptions due to extremely hot weathers which evaporated their hydro-power-sourced dams.¹¹¹ In such cases, it is beneficial to do something similar to what the Australian government agencies tried in Victoria instead of relying on fossil fuel energy as a backup power source. Thus, the proposal here is a combined implementation of smart meters in tandem with the V2G technology and grids predominantly sourced by RE.

Standardization of the charger connector and inlet types is imminent for the sustainability of both car OEMs and the charge point operators. Based on the data studied, CCS and NACS types seem to become viable public fast chargers in the years to come. Having said that, it is equally important to provide accessibility of chargers to the existing fleet. With millions of EVs in use, it is imperative to incorporate charging stations with different adaptors and/or cables to access, say, a CCS public fast charger by an EV user with a CHAdeMO inlet on the vehicle.¹¹² Wallbox is a smart EV charging

and energy management provider who claims to provide different cable options for each of their charging points.¹¹³ It will be useful to confirm if other providers offer similar options or understand if there are any concerns in doing so. As a counterpart to offering different cables, wireless charging was recently proven to be a viable option for seamless handshake and charging activity. Such a setup sets a great example for charging autonomous EVs. The presence of high voltage and current fields in this setup makes it crucial for the policymakers to regulate, monitor, and approve the safety requirements.

While car makers can strive to improve the battery specifications using state-of-the-art technologies and novel materials, a more immediate and sustainable approach would be data interoperability. This is where vehicle OEMs and charge point operators with the support of policymakers can establish a data interoperability framework via predefined communication protocols and mutually agreed terms of data-sharing (e.g., vehicle characteristics and duty cycle history). Apart from the ability to extend driving miles, batteries face another issue which is performance degradation. Such a battery (performance) degradation can happen in two ways: Calendar ageing which is a default ageing of any product and the cycling ageing. Cycling ageing is a result of repeated charging that further depends on EV usage, charging behaviour, and V2G integration.

There is a mixed interpretation about the impact of V2G integration on battery degradation. Several studies indicate that battery life gets reduced when integrated into V2G technology, while others identify that a combined usage of V2G and smart charging potentially improves battery life. A team at the University of Warwick applied a smart-grid algorithm and showed that the EV battery life got improved due to reduced

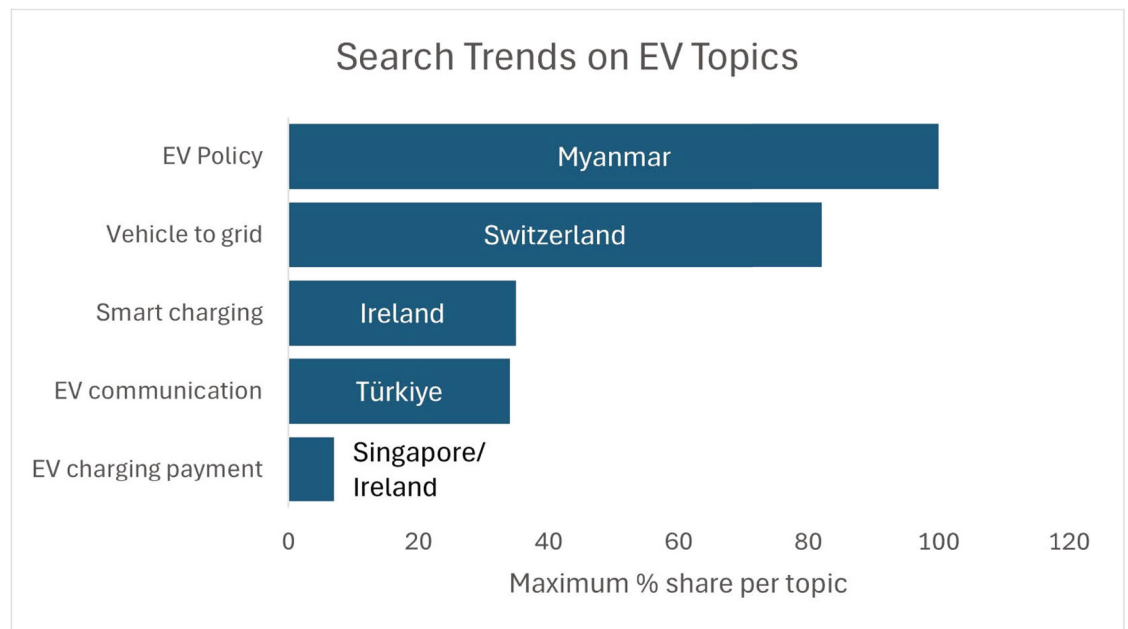


Fig 9 | Popularity of queries segregated by most interested regions

battery capacity fade and power fade.¹¹⁴ Capacity fade is the decline in the charge amount the battery can hold during recharge. Power fade is the decline in the battery's ability to power the equipment it is connected to, in our case the EV. Apart from ageing, weather conditions play a key role in affecting these metrics of battery degradation. The smart-grid algorithm estimated that more than half of the vehicles connected to the electricity network were prone to battery degradation with V2G. Battery state of health and degradation characteristics largely rely on charging and driving behaviour. Intensified driving profiles had leverage over reduced battery degradation upon applying smart charging and V2G, compared to gentle driving profiles.¹¹⁵ Battery wear can increase with V2G integration; however, the benefit of providing supply to the grid during high demand is more favourable compared to the minimal impact seen on battery life.¹¹⁶ These results indicate that there is scope for further understanding the implications of V2G on battery life using more real-world examples and case studies. Similarly, a profit modelling study showed that V2G can reduce battery degradation if the vehicle is discharged down to a 10% state of charge before charging again to 100%.¹¹⁷ Therefore, V2G may not affect battery life if certain guidelines are employed for the charging schedules depending on the driving profiles. Similar to the ICE owner manuals where different maintenance schedules are recommended for normal driving vs. rugged driving, the EV car makers may provide certain guidelines on charging schedules or even automate this activity with data-sharing when connected to a charging station.

The acceptance of EV among potential car buyers depends on several factors. Charging station availability, reduced charging times, more EV varieties, and continued incentive support are the desired factors for EV uptake. A key enabler which perhaps is a critical opportunity to policymakers, power suppliers, car makers, and scholars is to enhance the knowledge on EV ownership costs, technology use, and eco-friendliness. Based on the current statistics, it may take at least eight years for an EV ownership cost to get even with an equivalent ICEV. After eight years, battery replacement is done on the EV which raises the maintenance cost. Considering the same example while demonstrating the BeFrugal VCC, the annual savings for Hyundai Ioniq 5 BEV is \$975 compared to ICEV from the same vehicle category. Assuming a battery cost of \$6800 for the BEV, one option for the EV owner is to sell the vehicle with or without battery replacement instead of waiting for another seven years to recoup the battery cost. The option of selling without battery replacement would be via reduced sale price negotiations given the high depreciation costs of EVs compared to ICEV.

Concluding Remarks

This review completed a reality check on the charging infrastructure across various major global markets using data-driven calculations and sources dated

2023–2024. To achieve the targets set by different regulatory entities, it is clear to have a synergistic approach where interoperability becomes inevitable among different stakeholders of the e-mobility ecosystem. The well-to-wheels e-mobility ecosystem depicted in this study shows that there are action items for each of its members. Major parts of the world continue to rely on burning fossil fuels to generate electricity. Studies show that an EV powered up using fossil fuel does not provide any emission reduction benefit as opposed to those powered up with a low-carbon or carbon-neutral fuel.

- Renewable energy is ramping up in certain areas, and it is important to continue efforts towards more penetration of renewable sources for power plants and to label EVs as the true zero-emission vehicles. While RE has inherent issues such as inconsistent supplies, voltage fluctuations, and other losses, combining this energy-based power with V2G and smart charging seems to be the long-term solution. This was demonstrated using various case studies and regulatory agency strategies for both residential and commercial charging.
- Residential chargers will more likely become standardized with Level 1 chargers for the years to come as it is an economical choice with simpler installation and safety requirements for private consumers. Policymakers should come up with regional mandates on employment of smart meters in every household with certain incentive schemes on installation of solar panels.
- Public chargers (Level 2 and fast chargers) need a seamless integration of EVs, charging stations, and grid interoperability. Charging infrastructure plans should focus on both new building and existing stations. It is imperative to incorporate the interoperability measures on using different adaptors and/or cables to meet the needs of millions of EVs currently in use.
- For new charging stations, understanding the charging trends of EV users using extensive data collection can lead to a successful smart-enabled V2G framework. Participation of administrative groups in such a novel campaign will likely alleviate user anxiety expressed on data privacy and security. Also, charging stations shall be located such that the chosen location addresses the EV users' concerns on improved accessibility and network connectivity.
- Car makers are expected to collaborate with other members of the e-mobility ecosystem. For example, they need to standardize the on-board connector inlets working closely with the charge point operators. They need to collaborate with regulatory entities and charge point operators in determining robust communication protocols for a proper handshake between the vehicle and the charging station. Incorporating certain guidelines on charging schedules depending on

the driving patterns will be useful for reduced battery degradation and consequently extended range for EV owners.

Overall, the data-driven observations made from the current study emphasize the need for an uptake on EV incentive policies apart from those on the charging infrastructure. Such incentives can range from initial purchase price cuts, off-peak charging smart meters, home charger installation subsidies privilege of accessing high-occupancy lanes, parking fee waivers, and EV registration quotas. In addition, more awareness campaigns on vehicle cost ownership estimates and training sessions on VCCs can steadily increase consumer confidence and eventually EV sales' per cent. There are few topics which are worth investigating towards larger adoption of EVs in the mobility sector. Life cycle analysis with profit estimates for the EV owners, identifying the most appropriate AI tool(s) for the optimization of the charging station cost and location, and algorithms for optimal management of a grid in a V2G environment are some of them. Some of these topics have been covered in this study, but a more comprehensive discussion on the same is required given that EVs can act as 'saviours' in a blackout situation and a long-term solution for sustainable mobility.

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