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Standardisation of UK Electric Vehicle Charging Protocol, Payment and Charge Point Connection

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Abstract: Standardisation is fundamental to ensuring that new technologies develop and grow unhindered by manufacturer-led standards. Dismissing this vital issue can have a detrimental effect on society regarding adopting new technologies, particularly when government targets and regulations are crucial for their success. We have witnessed competing global industries struggle for dominance, such as Betamax versus VHS, where each had a similar user outcome, but the confusion of differing formats slowed growth. We analyse emerging standards for electric vehicle rapid charging and investigate how standardisation challenges affect stakeholders by reviewing the existing literature on single-mode and polymodal harmonisation. By assimilating existing evidence, we then develop a new understanding of the science behind multi-model standardisation (MMS) approaches. Our literature review reveals three primary standardisation issues: (1) charge connections, (2) car to charger communication protocols, and (3) charge payment methods. We then analyse each mode type's benefit, observing how each example contributes to the overall outcome, and suggest that their impact depends on car to charger handshake timing and intuitive user interaction. Using a structured survey of 282 respondents, we analyse end-user satisfaction for factors affecting growth in the EV sector and compare these findings with the factors identified during our literature review. We consequently articulate a programme for future research to understand EV rapid charger standardisation better, proposing recommendations for vested stakeholders that embrace sponsors in societal, technological and scientific transformation.

Keywords: battery-powered electric vehicle; EV charging infrastructure; electric vehicle growth; battery-backed electric vehicle charging; charge point anxiety; wireless EV charging; inductive EV charging; electric vehicles barriers to growth; EV charge point payment; charger to EV handshake

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1. Introduction

All EV sector actors recognise that electric vehicles (EVs) are becoming an integral part of sustainable and smart cities [1]. However, the lack of standardisation for EVs (i.e., differences between EVs in car and charge connectors, car to charger communication protocols, and charge payment complexity and transparency) has prevented their full-scale adoption in the UK [2].

During the last century, EVs were proclaimed to be the cars of the future [3]. Yet, with the exception of the early pioneering days of emerging powered transport in the late 19th and early 20th century, they have never achieved commercial viability [3]. EVs are once again in focus. Since the mid-2000s, there have been indications that longevity is occurring as a result of government intervention, the global push for lower carbon emissions, increased deployment of charging infrastructure, and the gradual lowering of battery costs. No longer seen as a niche sector, EVs are emerging as mainstream choices manufactured by traditional incumbents and new entry E-centric companies [4]. Currently, all pure mainstream EVs rely on regular cable-based charging to recharge the integrated battery packs, known as conductive charging, which requires supporting charging infrastructure to link them to the electricity network. Research carried out by PWC in 2018 [5] found that more than 35% of EV users charged their vehicles at home through the night, leaving 65% of respondents relying on public or work-based charging points during the day. Those who rely on daytime charging are often faced with either two types of slow AC charging connectors or the preferable rapid charging stations offering up to three different charging connector types. None are interchangeable, and all use one of two communication protocols that are not backwards compatible. Many attempts have been made to standardise EV connectors since the first EVs emerged in the late 19th century [6]. To further complicate matters, charge point payment systems have also developed independently, creating a complex web of technology that currently prevents complete harmonisation of connectors, communication and remote operability. The charge point payment system is almost as complex as connector and communication standardisation in the EV rapid charge network, discussed further in Section 1.13.

In this study, we discuss how the disparate connector standards have evolved and to what extent, if any, standardisation has materialised. Therefore, this analysis will focus on the hardware, the connectors that link the EV to the rapid charging system, and the 'handshake' communication protocol between the EV and the charging system. We also focus wholly on the DC high-voltage rapid charge infrastructure rather than the slower, lower-voltage AC charging infrastructure. We conclude by evaluating the economic, technological, behavioural, and regulatory obstacles of myriad rapid charge standards and communication protocols that may disrupt the full-scale rollout of EVs. We then provide suggestions to aid EV accessibility and wide-market adoption. To bolster the existing literature in these study areas, we conduct our own primary research utilising a survey of 282 EV motorway rapid charge EV users by employing a structured questionnaire based on the Likert scale [7].

We then compare and contrast our hypotheses with the survey and existing literature. Additionally, this study appraises key stakeholders, including car manufacturers, government, national electric grid planners, distributors, and end-users, by investigating their role in influencing a route to standardisation in hardware and software. Note that all nomenclature used for connectors and sockets is the terminology used in accordance with IEC Standard 62196 [8].

1.1. DC Charging and Interconnect Communication

Figure 1 highlights the four main DC socket and connector configurations, highlighting each type's maximum operating current and voltage rating. DC rapid charge connectors and cables are always tethered to the DC rapid charge unit for safety and safe operability. They often require frequent cooling while active due to high current delivery [9]. A typical DC rapid charger schematic diagram is represented in Figure 2, highlighting the relationship between its principal elements that collectively enable a rapid charge to initiate, accept, lock, charge, and unlock safely and effectively. The AC source can be either a low carbon solution using a renewable AC grid supply or a hybrid mixed energy main grid with renewable supply [10].

One of the major user issues for EV drivers is that the location of rapid chargers is generally determined by the grid supply and availability, not the most appropriate location for EV users. The lower block in Figure 2 represents a potential solution to this major hurdle using a micro-grid that stores DC current in an integrated battery energy storage system (BESS) generally from solar, converted AC wind power, or off-peak grid power. This component can be smart-managed by the grid operators for peak lopping, enabling off-grid battery-only charging to the EV at peak demand on the grid and introducing off-peak period charging capability, reducing grid demand and operational costs [10]. Figure 2 also illustrates the data control management communication path between the DC rapid charge unit and the EV, supplied in this instance with a zero-carbon supply from a renewable micro-grid to EV [11]. EV connection can be established using one of two protocols chosen by the manufacturer to communicate between the charger and vehicle [12]. For example, the Nissan Leaf EV uses a Controller Area Network (CAN) as its communication protocol. This is a robust vehicle bus protocol designed to permit microcontrollers and devices to connect with each other in applications without the use of a host computer or processor. This method of handshake communication is used primarily by a Japanese consortium of manufacturers through their CHAdeMO connector standard [13].

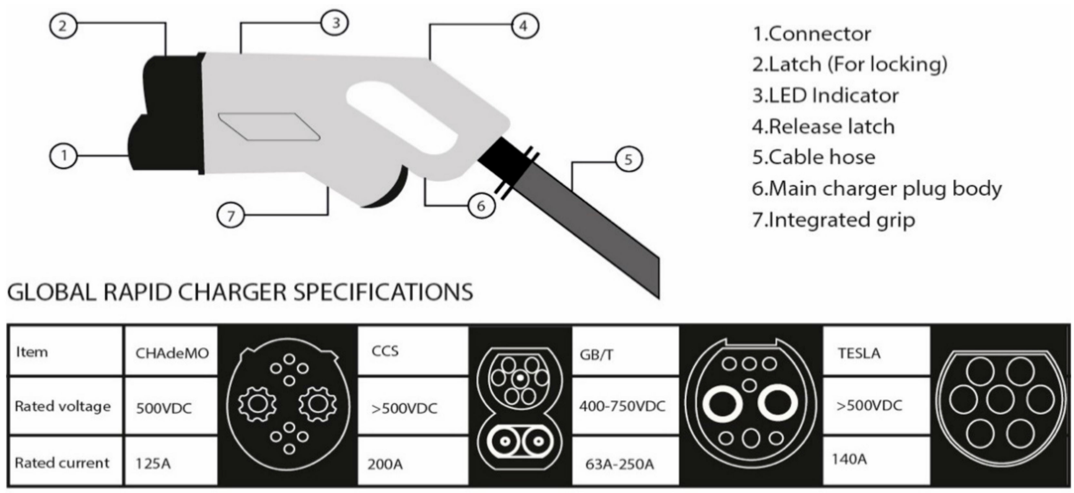
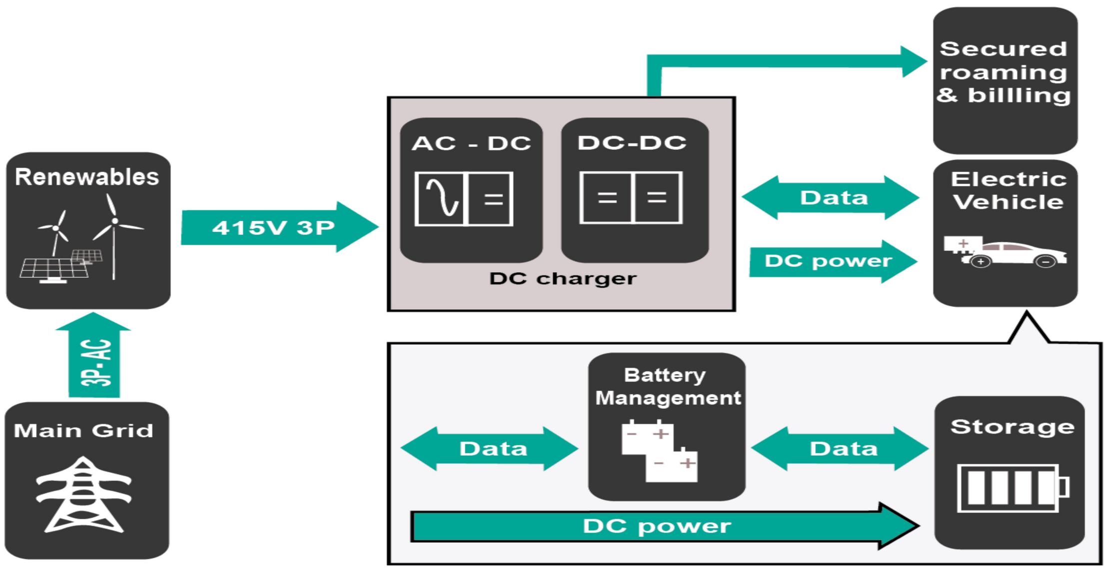


Figure 1. Global DC rapid charger connector configurations.



NB: 3P refers to 3 Phase AC

Figure 2. EV DC rapid charger elements illustrating communication—charger fed by renewable micro-grid. Adapted from Infineon [11].

Conversely, the BMW i3, Jaguar iPace and Tesla 3 use the Power Line Communication (PLC) protocol, becoming the de-facto handshake communication process between an EV and its host charger. PLC is the same system used for power grid communication, making it easy for the EV to connect with the grid as a smart device by sending signals through the power line. Neither of the two protocols are inter-communicable without an intermediary interface.

1.2. Contextual Standardisation Trends

The UK EV sector is home to many charging modes, all of which are manufacturer charge connection protocol and global connector type dependent. However, this study concentrates on rapid charging only and focuses exclusively on UK major trunk routes and motorways where the highest concentration of rapid chargers are situated and where a rapid charger is essential for EV users due to time constraints and long journey routes. Figure 3 illustrates all four modes for comparison [14]. In this paper, we will focus on Mode 4, where the EV is indirectly connected to the main supply using an off-board charger (rapid or ultra-charger) and typically a tethered charger cable that conforms to the technical specifications stated by the EV manufacturer and has local safety protocols in place.

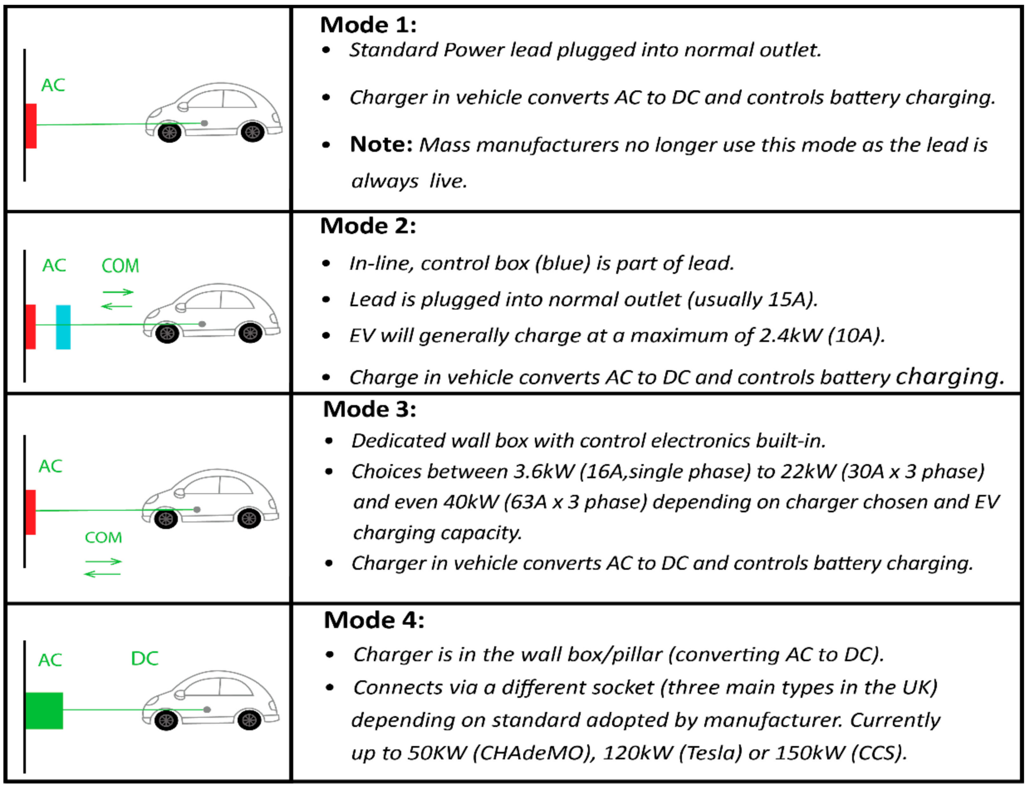


Figure 3. International EV charging modes [14].

The standardisation of EVs is a complex matter since the technology marries both automotive and electrical technologies, the international standardisation of which is treated by international bodies such as the International Organization for Standardization (ISO) [15] and the International Electrotechnical Commission (IEC) [16], respectively. Automotive manufacturers are traditionally vertically integrated and less reliant on external component suppliers and standards, while the electro-technology world has a stronger and longer tradition of harmonisation with the establishment of the IEC in the UK during 1906 [17]. Due to disparate cultural approaches to standardisation in these two technological fields, a consensus was established to set boundaries of the technology, with vehicle-centric aspects being dealt with by the ISO and infrastructure-centric aspects and electrical components dealt with by the IEC. The main committees responsible for the IEC and ISO are TC69 and TC22, respectively [18].

In 2006, the Society of Automotive Engineers (SAE) set up a task force to design a new set of standards to supersede existing protocols from 1990 that were designed for lower power levels [19]. In 2009, a new connector design was created and certified as being capable of greater power delivery and faster-charging speeds. The SAE approved this latest design in January of 2010, known as the SAE J1772 standard connector [19]. The connector enabled charging at 120V to 250V, including two additional features due to the presence of two additional pins, one being utilised for a safety feature and the other for communication between the charger and the on-board charge controller. Both features resulted in the development of smart fast chargers. The connector is classified as a type 1 connector, also known as the Yazaki plug derived from the manufacturer [20]. The connector was collaboratively developed with leading Japanese and USA automotive giants and, as a result, caters to the localised grid architecture and 110–250 V supply voltage design used in the Japanese and US markets, although this was only suitable for single-phase use.

In parallel, it was determined that the European grid system is more powerful and capable than the US and Japanese grid system, and, subsequently, type 1 connector specifications were deemed inappropriate for the European market. Instead, a different connector was designed to meet the higher power level requirements. Previously, type 1 connectors used fixed connector and cable design only, as untethered cables increased fear of theft and vandalism. Type 2 connectors could be used both tethered and untethered. Thus, a newer connector design evolved, jointly developed with major car manufacturers and electrical component companies. This new connector had comparable security and communication features, the major difference being increased power delivery capability and safety standards. This was classified as an IEC 62196 (Type 2) connector named Mennekes after the company that developed it [8]. Unlike type 1 connectors, Type 2 were capable of both single and three-phase operation and were widely accepted and implemented by major automotive companies across Europe.

The European standard for charging connectors appeared set until a group of French and Italian electrical equipment manufacturers organised themselves in the EV plug alliance and rejected the Type 2 connector design, choosing to propose their own instead. The alliance rejected the Type 2 connector based on an electrotechnical safety requirement that required shutters to be present in the plug's design to prevent children from being able to insert their fingers inside the Connector [8]. Therefore, an alternative connector was developed with the technical safety feature, named the Scame connector.

Following development of the Scame connector standard, it was accepted that this development alone would not meet new and future requirements. Thus, a new combined charging system was required in order to increase flexibility and ease of use. Mating Type 2 connectors with two added DC input pins, a combined charging system (CCS) could be used for both AC and DC charging without changing two different charging ports with varying types of connector [20]. Tesla, on the other hand, developed an independent standard for all its EVs, incorporating safety and power delivery protocols effectively, creating their very own Tesla ecosystem. Consequently, at this point, each country and manufacturer had its own set of standards, employing differing connector types dependent on local regulatory bodies and grid architecture.

1.3. Complexity in Harmonisation of Standards

The development of EV charging standards is a vital requirement recognised by all major stakeholders [1]. This would allow universal accessibility and allow for EVs to be widely accepted and shown to be a practical alternative to standard internal combustion engine (ICE) vehicles. It is understood from many sources that the practicality of EVs on longer trips is affected by the presence of compatible rapid chargers on longer routes.

EV charging standardisation seems slow to be realised due to a myriad of factors, which can be described by four primary categories: (1) grid network architecture, (2) standardisation bodies, (3) unionisation, and (4) CCS. Grid architecture differs in all countries. In the USA and Japan, type 1 is still widely in use. Type 2 is generally used in European countries for single and three-phase AC charging up to 22 kW. In contrast, type 3 AC fast charging has generally been replaced by type 4 DC rapid charging; countries tend to follow their own set of standardisation rules and have regulatory bodies that oversee the technical specifications and approval of new technology [8]. This makes it difficult for a consensus to be achieved. An exemplary scenario can be seen in the Type 2 connector and Scame connector case, where a widely accepted Type 2 connector was challenged on a technical basis to no avail. Next, each country has its own set of local regulations that are determined by its governing bodies. They are also influenced by the ease of use and production determined by the manufacturers. Such manipulation of standards in order to enable ease of use is a further obstacle in the development of universal standards. For example, a union of Japanese car manufacturers proceeded to develop their own connector and charge delivery mechanism despite the presence and usage of Type 1 connectors. This power delivery mechanism was named CHAdeMO [18]. This standard was primarily designed for the Japanese market, although, due to the export of Japanese cars, the use of a global CHAdeMO connector for all export countries was thought vital as their vehicles would be unusable without it. Thus, providing a clear argument as to why a unified standard is essential, since it would reduce significant capital investment and permit ease of access for all end users. Finally, the European-derived combined charging system (CCS) appears to be the panacea that could break the global deadlock. It is the first system that can use Type 2 single-phase or three-phase chargers and, additionally, through the same connector, be used for DC rapid charging. In principle, CHAdeMO could also do this, but not through Type 2 for normal universal fast charging. In the USA, a similar CCS is in use combined with a type one connector. Accordingly, we arrive at a comparable parallel point in history; the Betamax vs. VHS standardisation wars [21]. Once one standard dominated and was accepted by the market (VHS), growth in personal video recorders and players grew exponentially [21].

1.4. Standardisation—The Principal View

For EVs to replace current fossil fuel vehicles, a standard must be developed for all aspects of EV use. Service infrastructure, at least equivalent to that of fossil fuel, must develop for charging, operability, availability, and ongoing maintenance. For such infrastructure to be developed, certain standards and operating protocols must be employed. If a global standard is not created, it will be challenging for EVs to replace fossil fuel-powered vehicles completely. Differing standards and charging methods will prevent travel on long-haul routes due to the required rapid charger type's unavailability. For these reasons, an agreement must be prepared and decided between all actors on EV charge procedure, operability, availability, and free-roaming payment for electricity [15].

Standards play a vital role in the development and deployment of technology in society, providing a solid base for innovation and technological advancements and widespread acceptance of such technology. The presence of harmonised standards permits multilateral cooperation and innovation. Customers will be the key factors in the widespread commercial success of EVs. Standardisation will provide customers with a convenient and consistent experience with the freedom of choice, allowing them to choose from multiple electric suppliers without being limited by charge Connector types, communication protocol and cable limitations.

1.5. Implications and Options to Accelerate Polymodal Harmonisation

Harmonised standards for charging connectors and handshake protocol are not intercommunicable. For example, Japan, China, the USA and Europe use separate charging connector standards and disparate communication and handshake protocols [20]. Harmonised standards would lead to charge point interoperability, economies of scale and power EV growth in sales, and popularity. Not all EV models support both slow and rapid charging due to design and pricing limitations. Similarly, not all charging equipment can output all power levels or offer all connector types, resulting in complications for EV users in locating suitable charging stations. Exclusive contract chargers prevent EV users from freely using their vehicles due to the inability to charge using 'pay-as-you-go' or inter contract roaming. Standardisation of payment would allow for increased customer satisfaction. Layouts of charging stations are variable depending upon the provider and maintainer of the location. Such variability increases user anxiety due to the constant need to adapt to unfamiliar standards, protocols and needs.

Planning of charging stations in cities and highways is also limited due to planning restrictions imposed by both local authorities, governments, and grid network operators, propagating an artificially disjointed network of rapid chargers across the UK. This subsequently forces EV drivers to deviate from direct routes, resulting in greater mileage and journey times than conventionally powered vehicles. [22]. There is a consensus that the development of a globally harmonised charger standard and trunk route charger locations in line with conventional filling stations would provide peace of mind and familiarity in conjunction with encouraging healthy competition in the EV market to benefit the end-user [10].

Harmonisation of standards can reduce unnecessary or conflicting standards that may have developed individually. The objective is to discover commonalities and categorise critical requirements that must be preserved, reducing excessive or opposing standards that may have evolved independently. The goal is to find commonalities and to identify essential needs that must be maintained and deliver a collective standard. We have consequently investigated four differing approaches toward the harmonisation of standards in Figure 4.

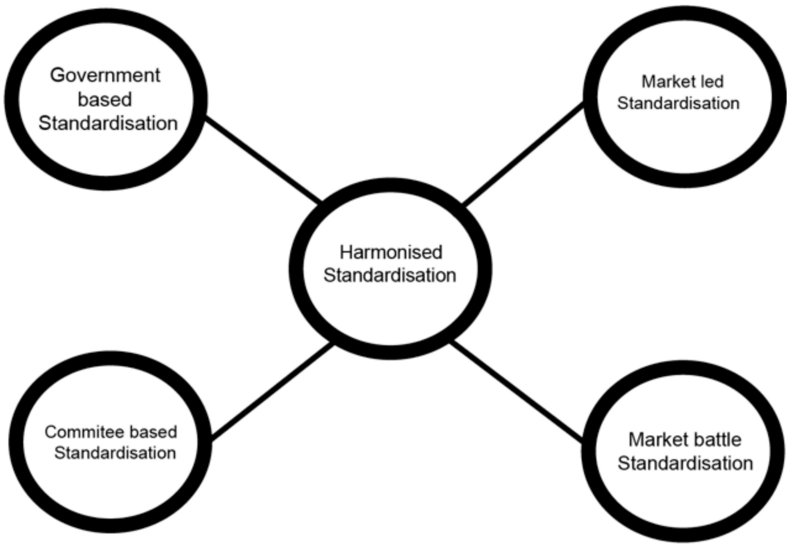


Figure 4. Multi-model standardisation approaches in an EV context.

1.6. Models of Standardisation Driving EV Protocol Harmonisation

1.6.1. Government-Based Standardisation

Government-based standardisation [22] uses the government's hierarchical powers to decree and impose a pre-developed standard established elsewhere or to self-develop standards. This form of standardisation is not generally employed in the EV infrastructure sector.

1.6.2. Market-Led Standardisation

Standards are established with collaboration between competitors to develop a collectively acceptable standard to the benefit of each party [23]. Such standardisation requires greater cooperation and effort but results in a harmonised standard that allows for further mutually beneficial research and development.

1.6.3. Committee-Based Standardisation

Standards developed by independent private entities responsible for testing and developing technical specifications in line with government regulations comprise committee-based standardisation [24]. Examples in the EV sector include SAE [19], ISO [25], IEC [8], CHAdeMO [26], all of which are private entities who are responsible for unified EV Infrastructure standardisation.

1.6.4. Market Battle Standardisation

Market competition exploitation to develop a common standard is known as market battle standardisation [24]. Multiple solutions are developed in this model, and eventually, a de-facto standard is established. Companies in the EV sector are slowly moving from this form of standardisation to a hybrid of committee-based and market-led standardisation.

1.7. Polymodal Harmonisation and Heterogeneity in a Technical Context

EV owners do not enjoy the freedom of standard refuelling systems accessible to conventionally powered vehicles. The development of harmonised EV charging standards has been slow and subject to frequent disruption. Hence, EV owners need incentives and support in addition to increased combined effort towards the development of standardisation. In the EV context, polymodal harmonisation is the effective fusion of four dominant charging connector types and two communication protocols to merge as one harmonised charge point standard to all stakeholders' benefit. This, in turn, will increase attainability and growth toward a zero-carbon transport future.

Significant innovation has developed in the EV industry with improvements in battery technology, decreased charge times, and increased energy density, delivering an increase in vehicle range, providing a per-charge range on par with conventional vehicle users. However, the most promising research is underway into wireless charging capabilities of EVs [20], with great attention focused on the technicalities and efficiency of systems associated with untethered charging, with a focus on safety related to the transfer of large amounts of power wirelessly. Efforts are also underway to standardise off-peak power rates from grid distribution operators and between various EV charge point companies.

1.7.1. Static Inductive (Wireless) Charging

Wireless or inductive charging appears to be the panacea for a universal EV conundrum. However, inductive charging is currently very inefficient, requires high infrastructure and hardware costs for both the charge point operator (CPO) and user, and the communication protocols are far from inter-operable. Figure 5 illustrates the difference between conductive and inductive charging. Although significant progress is being made by IEC [27], the lack of universal agreement on standards in static inductive chargers allows manufacturers to independently decide the charging features and protocols for each vehicle and each charger manufacturer. End-users are thus presented with myriad factors when choosing an inductive charger.

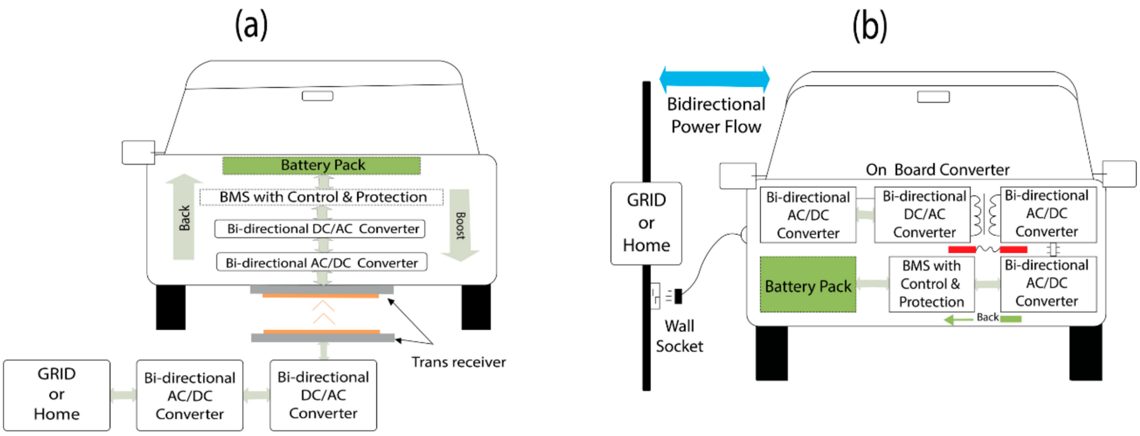


Figure 5. (**a**) Inductive and (**b**) conductive charging. Adapted from source [20].

Key considerations include the vehicle's handshake protocol, the availability of static EV charging stations employing a compatible plate inductor in their location or route, per-charge range of the EV, and on-board charger compatibility provided by the manufacturer. Additionally, home charger options do not include inductive charging for most users due to the high cost of installation. However, Type 2 home chargers provide lower-powered charging in single-phase form, resulting in increased charge cycling at a much lower purchase cost of installation, making conductive charging the preferred choice for most users. Both single and three-phase supplies can feed Type 2 chargers; the latter can charge at 22 kW. The plethora of technical considerations and initial installation costs due and lack of standardisation could point to a significant reason for EV buyer reluctance.

1.7.2. Charger to the Car Handshake Protocol

The complexity of charging an EV, generates a continuous flow of information and communication between the charger and the vehicle, including:

- Authentication state
- Battery capacity
- Charge time
- Correct voltage output
- Maximum charging current available
- Instructions to bypass the vehicles on-board AC-DC charger if utilising a DC fast charger
- State of charge.

Communication between EVs and chargers is vital for the user's safety and the longevity of the battery, charger and charge connectors. The vehicle must be able to determine that the connector is locked in place before drawing the current. The vehicle must detect when a latch or button is pressed for it to cease charging before allowing the Connector's removal, preventing an arc discharge. The EV must also determine which voltages are compatible with the EV electronic control system and battery management. The vehicle and charger must also be able to check for earthing faults in both the vehicle and charging system to prevent charge leakage. IEC 61851-25 is the international standard covering both protocols in a conductive charging system [16].

The two protocols that establish communication between EVs and their chargers are PLC and CAN-bus. Power Line Communication (PLC) is a standard used for communication between EVs and chargers. CCS uses the PLC protocol. All connector types have dedicated pins for uninterrupted communication through charge connectors from the charger to EV. Controller Area Network (CAN)-bus is the CHAdeMO connector communication standard, a robust vehicle bus protocol that allows devices to converse without using a host computer. IEC is currently undertaking the role in standardising wireless charging within the framework of IEC61980 [27].

1.8. Heterogeneous End User Payment Systems

We found only two approaches of accessing a public EV charge point (Figure 6) in the literature [2], subscription and pay as you go, although only one method is likely to satisfy the long-term demands of EV users. Specifically, subscription payment methods are contract-based using a mobile phone application or an RFID card. In contrast, pay as you go (PAYG) methods allow EV users to access a charge point anonymously with no connected services, typically using a credit card. The Department for Transport (DfT) consultation papers [2,28,29] and found that payment discrepancies using differing methods of end-user payment for energy at charging stations is a significant issue faced by EV users. Diverse peak hours, payment rates, and technical limitations result in interoperability issues and resultant charge point trauma amongst users. Through charging stations, disparate payment and identification systems range from the employment of radio frequency identification (RFID) to user IDs provided by the charging station management. Some stations offering vehicle-specific charging features such as stations maintained by EV companies that only allow EVs manufactured by them to access the charging stations, such as Tesla. The most common method used is RFID, limiting users to charging stations owned by the companies to which they are registered [30]. The PAYG option is still rare, but the UK government is pressing charge point operators (CPOs) to move towards a dual payment system offering both options. The positive outcome of PAYG is that it offers unrestricted access to all EV users, pending correct connector availability. In contrast, this option results in a reduction in the customer relationship and loyalty to the CPO network.

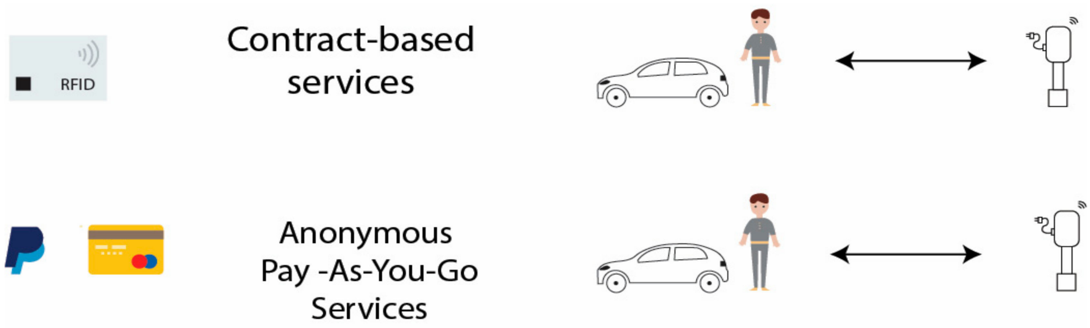


Figure 6. Public charge point payment access options. Adapted from source [31].

Momentum is gathering in the UK for a harmonised roaming charge point system, known as EV roaming (EVR) or charge point roaming (CPR) [32]. EV roaming is a market model in consumer based EV transport, denoting the contractual obligation, relationship and subsequent collaboration of the market actors.

1.9. Connection of Isolated Solutions

Charging stations are generally equipped with an exclusive billing system. Thus, the use of these charge points focused on a limited customer network, whereby only EV drivers who have established an agreement with the charge point operator can access it. EV roaming offers all EV users the option to charge their vehicles at any charge point—irrespective of any contractual agreement entered into with other CPOs. Subsequently, billing occurs through the EV user's own contracted CPO, similar to mobile phone roaming billing, illustrated in Figure 7.

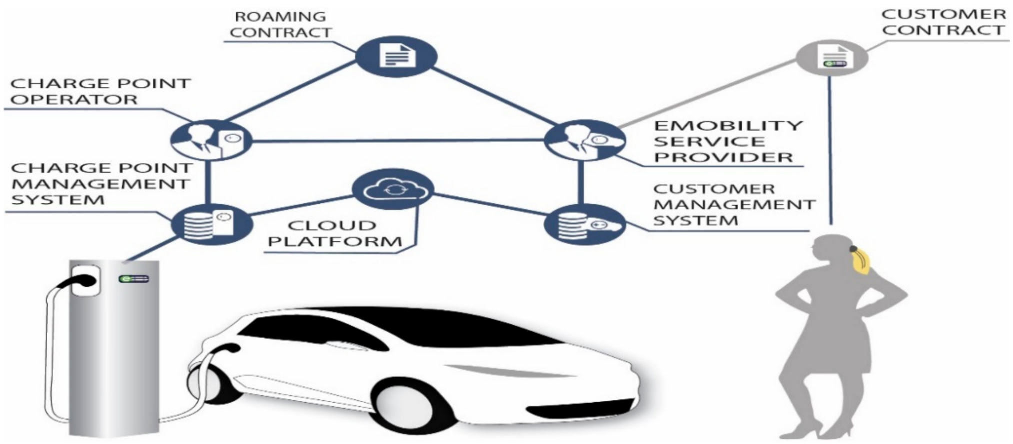


Figure 7. EV charge payment roaming—key elements [33].

Accordingly, the EV market is networked through individual business hubs and IT cloud-based platforms. This network, if harmonised, can provide a cross-CPO charging framework and is the long-term goal for the UK government [2], EV manufacturers, CPOs and consumers [31]. Despite new entrants developing platforms to support this harmonised architecture, the UK appears to be several years away from a fully harmonised system [18].

1.10. Current Evolution of Polymodal EV Connector Standardisation

Despite its early lead, the CHAdeMO protocol is now trailing in the race to become the connector of choice through its market battle standardisation model. Current EVs are designed for DC rapid charging rates of 100 kW or more, and carmakers are now overwhelmingly backing CCS as the standard charging protocol due to its ability to supply up to 350 kW charging and Type 2 7kW 1Phase AC and 11kW 3Phase AC [28]. Next-generation rapid charging deployment networks in the UK are also favouring CCS, reversing the growing deployment of CHAdeMO (Figure 8). Even Tesla, with its proprietary connector and comms protocol, has now switched to CCS on its Model 3 and Model Y EVs. This phenomenon across most major manufacturers is a synthesis of market-led and market battle standardisation, coordinated amongst EV manufacturers to expand consumer acceptance and confidence in their markets of sale. The next phase to harmonise existing multiple protocols with manufacturer recognition and approval will be through standard implementation based on multiple factors. For example, the CCS and Type 2 charging protocol has been dominating the competition over the past four years, though the majority of rapid charging stations continue to provide support for the main two connectors (CCS and CHAdeMO), whilst Tesla continues to deploy their own charging network.

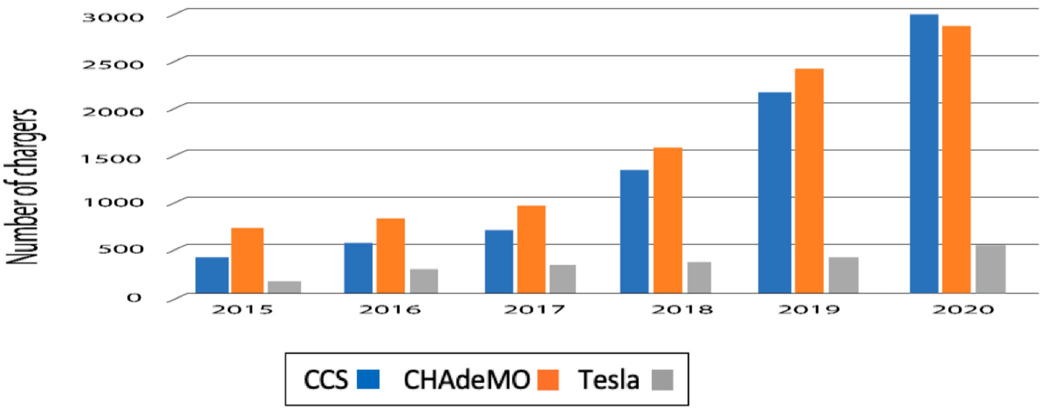


Figure 8. CCS vs. CHAdeMO vs Tesla UK charge point connector deployment [5,28].

The data in Figure 8. points to almost equal deployment of CHAdeMO and CCS charge points.

Government and Research-Based Findings

We have found that governments worldwide are becoming increasingly attentive to the development and growth of the EV market [28]. In the UK, the government is actively granting incentives to develop infrastructure to benefit EV users, including the provision of grants to customers purchasing an EV, albeit reduced from the original GBP 5000 to 2500 per EV under a capped threshold of GBP 35,000. The UK government has also increased investment into the EV sector with special packages crafted to stimulate and develop nationwide charging stations.

1.11. Infrastructure Investments Trends and the Growth in CCS Adoption

The initial development of multiple standards with manufacturers and countries opting for different protocols and manufacturers developing cars with other charging systems, led us to observe that the initial market chaos of charge point scarcity, coupled with multiple connector standards, left customers considering moving into EVs to view this as a high-risk market to enter [34]. With organic development and investment in fast-charging infrastructure, market growth and acceptability are gaining traction. The rate of investment into the UK EV rapid charging network based on actual and forecast data from SMMT 2020 [35] is revealed in Figure 9.

This study points to an underlying issue faced by consumers and EV makers concerning inadequate rapid charge points in the right place and with correct and available connectors for their cars. In order to develop a viable solution and for the EV market to continue to grow, the disjointed and uncontrolled deployment of EV-supporting infrastructure may flatten the curve of the sharp rise in UK EV adoption [36]. Furthermore, we would argue that this is a prime example of where government regulation is needed now to prevent significant user issues in the future.

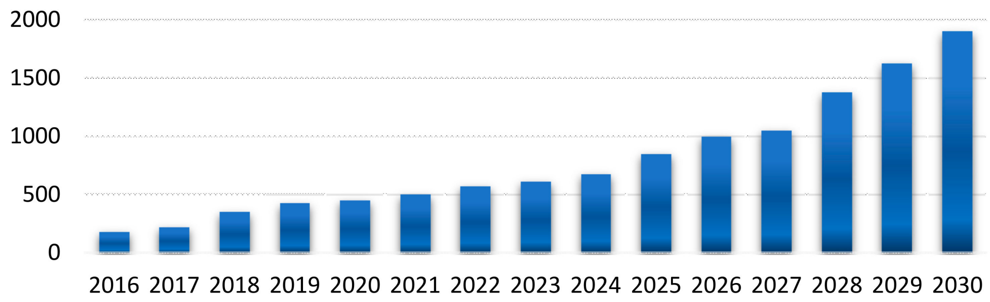


Figure 9. Annual UK investment in charging infrastructure (£millions) [35].

Evidence in Figure 10 illustrates that CCS EVs amount to 78% of all new car production, with only two pure EV manufacturers using CHAdeMO, namely Nissan and Lexus. However, Nissan has announced that its next model will move to CCS as its charging standard [37]. The remaining models use either Type 2 connectors only or Tesla proprietary connectors. Even then, we find that all new and future Tesla models will use the CCS protocol. Therefore, there is a huge disconnect in rapid charger connector type roll out, particularly as even Nissan, the only current user of CHAdeMO, is announcing that their current model, the Leaf, will be the last car they produce using the CHAdeMO protocol. We illustrate the CCS protocol's growth curve versus CHAdeMO and Tesla's proprietary connector protocol in Figure 10.

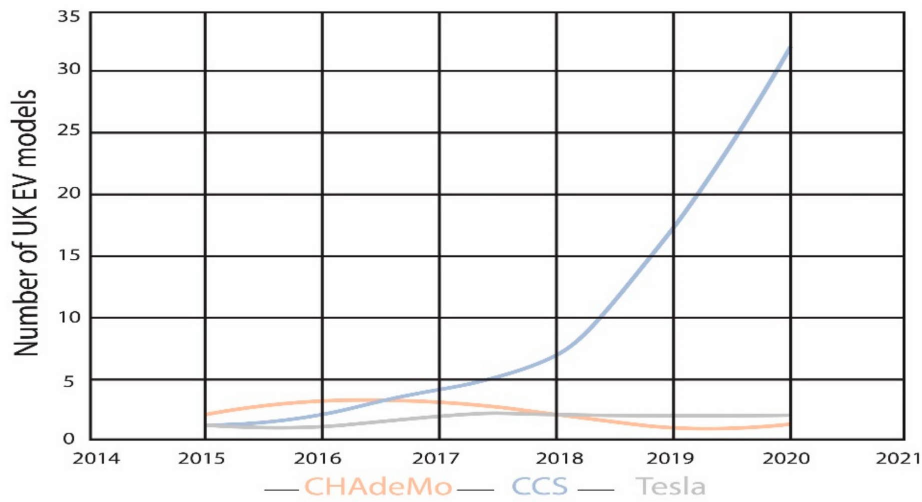


Figure 10. CCS adoption in UK, versus CHAdeMO and Tesla [38].

There is an increase in both government and commercial investment into the charging infrastructure. This will not meet the current and forecast demand of UK EV growth, as highlighted in Figure 9. It is made clear in Figure 11 that the number of new cars supporting the CHAdeMO charging protocol amounts to just one manufacturer. We discovered that every charge point being deployed in 2020 still includes an equal number of dual CCS and CHAdeMO charge outlets. This does not support or correlate with the higher growth and demand in the CCS EV market in Figure 10 and model specific data in Figure 11 and could lead to substantial availability issues for the dominant CCS type EV owners in the near future. This may lead to even greater consumer resistance, frustration, and slower growth.

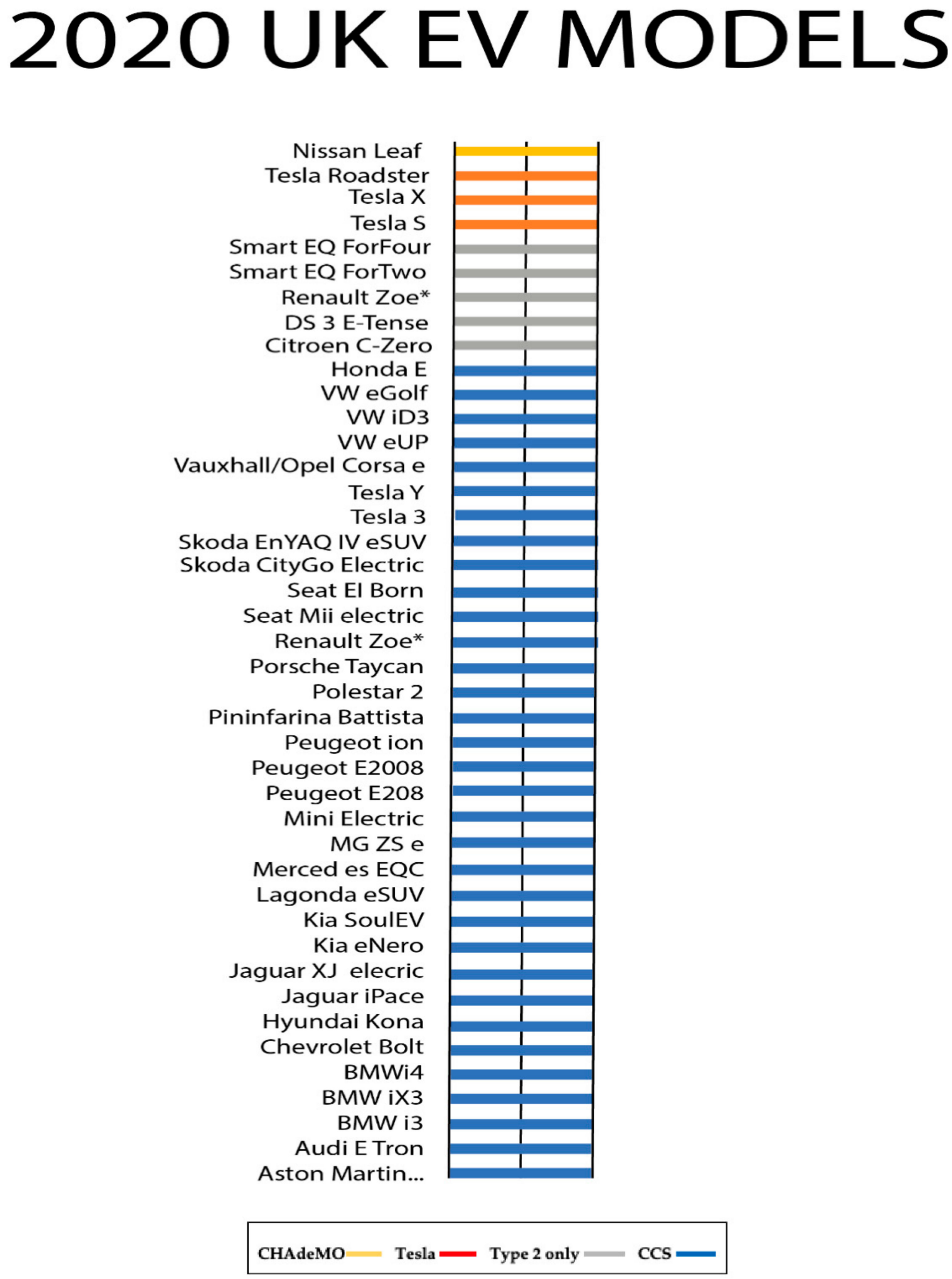


Figure 11. Charger connector types on UK EVs (sourced from each manufacturer—November 2020).

1.12. Theoretical Implications and Agenda for Deeper Research

We find that theoretical standardisation models need refinement in this area. We therefore recommend that further research should address multi-model harmonisation of standards using three viewpoints: (1) governmental role and other enabling actors, (2) policy formulation for individual actors, and (3) the impact of multi-model standardisation and how coordination affects the overall process.

1.12.1. Implications in Practice

We also discover a lack of cooperation between key actors, particularly horizontal compatibility [39], confirming how the development of charging standards and harmonisation of communication protocol will allow for increased practicality and acceptance to this new technology, allowing ease of transition towards a sustainable, emission-free mode of transport.

1.12.2. Polymodal Standardisation in a Technical Context

The study incorporates historical development of disparate standards from 2010 to 2020, including polymodal charge connector types, communication handshake protocols, and user payment systems and, although we discovered numerous papers and articles covering single standardisation issues [5,21,31,34,40], no significant collaborative single harmonisation of rapid charge point standards exists to date. Side issues exist concerning EVs effect on grid load capacity at peak times to service the forecasted growth in EV numbers, although most papers are now outdated [39]. Moreover, we argue that this can be countered through the use of battery energy storage systems (BESS) charged at off-peak times to complement, buffer and de-stress the grid at peak times, known as peak lopping or shaving [10].

However, in April 2020, at the International Green Car Congress, the CHAdeMO group announced a new Asian consortium that recently developed a new-generation connector standard, named CHAOJI. It can significantly advance CHAdeMO with a charge rate ability up to 1000 kW to a maximum of 1500 V DC [41]. Another advantage is that this new standard is backwards compatible with the two dominant incumbents, CCS and CHAdeMO. CHAOJI is bi-directional, capable of enabling the EV to act as a stand-alone generator [6] It is clear that the EV world has not yet reached the point of total harmonisation in the rapid charging protocol and connection, and as technology progresses, we believe that this barrier to growth will mutate and proliferate for many years to come. Figure 12 illustrates key topics in this field, pointing to further areas of enquiry.

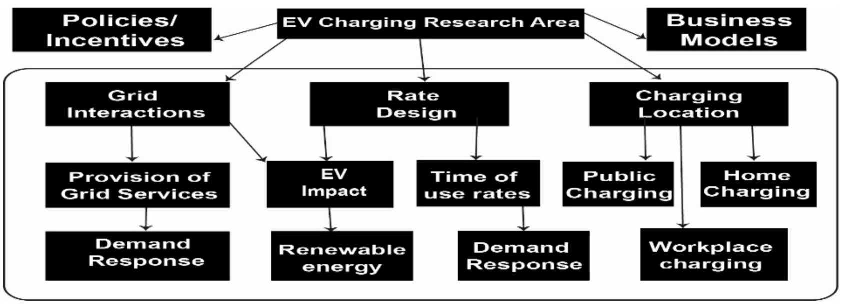


Figure 12. UK EV charging protocol and charger to car connection research analysis [42].

1.13. Standardisation and Its Impact on Innovation

Our research reviews the role of EV charge point standards and standardisation through the many phases of innovative progression ranging from the grid supply side to the demand side, such as commercial procurement. Furthermore, intellectual property rights, particularly patents, should be considered. Previously, principles have been studied periodically in standards development to encourage innovation [43]. Hence, the volume of experiential studies evaluating the influence of the harmonisation of standards on innovation is somewhat inadequate. Conversely, compared to the conventional perception of a conflicting relationship, this study finds that the problem encourages innovation, particularly if numerous structural circumstances such as the openness of the harmonisation process are available for scrutiny and mutual improvement. Thus, future innovative protocols and success can be measured by the opportunities that harmonisation of EV rapid charge point standards offer.

Notwithstanding the mounting significance of polymodal standardisation, it has received surprisingly little consideration in research. The principal view in the literature [44] assumes that every standardisation development relies solely on one of the four modes that we investigated. Though we found many historical instances, such as the market battle between Betamax and VHS [21] and ISO 9001's committee-based harmonisation, that conform with this view, it remains that a mounting quantity of cases remain unresolved. In this investigation, we contribute to engendering a greater acceptance of these developments and the related standardisation models.

2. Results and Discussion from Structured Interviews and Qualitative Validation

2.1. Methodology

Data sets describing user preferences and habits were collected using a series of structured interviews based on the four-point Likert scale system [7] using a sample of 282 EV end-users, spread across eight public rapid charge point centres on the main UK motorway network over three months. Our choice of location was based on the fact that most long UK journeys requiring charge-ups along the way occur on the UK motorway network. Therefore, eight strategic sites all grouped on known commuting routes and amongst the country's busiest service areas [45], including the major conurbations of Manchester, Birmingham, Bristol, and London, were selected, including the world's longest city ring road, the M25, encircling the city of London. Survey data was gathered from 282 rapid charge point user respondents from a total of 363 potential EV users invited to participate. Interviews were conducted over 12 weeks to capture both commuters and leisure based EV users to minimise user profile bias. Since time was often a constraint for interviewees, a standard structured questionnaire was used for the interview process. The only personal details asked were age group, gender, average mileage using pure EV and length of time that the vehicle was owned, rented or leased. No questions were user identifiable, whilst most questions were simplified using a four-number ranking user satisfaction system for data analysis ease.

The core survey questions included usability, operability (charger out of action), cost of charge, charge time, charge time satisfaction, car model, vehicle range satisfaction, and ease of making payment. The full survey results are highlighted in the Appendix A. The average survey completion time for respondents was nineteen minutes.

All predesigned questionnaire interviews were recorded in real-time using a computer tablet. The interview responses were instantly backed up using a dedicated 4G cloud server to ensure secure data capture. Collected data was then transcribed in preparation for analysis. Figure 13 shows the number of survey respondents at each location.

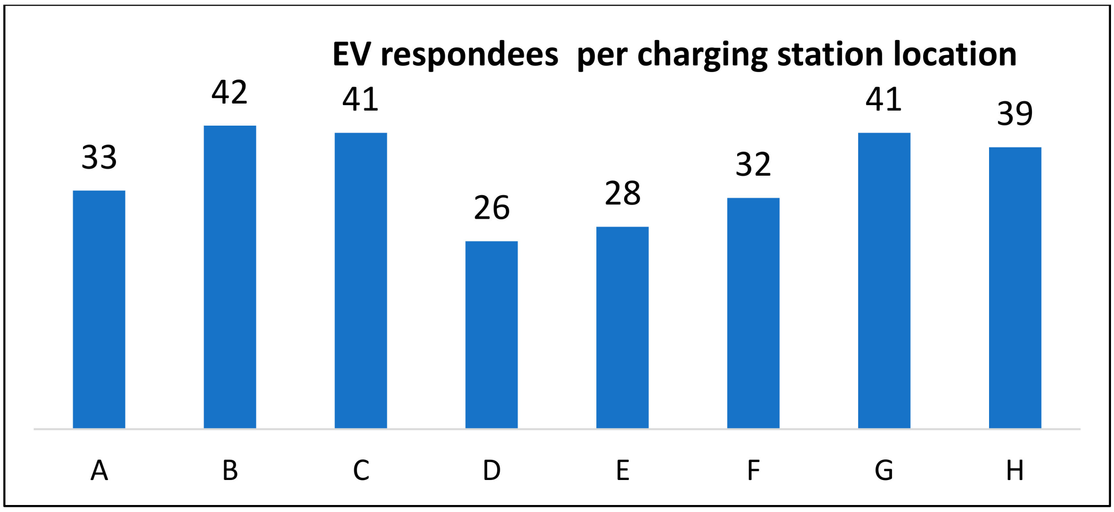


Figure 13. Primary survey investigation at 8 locations. September–October 2019.

Following the interview process, data was gathered and analysed. Secondary research was performed to cross-check and examine the collected data for overlaps or inconsistencies between the participants' experiences. This analysis was validated and verified using the Red Amber Green (RAG) system to ensure that the most relevant data were used for each subject matter. The coding and verification process is based on an original framework designed by a research group at Columbia University, New York [46].

2.2. Results

Survey Summary

The survey of 282 adult EV drivers across a sample of the busiest trunk routes and service stations of the UK from 4 September 2019 to 21 November 2019 questioned UK EV users about their satisfaction ratings concerning their own user experience on a range of questions focused on the UK motorway service EV rapid charge point stations. This section provides a summary and overview of key analytical points of the survey. Figure 13 indicates the number of respondents surveyed at each location.

We found that just 16% of female EV drivers used the rapid charging stations compared to 83% of male EV drivers, with the 61–75 age range making up the highest percentage (shown in Figure 14). The ratio of female EV drivers using rapid charge points does not correlate with the ratio of female drivers using conventional fuel stations on the motorway, which equates to 35% of all drivers [47]. By comparison, the female to male ratio of drivers overall in the UK is even greater, at 46% [29], suggesting that most long-distance travel in the UK is made by male drivers overall. Just one person declined to confirm gender, the consequence of which is not significant to the outcome of this survey.

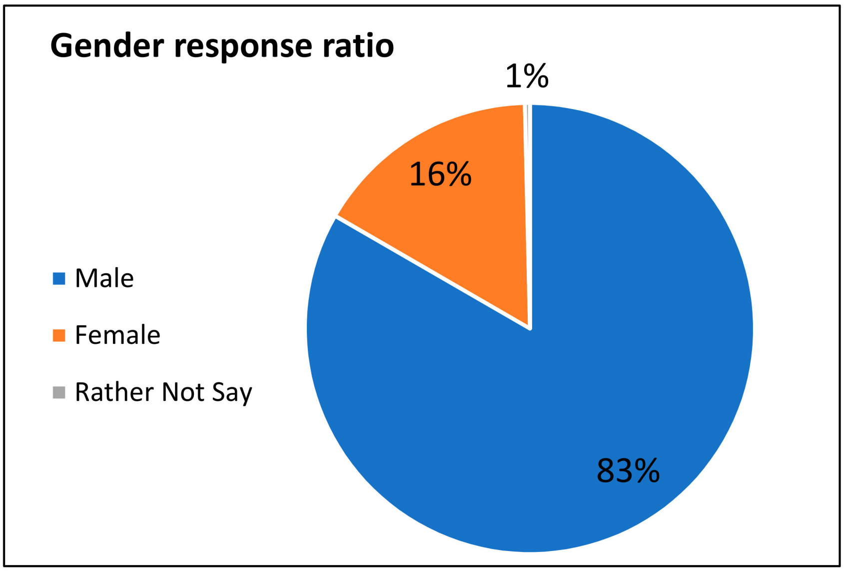


Figure 14. Survey gender response percentage.

The age range of EV user responders (Figure 15) varied from 17 to over 75, with the largest age range of EV users being 31–45, correlating closely with conventional ICE drivers using traditional fossil fuel service stations on the UK motorways [29].

The average EV user annual mileage per annum (Figure 16) was between 5000 and 15,000 mpa, with a more significant percentage of EV drivers in this survey averaging between 5000 and 12,000 miles per annum. This outcome correlates closely with two DfT surveys carried out over the past five years, suggesting that EV drivers use their cars similarly to conventional car drivers (2, 29).

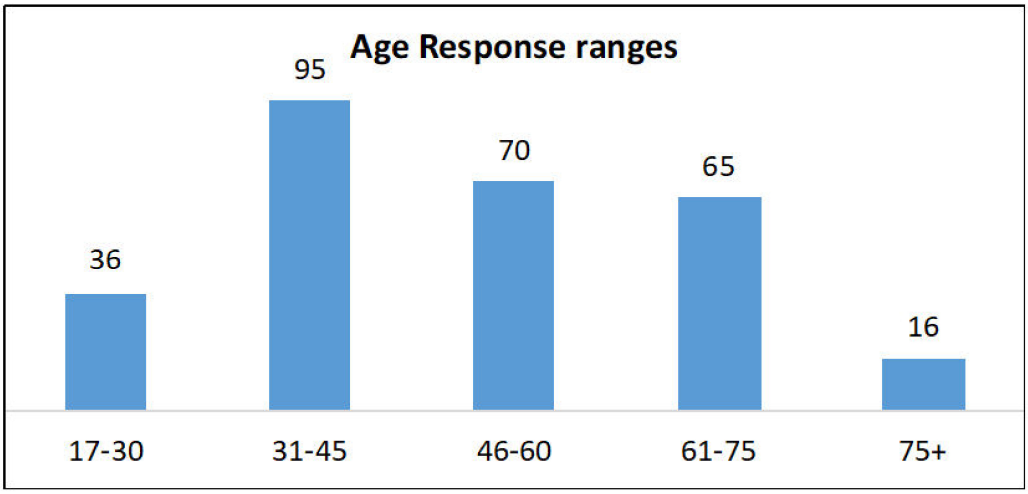


Figure 15. Number of survey responses for each age group.

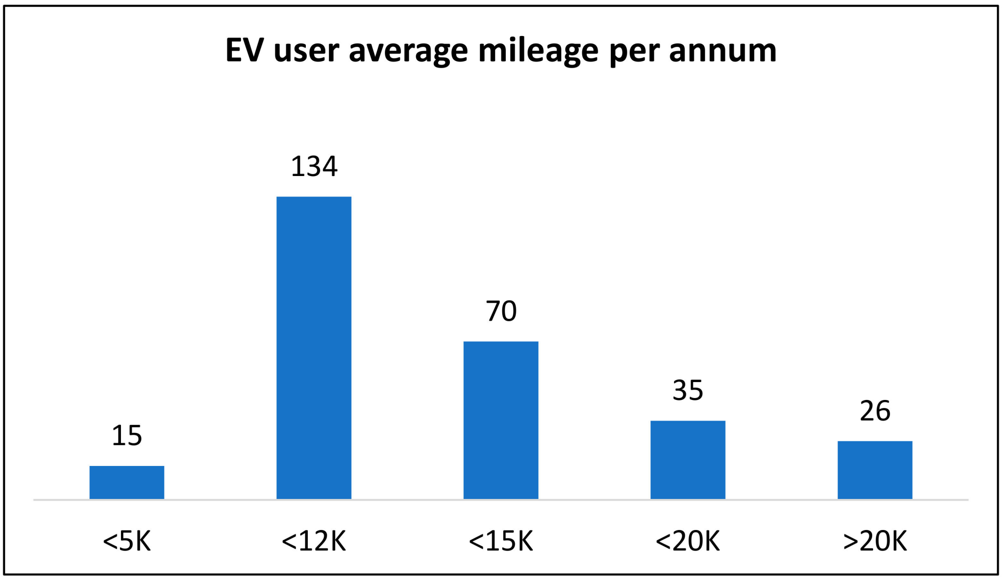


Figure 16. Number of survey responses by mileage group.

The EV ownership period per EV driver for this relatively new mass form of transport is, not surprisingly, low, with the most significant number of drivers only having owned an EV for less than six months and only 18% of respondents having owned an EV for longer than 18 months (Figure 17).

Using an adaption of the Likert scale for this nine-question section of our survey [7], we opted for a four-answer structured methodology to avoid any neutral answers. This questionnaire design method is frequently cited as having bipolar dimensions since responses can be presumed to underlie the semantic differential, according to a publication by Green and Godfried (1965). However, this prevalent rating scale was deemed ideal for our investigation. It was simple for the responders to understand, it averted a neutral response and was quick to complete and simple to conduct data analysis. The questionnaire template (Figure 18) was used on both a tablet auto-linked to our cloud-enabled 4G connected database and in paper form. The template was concise and intuitive to use, and simple to populate for both interviewer and respondent.

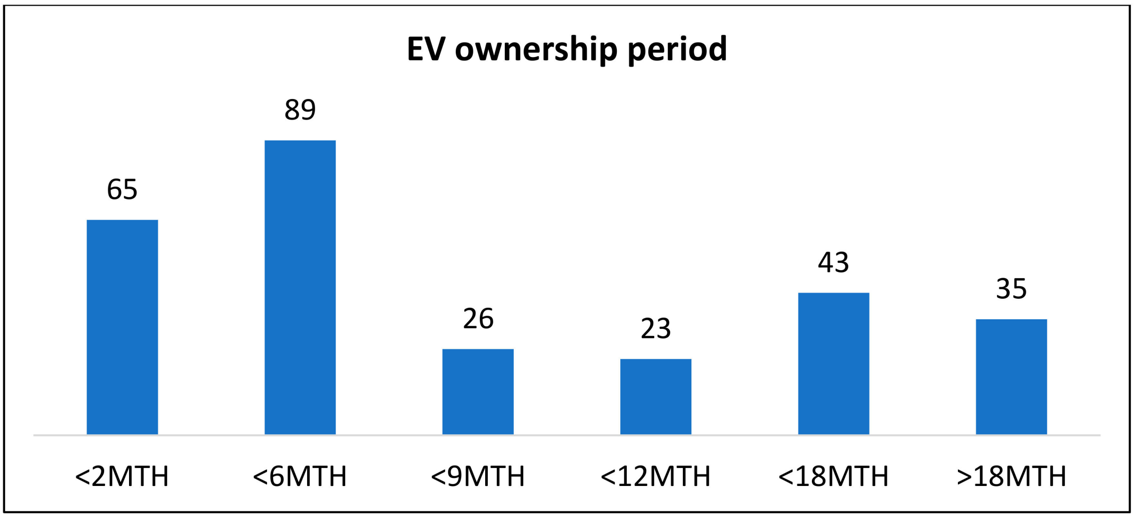


Figure 17. Length of EV ownership per response group.

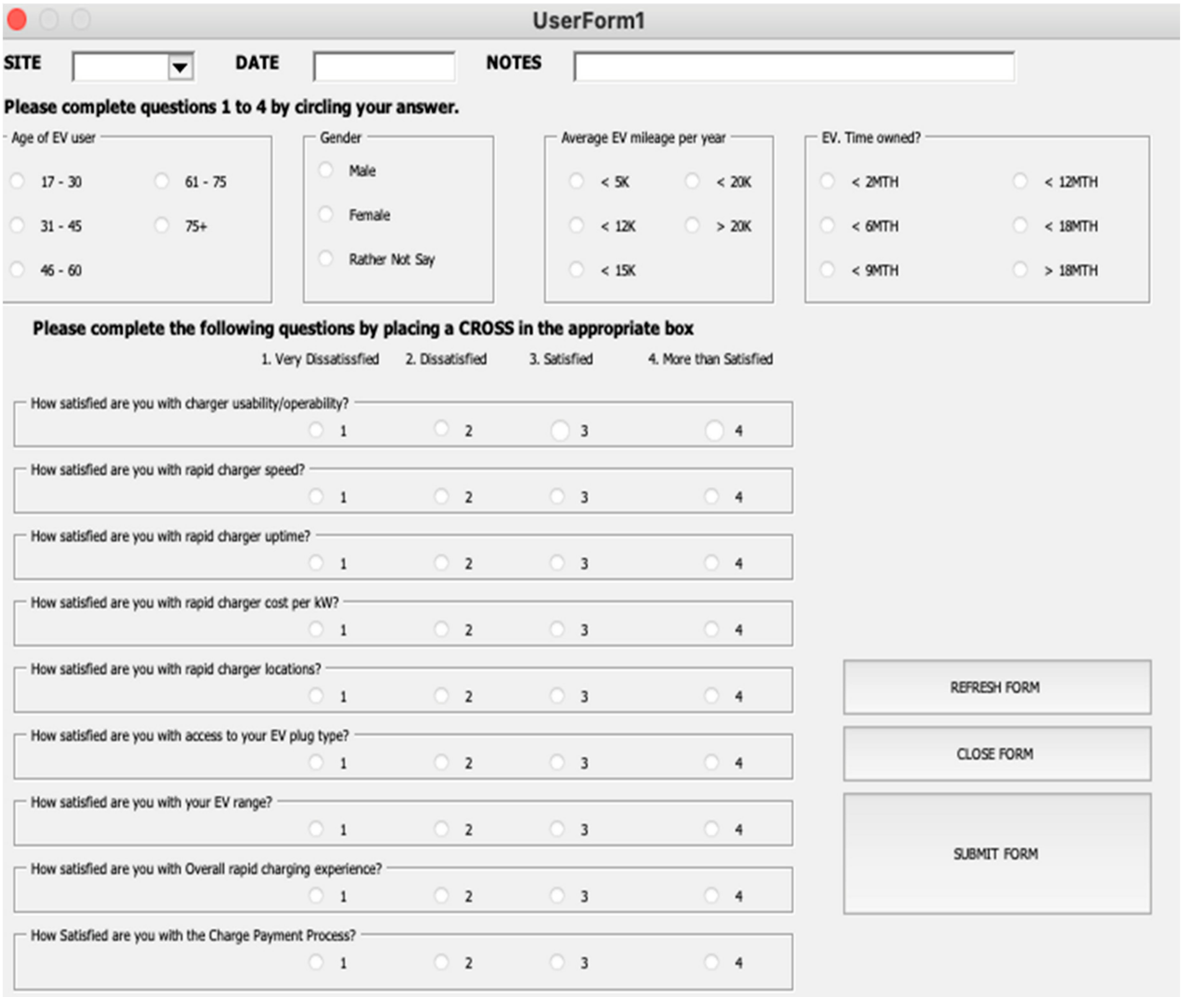


Figure 18. Survey data input template used in both tablet and paper form.

In conducting this section of the survey, we asked nine relevant questions, in which their answers could indicate whether or not our hypotheses could be proved or disproved from the survey outcome. Question eight asked respondents to rate their overall satisfaction for their rapid charging experience.

In the first question, the EV users were asked for their satisfaction rating of rapid charger useability and operability (Figure 19). This covered whether the charger was operating on arrival and, if so, how easy it was to use. The results show that a significant number of users were satisfied (76%) or very satisfied (17%), with only 7% dissatisfied or very dissatisfied. This contrasts markedly with our hypothesis and is the reverse result of a recent survey by UK DfT [2].

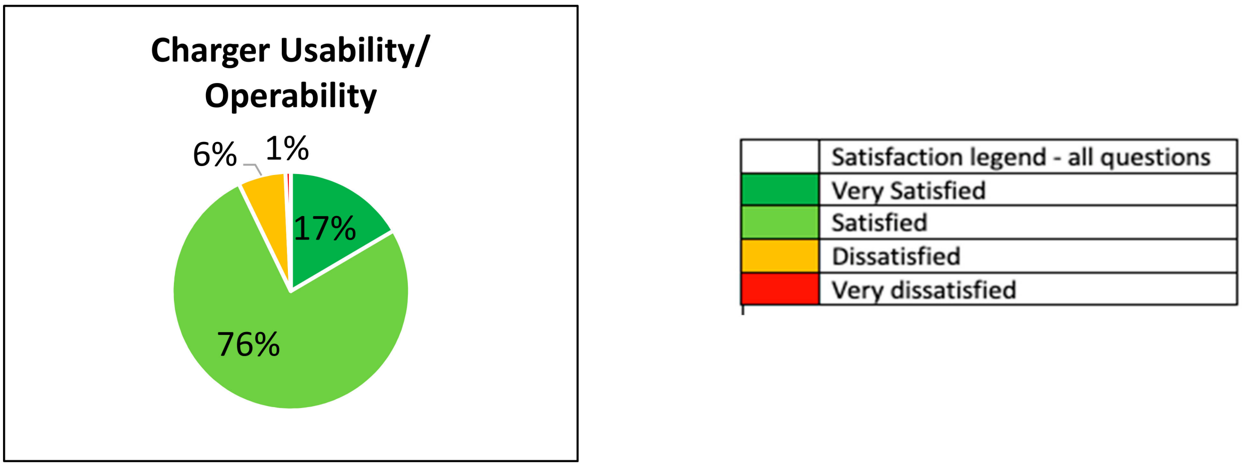


Figure 19. Rapid charge usability, availability and operability satisfaction—with Legend.

The second survey question asked for the EV users satisfaction ranking regarding the charge point charging speed (Figure 20). Again, this produced a positive result, with just 17% of respondents citing dissatisfaction, and may suggest that the user is achieving full or adequate charging speed when charging.

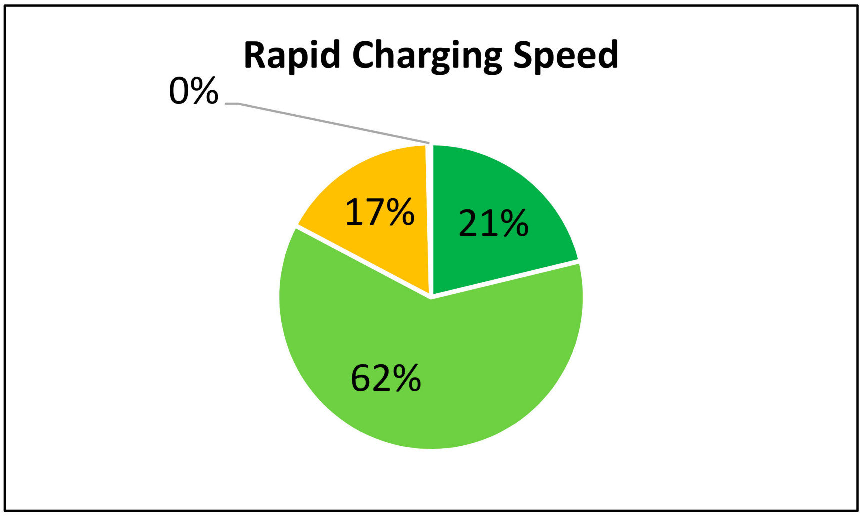


Figure 20. User satisfaction toward rapid charge point speed.

In the third question, the EV users were asked for their satisfaction ranking for charger uptime availability (Figure 21). The results conflict with question one because they are both related to the rapid charger network reliability. Fifty-four per cent of respondents cited being very dissatisfied or dissatisfied, versus 46% being either satisfied or very satisfied. This is backed up by a recent survey for the Times UK by ZapMap [38].

Question four relates to the user's experience with charge payment, particularly cost per kW of charge (Figure 22). The result of this question was overwhelmingly negative, with the percentage of respondents either dissatisfied or very dissatisfied amounting to

95%. This sentiment is backed up by several publications including Serradilla, J. et al. [48] pointing to the dissatisfaction of long-haul EV users that rely on rapid charging systems, backed by a statement made by BP Pulse on their website that they charge GBP 0.42 per kWh, costing the average long haul EV user GBP £37.80 per 230 miles, which is effectively more expensive to refuel than, say, a medium-size petrol or diesel powered SUV [5].

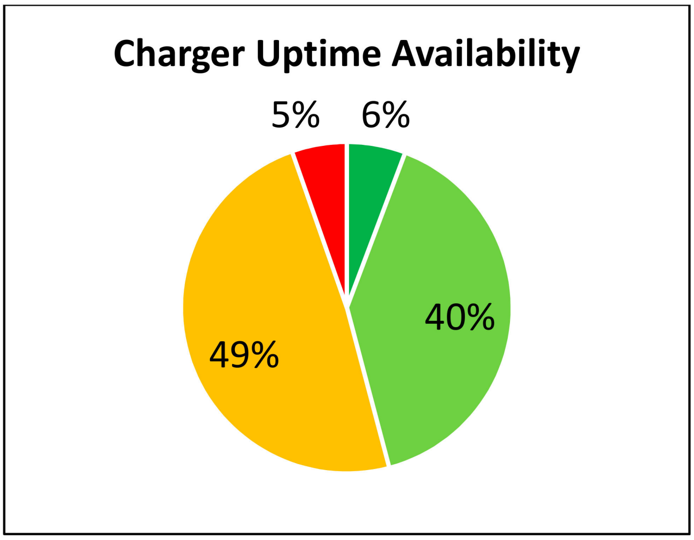


Figure 21. Rapid charge point uptime availability satisfaction.

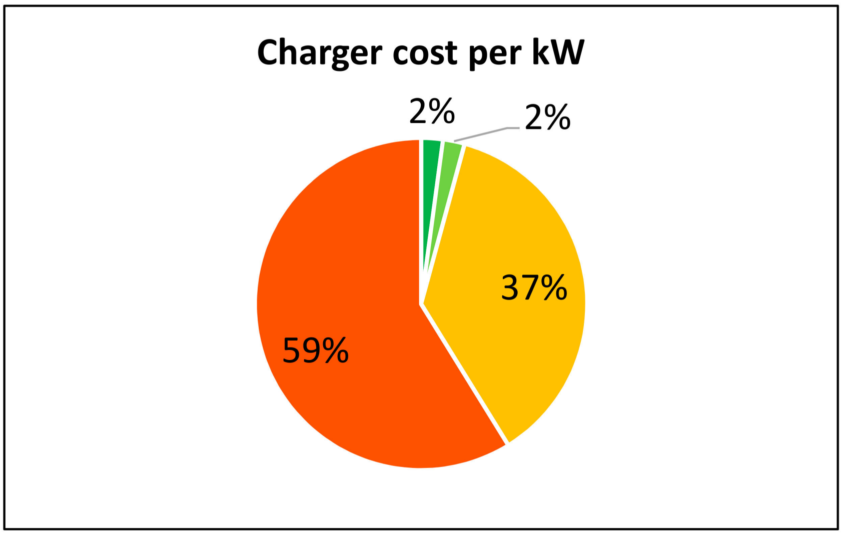


Figure 22. Satisfaction of charger cost per kW.

The fifth question in the survey relates to where the rapid chargers are located (Figure 23). We asked each respondent how satisfied they were with the location of rapid chargers within the service station. Ninety-seven per cent of respondents were either dissatisfied or very dissatisfied with the rapid charging network location in general. We failed to find any reputable journal or report to back up or counter this evidence.

Question six asks the EV users how satisfied they were with access to the EV charger plug type for their vehicle (Figure 24). Ninety-eight per cent of respondents cited that they were either satisfied or very satisfied, suggesting that dual-mode chargers' roll-out is the solution for almost all EV drivers.

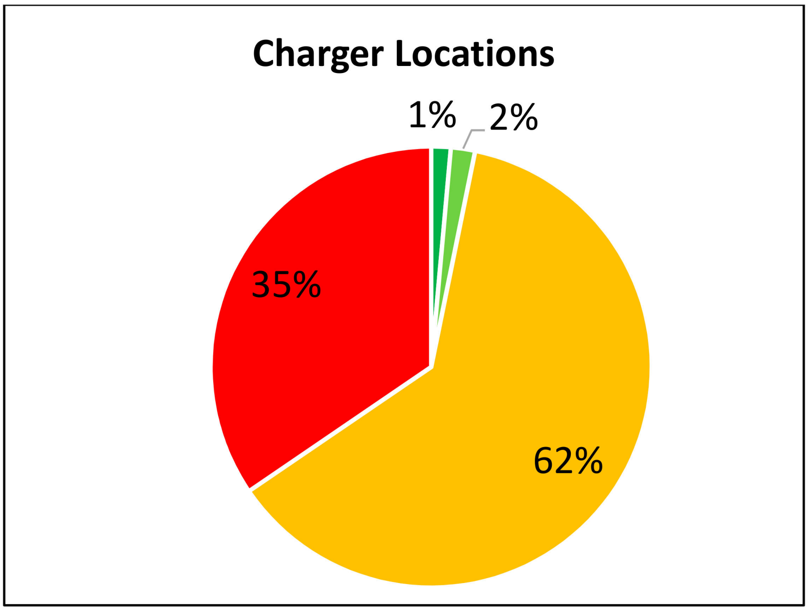


Figure 23. Respondent's satisfaction of rapid charger locations.

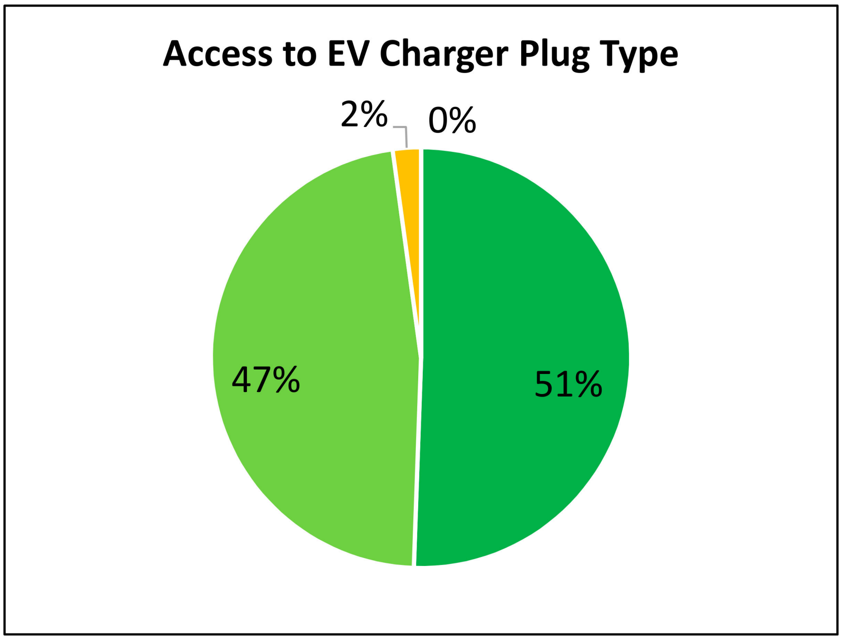


Figure 24. User satisfaction toward availability of charger connector.

In question seven, the EV users were asked how satisfied they were with their EV range (Figure 25). The purpose of this question was to check that their EV range was not influencing a subconscious bias on the EV user's response to the questions overall. In the event, a significant 74% of EV users were either satisfied or very satisfied with their vehicle's range.

Question 8 in our survey asked the respondents for their overall rapid charging experience (Figure 26). Eighty-four per cent indicated that they were either satisfied or very satisfied with their overall rapid charging experience. We later compare and contrast this with an automated generation of their combined responses from each question.

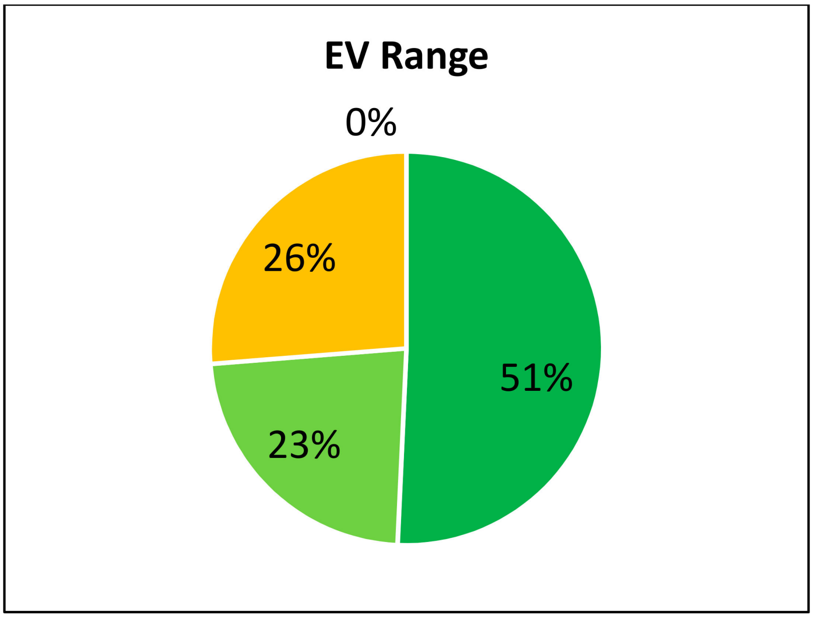


Figure 25. User satisfaction of their EV range.

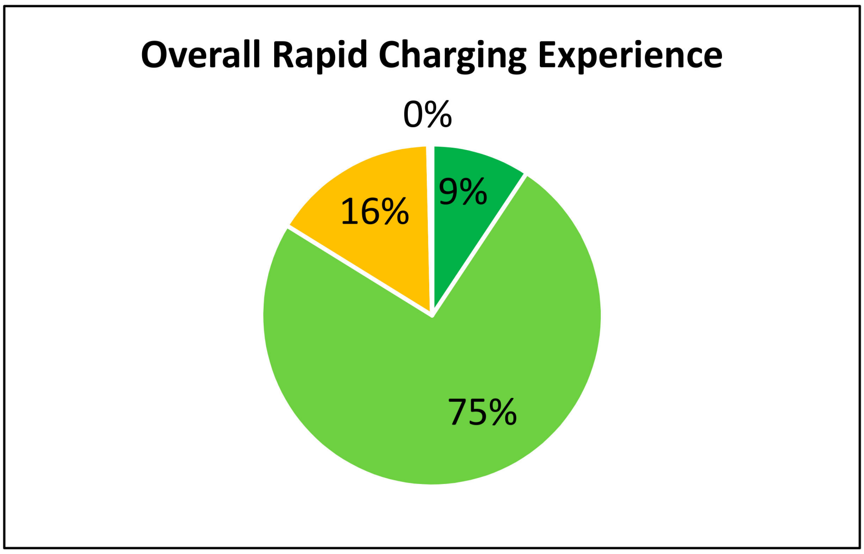


Figure 26. Users' overall rapid charging experience.

The final survey question asked EV users how satisfied they were with the charge payment system of rapid chargers (Figure 27). A significant number of respondents indicated that they were either dissatisfied or very dissatisfied with the charge payment system. This amounted to 73% of respondents and was similar in outcome to question 4, which was also related to the charge payment system, concurring with recent findings regarding charge payment harmonisation and standardisation [5,28,37].

We then cross-checked with a system-generated user satisfaction outcome across all questions combined. We found a conflict between user sentiment in question 8 versus a combined satisfaction outcome across all questions using the system generated result (Figure 28).

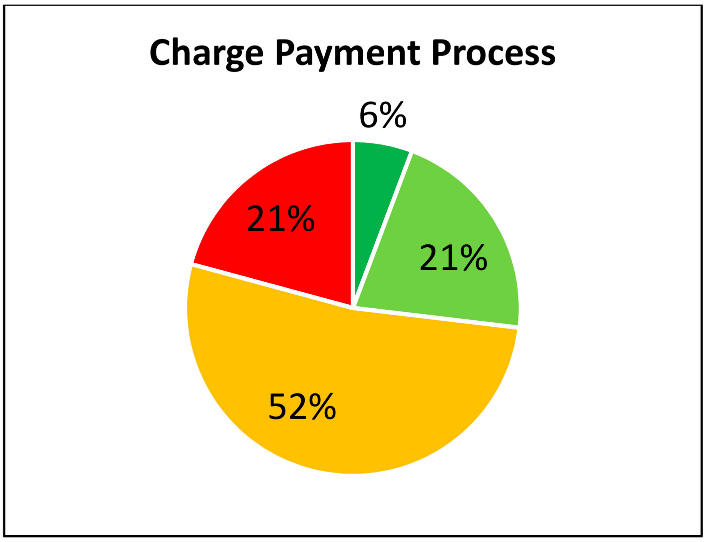


Figure 27. User charge payment process satisfaction.

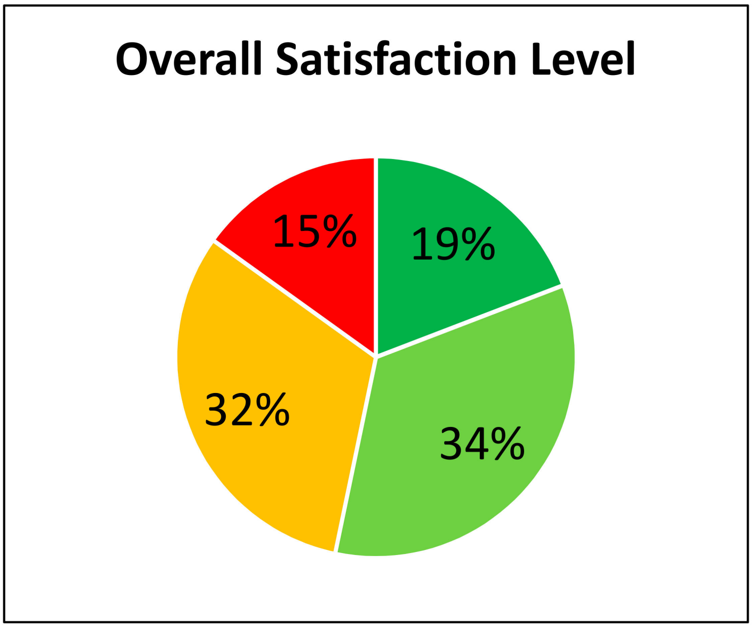


Figure 28. System generated overall satisfaction level.

2.3. Discussion

Our interview results suggest that the effect of a 'Winner-takes-all' strategy, paralleled in a study by Evens, T. and Donders, K. [49], maybe influencing the fragmented standards that are indirectly causing user dissatisfaction in some areas, such as charger location and payment experiences. Though the sector of their research is not directly related to rapid charging, the commercial outcomes reflect a similar cause and effect, resulting in a race to establish a championed standard for charge point connection. This phenomenon may be a factor that leads to EV user anxiety that might create barriers to EV growth by propagating negative user experience through mainstream media, word of mouth and social media. This was evident, particularly in the areas of charger usability, charger operability, location of charge points and charger payment experiences, graphically illustrated in the full results of our survey in the Appendix A.

Additionally, it is vital to not merely recognise historical secondary data within this dynamic and fast-moving technological field, but rather to refine under what circumstances current and future EV user issues will create barriers to growth. Furthermore, we investigate whether this data will be dominated by certain results exhibiting biases, leading researchers to the resources they seek, thus pointing to a variety of outcomes. Our primary research's particular characteristics will increasingly determine whether government intervention can evolve as the panacea in this market battle, leading to the mutual benefit of all actors as either facilitator or as an influential gatekeeper in EV process harmonisation. In practice, the two are hugely influential and intertwined.

In our survey's design and methodology, we were careful not to mention (both verbally or implicitly) standardisation or harmonisation, nor did we mention any of the three key areas that formed the basis of our study. We believed that to do so would have influenced the user's answers and introduced an element of bias. Thus, the questions concerning this investigation were purposely agnostic by design, aimed at achieving minimal response bias.

Each question is either directly or indirectly linked to one of our three main question areas, known henceforth as H1, H2 or H3, with H covering two or more main question areas, and general user questions known as G. We illustrate dominant responses to each survey question in Figure 29.

	Questions				Subject	H
	Very Satisfied	Satisfied	Dissatisfied	Very Dissatisfied		
Q1		76%			Charger usability and availability	H1
Q2		62%			Charger speed	H1
Q3			49%		Charger uptime and operability	H1
Q4				58%	Charge cost	H
Q5			62%		Charger locations	H1
Q6	51%				Connector availability	H3
Q7	51%				EV range	G
Q8		75%			Overall experience	H
Q9			52%		Payment process	H3
CGA		34%			Satisfaction level average	H

Figure 29. Dominant results from each survey question.

- H1 Does non-standardisation of charge connection and the three dominant connector types (CCS, CHAdeMO and Tesla) affect charge point availability and user satisfaction, or are they the product of other contributing factors?
- H2 Will standardisation of the two dominant car to charger communication protocols improve user satisfaction and benefit all stakeholders?
- H3 Will charge point payment standardisation benefit all stakeholders in the long term, and most importantly, improve user satisfaction?
- H Subject covering more than one standardisation area
- G General user satisfaction questions.

Key

- Q1, etc. Question number.
- CGA Computer-generated average.
- H Hypothesis match—1–3.
- G General question relating to user EV

Analysis of Survey Data

While it was never certain that all questions in our survey would yield tangible pathways to reduce barriers to growth in the EV sector, we anticipated some areas that would help shape and drive standardisation for UK rapid charging infrastructure in the future, to the benefit of the end-user.

Question 1 was an area that we felt would not produce positive responses from EV users, particularly as a recent article [38] ranked UK motorway rapid charging bottom of an EV user survey. Yet, 93% of respondents in our study were either very satisfied or satisfied with charger usability and availability. This area needs further investigation using either workshops or semi-structured interviewing techniques and may result in a slightly different outcome. Our survey result suggests that despite known downtime issues on the UK motorway rapid charge network, EV users appear to have high tolerance levels towards low levels of service availability. It is clear that existing users' experience in this area does not introduce a barrier to growth where harmonisation of standards is well catered for, with all three connectors available at every motorway rapid charging station.

Question 2 is an area that demonstrates higher levels of tolerance towards rapid charge speed than anticipated. One area that does distort the overall outcome of both question one and two is that 15% of all respondents had access to the Tesla motorway supercharger network. This network scored highly in the recent survey of UK motorway network ranking [38], although 83% of users ranked this area overall as very satisfied and satisfied combined. Thus, if we remove the Tesla network influence, the satisfaction level is still good at 63%. Despite the main charger stations providing a maximum of 50 kW, the high user tolerance to relatively low speed levels appear to have little effect on user satisfaction. Therefore, it cannot be claimed that harmonisation of standards would improve user satisfaction significantly.

Question 3 relates to charger uptime availability and is the first result in our survey that shows a high user dissatisfaction level. The study found that 54% of EV users were either dissatisfied or very dissatisfied with the charger uptime or reliability. The UK motorway network was installed more than ten years ago when CHAdeMO was the dominant charge point connector [38]. The network later upgraded its chargers to accept CCS, and it is known that this CCS upgrade has always proved an issue, especially in the handshake protocol between car and charger. Therefore, this is a crucial area where harmonisation of standards would help raise user satisfaction to the benefit of all stakeholders, as CCS now accounts for 88% [38] of all-new EVs.

Question 4 focuses on charge payment for power used by the EV. This is the second outcome revealing high levels of dissatisfaction at 96%. Costs of up to GBP £0.40/kW for non-Ecotricity (the company that owns the motorway charging network) members are noted, meaning the cost to charge an average EV can be close to the cost of fuelling a petrol car, compared to charging from home, that is typically GBP £0.10/kW. This and one other area in question nine leads us to the conclusion that the fragmented UK payment process for rapid charging is an area where harmonisation of standards is needed now. More than 20 major charge point companies operate in the UK [30], with few roaming agreements, some PAYG, but mostly members-only clubs with charger access typically by RFID card or a mobile phone application. Compare this experience with refuelling a conventional car, and it is clear why some EV drivers become anxious to travel long distance in an EV.

Question 5 is an area that centres on the location of rapid chargers. The UK rapid charger network is often tucked away at the far side of a service area car park, rarely close to the conventional petrol filling station. At times of renovation, it can be shut down without notice [38], often leaving EV drivers stranded. The location directly correlates with the growing sentiment of EV users [50] to a huge dissatisfaction level, amounting to 97% of respondents. This issue can only be resolved if UK EV drivers are treated with similar harmonised standards that conventionally fuelled drivers enjoy. This study suggests that whilst the outcome alone may not deter new entrants to the EV market, it may encourage EV drivers to return to conventional vehicles and thus act as a barrier to growth.

Question 6 relates directly to the EV user's direct access to the correct EV charger connector on arrival at a charging bay. An overwhelming 98% of users were either satisfied or very satisfied that they had good access to the correct charger plug on arrival. However, further research will need to be implemented soon to see if this is still the case, as a growing number of exclusively CCS EVs enter the market. Therefore, these results do not currently suggest that the lack of harmonisation of standards affects EV user satisfaction in this area. Still, as the market grows, the study indicates that a lack of CCS charge points may be a growing concern as connector standards head towards a market predominantly equipped with CCS connection.

Question 7 does not directly relate to the harmonisation of standards, but it indirectly has a shared link, where EV owners with lower range models rely more on rapid chargers, especially on longer commutes. Thus, we asked each respondent how satisfied they were with their EV range. The result was predictable due to a small percentage of drivers that were still using first generation EVs. Each respondent in this first-generation EV category cited dissatisfaction with their EV range. The lower the battery range, the more stops to recharge are made on average for the same distance compared with a newer EV. Thus, these drivers must have easy and open access to the rapid charge network. Almost all drivers in this category drove cars equipped with CHAdeMO charge point connection. Whilst this issue will not directly slow EV growth, it does highlight the need for harmonisation of connecting and payment standards.

Question 8 is centred on how each EV driver rates their overall rapid charging experience. We discovered that on the whole, 84% of EV drivers, especially those with vehicles less than eighteen months old, were either satisfied or very satisfied with the rapid charging process. No respondents were very dissatisfied, suggesting that overall, the rapid charging experience had a positive outcome, considering this is a relatively new technology.

Question 9 is specifically related to the overall charge payment process on rapid chargers. The survey outcome reveals that 73% of respondents were either dissatisfied or very dissatisfied with the charge payment system and concurs with recent findings regarding charge payment harmonisation of standards [5,28,37]. The response to this question is similar to question 4 (Charge cost satisfaction). It again leads us to deduce that harmonisation of standards is vital for the confusing UK payment process for rapid charging. With more than 30 major charge point operators in the UK [30], and few roaming agreements, many member-only clubs using RFID or dedicated apps outnumber charge points that operate on an open PAYG system by a ratio of 10:1 [50]. Compare this experience with refuelling a conventional car, and it is clear why some EV drivers develop anxiety when embarking on long-distance trips in an EV.

Figure 28 reveals a simple computer-generated cross-check combination of data from all questions to simply compare and contrast, particularly with question eight, in which EV users were asked to state their overall rapid charging experience. One would expect that this outcome would more or less mirror the result in question eight. However, the effect was a marked contrast that showed that 53% were either satisfied or very satisfied with EV charging in the computer-generated calculation based on actual question results, compared to EV users own general preference. This phenomenon is known as hypothetical bias and is common in stated preference questionnaires, confirming that further study in this area should be semi-structured in construction and delivery, to improve data quality [51].

3. Conclusions and Future Work: Implications for Practice and Further Research

This investigation emphasised implications for theory building that is also relevant in practice. Our own primary research suggests that all stakeholders in the ongoing technological and greater social transformation are likely to be impacted by the consequence of EV rapid charger standardisation practice for charge connections and communication, which we anticipate will become monomodal over the next decade. Business actors, NGOs, and research and trade associations should therefore be cognisant of standards development. Should they choose to contribute to the process, they must consider the range of choices that polymodal harmonisation can contribute to their policies by offering single point, 'available to all' rapid charge points, similar to traditional fuel service stations' forecourts. A single standardisation model can be achieved by encouraging government intervention, which demands appropriate resources, timing, and consideration.

From our survey results, although end-users are generally satisfied with their EV as a whole, significant areas of dissatisfaction persist, including charger uptime and availability, charge cost, charger location and payment processes, all of which would be positively impacted by systemic standardisation. Furthermore, a lack of charge point connector standardisation has resulted in the introduction and adoption of new node-specific charge point communication protocols over the past decade, resulting in handshake issues between the car and charge point, initiating reduced charger uptime and availability.

Additionally, charge cost, charger locations and payment methods, the high price of charging away from home, and the lack of convenient locations directly result from the lack of standardisation among charge point operators (CPO's) and EV manufacturers. The majority of CPOs require paid monthly membership, depriving EV drivers of the freedom to simply charge their EV at the station offering the lowest price, with limited payment options. Additionally, not all EV connectors are supported at every charging station, and the need for charge support for multiple charge point options limits the number of chargers available to users. Multi-level systemic standardisation can be used to solve these issues, supported by our detailed literature review in Section 1. In addition to improving general user satisfaction, addressing these issues would also lower barriers that currently act as a deterrent to new end users entering the EV market. This approach will benefit all stakeholders, leading to a ubiquitous EV charge delivery system on par with the universal standardisation experienced by non-EV drivers at traditional fossil fuel stations.

Moreover, we have demonstrated that stakeholders who do so gain a wide variety of options to encourage standardisation, many of which only materialise at key stages of the process. To employ these choices as part of a reasoned approach, actors should be mindful of the subtleties that are liable to result from this. Participants must be prepared for competitor's actions if they decide not to harmonise specific modes. Additionally, they must reflect on whether to introduce new processes and methods and avoid being rushed by outcomes resulting from dormant modes, such as the continued roll-out of CHAdeMO relating to just one outgoing model by Nissan.

We argue that regulators need to mould their processes in such a way that they are reactive to stimuli from other approaches and appealing for participating actors who have the choice between engaging in panel-based standardisation and other modes. They should also be prepared for increased competition within the panel-based model, since actors from other sectors such as IT are establishing potentially appropriate opportunities for standard development or because of the rise of new entrants such as open-source groups. Policies to maintain suitability in this setting may comprise managing harmonisation schemes, so that standards are not just established and sanctioned, but additionally, their deployment is stimulated and sustained. Moreover, sector actors could highlight their strengths, then agreement among varied groups of stakeholders might focus their input where these strengths are most significant. For instance, sector actors could promote committee-based collaboration to outline all-embracing frameworks and designs for new large-scale harmonised rapid charger systems that provide activities in the sector to create standards for the individual elements within them, such as connectors, communication protocols and payment systems. When solutions that meet sector demands for a standard develop in the market, it may be appropriate to merge them into a fully scaled harmonised standard, thus avoiding replication of effort. Comparable consequences are possible to apply to other industry- or government-based groups pursuing panel or committee-based harmonisation events, such as groups of open-source or practice communities, that may additionally need to attract active participants to guarantee that their resolutions are widely implemented.

Legislative policymakers can follow our conclusions by adopting harmonisation of EV rapid charger standards to reinforce public policy or when they contemplate intervention in the regulation of standards, particularly where there is strong opposition and significant societal consequences. Where standards are used to reinforce policies, we observed that these came mainly from actors in a committee-based standardisation model, whereas the prominence of market-based standardisation in certain sub-sectors implies that government might further benefit by combining standards into their greater policy portfolio, rather than adopting the development of new committee-based standards with established practices. This is particularly relevant in the context of EV rapid charging and its associated complex enablement systems, where standards cannot stand alone long-term but instead must be aligned, thus preventing the emergence and permanent fragmentation of rapid charging standards in a UK context. Hierarchical mediation may consequently be needed as a last-ditch attempt where committees and sector actors such as Tesla, CCS and Chajio with their opposing agendas are likely to lead to unsatisfactory long-term results.

Aside from the well-defined polymodal connector standards, our survey established that improved EV connectivity and crucial data sharing point to the need for a homogenous smart charging solution founded on actual consumer behaviour and real-time status of both vehicles and chargers. This is in stark contrast to the current situation that requires drivers to manually advise some charge point operators of their proximity and current state of charge via their in-car systems or mobile applications to obtain GPS coordinates and availability of the nearest working charge point [52].

During this study, the evidence confirms that the single most urgent element of rapid charger harmonised standards is the ability to plug any EV into any rapid charge point at the most appropriate location. We found that the market-led CCS standard is rapidly becoming the de-facto standard in all cars with a rapid charge facility, with the exception of the CHAdeMO-based Nissan Leaf. Nevertheless, we observed that the CHAdeMO consortium has now developed a new Far East standard named Chaoji [13] that is gaining rapid acceptance in China and Japan. In direct competition with this new Asian standard, the CCS consortium is developing a similar advanced standard. This suggests that the market battle for standardisation is not yet won. Figure 30 illustrates a rapid charge protocol harmonisation model, illustrating the transition from a polymodal to a monomodal outcome, based on our investigation using primary and secondary data and historical trends, noting past socio-technical market battles such as Betamax versus VHS [21].

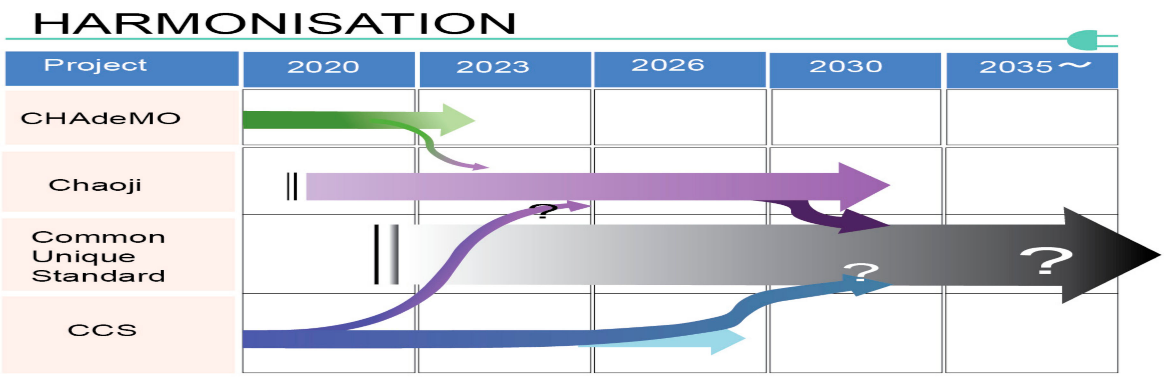


Figure 30. Polymodal to monomodal EV rapid charge connector model. Adapted from source [41].

Additionally, there is significant evidence [20,22] to suggest that improved EV sharing of data and the implementation of direct EV connectivity can encourage innovative smart charging solutions that are founded upon genuine EV status monitoring and customer behaviour, thus eliminating manual user and operator intervention. Little research has been carried out in this important field of EV infrastructure automation. Moreover, the by-product of not resolving the current process flaw of multi-communication protocol and polymodal connector standards will remain a constant user issue and barrier to growth amongst the UK ICE and EV user community. Moreover, there has been a great deal of research on range anxiety, and there still remain many unanswered questions in this field of research. However, as new EVs enter the market with greater range and faster charge capabilities, range anxiety may become a distant memory as we pass through this developmental stage of the EVs resurgent lineage. This, we suggest, can be bolstered by government intervention through more attractive plug-in grants (PIG) and UK government incentives to promote a broader range of EV usage.

We therefore find that if our conclusions are recognised and acted upon by both government and industry actors, then any user anxiety may dissipate as a key barrier to EV adoption in the UK market. Nevertheless, a more inclusive electric transport strategy is required to encourage the growth of EVs in the UK to achieve the UK government's ambitious 'road to zero' targets. Our research is but a fraction of the more significant challenges that lie ahead. EVs will undoubtedly become a key element leading to sustainable cities through large scale acceptance. Such transformation may alter the UK's political and economic dynamics. Our investigation and conclusions are effectively the start of this process but can be used to guide regulation that may shape transport and energy policy into the future. Furthermore, the findings can direct EV developers and manufacturers to integrate user preferences into future EV infrastructure and electric vehicle design.

3.1. Research Limitations/Implications

We focus on the discussion of the interactions between EV users and UK rapid charge points by evaluating their experience and outcomes without fully considering the impact of social environment and educational background that could have an effect on user behaviour and perception. Moreover, this study focuses on only eight of the UKs rapid charger locations, that are sited exclusively alongside the main arterial motorway routes of the UK, purposely dismissing slower charge points in low-traffic volume areas. We designed a qualitative research method to construct the relationships between UK EV CP users on trunk routes because we were mainly interested in how users would respond psychologically and emotionally to the complete EV rapid charging experience on long-distance trunk routes.

3.2. Practical Considerations

The study extended the application of EV user experience and satisfaction levels to expand standardisation theory and how it can eliminate barriers to growth in this relatively new, fast-growing transport market. Additionally, the research method and model used in this paper may serve as a guide to other interested scholars who intend to explore relevant variables and perform further research on the influencing factors of the harmonisation of standards in the EV sector.

Since commencing this study, a private consortium [53] has announced that following government criticism [2], the UK motorway rapid charger network will be completely replaced and upgraded to 150–350kW superchargers. Therefore, it is suggested that a further survey be implemented on completion of this deployment, to contrast and compare satisfaction levels and determine how this then affects EV growth in the UK market. The survey suggests that EV users tolerate slower speeds than are available off the main motorway network. Therefore, charge speed does not appear to be a negative issue for existing users and harmonisation of charger standards is not currently adversely affecting sales growth.

3.3. Social Implications

In this study, numerical data are collected in a structured manner, ensuring reliability, thus maintaining respondent consistency, though restricted by the multiple-choice questions in the survey. This chosen method reduced survey time with busy commuters and identified new variables on this critical subject. As a result, we extracted the fundamental causes of user satisfaction or dissatisfaction in EV users charging experience and potential connections with our three main hypotheses. Appropriate scholars, EV users, and commerce may analyse, manage and forecast EV users' rapid charging anxieties and behaviour, providing guidance for the proposal of corresponding future deployment strategies.

3.4. Study Value and Originality

Relevant investigations in this area generally focus on the EV purchase price and EV range, with a scarcity of EV rapid charging studies from the EV user's perspective, particularly in the UK. Furthermore, in contrast to this study, there is limited research that investigates standardisation of connection, charging protocols, car to charger communication and charge payment process analysis through the examination of EV user experience and satisfaction outcomes.

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Appendix A

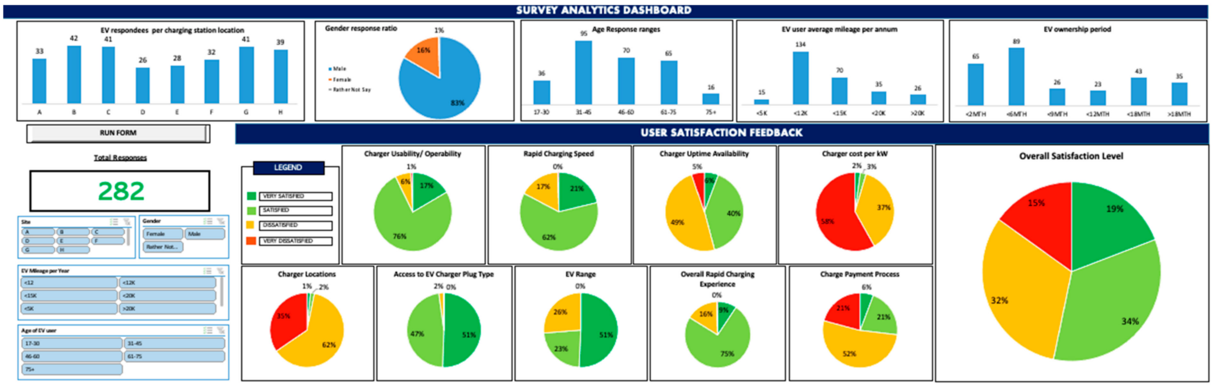

Figure A1. Survey database front end dashboard highlighting all responses.

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