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A Novel Model to Predict Electric Vehicle Rapid Charging Deployment on the UK Motorway Network

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Abstract: Recent transformations from internal combustion engines (ICE) to electric vehicles (EVs) are challenged by limited the driving range per charge, thereby requiring the improvement or substantial deployment of rapid charging infrastructure to stimulate sufficient confidence in EV drivers. This study aims to establish the necessary level of EV motorway service station infrastructure for the United Kingdom (UK) based market. The investigation is founded on increasing the appropriate rapid charger availability and shorter charging times. EV charging patterns are determined, focusing on two Volkswagen iD3 EV models by measuring power curves across field-based rapid chargers at one-minute intervals. Datasets are analysed throughout rapid charging field tests. Additionally, variance synthesis is applied to establish variables within this study's assessment for rapid charger capacity requirements in the UK. The operational performance for the utilised rapid chargers is correspondingly recorded, whilst the EV range is calculated at 3 miles per kWh, revealing a mean power delivery rate of just 27 kW per hour using a 50 kW rapid charger. Time-of-day charging sessions are used to generate data that is then amalgamated into our previous study data, confirming that rapid charging points on UK motorways are used primarily for EV journey range extension. If fully utilised for an entire 24h period, 434 chargers (with a variance consolidation number of 81) are required to service the UK-based motorway EV user base. Moreover, this study establishes that simply replacing current fuel pumps with individual rapid chargers on a like-for-like basis reduces availability and support for novel and existing users and may impact short-term grid availability.

Keywords: VWiD3; charger deployment; rapid charging; charger prediction; behavioural change

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1. Introduction

Throughout the industrialised and developing world, there has been a gradual transition from the ICE to EVs, as noted by the Department for Transport (DfT) [1] and the Office for Low Emission Vehicles (OLEV) [2]. Furthermore, the rapid development and use of lithium-ion batteries, such as for storing electricity for grid supply and powering EVs, requires more reliable methods to understand and predict battery performance, range, and life. However, the importance of this novel study is focused on creating a forecasting model that can calculate the quantity of UK motorway rapid chargers for any given number of EVs, speed of rapid chargers, or battery size and chemistry. The benefit of this approach is that the forecasting model is not historic in its outcome but is scalable and future-proof through key variables in our computations.

According to Neaimeh et al. [3], in 2017, EVs were inferior to traditional ICE vehicles mainly due to range. However, more recent figures from sources such as the established publication Autocar [4] suggest that some 2022 model EVs, such as the BMW iX, Mercedes EQS, and Tesla Model X, have crossed the Worldwide Harmonised Light Vehicles Test Procedure (WLPT) 350-mile range threshold. Although the RAC suggests that an average daily range of twenty-six miles is acceptable [5], there is a natural restraint to travelling beyond an EV's range without the certainty of charging services en route. In 2014, 61%

of Norwegian EV (electric vehicle) owners took their cars on holiday journeys, although by 2016 this had been reduced to 37%. Figenbaum et al. explained this phenomenon as the normalisation of the EV as a vehicle type [6], whilst Namdeo et al. [7] suggested that the limited range of electric vehicles is still seen by many as the critical barrier to the mass uptake of EVs. Two methods could be used to address this. The EV range needs to be improved, and a substantial deployment of rapid charging infrastructure must stimulate confidence in EV drivers to complete their journeys and top up their charge as required. This has resulted in the archetypal early adopter, who is content to tolerate an apparent lifestyle adjustment and perceived inconvenience. However, this is arguable, with much of the population still to be convinced of the evident benefits of EV adoption. In studying people and social phenomena, this consumerism characteristic applies mainly to the physical EV. The UK charging infrastructure is still maturing and does not satisfy the demand or locational siting to offer genuine consumer choice.

Previous research [8,9] shows that the current UK rapid charging environment splits EV users into two groups. In scenario one, there are EV drivers who, given the option, will make a value judgement in an urban or rural environment. In the second scenario, motorway EV users are confronted with a largely unregulated, expensive, and unreliable monopolised network [9], facing a phenomenon that is often referred to as the Nash equilibrium [10] or a zero-sum phenomenon [11]. Both concepts reflect a situation that involves two perspectives, in this case an EV driver and charging supplier, where the result is an advantage for one side and an equivalent loss for the other. Thus, the driver can search for a better deal at a net loss to the supplier, but this differs significantly between urban and national motorway networks. We have witnessed a similar pricing development in the urban environment, as private operators of rapid chargers are imposing margins, frequently more than 100% of a standard kW price [9]. In contrast, many local authorities are offering free AC low-speed charging at the point of use. Furthermore, Neaimeh et al. [12] observed consumer information from manufacturers and the UK government regarding EVs and how to charge. However, there is no tangible evidence of a national strategy to deploy a nationwide network of rapid chargers. Dependence on network progress relies mainly on an independent website, Zap Map [13], reporting charger deployment progress and availability rather than strategy. Figure 1 reveals the results of a recent survey in 2021 highlighting five critical areas of concern for existing EV drivers and mirrors concerns cited on vehicle blog sites globally as reasons for not making the transition from ICEs to EVs.

Figure 1. Significant concerns discouraging drivers from purchasing an EV [9].

EVs are often compared with other electrical consumer devices, with similarities drawn with other revolutionary technologies such as compact discs and mobile phones. In their early evolution, high-technology mobile phones and compact disc players were introduced to the public with a similar lack of supporting infrastructure. Mobile phones initially only supported use in large conurbations as operators deployed their transmission networks, and compact disc players were launched with just a handful of albums available in their early years. We argue that it was a clear risk for car producers to introduce products with an evident operating limitation in the expectation that infrastructure would match demand to encourage new EV buyers to buy a new technology with blind trust. Although both EVs and mobile phones need a charging facility, the significance of a mobile phone exhausting its charge is far less than an EV. Therefore, we argue that to facilitate the adoption of EVs, a contiguous national network of charging points must be developed to supplement the option of charging at home [8]. As with all commercial strategies, there must be a business case to back investment from either private or government funding and support options.

However, evolving variables are propagating. Despite EV manufacturers needing to gain a competitive advantage, they often fail to publish their model's real-world range, instead relying on the very conservative measuring protocol laid down by WLTP rules [9]. Additionally, the charging infrastructure sector is developing and providing installations offering greater charge rates than most EVs can utilise. We have also witnessed traditional fuel companies entering the EV sector by installing charge points (BP and Shell, London, UK). Furthermore, independent EV OEMs (Tesla, Austin, TX, USA and Ionity, Munich, Germany) are expanding their networks. Our previous research [8,9] shows that DC rapid chargers are in demand from by EV owners and the new EV buying population nationally and are critical to providing an extended range for longer journeys.

One conundrum discussed at national and local government levels is how many EV charging bays does a motorway service station require? Hence, the overall goal of this investigation is to establish which infrastructure is necessary for a given population of EVs by service station, based on the direct replacement of the power requirement and filling time from fossil fuel to electric supply with an assumption of rapid charge dependence. We ascertain the theoretical maximum demand specifically for high-power rapid charging and its grid impact. A world-leading countrywide example of EV adoption is Norway. Thus, data from Norwegian research is also applied in this work. The methodology applied is not specific to any one country, although the data are. Currently, the EV owner or user has four basic choices: (1) charge at home; (2) charge at work; (3) charge at a slow-charging public charge point; (4) charge quickly at a rapid charging point. We know from recent research that 35% of households have no access to off-street parking outside Greater London. In inner London, this percentage rises to 63% [14]. The societal challenge is that the OEMs understand how their product is operating in the market based on sales achieved or pre-orders placed. The infrastructure is not optional for the prevalent paradigm (ICE vehicles) since the owner must travel to a filling station. The ICE home or work charging choices are not an option for most of the population. However, for EV users, the customer can choose where they want to charge, and these options may include car parks, the home, public spaces, hotels, service stations, and supermarkets. It is forecast [5] that the EV filling station equivalent of a petrol station with rapid chargers will develop rapidly, such as the UK's first electric-only service station shown in Figure 2.

However, the authors argue that EV technology in vehicles and infrastructure is still evolving and is continually developing in parallel with sales. Theoretically, according to the independent EV Database UK, in quarter one of 2022, the mean average useable capacity of UK-sold EVs stands at 62.5 kWh [15]. Additionally, the average real-world range (not the higher measure shown by WLPT rules) during the same period stands at 201 miles [16]. The following methodology has been established to determine the most appropriate approach and to investigate the correct infrastructure level in UK-based rapid charging. Driver behaviour is based on the current mean average battery size of 62.5 kWh as the norm for EVs. We then determine how these EVs charge in relation to power tolerance versus time.

We look at the mean average of the maximum charge rate as of quarter one 2022. We know from past research [8,9] that several variables affect the total grid power requirements for a given EV population to travel the distances in a day that traditional ICE vehicles achieve.

Figure 2. Gridserve Electric Forecourt®, Essex, UK. Source: Gridserve™ 2022. https://www.gridserve.com/braintree-overview/ (accessed on 9 June 2020).

Currently, there are only two high-power national EV charging networks. (1) The first is the Ionity open high-power 350 kW hub network [17], jointly owned by a consortium of OEMs including BMW Group, Mercedes-Benz, and Volkswagen Group, along with Audi, Porsche, Ford, and Hyundai. The remaining UK nationwide high-power network is owned by Tesla, although this is currently dedicated for use by Tesla owners only. Other open national networks such as the Gridserve Electric Highway at most motorway service stations are open to all vehicles, including CCS-compatible Tesla cars. Ionity provides up to 350 kW CCS charging, whilst Tesla delivers a peak rate of up to 250 kW. The power delivery range from a rapid charger is presently 50 kW (DC) to 350 kW (DC) and covers the current maximum power accepted by mainstream EVs from 50 kW to 275 kW. Besides the Tesla network, 441 rapid chargers [13] are installed across UK motorway services. The usage and siting of rapid chargers have been the focus of far-reaching analyses. For instance, Dong et al. [18] studied concerns around the location and siting of rapid charging stations. Furthermore, the European Commission part-funded a pilot of the Rapid Charge Network (RCN) in 2015 [3], comprising an investigation into driver reactions.

An extensive trial studied the behaviour of drivers as well as their usage patterns of rapid chargers [3]. This investigation provided the basis for an account surrounding the role of rapid chargers in the adoption of EVs [12]. In contrast, Latinopoulos et al. [19] explored the reaction of EV users to pricing strategies concerning dynamic charging. A recent investigation has focused on the significance of rapid chargers and EV driver's usage habits. However, this research does not account for the volume of chargers that will be required. An investigation by Harrison and Theil [20] presented the concept of an EV charging infrastructure based on a charging methodology that accounts for deployment, equipment costs, and running costs versus the desired return on investment (ROI). However, whilst this is a tried and tested standard commercial formula, it may not address public requirements.

Furthermore, the International Energy Agency (IEA, Paris, France) recently published its Global EV Outlook 2021: Technology report [21], in which they summarise that notwithstanding the wide variability of the scarce electric car market and stock shares, the EV/EVSE (Electric Vehicle Supply Equipment) ratios have been projected to converge towards 130 EVs per openly available rapid charger. These calculated results were founded on EV deployment projections and assumptions of the EV/EVSE ratios (at charger level). The derived beliefs were based on an overview of the past expansion of the EV/EVSE ratios, where the EV/EVSE ratios are mapped against both the EV car market share and the

EV stock share. This investigation looks at the quantity of rapid chargers needed based on power (kWh) delivery and EV consumer behaviours. The outcome of this study provides a figure of 434 rapid chargers for a given population of EVs that relies on rapid chargers for mobility requirements, which is less than a 5% variation from the figures produced by the two different approaches. In defining the quantity of chargers required, we include EVs that cannot be charged at work, in the street, or at home, or that cannot partake in long-distance commuting. Unlike the current internal combustion engine vehicles, EVs differ since the yield of fuel during the filling or recharge process is determined by the unique battery control system integrated into each vehicle, being non-linear and differing from EV to EV.

This investigation introduces a methodology that provides an infrastructure figure specifically relating to motorway service stations. These facilities will be the most common form of recharge options used by long-distance EV users. This is based on a consideration of logical components and an analysis of existing technology both on and off car, studying what volume of power delivery can genuinely be delivered from a specified rapid charger. Recent studies such as that by Buzna et al. [22] have investigated how EV and charging infrastructure expansion will impact grid supplies on a regional basis. They argue that electric vehicle load forecasting is problematic at a hierarchical level, further suggesting that a robust model must be applied to forecast the load at the hierarchical level, since EV charging curves and power delivery differ significantly from model to model. This, they suggest, should be factored into any long-term forecasting to increase the accuracy of the problematic forecasting compared with non-hierarchical approaches.

Hence, a significant consideration is that delivering power to an EV is not constant during its charging cycle. Whereas the traditional delivery method for an ICE vehicle is that the petrol pump can supply a linear volume of fuel over a given period, which when allowing for customer rotation in the filling bays, permits the calculation of the maximum volume of fuel delivered if needed. In a recent study by Arias et al. [23], the investigation concluded that to realistically predict EV charging power demand, the model must account for charging power differences between EVs. It was discovered that differing charging patterns at various charging stations produced non-replicating differing patterns. The study's outcome cites that peak grid demand times almost mirrored peak charging times at motorway service stations. Therefore, a form of dynamic power management connected to the generator was recommended to smooth maximum demand peaks. This outcome will form the basis for future research outside the scope of this study.

The current UK pure EV population size of 420,400 is not a large enough sample to build a balance of requirements for constant usage in terms of back-to-back charging versus traditional registered UK ICE vehicles numbering more than 32 million. The representative power delivery constituent in the estimation for charging infrastructure numbers requires an evaluation of what is probable to be adequate charging behaviour of 1h segments over a 24 h timescale with nominal 10 min vehicle changes over a period.

The following sections explain the source of the base formula used to calculate a charging infrastructure figure. Accurate power delivery is a fundamental element. We present a methodology in Section 2, explaining the importance of the sample EV types used in this study and the significance on the broader EV sector. Section 2.1 then explains the data inputs. Their justification is then described, demonstrating the statistical consistency and how and why the variables are selected, followed by the analysis of how the study will calculate rapid charger quantities. Section 3 then emphasises the relationship of the battery charge versus time, describing how the average power delivery is calculated and explaining the calculation of the average power delivery. Section 3.2.4 then focuses on establishing a developed model that will estimate power in kW charge per hour using significant variables in the calculations. Section 3.2.7 explains how this study aims to predict the necessary rapid chargers for current and future EV user demand. Section 4 introduces a summary of the previous chapters and outcomes for discussion, explaining why the results are significant and highlighting the study's implications for future use due to the inherent scalability of current and future EVs and charging systems. Finally, the conclusions are presented in Section 5, which summarises the salient points of the study, explaining the importance of forecasting the power consumption in an archetypal EV. This is interpreted in terms of probable user behaviour, describing the statistical reliability of the suggested number of rapid chargers assessed based on the variability of the elements creating the calculation [24]. Therefore, average power consumption and delivery numbers are used to evaluate operational efficiency and to evaluate the present and future rapid charger infrastructure needs.

2. Methodology

2.1. Developing a Forecasting Method to Calculate Rapid Charger Requirements

When analysing the varying complicating factors whilst planning charger numbers to satisfy user demands, the critical issues include EV numbers, EV average daily activity and power demands, and the EV time required in the charging bay to meet the vehicle's power requirements. Typical input data from varied sources are employed to challenge these issues (Table 1). Realistic statistics for some of these components are derived from open data sources, whilst elements with no official data are based on assumptions. Although the tabulated values are best estimates, they are still beneficial in evolving a methodology and delivering a realistic figure on which to base calculations.

Table 1. Statistical inputs.

Variable	Variable	Data	Derivation	Source
B	Volume of UK cars (all types)	32 M	Resultant	[5]
C	Distance driven daily—per car	26 miles	Resultant	[5]
$B \times C \times 365$	Miles driven per year in total (UK)	303 bn	Resultant	[5]
A	Percentage of cars that are pure EV	1.32%	Resultant	[14]
E	Mean average miles per kWh	3 miles	Resultant	Actual performance of a 45 kWh VW iD3
F	Mean average power delivery —50 kW rapid charger	27 kW	Calculated	As described previously—experimental
D	Percentage of EV drivers charging at work or home	85%	Implicit	Considered prediction
	Charge time	60 min	Established	Employing 80% rule over 30 min
$A \times B$	Current number of registered EVs (UK)	422,000	Resultant	[14]

Employing data provided by the RAC [5], it is known that there are 32 M cars in the UK, of which the current % of EVs is 1.32%. Thus, we have 422,400 EVs (1.32% of 32M). This study assumes that all EVs can accept rapid charging. The RAC [5] cites 26 miles on an average journey per car per day (all car types). Employing this mileage, the sum of miles driven in EVs per day is 422,400 × 26 miles = 10.98M miles per day. We also know from observation and publication [15] that an EV can deliver a mean average across all models (2022) of 3 miles per kWh (this is a driving-style-dependent and best case per EV model). Therefore, the energy required to cover 10.98M miles is 3.66 MWh.

In line with ICE driver behaviour, EV drivers do not generally recharge every day, although some long-haul EV commuters will charge and discharge frequently. In contrast, remaining EV rapid charge drivers will use them since there is no local alternative, even though they still maintain the average daily mileage. Hence, the utilisation ratio of rapid chargers will be distinguished by comparing urban EV users versus long-distance users. The power delivery per rapid charger and the number of hours each device is used per day will be significant factors in calculating the number of rapid chargers required to satisfy demand. Table 1 highlights the average power delivery from a base 50 kW rapid charger against charge time. The following section describes a sensible method used to conduct a real-world investigation by applying a technique of inverse engineering, as described in the next section, since there are no published data for average power delivery. A suggestion for the charge time is made based on the experiment results.

2.2. Selection of Test EVs and Rationale for Use

All long-distance EVs are capable of being rapidly charged and are ideal for long motorway commutes [9]. The VW iD3 45 kWh and 58 kWh have been used as examples because they are currently among the most common family sized long-range EVs. We selected the VW iD3 45 kW and 58 kW models since they use the common Volkswagen Audi Group (VAG, Wolfsburg, Germany) EV platform, known as ***M**odularer **E**-Antriebs-**B**aukasten* (MEB). The chassis and a combination of its batteries are used on more than 100 different models globally, across five distinct brands, including VW, Audi, Skoda, Seat, Cupra, and all VAG commercial EVs. Additionally, the MEB platform is licensed to Ford globally for its current and future models [25]. Therefore, this makes the MEB module, illustrated in Figure 3, the most widely used EV-only chassis and battery architecture globally and an ideal platform on which to base this study.

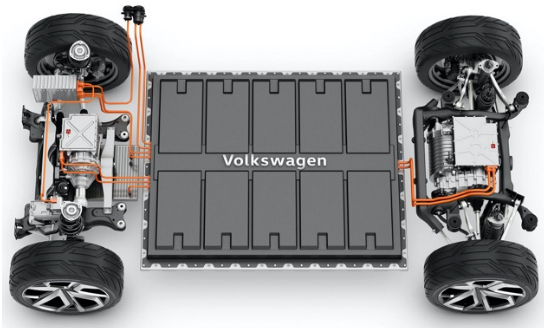

Figure 3. VAG–MEB EV platform. Source: VAG™ 2021.

2.3. Applied Experiment Demonstrating Average Power Delivery

The EV regulates the flow of power when a DC rapid charger is connected and delivering a charge. The power delivery is not linear or constant and fluctuates considerably from EV to EV, even between the same make and model. The investigation uses existing technology, but references will be made to more powerful batteries and higher-power charging devices. Power curves were measured on Gridserve™ rapid chargers at one-minute intervals. The test was carried out at varying external temperatures (from 5 to 18 degrees Celsius) to understand the influence of ambient temperature. The group of data was then used again for the higher-capacity battery.

Data from the following elements were gathered by the minute:

- State of charge.
- Time interval.
- Volts.
- Amps.

Data collection was carried out five times with a standard 45 kWh battery and twice with a 58 kWh battery. This method was employed to reproduce driver behaviour as their confidence in the EV range developed. Hence, users should be arriving with a state of charge (SoC) of approximately 10%. Neaimeh et al. [12] discovered that drivers often arrive with up to 40% SoC. Consequently, these scenarios were similarly incorporated.

2.4. Statistical Consistency in Rapid Charger Quantities

We established a need to recognise the uncertainty in the estimates, aside from advocating for the magnitude of chargers required. Employing the variance synthesis method described by Morrison [24], the difference in the assessment is estimated by a weighted grouping of the variances of the individual elements. The partial differentials are evaluated based on the variable's mean value, whilst the weights are the squared partial differentials of the estimate concerning the variable.

Variance (K = number of chargers) ~ sum of {(partial differential of K for each variable)^2 $\times$ variance of variable}. Although the differences of the elements are not known, these must be previsioned.

2.5. Functional Performance

The resulting equation is based on a recognised industry gauge of overall operational effectiveness (OEE) that comprises the availability $\times$ speed against design $\times$ quality of the product. To measure the performance of a charger in our investigation, the operational performance (OP) is determined as the power $\times$ utilisation (design vs. delivery) $\times$ availability.

3. Outcome and Analysis

3.1. Calculation

The calculation for the suggested number of chargers is a compound of the different elements.

The number of chargers is K = $\frac{A \times B \times C \times D}{E \times F \times G}$

Thus:

A = % of UK cars that are EVs.
B = number of cars.
C = average daily mileage.
D = % of mileage needing rapid charging.
E = miles per kWh.
F = average delivered power in kWh (charge time-dependent) assumed at 60 min.
G = total hours charger is in use.
K = the scale of K is $\frac{\text{miles per day}}{(\text{miles/kW}) \times \text{kW} \times \text{hours per day}}$ and is dimensionless; values are acquired from numerous sources and presented in Table 1.

3.2. Calculating Average Power Delivery

3.2.1. SoC vs. Time

It is established that a 58 kWh vehicle has the same charging time to 80% state of charge (SoC) as the 45 kWh vehicle. This is achieved by the 58 kWh battery accepting more power at circa 350–410 V volts DC. The results are shown in Figure 4. The chart also highlights that an additional 15% of charge adds a further 25 min to the charge time.

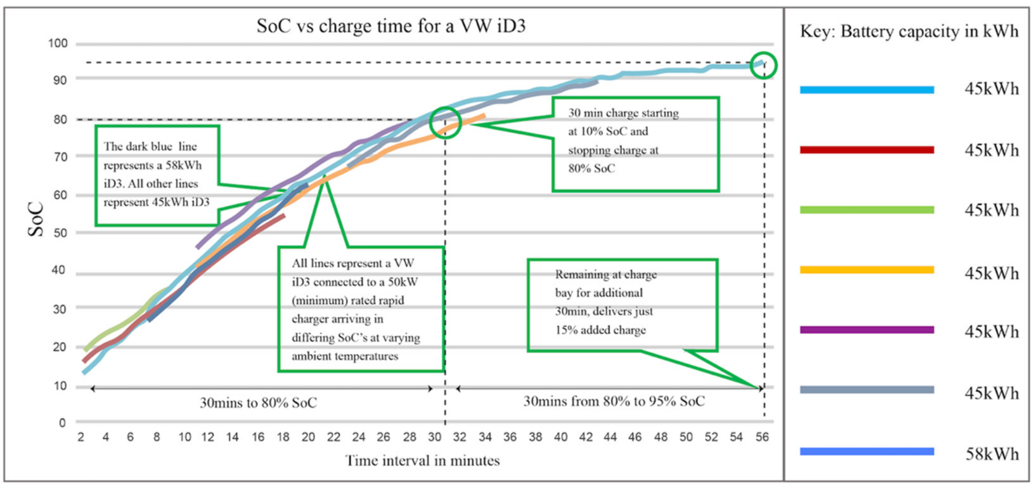

Figure 4. SoC vs. time for a Volkswagen iD3 58 kWh and 45 kWh.

The individual lines represent different ambient temperatures. Our study confirms that ambient temperature had little impact on the charging curve. The start temperatures when data were collected varied from 4 to 16 degrees Celsius. By referencing Meteorological Office data (2010–2020), the average minimum temperature for the UK is 6.4 degrees, and the maximum temperature is 14 degrees Celsius, although this variable was dismissed for this study [26].

3.2.2. Power Delivery Significance

Watts or power is then calculated (volts × amps). The variables are amps (Figure 4) and power (in W) on the vertical axis and percentage of the SoC on the horizontal axis. The distinctive plots denote ambient temperature. The variance between the 45 kWh and 58 kWh iD3 is evident, since the 58 kWh iD3 is taking a greater current level for an extended period. The significant crossover points in Figure 5 are:

- SoC of 65% in 20 min.
- SoC of 85% in 30 min.
- Charge of 95% SoC in 55 min.

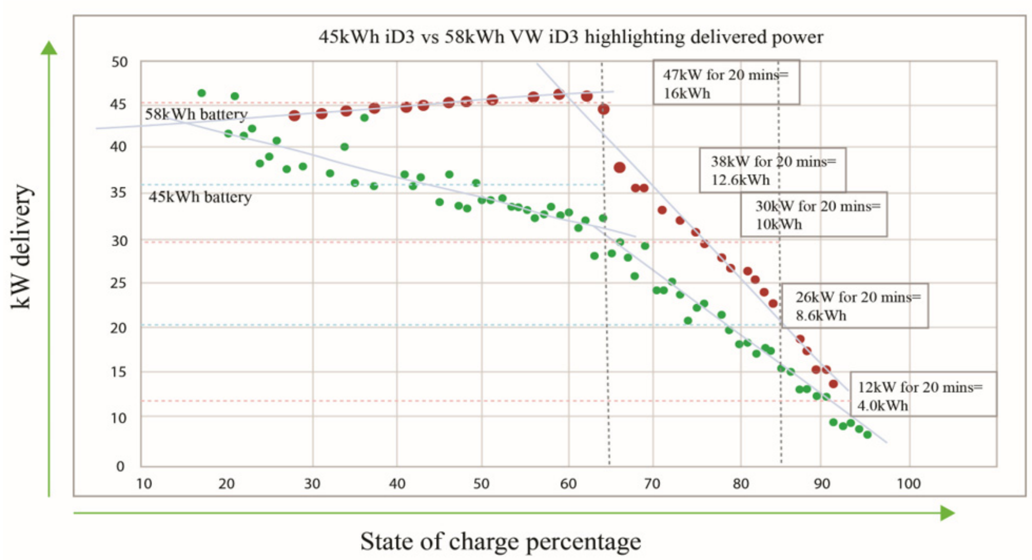

Figure 5. Power delivery as the state of charge increases, using averages for the 45 kWh VW iD3 (green dots) and 58 kWh VW iD3 (red dots).

Figure 5 demonstrates that the 58 kWh VW iD3 sustains high power (received), capturing approximately 380 volts and 106 amps (40 kW) up to a 65% SoC, then it systematically reduces as the SoC increases. In comparison, the 45 kWh iD3 demonstrates a significant drop in power from the start of its charging cycle. Furthermore, it is also evident that the power decreases for both the 45 kWh and 58 kWh batteries following a comparable power curve after 65% SoC. At 65% SOC, it is significant to note in Figure 5 that this power reduction appears after 20 min. At 85%, one can also witness a similar power slope, as this point marked the termination point of the trajectory following 30 min. The ensuing period (Figure 5) established the average power delivery to a 65% SoC and then 66% to an 85% SoC. Contradicting data from a RAC Foundation report [5] assumed mistakenly that a 30 min charge from a 50 kW charger will deliver 25kW but acknowledged it will not be a linear charging line. However, this analysis (Figure 5) shows disparity within and among models from the same manufacturer (VW iD3 45 kWh and 58 kWh) and demonstrates the non-linearity of the charge rates in EVs.

3.2.3. Average Power Delivery Development

From the analysis of data in Figure 5 collected from trials, it is now possible to determine that the charging traits for a 45 kWh iD3 EV connected for 30 min are:

- 41 kW for 20 min, which is 22.66 kWh.
- 20 kW for 10 min, which is 7.8 kWh.

Thus, one 45 kWh car charging for 30 min will consume 30.46 kWh. Moreover, statistics from the Electric Vehicle Database [15] suggest delivery over 30 min will be greater if a 58 kWh battery is charging. Thus, assessing an EV car group of 2 million cars will result in a significant energy miscalculation.

3.2.4. Developing a Model to Estimate Power (kW) Charge per Hour

Figure 5 demonstrates the origin and rationale supporting the average 30 min 80% SoC published in some manufacturer's declarations. This curve provides reference data for the necessary calculation of the delivered kW per 1h period. From our previous research [8], we recognise that alternative payment methods are now established as follows:

- Payment by units of time.
- Pay per kW plus a connection charge.
- Fixed fee per month for unlimited charging per vehicle.
- PAYG via contactless card per kW.
- Subscription with a monthly fee plus reduced charge per kW used.

The research confirms that the average changeover time from one EV completing a charge to an uncharged EV reconnecting in the same charging bay is 9.5 min [9]; hence, a minimal changeover time of ten minutes has been provisioned. The previous study [9] showed that ICE drivers at fuel stations drive straight in, refuel, and then drive out, and the average changeover time was 4.5 min. However, EV drivers generally reverse into a bay and use an app to initiate the charge, and this whole process has been proven to take twice as long as an ICE driver in a traditional filling station.

Factoring in the changeover time, there is a fifty-minute recharge session per hour. We do not predict continual use for 24h. The charger operation calculation will employ a diversity factor. Numerous charge point operators (CPOs) are investigating diverse payment techniques [8] primarily founded on three standard methods: a kW delivered cost plus a single connection charge, a straightforward kW unit cost multiplied by the time used, or a subscription model based on a combination of the two. UK studies in the past were commonly investigated through an era when UK motorway charging was payment-free at delivery to the EV user. The leading free charging CPOs were provided by Tesla and Ecotricity. However, payment was ultimately introduced by these and subsequent CPOs in 2018 on the UK motorway network. The effect of applying a rapid charging payment has not been widely researched. This may present evaluation challenges over the next decade as competing CPOs test and evaluate suitable payment models across the charging network. This requires investigation of whether the EV user will be significantly influenced by price, despite several global factors that have occurred during this study that have enforced severe price increases, such as the COVID-19 pandemic affecting supply chains, the 2022 Ukraine war, and substantial global increases in energy costs. To appraise the average power provided by a charger, the detected power provision curve (Figure 5) demonstrates a clear power provision trend to 65% SoC up to 20 min, followed by reduced delivery after ten minutes to 85%. Thus, a thirty-minute charge is calculated as twenty minutes plus ten minutes. Furthermore, a mean average ten-minute switch between EV users is considered and included in the calculations with a diversity factor to simulate real-world daily use using data gathered from our previous study [9].

Figure 6 displays the most prevalent charge point utilisation times of the day on a combined percentage use basis.

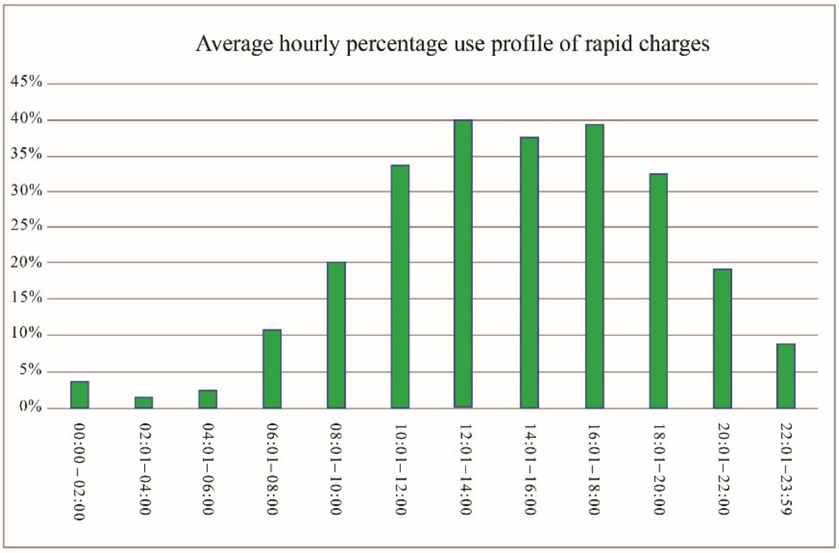

Figure 6. Daily charging characteristics versus time as a percentage [9].

Figure 7 illustrates the aggregated figure for an entire study based on the time of day.

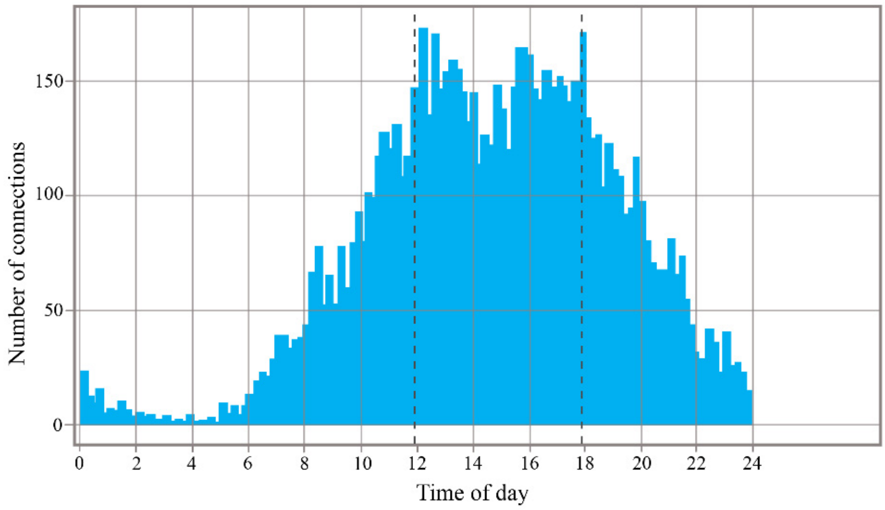

Figure 7. Volume of connections versus time [9].

Figure 7 illustrates a contiguous national charging network employed per hour and per day. Moreover, Figures 6 and 7 above challenge widely held theories. Our study mirrors articles from the DoT [14] and National Grid [27] that demand that rapid charging occur during busy daytime commuter periods, with peaks for rapid charging occurring in the morning and evening rush hours. The statistics reveal that the core 60% of total consumption occurs between 10 am and 6 pm, supporting a study by Neaimeh et al. [3] and research by the DoT [1]. Rapid charge network utilisation rates are illustrated in Figure 8, providing greater detail, and revealing well-defined daily behaviours regarding usage, mirroring a recent study highlighted in Figure 9. Observing assumed peak times per 24 h (06:00 to 20:00), the data comprises approximately 4% of the total utilisation, the period from 8 am until 10 am constitutes 8% of the total utilisation, while the evening (18:00 to 20:00) equates to 13% of the total utilisation. Our investigation confirms that the urban morning rush hour ends by approximately 09:00.

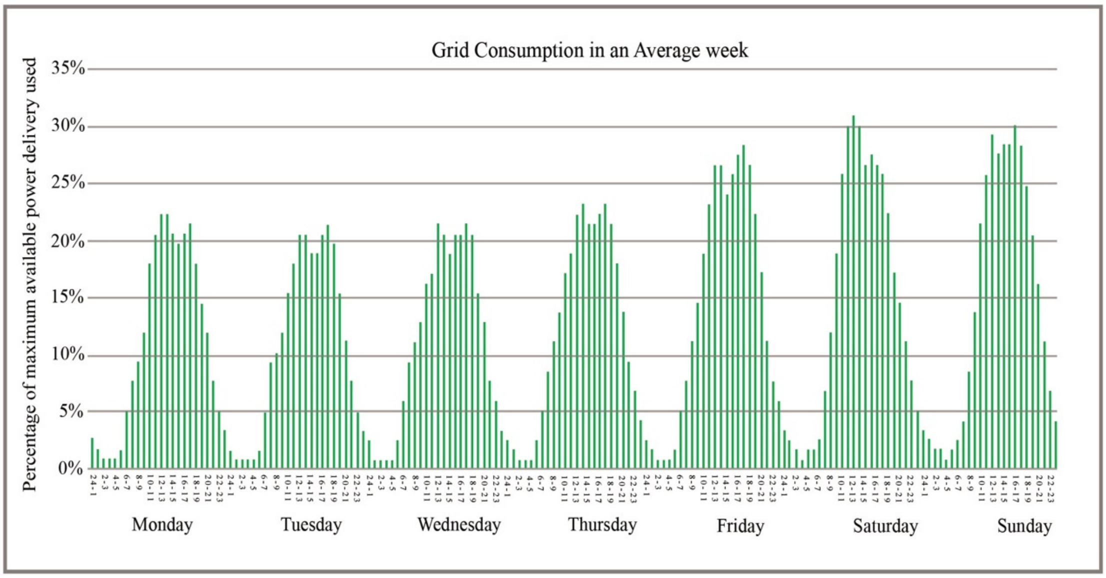

Figure 8. Daily percentage of grid supply usage versus time [8].

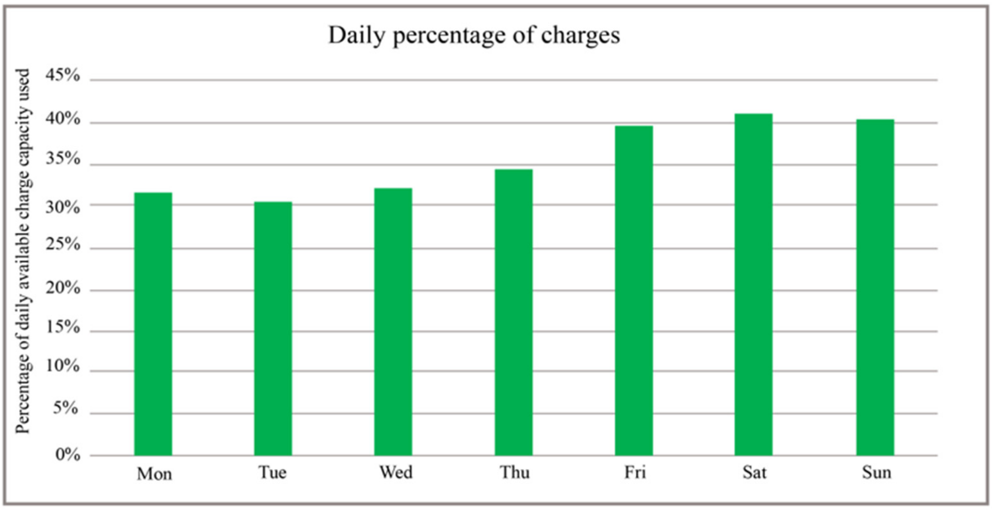

Figure 9. Charging activity shown as a percentage per day.

In comparison, motorway traffic volumes increase around 09:00 through to 20:00. Thus, the morning urban peak period experiences lower grid utilisation at under 12%, less than assumed before this study. However, the peak evening period is more condensed on the motorway network and generally reduces by 20:00, demonstrating a comparable utilisation of the morning peak at 13%. This suggests that rapid chargers are being used specifically for the intended role; that is, to extend the range of EV journeys rather than for commuting. Gathering a more significant sample of data on how rapid chargers are used may ratify this notion, although presently this may be too commercially complex.

One can witness a minor utilisation variation on weekdays by observing the extent of charging per day (Figure 9) from the same CPO. However, there is more significant usage on Friday and the weekend. This, we have assumed, indicates long-distance leisure travel that necessitates rapid charging.

The impacts of EV batteries larger than 58 kWh and higher-power charging will need further evaluation in future studies. This investigation assumes that most rapid charging by VW iD3 cars requires rapid charging CPOs to further develop the UK motorway network for long-distance travel. To establish a notional maximum charge delivery, this study assumes consecutive charging moderated by a diversity factor. Our investigation has revealed that the customer, rather than the infrastructure or vehicle, determines the time spent on a rapid charger, with most users overriding a complete charge cycle at an average SoC of 85–90%. Figure 10 illustrates the typical EV usage over one hour.

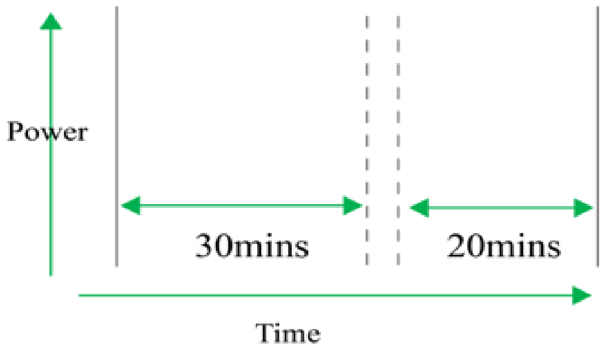

Figure 10. Characteristic hourly charging period.

3.2.5. Power Delivery Profiling

One 45 kWh iD3 charge proceeded by a second 45 kW iD3 charge = 39.92 kWh (50 kW for 20 min is 16.66 kWh plus 50 kWh for 10 min equating to 8.33 kWh, plus 50 kWh for 20 min amounting to 16.66 kWh).

Figure 11 highlights 39.92 kWh delivery for three iD3 EVs charging consecutively, allowing a 10 min changeover period.

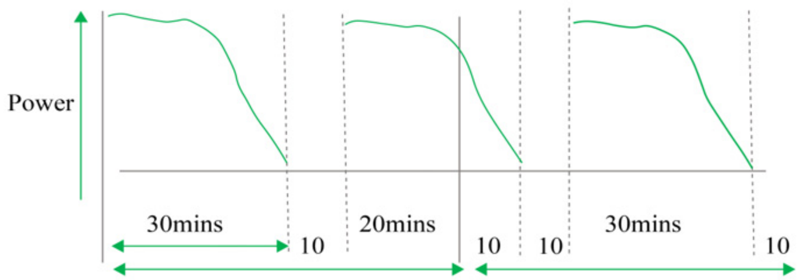

Figure 11. The charger utilisation is established by price, requirement, and location.

Assuming consecutive full-use rapid charging, then using the 45 kWh + 45 kWh + 45 kWh car pattern illustrated in Figure 11, a total power delivery amount of (23.32 + 0 + 13.66) + (8.33 + 0 + 24.99 + 0) = 70.30 kWh over 2h or 35.15 kWh per hour is achieved.

Providing EV users with the choice of a 50 min delivery period on a 50 kW charger will require more rapid chargers to meet current demand at charge point sites and service stations. An additional 15 min charge will provide an average of 9 kWh. The significance of this is that rapid charging bays will be fully occupied, although delivering small amounts of power towards the end of the charge cycle, creating a commercial challenge between an EV user who wishes to obtain a full charge before setting off and the commercial and countrywide necessity to supply the most significant amount of power within the shortest period. This problem was illustrated by Neaimeh et al. [12], revealing that regarding the charge period, 32% of these events in the UK and 21% of similar events in the USA stood above 30 min. In line with our investigation, the charging rate reduces when the battery nears complete SoC controlled by the car's battery management system, extending charging sessions that affect the rapid charger's availability for a new EV user.

The above assumes consecutive charging, whereby larger batteries will become the standard. Furthermore, by accepting that higher capacity batteries will continue the trend of extending the EV range, the figure of 35.15 kWh is selected as the basis for our calculations.

3.2.6. Calculation to Predict Required Rapid Charger Requirement

The quantity of chargers can now be considered as $K = \frac{A \times B \times C \times D}{E \times F \times G}$:

A. 32% of cars that are EVs.
B. 32 M number of cars.
C. 26 average daily mileage.
D. 10% of mileage needing rapid charging.
E. 3—Miles per kWh.
F. 35.15 kWh average power delivery.
G. 24 h profile charger is in use.
K. 434 is derived as follows: A = 1.32% current proportion of the total of all types of UK registered cars (B = 32 M) are EVs, equating to 422,400 EVs. Average daily mileage is calculated at C = 26 miles.

The miles per kWh is E = 3; thus, 422,400 $\times \frac{26}{3}$ = 3,660,800 kWh is needed per day

If 90% of charging is performed at home or work, then 10% of the national mileage per day requires rapid charging, so D = 10% of the national EV mileage per day requires rapid charging; thus, 366,080 kWh maximum is consumed

A 50kW rapid charger can currently deliver F = 35.15 kW per hour for G = 24 h, which is 843 kWh of energy.

Thus, this is calculated as $\frac{366{,}008 kWh}{843 kWh} = K = 434$ chargers.

This assumes that all rapid chargers will be working 24h a day, which will not be the norm.

According to Zap Map data [28], there are 5497 rapid chargers in the UK. We, therefore, calculate a requirement of 434 chargers working at 100% utilisation. This suggests the network is currently running at 7.89% utilisation, almost mirroring the average figure supplied by a selection of CPOs [29]. The assumption is made that all charges are for 100% EVs, as few hybrid plug-ins can take a one hour 50 kW charge. Furthermore, it is known that specific rapid chargers will be heavily used by EV users on busy commuter routes and motorways, and some that are deployed to allow ad hoc speculative travel will be somewhat underutilised. Throughout the initial phase of EV adoption, it is noted by many researchers [2,9,14,22] that a more significant percentage of EV users will charge at home where feasible and receive 100% charge, predominantly overnight. Thus, this phenomenon misrepresents rapid charger deployment by decreasing dependence.

Presenting the current rapid charger deployment of 5497 at full use and 10% use by the EV population would support a UK population of 1.4 m EV. Furthermore, by employing 42,240 vehicles (10% of 422,400) currently using rapid chargers, we are presented with approximately eight cars to each rapid charger if operating at their conjectural 24 h utilisation rate rather than the operational utilisation rate.

3.2.7. Statistical Consistency of the Number of Rapid Chargers

The statistical consistency of the suggested rapid charger numbers (434) can be assessed based on the irregularity of the elements forming the calculation using variance synthesis [24].

The statistical consistency of the number of chargers will be:

$$\begin{gathered}\text{consistency (number of chargers)} \sim \text{sum of} \\ \{(\text{partial differential of K regarding each variable})^2 \times \text{consistency of variable}\}\end{gathered} \tag{1}$$

Calculating the partial differentiation of the equation for K, the variability of the number of chargers is as follows:

$$\begin{gathered}K = \left(\frac{B \times C \times D}{E \times F \times G}\right)^2 [(VarA) + (VarB) + (VarC) + (VarD) + (-1)(A \times B \times C \times D) \\ (E \times F \times G)^{-2} [(F \times G)\mathrm{Var}(E) + (E \times G)\ \mathrm{Var}(F) + \times (E \times F)\ \mathrm{Var}(G)]\end{gathered} \tag{2}$$

The partial differentials are calculated at the mean value point of the variable. The variability is the square of the standard deviation.

In this study, standard deviations are best predicted from familiarity in the methodology used for the obtained values (*A* to *G*). By applying the means and standard deviations in the table, the number of chargers is 81, calculated from the sum of the influencers illustrated in Table 2 in the bottom row. Table 2 highlights the conflict largely dominated by *D*, since its influence on the variance is significant. Thus, the variance can be assumed as a confident sum for the number of rapid chargers. Reliance on 1% charging, as shown in Table 2, has a significant influence on the consistency of the sum of the number of rapid chargers. However, the ambiguity in the number of vehicles has little effect.

Table 2. Variance consolidation.

Variable	*A* % EV	*B*—Cars	*C*—Miles	*D* % Charging	*E* kWh	*F*—kW	*G*—Hours
Mean	1.2	32,000,000	26	0.1	3	35	24
Standard deviation	0.0001	320,000	1	0.01	0.2	1	0.1
Coefficient	24.074	0.00	3	722	−14	3	−3
Influence	6	0	8	52	8	7	0

By employing a 95% tolerance period for the number of rapid chargers, we can calculate twice the standard deviation on either side of 72. The standard deviation is the square root of the variance; therefore, standard deviation = 9. Moreover, a 95% tolerance period is circa 72 ± 18, resulting in 54 to 90 chargers. Consequently, it is essential to consider any doubt in the estimate of the number of rapid chargers, since this helps strengthen the fact that it relies on the current estimation.

3.2.8. Operational Functionality

The performance of a rapid charger or the operational functionality will be calculated as: utilisation × power (delivery vs. design) × availability or hours utilised/24.

Thus, power vs. design is the power transfer figure of 35.15 kW divided by the maximum power transfer from a charger that is rated for 50 kW.

Thus, a charger operating for a total of 1.5h per day (6% usage) and with an availability of 97% is calculated as:

$$100 \times \frac{26.5}{50} \times 0.97 \times 0.06 = 3.08\% \tag{3}$$

- Power transfer is restricted by the EV battery and its capability.
- Availability is established by the frequency of utilisation, design, and maintenance.

The calculation to deliver operational functionality indicates a level of 6% for the CPO network, suggesting that a portfolio of 1200 chargers operating at 6% would provide the same as 72 at 100% capacity usage.

Consequently, assuming we incorporate the present range and utilisation, this equates to approximately to 5481, almost mirroring the current UK rapid charger network deployment. An average figure is used here, since some chargers will receive light utilisation, whilst others will experience heavy use.

4. Summary and Discussion

The results above are based on a continual flow of EVs and drivers. As we are forecasting toward the future, batteries lower than 45 kWh are disregarded, since EV manufacturers are already introducing larger batteries, and this trend will endure. Thus, the modelling must consider the advent of 45 kWh to more than 110 kWh batteries, notwithstanding the onset of next-generation superchargers such as 150 kW to 350 kW batteries. We have focused on the popular family EV segment, in which batteries average 50 kWh; therefore, we have discounted larger-capacity batteries' charging characteristics. Moreover, the overarching technical control features suggest that it is the capability of the car to receive and control the delivery of power rather than the sole ability of the charger to deliver and control power that is important. This engineered hierarchy determines the power delivery from the charge point to the EV and the time taken to provide the charge.

Competences in range and the ability to accept higher charge rates are already emerging in some EVs, and in-car battery management system (BMS) efficiencies are improving. High-voltage DC systems are now the de facto choice for some manufacturers, such as Porsche, Audi, Hyundai, and Kia, doubling the standard EV voltage from 400 V to 800 V. This enables much higher charging rates, lower currents, lower heat transfer rates, and smaller battery and charge delivery cables [8]. Furthermore, the modelling in this study is infinitely variable and scalable, providing the ability to introduce variables such as ultra-rapid charging speeds, currently up to 360 kW, but additionally capable of future charger calculations as the sector heads toward hyper charging speeds of above 1 MW. In theory, hyper chargers (1 MW+) can charge an average EV battery in less than six minutes [9], thereby negating the need for ever-larger EV batteries accompanied by incremental weight increases. The main obstacle to true hyper charging [30] is the EV battery capability, which at best is 270 kw across a small percentage of all EVs.

The large-scale deployment of pure EVs, combined with the government mandate that prevents the manufacture of petrol- and diesel-engined cars by 2030, requires a sustainable rapid charging infrastructure for all classes of EVs, thereby reducing range anxiety and charge point trauma [9]. There has not been a viable model to determine which rapid charging network is necessary to support the considerable forecasted growth of EVs up to 2030. This will be founded on acknowledged assumptions and identified variables. Leading up to 2030 and beyond, vehicle charging equipment technology improvements will develop at pace. The charging behaviours of EV drivers are still materialising based on variables such as payment and power delivery models. This study calculates the present UK situation based on theoretical rapid charge delivery. Further knowledge that may assist in future predictions could be derived from investigating other similarly deployed technology networks, such as AC charging posts, or visual advertising cabinet networks, focusing on location, volume, and contiguous distribution modelling.

It must be noted that this study, comparable to mobile telecom development and the growth of compact discs (CDs) in the 1980s, is to a certain extent entering unknown territory. The transition to EV is being attempted on a scale without precedent. The variables are tangible given that business processes, considering both EV charging protocols and payment technology [9], are evolving rapidly. The EV user is confronted with ongoing upgrades and field trials of payment choices testing the market. Additionally, CPOs and manufacturers must decide what charging rate is satisfactory and determine what ROI (return on investment) will be necessary to strike a balance between OEM and CPO investment versus an acceptable charging rate for the consumer, notably via the deployment of unregulated rapid charge points by developing a non-contiguous network that only satisfies and meets the needs of EV users in and around major conurbations. This strategy could isolate potential EV users and purchasers by creating a barrier to growth due to the lack of rapid charging infrastructure. Some areas such as the Southwest of the UK are provided with rapid chargers on most motorways and A-class road networks [28], which are adequate for the off-peak tourist-focused winter months. However, recent research in 2021 [9] suggests that the design and planning of the UK's Southwest rapid charging network has not considered the transient tourist population and is wholly inadequate as an all-year-round public rapid charging network. It is clear from this current research that there is no strategic link between real-world usage [9] and desktop forecasting, suggesting that the UK's current energy policy regarding supporting EV growth to 2030 is not linked to reality and is out of step with real EV user's needs.

The data output of this study reveals that the current UK motorway charging network requires reinforcement and the deployment of additional charging devices to cope with peak utilisation and current utilisation in known pinch-points. Furthermore, as more

EVs enter the UK car sector with higher-capacity charge rate specifications, greater focus should be targeted toward reinforcing the local grid to allow and achieve the installation of ultra-rapid chargers. This practical approach will shorten charging times at the point of delivery and allow greater throughput of EV users per charge point, thereby reducing waiting and queuing times, providing a greater overall customer experience and acceptance of this new technology. A further study should build on the work of this investigation by monitoring traffic flow and EV driver behaviour at the charge point level rather than using prediction techniques and charting transient motorway seasonal peaks over twelve months. Although the usage figure of less than 5%, if accurate, indicates sufficient infrastructure from a commercial perspective, location and peak usage data have not previously been considered, suggesting a deficit in available rapid charging for some EV users at peak times during the day.

For ICE drivers to make the transition to EVs, essential factors involved in charging an EV, such as the time at a charge point, delivery of charge, ease of payment, price parity between EV and ICE vehicles, and location convenience, must be considered for this significant transformation to happen. Furthermore, there is a business investment case versus the need for contiguous coverage, not just in the lucrative urban conurbations but also in less densely populated areas. This we suggest will require greater government intervention and funding to enable the deployment of nationwide infrastructure. Future traffic predictions should be utilised to forecast and plot infrastructure requirements. Another issue is the total infrastructure deployment cost, including the grid reinforcement, connection, and appropriate equipment specifications. While the grid's impact through rapid charger expansion is recognised, grid reinforcement and deployment costs have not been considered. Furthermore, while the EV population could benefit the grid through V2G (vehicle-to-grid) applications, this future technology has not been considered. However, it is accepted that the UK national grid must preserve an operating baseload, which must form part of any overall future electric transport strategy.

However, as EV batteries increase in capacity and EV users' confidence grows through newer usable being infrastructure deployed, additional long-distance commutes might increase per user. What is certain from our investigation is that as CPOs have made charging an EV more practical, simpler to use, and quicker to charge, one element guaranteed to increase is the overall demand on the UK's national grid. Previous studies [8,9] established that additional grid load could be mitigated by using green energy in combination with grid-scale battery energy storage systems (BESS).

5. Conclusions

The data output of this study reveals that the current UK motorway rapid charging network requires the reinforcement and deployment of additional devices to manage peak utilisation. Greater focus should be targeted towards reinforcing the local grid to allow the installation of ultra-rapid chargers. For ICE drivers to make the transition to EVs, essential factors involved in the charging process, such as the time at a charge point, delivery at charge, ease of payment, price parity between EV and ICE vehicles, and location convenience, must be considered for this significant transformation to materialise. Further research may focus on siting clean energy production and storage systems close to the rapid charging stations. This may include grid-scale solar farms, BESS to capture off-peak grid and solar power, or wind power, which can be exploited to benefit all rapid charge stakeholders, now and in the future. Finally, future research would benefit from a larger sample and mix of electric vehicles, deeper research into ever-improving in-car battery management systems (BMS), and new battery technologies that are yet to be exploited.

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