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“Evaluating the viability of V2G power dispatch for a decarbonized grid scenario”

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Abstract

This research study proposes a charging-discharging strategy to frame an aggregation model for the Vehicle to Grid technology to utilise the maximum potential of EVs as a portable utility-scale storage source through an agent-based modelling approach. The model intends to ensure the maximum utilisation of idle vehicle conditions along with a discussion upon the potential players for the same and develop an aggregation model with the proportion of charging-discharging vehicles in the three proposed scenarios and comparison of charging participation, demand, and injection potential in each of the scenario based upon the expected number of EVs capable of performing V2G in the UK market by 2050.

We have then utilised the scenarios for evaluating the overall aggregation feasibility while ensuring sufficient charging simultaneously during the participation. Subsequently, we have compared all three framed scenarios with the forecasted demand as well as the forecasted wind and solar energy generation followed by the balancing of demand and generation through multivariate regression and have analysed multiple possible scenarios using the Monte-Carlo approach. Finally, we have examined the requirement of extra spinning reserve apart from the solar, wind and injected V2G concluding with the comparison of the least dependency and the highest dependency scenario.

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INTRODUCTION

Background Study

Growing urgency to shift towards decarbonisation for mitigating the adverse climate change effects across the globe has made policymakers and researchers to look for the alternatives to fossils and promote carbon-neutral sources of power generations with the renewable revolution that is predominantly led by Solar and Wind both in developed and developing economies based upon their geographical constraints and the dynamics of their energy market. The growth in adoption has been backed by the government's policies, cost reduction and the quick R&D spill overs of these technologies between the industries and the fields. However, the susceptibility to intermittencies, seasonality and relatively high supply variability reduces the capacity factors of these assets thus affecting the economic and social adaption cost (Gowrisankaran, Reynolds and Samano, 2016). These intermittencies are often takeover by carbon-intensive contingency reserves and lead to significant emissions.

To substitute these spinning reserves with reliable supply sources, Energy storage technologies for varying time spaces, generation capabilities and geographical dependencies are evolving through holistic approaches to tackle complexities of uninterrupted dynamic generations and supplies that include pump-storage facilities, hydrogen, and ammonia conversions through electrolysis as well as the utility-scale storages. However, some of these processes have not been found to be economically viable due to higher capital expenditures primarily due to excessive infrastructure investment costs and have numerous limitation factors restricting their widespread adoption. Among the recent developments that have taken place in dispatch strategies for utilityscale storage, Energy storage and utilization potential of EVs through Vehicle to Grid (V2G) and Vehicle to Infrastructure (V2I) technologies have gathered a lot of interest among researchers and have an ability to revolutionize the power grid with the implementation and operation through balanced dispatch strategies to meet real-time energy demand-supply. While V2G can be seen as the substitute to fossil-based generators in a decarbonized power grid at a time with sufficient renewable generation sources by providing enough storage potential to mitigate intermittencies, societal benefits of additional revenues and incentives for contribution to grid stability can motivate consumers for quick adoption of EVs (Kempton and Tomić, 2005a).

The UK government's strategy to phase out sales of fossil-based vehicles by 2030, incentives including plug-in grants and the rising fuel prices have led to growth in the popularity of EVs potentially among new buyers. The overall EV registrations grew to 3,11,505 with 1,91,359 belonging to Battery Electric Vehicles (BEVs) category just in 2021 (Statista, 2021). The

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deployments of public charging facilities, growth in commercial fleets and the incentives to support domestic charging infrastructure in the 2035 delivery plan are highly promising to support regional power system flexibility and sufficient space to meet energy demands when in need. However, the variability due to the movements of vehicles throughout the day requires robust and highly dynamic dispatch strategies due to grid constraints and feeding capabilities. Technologies in parking spaces to make sure that there is a certain amount of V2G participation during the peak demands while ensuring sufficient mileage based upon consumer's convenience to tackle complex conjunctions of range anxiety and social adaptation of technology over the long run with significant aggregation capabilities are some of the daunting tasks which are currently being transformed by the developments in smart grids with digital twin technology and through telecommunications for co-ordinated charging implementations (Alam and Lee, 2021) .

The recent investments by the UK government of £30 million in up to twenty-one V2G pilot projects and schemes to boost innovation and evaluate emission reduction potentials along with the trials of various business models varying from commercial fleet operators to residential EV owners indicates the inclination of policymakers towards the technology (Department for Transport and Office for Low Emission Vehicles, 2021) . The network operators and aggregators have an extra potential to acquire investments for new business models and energy trading as well as grid balancing by introducing a new framework for V2G infrastructure integration in the capacity markets and frequency markets eliminating the need for expensive fossil-based spinning reserves.

Modernization of the current grid infrastructure to support the bidirectional power flow, which is majorly unidirectional across the industries, strategizing charge, and discharge cycle of V2G with the inclusion of solar has the potential to accommodate and accelerate peak shaving for reducing the higher prices and higher load phases of supply-demand cycles. With the vehicles parked average of 95% of the time, an ability to ensure these vehicles in idle conditions are connected through bidirectional power flow infrastructure can help establish efficient aggregation business models.

To understand the significance of vehicle-to-grid technology in a carbon-neutral grid, this study aims to propose and evaluate the feasibility of a vehicle to grid aggregation business model performing charging as well as discharging in each cycle and further intends to analyse the extent of its dispatch penetration in the energy mix based upon the expected figures of EVs in the UK market at various levels and times during the day with the consideration at multiple scenarios.

Research Questions and Contributions

Considering the opportunity to utilise the energy storage advantage of EVs in a decarbonized grid scenario, this research aims to shed some light on the aggregation potential through the vehicle to grid technology based on the UK government's figures for net-zero power generation infrastructure by 2050. While V2G hasn't been evaluated and tested at a large scale, the aggregation space involves the participation of EV owners which depends upon their willingness and non-quantifiable attributes involving general human behaviours. To simulate such an environment for vehicle availability and energy aggregation this thesis demonstrates the power

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injection potential through the following methodological and application contribution for future dispatch strategy implementation in a real-world scenario:

1. Methodological Contribution:

   (a) Evaluating the possibility of vehicles' participation in a vehicle to grid and their contribution in dispatch during different hours of the day.
   (b) Development of an agent-based model for evaluating the aggregation significance and participation to simulate the energy dispatch through V2G.

2. Application Contribution:

   (a) Recommendation of a strategy to utilise the vehicle to grid technology for the demand response simultaneously while providing charging to the involved vehicles.
   (b) Obtaining the dependency extent on spinning reserves for meeting the forecasted demand and generation obtained based on the modelling.

Structure of the research study

Since the technology is in its early stages, the parameters and the model choice processes are highly driven by the research and findings to create the dispatch environment and simulate the process where the research objective has been carefully defined to bridge the gap between the current studies and the necessary future objectives. A fishbone plot has been shown below in figure 1 to discuss the approach used for performing this research study.

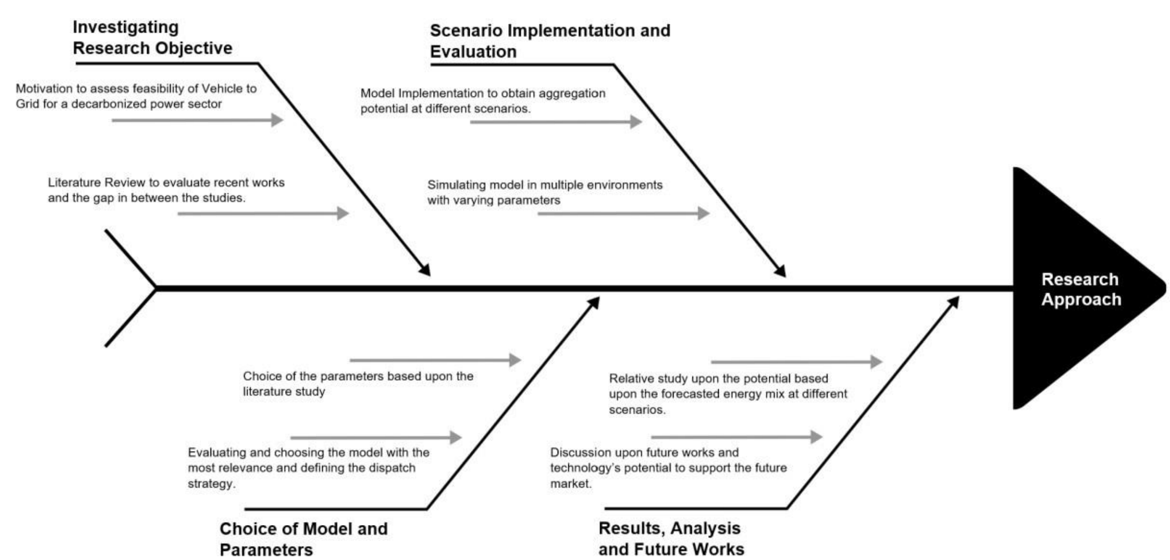

Figure 1: Fish-bone plot for the steps involved in performing this study

The results obtained through the aggregation potential with a bottom-up modelling approach are being compared to the current energy market dynamics for justifying the significance and impact of the discharging and charging strategy.

LITERATURE REVIEW

Overview

The most recent studies in the energy industry especially in grid balancing have worked around the challenges to tackle capacity factors and generation inefficiency constraints of renewables with the scenarios of forecasting the energy mix in a solar and wind-dominated power system.

The literature review for the project has been split into three parts. The first part focuses to understand the viability of V2G for tackling the intermittencies in sub-section 1 followed by the recent works to dig deep into the recent developments done to integrate the technology with the current conventional infrastructure in sub-section 2. While the EV adoption rate remains significantly low, the economic and societal parameters to evaluate the technology's feasibility rate based on some recent studies have been discussed in sub-section 3 below.

Significance of Vehicle to Grid in mitigating Renewable's Intermittency

Spillage of excess renewable power generations limiting the positive economic returns and failure in restricting overall emissions are some of the major concerns of policymakers at a time where the current decade has witnessed an increase of investments in large-scale solar and wind generation projects for the future of a net-zero economy. The intermittency and balancing of the real-time supply-demand of electricity can be fulfilled by the EVs through utilising their ability of extra energy storage capabilities to supplement the grid by feeding bulk power during the demand time (Lund and Kempton, 2008). The varying geographical conditions over the regions and the requirement of large land acquisitions restrict the deployment of renewable generation plants especially in the case of solar and wind. V2G in these operating environments can serve the purpose of enhanced control of power supply-demand cycles and cutting down expensive investments in the utility scale storage and network upgrades through the inclusion of large scale of EV owners in vehicle-to-grid power transfer transactions around the locality with a basic assumption of the unutilized potential of EVs considering aggregation of available potential is significant and the demand isn't in the co-incidence with the peak traffic hours, a sufficient number of EVs are off the traffic and feeding the stored power back to the grid (Mullan et al., 2012). Integration of V2G to the grid infrastructure comes with the challenge of tackling huge databases which include the details of a large number of users with the necessity to ensure privacy preservation considering the identity details, energy consumption records and transaction information can be vulnerable to data leakages and misuse through cyber-attacks through data minimization, suppression and generalization followed by implementation of privacy preservation ways by modifying authentication processes by signature techniques at various organizational level (Han and Xiao, 2016).

Wind Energy both off-shore and on-shore have gained significant investments and market growth, especially in developed and developing economies along with supply shortages to meet demands. Solar has come with two primary submarkets including Photovoltaic (PV), especially in

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decentralized domestic and industrial utilization supported by aggressive feed-in tariff policies at earlier stages as well as concentrating solar power (CSP) at a large scale driven by the reduction in equipment costs and growing efficiencies leading to a significant reduction in the Levelized cost of generation. The bioenergy and geothermal energy market continue to grow; however, the lack of abundance and low efficiencies have led to higher knowledge transfer costs. With the maturing of technologies, the renewable sources have been befitted by the economies of scale, systemlevel integration of these sources has increased dependencies on fossil operated reserve generation sources to fill these intermittencies and demand variation & increasing GHG emissions (Arent, Wise and Gelman, 2011; Guivarch and Monjon, 2017).

Distributed generation sources and their integration into the current grid infrastructure have given users to receive connection incentives mostly through the feed-in-tariffs and subsidies in the form of Contract for Difference and Renewable Obligation Certificates (ROCs). In order to shave peaks and deal with the volatility of renewable power generation for a clean energy mix, V2G can act as a co-ordinated power supply through comprehensive communication between the agents apart from the energy exchange through technological advancements and relative policies to define revenue frameworks, distribution & generation load along with the influence of heterogenous factors including consumer's choice and efficacy to ensure commitment towards the participation considering power discharge time and the capacity allotments. V2G has the tendency to frame feasible valley filling solutions through price elasticity and support the purpose to reduce baseload generation requirements which are usually dependent upon fossil-intensive power generation sources with high-capacity factors (Ma, Yi and Fan, 2022). Uncertainty factors are crucial in determining the reliability of the microgrid which varies from societal factors to technological limitations. A robust optimization technique can be used to confine uncertainty in aggregation while the seasonality in renewable power generation can be addressed through stochastic programming. Short-term and long-term market strategies can be framed via two different approaches where the short-term evaluation can focus on daily, weekly, and monthly engagements to the model operational planning while the long-term strategies need to focus on investment planning and expansion policies along with risk and reliability assessments (Battistelli, Baringo and Conejo, 2012). Pilot projects and practical studies in islanded regions done with dumb charging schemes and wind energy as the primary generation source and utilise V2G during off-generation hours found that the process was robust for the frequency balancing and couldn’t do well for the demand balancing due to lack of efficient transmission and geo-priority dispatch leading to underperformance (Pecas Lopes, Rocha Almeida and Soares, 2009). On the other hand, some studies to evaluate and optimise the energy use of the V2G to substitute utilityscale storage in the independent wind and solar-based decentralised infrastructure have gained interest among researchers however, the V2G supply tends to provide poor power quality during dispatch restricting its popularity and limiting its capability when compared to the fossil-based sources for the backup (Lehtola and Zahedi, 2019).

Following the limitations of the vehicle-to-grid technology, while injecting back the support energy into the system, technological advancements and opportunities have been explored in the next section based on the research studies available.

Technological Pathways for V2G adoption

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A multi-level perspective to analyse the diffusion process of V2G and V2X technologies in the transition process towards the technology diffusion can be defined by creating categories at the user level involving user-producers, intermediaries, citizens, and consumers. It becomes essential to provide open space for different social groups to inject different perspectives for ensuring flexibility by Social Construction of Technology (SCOT) in the diffusion process. The technology stands at a very early stage and needs input on the tinkering side to evaluate and define the most viable socio-economic and techno-economic strategy. Expectation growth, network development and widespread technological learning remain the core processes by allowing an open design space to innovate especially at the user level through innovations along with encouragement through incentives and technical support (SAHIN, 2006; Sovacool *et al.*, 2018). A couple of scenarios assuming highly decarbonised and slightly decarbonised power grid operator has been evaluated for Germany by 2030 based upon high oil and gas prices and dominance of solar and wind as the primary source of power generation whereas acceptable oil and gas prices for the second scenario. The load profiles induced by EVs are determined through the user's charging pattern and parking behaviour for an individual segment of the vehicle in both scenarios to evaluate cost-benefit analysis for each aggregator with an emphasis on revenue and degradation cost for the vehicles participating in the schemes as well as system benefits for power aggregators acting as a generating firm (Loisel, Pasaoglu and Thiel, 2014). The pay-as-you-go model have been utilised for providing revenues to users over parked EVs by the aggregators through the contractual and non-contractual form as a compensation to overcome high upfront costs. At the aggregator level, the power market may depend on the spinning reserve vs regulation power supplies. Contracts have been found to be inefficient compared to the prepaid and pay-as you go over model for the users' taking uncertainties in parking hours and restrictions in overall flexibility (SHI, LV and WANG, 2019).

Fundamentals of the dependency on the wind and solar integration in any scenario relies upon the storage technologies with short-term supplies and seasonal storage possibilities restricting the transmission losses and keeping minimum proximity to the load (Pietzcker *et al.*, 2017). It is necessary to capture the vehicle park and movement conditions for framing a realistic urban power distribution system which can be performed through co-ordinated supplied by the GIS (geographical incorporation systems) with controls through charge and discharge algorithms if the load can accept intelligent charging algorithm (Galus, Wietor and Andersson, 2012). Considering the nature of low disposable storage for V2G of EVs, the integration of this commodity must be performed at the distribution level and can act as both storage and distribution devices. The fast response capabilities can be utilized keeping the State of Charge (S.o.C) and the Depth of Discharge (D.o.D) upon the user's availability and reliability (Guille and Gross, 2009). The charging and Depletion model can be defined through linear equations keeping the charging and depletion constants over the timestamps. E-vehicle mobility can be supplemented by a decision logic for route adaption based upon the recharge requirements which can be evaluated through basis and attraction model shift for the purpose-driven navigation and prioritize based on the regional requirements (Hess *et al.*, 2012). Ambient temperature and Depth of Discharge (DoD) for an EV are the major parameters to determine the effective cost for the battery wear compensations while considering that the frequent charging and discharging activities can reduce the battery cycle life and can be estimated through the vehicle's manufacturing data upon the ambient-temperature, charging-discharging losses, and DoD. The fraction of power consumption during the battery's power drain instance both in the V2X and G2V situations can be considered as under the worst-case scenario to be zero in the modelling purpose for restricting the

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complexities in evaluation (Zhou *et al.*, 2011). In terms of quantifying participation, the proportion of owners based upon the social attributes who are willing to participate in the electric vehicle charging scheduling (EVCS) helping the smart grid technology in balancing, users had responded to favour charge location scheduling and charge dispatch scheduling with a target audience of private EV fleets. The study was supported by the technological advancement model to determine the extent of acceptance of the mechanism post-implementation (Wang *et al.*, 2022).

The technology has been found to be viable for peak shaving events with an assumption that the event lasted less than one hour per day utilising the advantage of lesser transmission losses and lower line congestions. The assumption of BMS interfacing with the communication for V2G assistance holds on a real-time basis. The system topologies can be defined through two major architectures i.e., deterministic and aggregative. The aggregative architecture involves a central controller and smart grid infrastructure to facilitate lower restrictions in deliveries whereas the deterministic architecture can be inefficient in supporting higher demands and minimum energy thresholds (Uddin *et al.*, 2017). Long parking facilities primarily in housing societies tend to provide flexible duration to offer charge-discharge cycles and serve as a beneficial source for user revenue without compensating with the minimum necessary requirements and define trade model strategy to offer better compensation than feed-in tariffs of renewable. To frame systematic coordination management for the integration, central architecture followed by the hierarchical coordination at each level to segregate dynamic integration of participating EV on a real-time basis for load distribution can be performed (SHI, LV and WANG, 2019). Another study to integrate V2G with the Building Energy Management System (BEMS) specifically in the urban locality with parking spaces of high rising buildings in Singapore were found to have dispatchable energy sufficient for the building's load and had the potential to act as a distributed storage system (Kumar *et al.*, 2014). Technological advancements varying from communication protocols to discharge standards are critical and the strategy needs to be defined along with the cooperation of the automotive industry as well as the power & utility sector for their roadmap with the involvement of stakeholders varying from grid operators to telemetry communication systems (Daim *et al.*, 2016).

While the technological advancements still stand at the very preliminary stage, it becomes important to evaluate the social adoption and the economic perspective, as well as the performance based upon the investments and the next section of the literature review, aims to capture the same.

Economic and Societal indicators for V2G performance

Heterogeneity in consumer choice and willingness to participate & share EV's storage can be significantly increased by bill savings sharing and participation incentives. Discrete choice methods can be utilized to estimate the demand and consumer preferences based upon various chargeable parameters and compensation for the service providers (Richter and Pollitt, 2018). The interest of consumers inclines toward the minimum permissible driving range, plug-in duration requirements and the annual revenue for participation in both the frequency regulation and ancillary services market as the most socio-economically valuable business. The deployment of V2G depends upon the effective promotion of services (charging and transmission infrastructure), market structure (supply-chain integration) as well as the system governance to ensure supporting policies and adequate rules for the aggregators keeping profits, consumer interest and discipline

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as the primary interest. Most of the business models have been analysed as productoriented and service-oriented models. The choice experiments for user's preference of choosing an Electric Vehicle (EV) over an Internal Combustion (IC) vehicle depends upon the attributes including the vehicle's offering range, acceleration and charging duration whereas the choice of electricity generation source wasn't found as a confusion parameter from the users (Noel *et al.*, 2019).

Constraints of minimum power capacity requirements make the involvement of aggregators highly important since the bidding participation has higher thresholds of minimum power supply allowances along with an assurance of stability and flexibility to the market (Sovacool *et al.*, 2020).

Vehicle aggregation has been found to be the only profitable business case for V2G implementations. The characteristics of EV cell pack charging involve parameters such as Quality of Service (QoS) determining charge and discharge period of batteries, energy pricing, delay in charging cycles and charging method's impact upon battery's performance. Agent based models have been used to differentiate the mobility types of various users varying based upon the comfort orientation, cost-optimization, innovation oriented and eco-efficient inclination along with the ownership preference market depending upon the long haul and short distance drivers, family and multi-utility purposes, secondary vehicle ownership, commercial and taxi purpose ownership as well as off-road fleets for industrial and leisure facilities built purposely for especially internal logistic facilities (Wolf *et al.*, 2015). The socio-technical and environmental advantage of V2G seems to be promising especially in the urban economy where the EVs have higher market penetration to minimize emissions supported by the dense charging infrastructure around the locality. Multi-method cross-comparative studies to involve both social and technological consideration is crucial to define the market segment and frame a competitive business model with a cautious evaluation of disaster situations such as flooding, earthquake, and major blackouts under which this technology could become more of a liability than the asset (Williams and Kurani, 2007). The driving calls are often predictable as compared to the spinning reserve and power regulation calls thus making implantation through fleet management and technological development a feasible choice. Spinning reserves require very less power supply constraints at an instance, thus turning up to be an optimal revenue generation source at the initial stage of technological developments (Kempton and Tomić, 2005b). These distributed generation sources tend to be profitable with the proposition of smart connection incentives by reducing network upgradation investments and diversifying developments at the generation sources where the costs are taken up by the consumers along with the study upon social discount and investments cost estimations (Anaya and Pollitt, 2017). Flexibility in framing the charging and discharging scheduling of EVs based on their availability and user preferences can lead to economical strategies at different rates and tariffs varying based on the energy market dynamics. Although smart charging has been efficient in load shifting of charging to off-peak hours, the dynamics and economic viability of V2G can vary for each country with the challenges of old traditional grid infrastructure, de-regulated competitive market, and co-ordination of regulating authority for transport and power transmission sectors to evaluate and balance the demand-supply on peak load hours, However, the extent of social adoption and investments on modernisation for the smart infrastructure are processes carried on simultaneously which makes the impact assessments complex considering technological and social policies investments go hand-to-hand (Almehizia and Snodgrass, 2018b).

A synthetic population with the agents and the demographic attributes including location choice modelling, and socio-network modelling to optimally choose a location where EV concentration

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and participation commitment are high can be used to evaluate multiple regional accumulations (van der Kam *et al.*, 2019). Environmental impacts and employee motivation play a crucial role in determining the organizational innovation and inclination to adopt EVs in their commercial fleets. However, the transition and adoption process is dependent upon the institution's financial conditions and long-term strategies which are often subject to the government's policies and market dynamics. The organizational influencing factors of adoption can be studied through regression analysis (Globisch, Dütschke and Wietschel, 2018). Industrial characters, daily mileage requirements for the tours and the socio-economic factors are primarily associated to assess the influence of EVs in their fleets apart from financial affordability (Kaplan *et al.*, 2016).

The public charging infrastructures are often expensive due to the investment costs, supplier charges and location costs since the areas are privately owned and involve service charges for the network access, metering charges and further especially in franchise business models (San Román *et al.*, 2011).

Multimodal assessment to assess the Merit order effect due to drastic cost reduction in renewable energy generation in an energy mix has been seen as a critical process for a liberalized energy market where renewable energy generation is still competing to the base load requirements at a limited extent (Antweiler and Muesgens, 2021). Value at risk propositions can be used to evaluate the potential risk and ensure the viability of investment adjustments with skewed distribution data and precise risk forecasts since the data generating process has the tendency of an adequacy. However, based on the previous variation between the forecasted and obtained asset value, historical risk assessments can be performed for evaluating the returns (Andriosopoulos and Nomikos, 2012). Studies have used Monte Carlo simulation to mimic charging behaviour based upon the federal government data and design optimal coordinated charging architecture. The model targeted to evaluate charging behaviour and potential of energy aggregation to support the auxiliary services with the change in charging behaviour pattern and through the simulation values obtained for a day ahead forecast (Jin *et al.*, 2020).

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METHEDOLOGY, MODELLING PARAMETERS AND MODEL DEVELOPMENT

Overview

This section gives an outline of the approach taken into consideration for determining the various parameters for the model's environment and the procedure performed as shown in figure 2 below along with the individual steps involved in extending the model implementations, followed by the analysis, results and study upon the outcomes later in the next section.

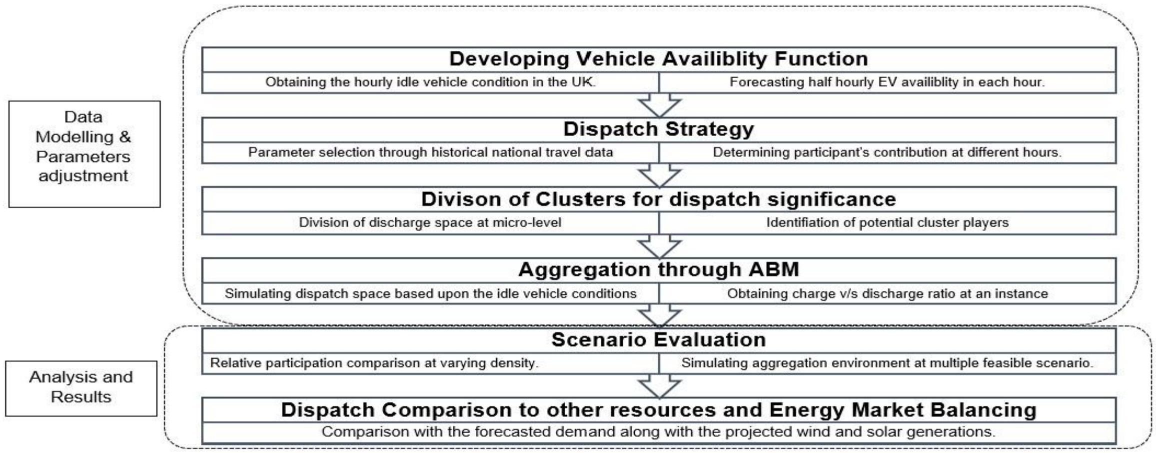

Figure 2: Steps involved for defining the methodology and analysis.

The parameters involved in developing the model have been defined in the first two stages followed by the modelling of the environment. Currently, Nissan Leaf stands as the only EV in the UK with Vehicle to Grid (V2G) and Vehicle to Infrastructure (V2I) capabilities. Since most of the pilot studies and experiments across the UK have Nissan Leaf as the only primary vehicle participating in the smart optimized energy dispatch, therefore all the distance to energy conversion figures is being considered based upon the ideal specifications as shown in table 1 below (EVDatabase, 2018).

Table 1: Nissan Leaf EV Specifications

Battery Capacity	Mileage	Average	Charging Duration
40kWh	140miles	0.28kWh/mile	8 hours

The charging & discharging values as well as the parameters have been considered based upon the Nissan Leaf's specification throughout the modelling approach considering negligible losses in the energy equivalence conversions.

Availability of an EV in an idle condition

In order to approximate the number of vehicles off the roads at each hour of the day so that the idle potential vehicles can participate in the power dispatch, the normalized probability of vehicles in rest position has been obtained based upon the distribution at the peak traffic hours that often occur between 07:00 to 09:00 as well as between 16:00 to 19:00 (National statistics, 2021). While the majority of personal motor vehicles are involved for typical routine commuting purposes, commercial motor vehicles are potentially idle during the late evening hours giving adequate availability for energy storage potential. The idle vehicle condition at an instance has been obtained by inversing the traffic distribution whereas the time has been considered in twenty-four formats to determine the function. For predicting the idle vehicle density, the average traffic distribution is being inversed, and the relative normalized density has been obtained using equation-1 below.

$x-min(x)$

$$x^{norm} = {}_{max(x)-min(x)} \quad (1)$$

Through the least square method with minimizing the variance of coefficients, polynomial regression has been used to estimate the idle vehicle density function. The normalized density is then fitted through a linear fitting for the 10th order polynomial for approximating the vehicle availability function at any instance as shown below in figure 3.

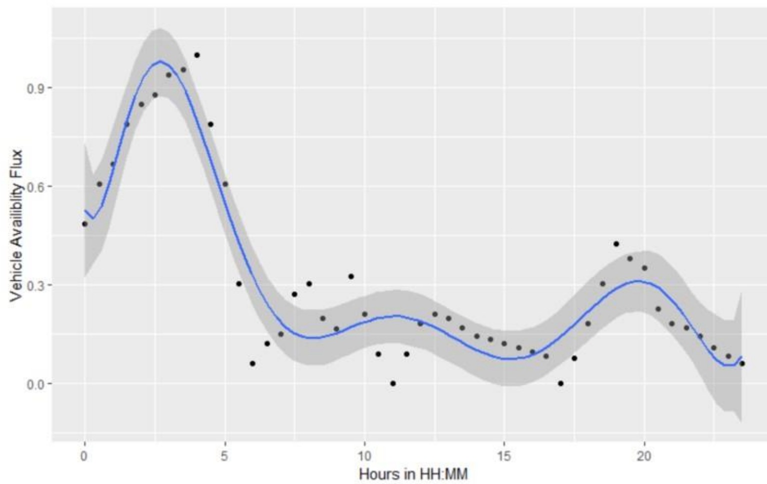

Figure 3: Density function for idle vehicle condition

The goodness of fit has been obtained for the 10th order polynomial equivalent to 89% as shown below in table 2.

Table 2: Summary of idle vehicle condition function

Residual Standard Error	**Multiple R-Squared**	**Adjusted R-Squared**	**p-value**
0.1043	0.8926	0.8636	6.212e-15

The peak availability can be seen between 00:00 and 05:00 with the other two local maxima visible around 12:00 and 20:00 respectively. The highly dynamic nature of vehicle availability is often susceptible to variation in human behaviours and travelling patterns. However, the usual travel pattern can be seen as dominated by the average working hours where most of the commuting occurs between the early morning and the late evening hours. While the vehicle availability at an instance is crucial, the safe participation energy is equally important for ensuring the reliability and flexibility of users. Based upon the density of vehicle availability, the highest idle conditions of EVs have been found to be in between 12AM-5AM whereas the lowest vehicle availability was seen in between 10AM-3PM as shown in figure 4 below.

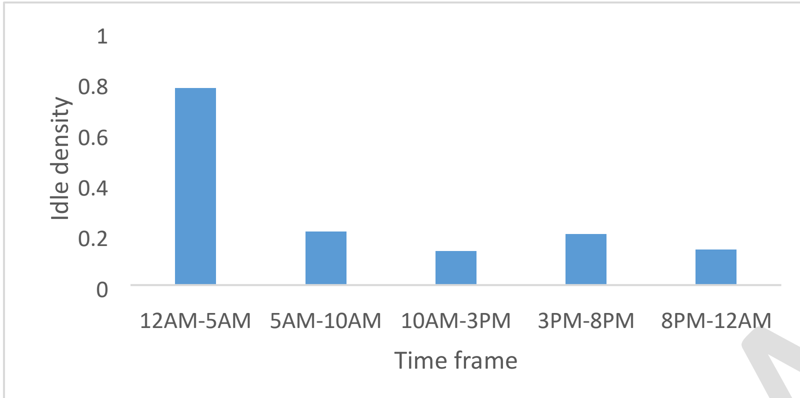

Figure 4: Idle vehicle densities at different time frames.

These individual time frames have been utilized ahead for evaluating the maximum possible dispatchable energy through V2G keeping in mind the overall availability and participation of the EVs based on the scenarios. Considering the vehicle's availability in these five-time frames, the model and the study have been made to capture relative possible energy dispatch and its comparison with the other generation sources along with the forecasted demand.

Historical Travel Data and Dispatch Strategy

For evaluating the safe energy dispatch to avoid range anxiety constraints and ensure equivalent participation, the average annual trips and miles for different age groups as individual drivers have been considered. The trip distances were relatively low during 2020 potentially due to the pandemic yet the annual trip distances remain lower for age group of 21-29 and above 70 age group throughout 2020-2015 whereas the maximum number of trips as well as the distance covered are higher for the age groups between 40-49 and 50-59 age groups as shown in figure 5 below. Thus, the average distance per trip also tends to be higher among these two groups.

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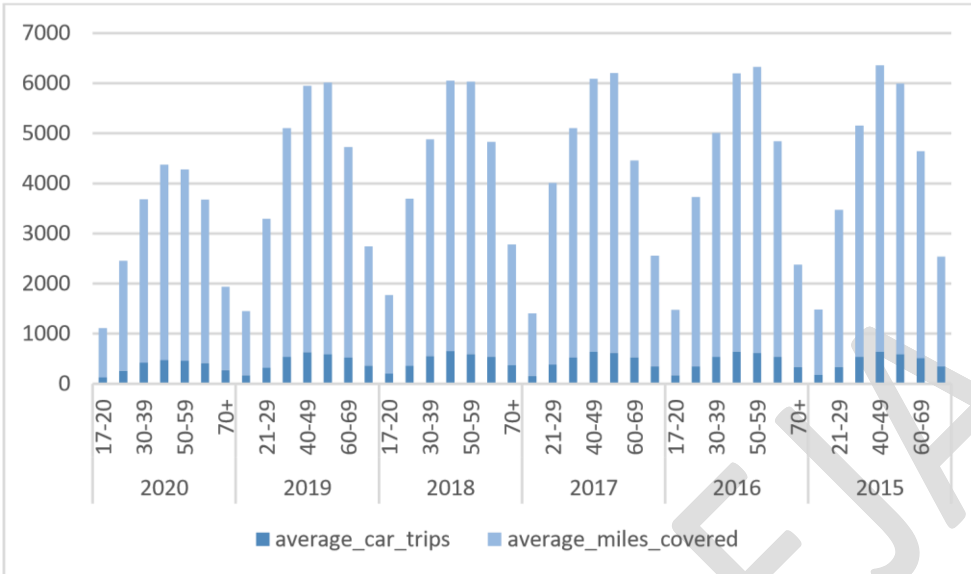

Figure 5: Age v/s Average number of trips and average trip distances in the UK for individual drivers

For ensuring an equal participation potential along with considering homogeneity in the age group, the average distance covered per trip in the UK has been calculated between 2020-2005. Through historical value at risk (VaR), the average trip distance of an individual has been calculated and considered to be the dispatchable energy equivalent for an individual participating. The historical VaR can be given as equation (2) below where v_m is equivalent to the mean of average distance per trip whereas v_i and v_{i-1} are the successive and current average distance per trip coefficients respectively when arranged in ascending order for calculating the safest trip distance which an individual could be willing to contribute for the regular participation at 10% risk.

$$VaR = \frac{v^i}{v_{i-1}} v_m \qquad (2)$$

At 90% confidence, the trip distance per mile was equivalent to 6.176 miles as shown in figure 6 below.

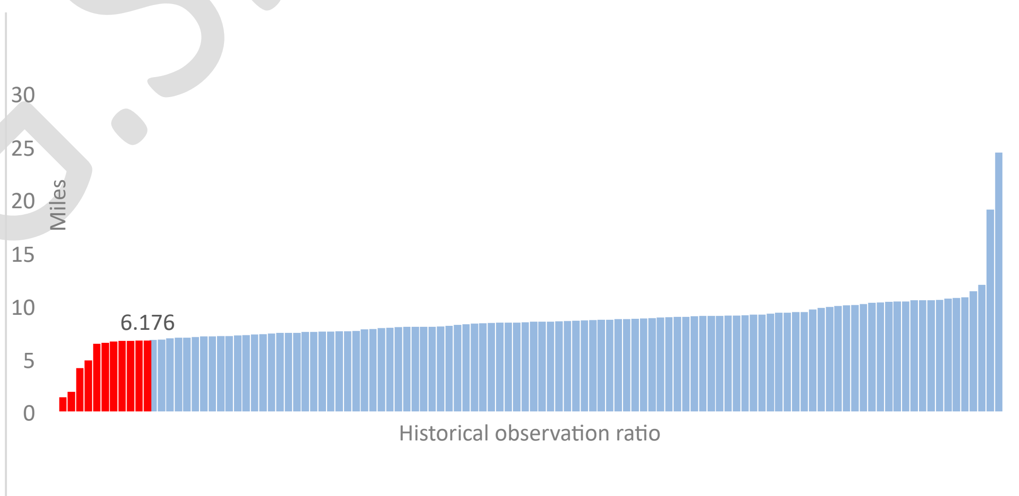

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Figure 6: Historical VaR for Miles per trip between 2005-2020

Based upon the mileage parameters of the Nissan Leaf EV as described in table 1, the energy equivalent to 1.72kWh was obtained for 6.176 miles. For modelling the dispatch during idle conditions of the EVs, dispatch energy equivalent to 1.729kWh has been considered ahead for the aggregation. Thus, with a homogeneity among the agents considered, each EV in an environment injects equivalent V2G energy in the participating time frame. On the other hand, for ensuring that each vehicle is being supplied with sufficient charging during the participation cycle energy equivalent to the national average trip mileage of 19 miles (NimbleFins; Department for Transport, 2020) has been proposed. Based on the calculations, net energy injected to an EV during the charging cycle is to be considered as the summation of average daily national mileage and the discharge allowance proposed which is equivalent to 7.05kWh.

Division into Clusters for small aggregations

For maximum governance and minimal distribution losses, a strategy to implement geolocation priority dispatch can play a crucial role in grid balancing and can act as a supplementary energy source for a decentralized infrastructure as a distributed storage source. While the market balancing would need more regulatory frameworks and discipline in dispatch, aggregating at a small scale could play a critical job and the clusters can potentially support the current infrastructure.

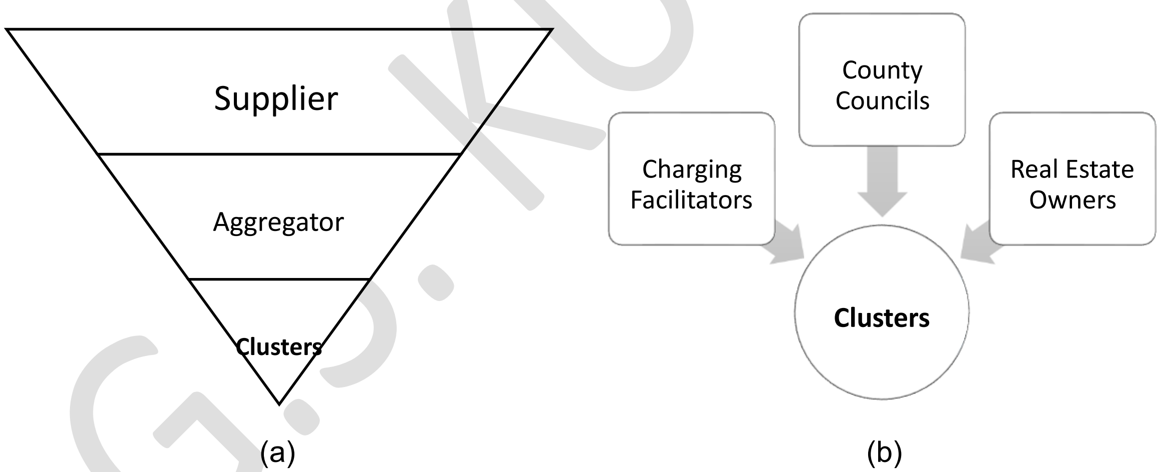

Figure 7: (a) Arrangement of aggregation players in terms of scale (b) Potential Cluster Players for the energy market

The distribution of aggregation potential and regulation can be framed as shown in figure 7(a) in an order where cluster aggregates at low levels in comparison to the aggregator whereas the potential governing bodies can be the small regulators as shown in figure 7(b) involving private players and council governing bodies which are playing critical roles in developing infrastructures across the EV charging facilitators in most of the countries. The aggregation at a small scale for maximum efficiency is essentially dependent on the parameters as shown in figure 8 below.

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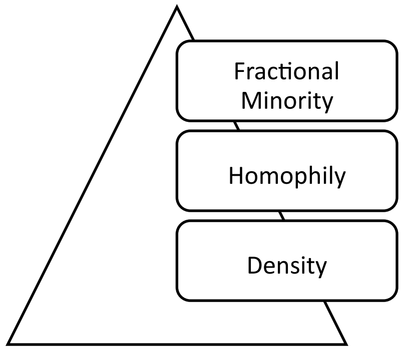

Figure 8: Parameters associated with an aggregation simulation environment

For establishing a robust and reliable dispatch proposition, the ratio between the participating and the non-participating vehicles should be effective enough along with a significant number of vehicles involved in the dispatch at any instance. The parameters are essential to ensure minimum transmission and aggregation efficiency losses. With the developments in the smart grid and the government's plans to upgrade and extend EV charging spaces through workplace charging and EV home charging schemes for charging infrastructure varying from large public parking spaces to personal home parking throughout the country, the charging infrastructure has been growing rapidly and aligned to the policy to phase out sales of IC Engine cars by 2030 and PHEV by 2035. The extent of the potential for harnessing the utility-scale storage capabilities of EVs can be thought of with the fact that the estimated number of EVs in the UK market will be equivalent to 37.4 million and with 45% of the vehicles capable of participating in grid balancing activities through V2G technologies (NationalgridESO, 2022). To ensure equal participation probability, the charging and aggregation in the environment need to be evaluated sequentially. Based upon the expected V2G capable EVs count, three scenarios with 80%, 50% and 30% of the achieved expected figure have been evaluated during the agent-based modelling ahead in the next section.

Aggregation potential evaluation and agent-based modelling

For a bottom-up modelling to visualize and evaluate the cyclic charging and discharging scheme over the EVs participating in the process, the MESA library has been used while considering EVs as an individual agent occupying each space in an energy aggregation environment. The environmental arrangement of agents in each of the tiles with an extent of autonomy having dynamic positioning and charging-injecting capabilities make them unique and identifiable. These agents are coming together to frame a macro-phenomenon that can help in investigating the relative potentials and understanding this dynamic process in a disciplined manner. For evaluating the overall potential in different scenarios with the government's estimated figures following calculations and formulations have been made. Based upon the equations and values mentioned in between equations (3) and (8), the parameters of the simulation environment for the three scenarios have been established.

$$Expected\ EVs\ in\ the\ UK\ Market = EV_{overall} = 37.4\ million \tag{3}$$
$$Expected\ V2G\ compatiblity\ share = P_{v2g} = 0.45 \tag{4}$$

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$$Expected\ V2G\ compatible\ EVs\ in\ the\ Market = EV_{v2g} = P_{v2g} * EV_{overall} \tag{5}$$

$$Scenario\ with\ 80\%\ of\ Expected\ V2G\ capable\ EVs\ participating = 0.8 * EV_{v2g} \tag{6}$$

$$Scenario\ with\ 50\%\ of\ Expected\ V2G\ capable\ EVs\ participating = 0.5 * EV_{v2g} \tag{7}$$

$$Scenario\ with\ 30\%\ of\ Expected\ V2G\ capable\ EVs\ participating = 0.3 * EV_{v2g} \tag{8}$$

Thus, for each simulation,

$$Height/Width\ of\ each\ dispatch\ space\ during\ 80\%\ occupancy = d_{0.8} = \sqrt{0.8 * EV_{v2g}} \tag{9}$$

$$Height/Width\ of\ each\ dispatch\ space\ during\ 50\%\ occupancy = d_{0.5} = \sqrt{0.5 * EV_{v2g}} \tag{10}$$

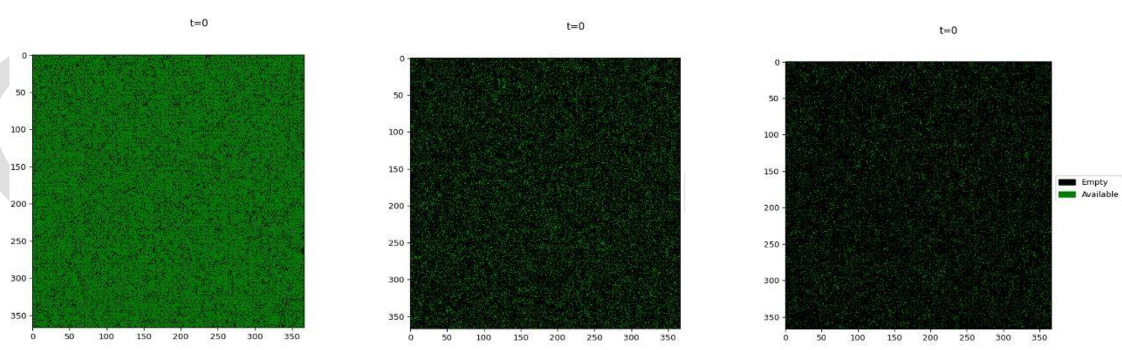
$$Height/Width\ of\ each\ dispatch\ space\ during\ 30\%\ occupancy = d_{0.3} = \sqrt{0.3 * EV_{v2g}} \tag{11}$$

The density of environment has been varied for the five different time frames based upon the average density observed in section 3.2. The height and the width for the simulation environment are to be varied based upon the percentage occupancies as calculated in equation 9, 10 and 11 where,

$$Height/Width\ for\ each\ dispatch\ space = d_i$$

$$i = Fraction\ of\ occupancy\ in\ an\ individual\ scenario$$

At a time, the maximum vehicle availability is most likely to occur between 12 AM-5 AM, the rest of the four-time frames had vehicle availability close to 0.13 and 0.20. Based on the observed density, aggregation space was obtained as shown in figure 9 below.



0.77 0.20 0.13

Figure 9: Dispatch space simulated in Mesa

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Further to simulate energy injection and charging, the time cycle for assigning EV a chargingdischarging cycle for stochastic and dynamic behavior has been assigned randomly and the number of EVs participating at each instance has been shown in equation 12 below.

$$Charging\ at\ each\ instance: c_t = 7.05kWh * \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} EV_{j,k} \tag{12}$$

$$EV_{j,k} = \{\ 0,1\ \}$$

$$Available\ injectable\ energy\ at\ the\ instance : i_t = 1.73kWh * [\ (d_i)^2 - \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} EV_{j,k}\ ] \tag{13}$$

Were,

$$Height\ of\ charging\ space\ at\ an\ instance = m_i$$

$$Width\ of\ charging\ space\ at\ an\ instance = n_i$$

$$EV_{\mathrm{j,k}} = State\ of\ participation\ of\ vehicle\ at\ positon\ (\mathrm{j, k})$$

$$0: Vehicle\ not\ involved\ in\ charging\ at\ an\ instance$$

$$1: Vehicle\ involved\ in\ charging\ at\ an\ instance$$

While the vehicles across the height (m_i) and (n_i) are charging dynamically, the rest of the EVs in the environment have been participating in the energy injection to the grid. The dynamic charging allocation is getting initiated from one of the ends of the model's environment and charging EVs across the width n_i and height m_i varying until the completion of a cycle as shown in figure 10 below.

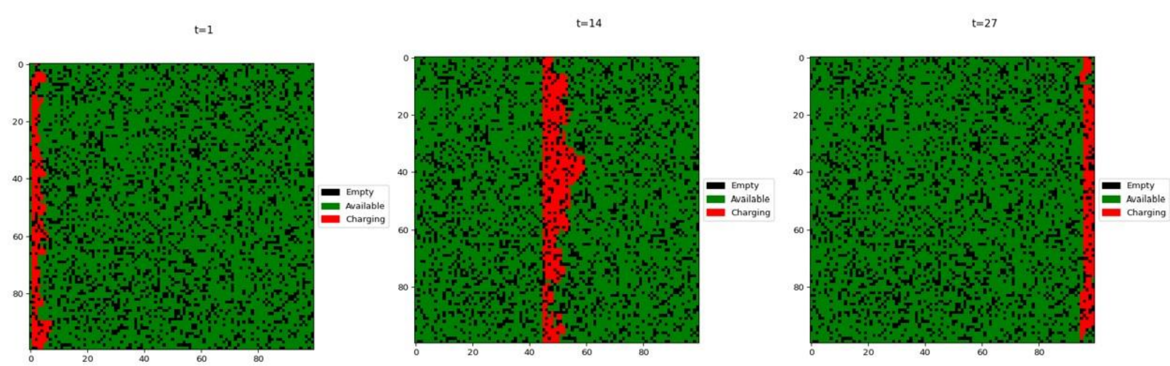

Figure 10: Charging and Injecting cycle in each simulation

The simultaneous charging and discharging in an environment with a cyclic simulation in each of the time frames along with the overall number of participants in each of the environments have been used ahead to evaluate and establish our results in the next section under sub-section 2.

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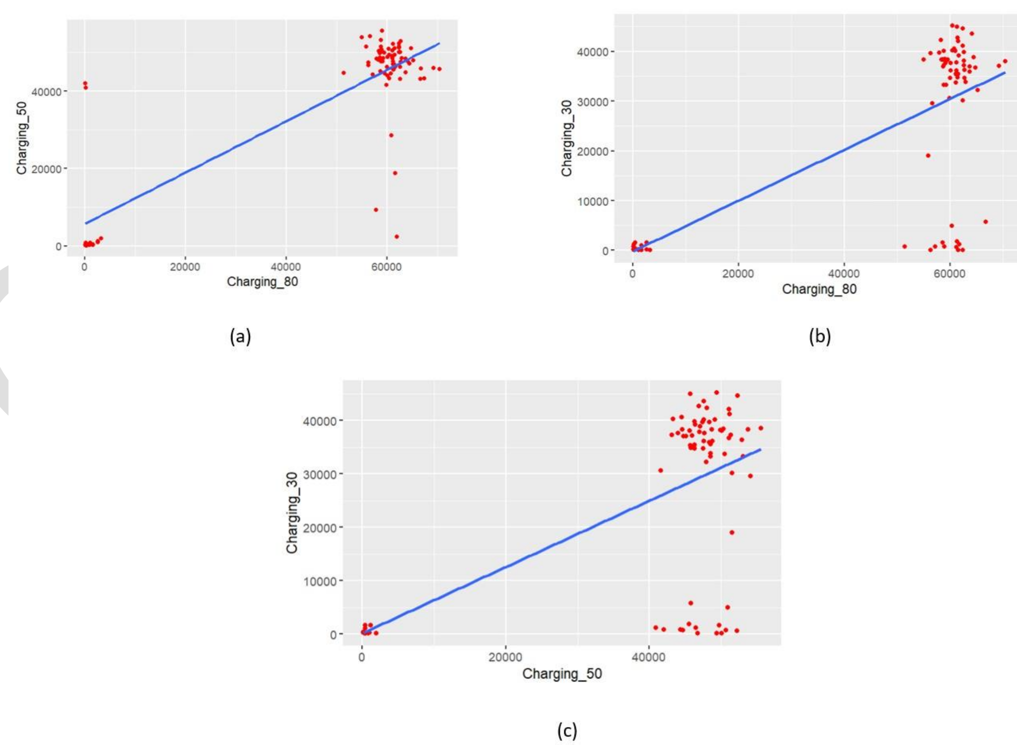
RESULTS, ANALYSIS AND DISCUSSION

Overview

This section aims to discuss the outcomes and the projected dispatch potential observed through the arrangements made and the modelling performed in the last section. Based upon the model obtained by charging and discharging in the given environment, a relative comparison of vehicles charging at each instance with various occupancies has been estimated along with the analysis over predicting energy dispatch potential during different hours of the day followed by relative comparison to the forecasted energy mix aligned with the forecasted contribution of wind and solar on an average half-hourly basis. The section concludes with the comparison of current demand and the projected demand by the year 2050 along with an analysis of the requirement for extra generation sources for demand balancing.

Comparison of Charging Participation in different scenarios

At different densities, the charging vehicle's number varies significantly while implementing a cyclic charging scheme over the environment. Considering the dynamic charging capability of EVs in the environment with a mean of 7.05kWh of energy dispatch for an individual vehicle, the charging figures obtained at each simulation with varying densities have been regressed to evaluate the extent of similarity in charging participation as shown in figure 11 below.



(a) (b)

(c)

Figure 11: Regression plots for the vehicles involved in charging (a) At 50% occupancy vs at 80% occupancy (b) At 30% occupancy vs at 80% occupancy (c) At 30% occupancy vs at 50% occupancy

For the three varying arrangements, the summary of all three regression models obtained has been shown below in table 3.

Table 3: Summary of linear regression models

S.No.	Model	Multiple RSquared	Adjusted RSquared	F-Statistic	p-value
1	Charging at 50% occupancy vs Charging at 80% occupancy at each instance	0.7079	0.7045	208.4	<2.2e-16
2	Charging at 30% occupancy vs Charging at 80% occupancy at each instance	0.4807	0.4742	74.06	5.227e-13
3	Charging at 30% occupancy vs Charging at 50% occupancy at each instance	0.4056	0.3981	54.58	1.264e-10

While the proportion of variance is maximum for the vehicles getting charged at each instance in 50% occupancy and 80% occupancy with $R^2 = 0.70$, the number of vehicles charging at these two figures tends to be forecasted through a linear model whereas the lower significant R^2 equivalent to 0.48 for 30% - 80% charging scenarios and 0.40 for 30% and 50% charging figures indicates that the proportion of vehicles charging at each instance in these two arrangements is varying due to the lack of aggregation significance because of lower density and occupancy fraction. A similar conclusion can be drawn through the F-statistic and the lower p-value making the results statistically significant. Thus, with the decrease in density and fractional minority, the proportion of vehicles charging at each instance decreases. This makes the presented aggregation and cyclic charging model more efficient for occupancy figures with more than 50% compared to the least achieved instances.

Dispatchable Energy at various time frames

Based upon the dispatch time frame as shown in figure 4 with the average vehicle idle conditions, on evaluating the sum of a total number of agents placed in the environment during simulation for each of the compatible spaces, all the EVs participating have been made to dispatch energy equivalent obtained for the safe dispatch at VaR as proposed to 1.73kWh. With 80% of the V2G compatibility figures expected, the dispatch can be seen to be the highest as shown in figure 12 below.

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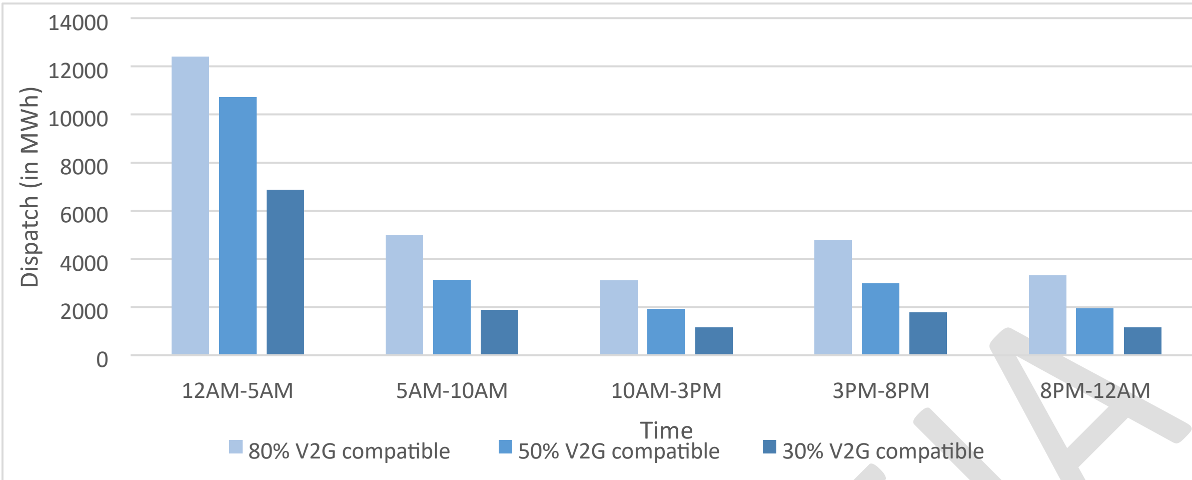

Figure 12: Dispatch through V2G at different time frames.

The maximum dispatch of 12GWh can be expected through the given aggregation model while the dispatch proportion remains significantly lower during the late evening hours and during the late morning and early afternoon hours. The dispatch capabilities are as low as 1.7GWh with 30% of expected figures achieved during 10 AM-3 PM. With the cyclic charging and discharging proportion of EVs performed during each of the time frames, the energy injected vs dispatched can be seen below in figure 13.

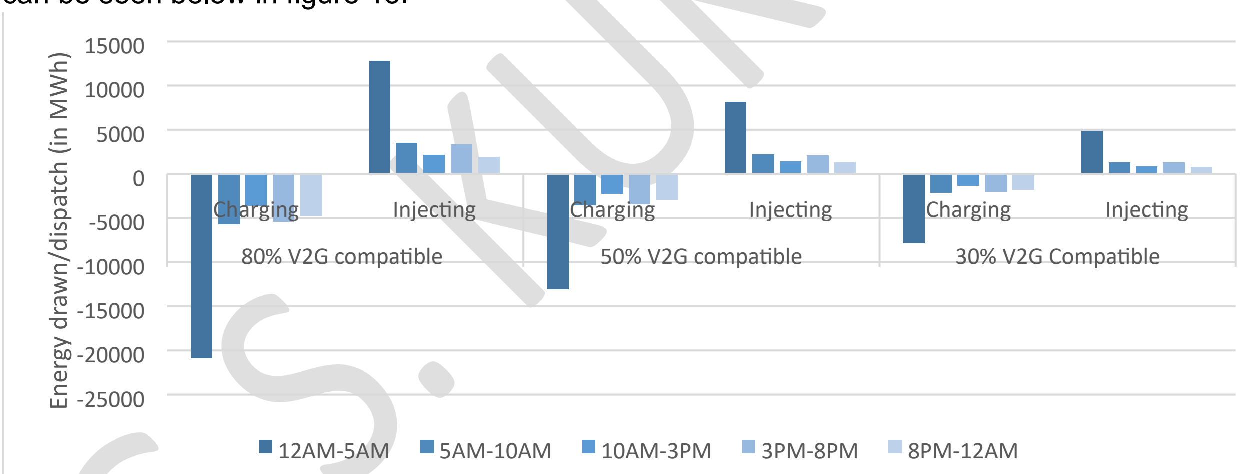

Figure 13: Overall Energy injected to grid vs Energy used in Charging in each cycle

The maximum amount of the energy demand required to fulfil the charging of the participating EVs during each instance of the allocated time frame up to energy equivalent to the participation commitment and average daily national mileage of 19miles were being supplied. With each EV subjected to a charge and discharge cycle, an average of three and a half cycles were required considering the standard charging conditions taking approximately eighty-four minutes to charge an individual EV up to 7.05kWh while the rest of the EVs available in the environment inject the committed energy equivalent to 1.73kWh. The peak dispatch for each cycle can be seen between 12 AM-5 AM while the maximum demand to schedule charging for the EVs remains high during the same period. Although the injected energy has relatively high potential in an aggregation model, the simultaneous demand required for matching up the charging requirements can be as

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high as twenty gigawatts during the same period. Extension of the study for the demand-supply scenario and the potential of V2G to complement the wind and solar-dominated power grid for dispatch scheduling and market balancing is needed for evaluating the benefits of participation.

Energy dispatch potential of V2G to support wind and solar mix

Considering that wind and solar have intermittencies and relatively low-capacity factors, it is important to evaluate the average generation efficiency of both generation sources. As of 2021, the UK's solar installed capacity was equivalent to 13.08GW whereas the wind energy capacity was found to be 6.5GW. Based on the half-hourly generation data of 2021 for solar and wind, the average generation efficiencies were calculated and have been plotted as shown in figure 14 below.

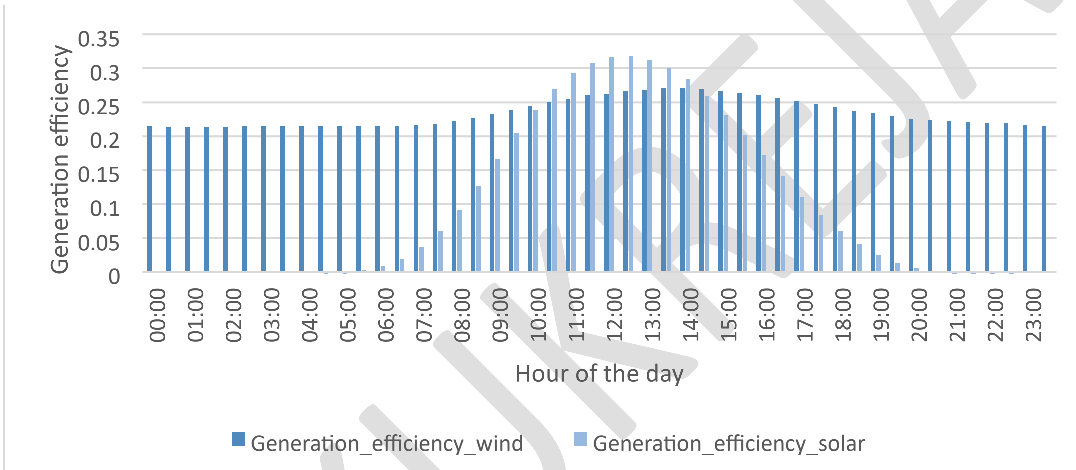

Figure 14: Average half-hourly generation capacities for Solar and Wind for 2021

On evaluating the generation efficiencies obtained through averaging the hourly energy produced for 2021, solar tends to peak its generation efficiency close to 32% during the mid-day between 11 AM-1 PM while the wind has an average between 20-25% throughout the day with slight peaks between the 11 AM-5 PM. While this lower operational efficiency due to intermittency increases, the requirements of fossil-dependent spinning reserves for higher flexibility and generation efficiency grows and the V2G can complement these intermittent generation sources to establish a reliable dispatch strategy. Based upon the expected installed capacity of 75GW of solar and 100GW of wind by 2050 ('Sixth Carbon Budget'. Climate Change Committee, 2020) and the daily average half-hourly generation efficiency obtained for both the resources as shown in figure 14 for 2021, the overall estimated relative dispatch in each period has been shown below in figure 15.

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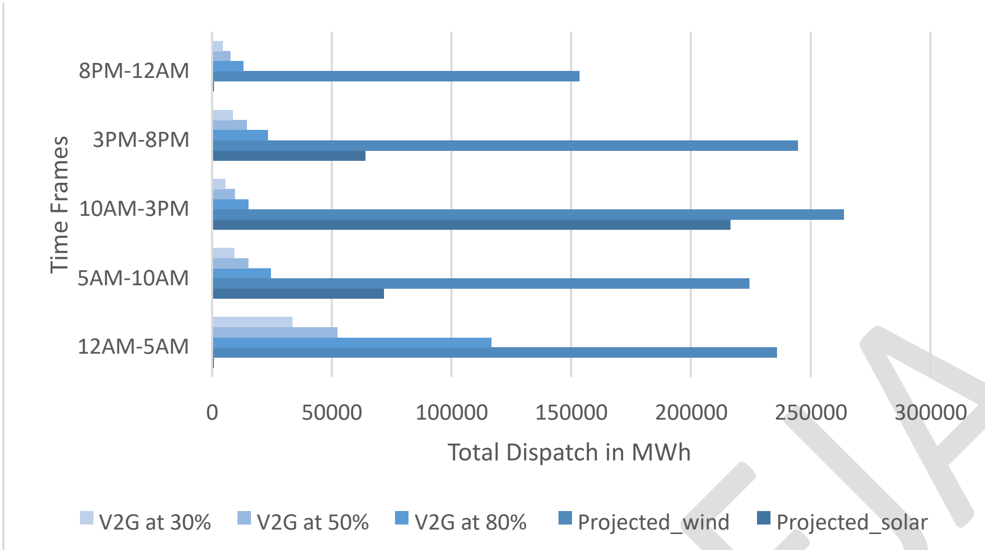

Figure 15: Forecasted Energy dispatch in each time frame

With the peak in availability between midnight, the dispatchable energy based upon the forecasted number of EVs having participation potential at 1.73kWh have been evaluated based on their supply potential. While comparing the half-hourly vehicle dispatchable energy with the half-hourly demand as of 2021, the V2G dispatchable energy for the scenario with 80% of the expected figure achieved was found to have enough potential to match the current net energy demand during the early morning hours as shown below in figure 16.

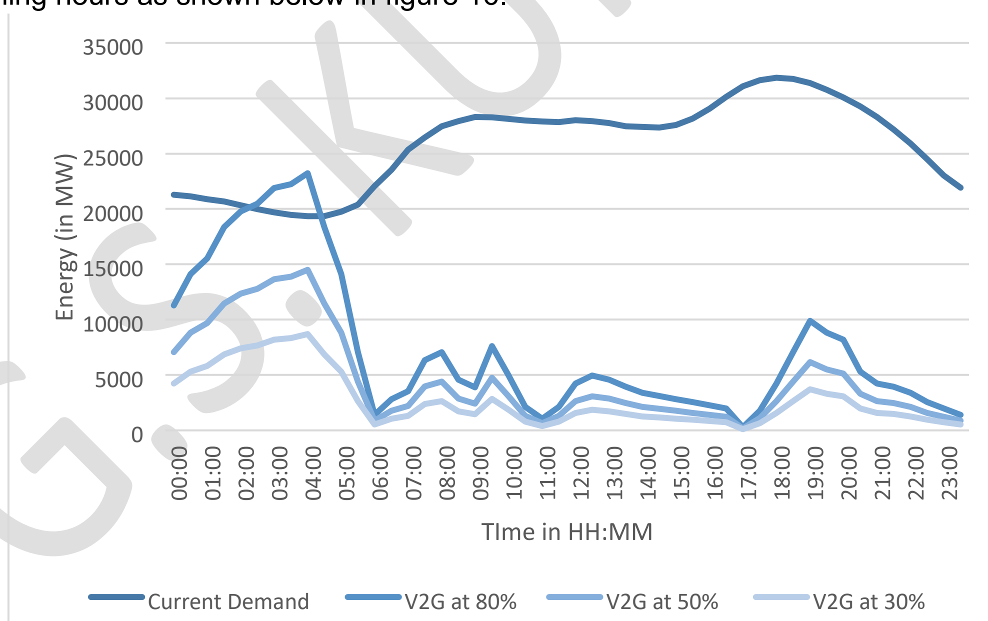

Figure 16: Average half hourly Demand in 2021 vs Energy dispatch potential through V2G at different scenarios.

With the growth in EV adoption and the expected demand for routine charge scheduling to supply the national mileage and the discharge commitment value i.e., 7.05kWh, the half-hourly demands were being forecasted by adding the energy demand of EVs upon the 2021 half hourly demand.

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Based upon the total number of vehicles participating in 80%, 50% and 30% of achieved V2G capability fraction and the forecasted solar and wind generation capacities along with the forecasted demand, the energy mix along with the generation potential through V2G at different scenarios have been calculated. Figure 17 below shows the relative comparison of generation through different resources and the forecasted demand.

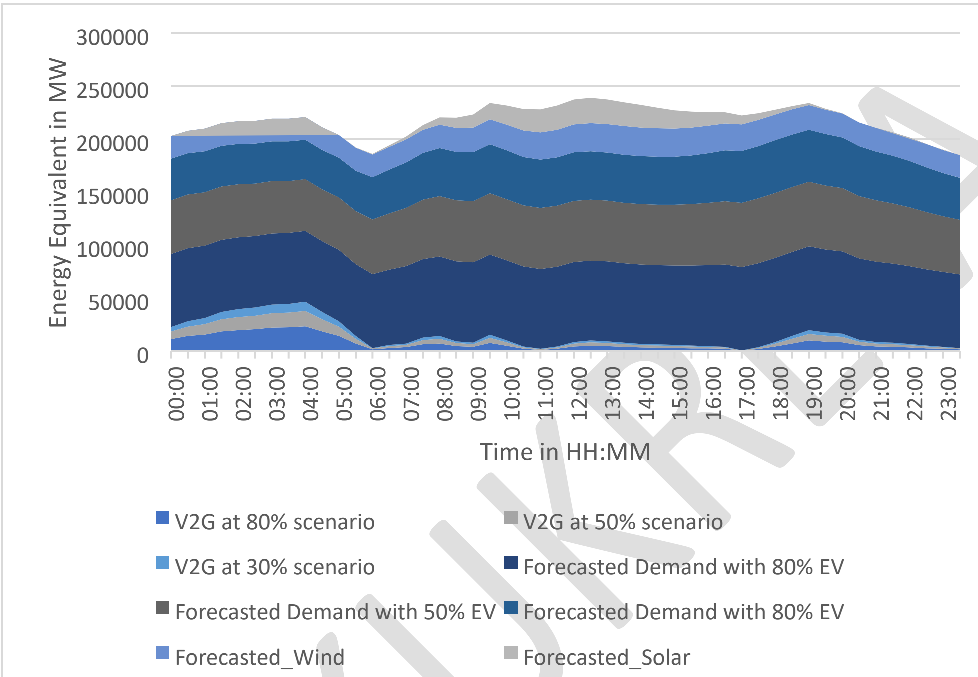


Figure 17: Forecasted Energy demand with respect to generation potential through solar, wind and V2G

With the average injecting potential in all three scenarios established, V2G at midnight tends to supplement the wind energy and mitigate the lack of solar energy during the late-night hours for balancing. While the forecasted generation potential during mid-day hours seems to be promising with the solar and wind mix even with the lowest number of V2G participation due to the clash of traffic hours with the peak demand hours, the low carbon-based spinning reserves including gas and nuclear can play a crucial role in coping up with the demand supplies during those peak load hours. A study has been done to evaluate the extent of reliability for a carbon-neutral grid by considering solar, wind and vehicle to grid along with the forecasted demand and the extent of generation required from the other sources in the next sub-section.

Evaluation of generation and forecasted demand at multiple scenarios through Monte-Carlo and Multi-variate Regression

With the forecasted demand based upon the charging scheme proposed ensuring the energy consumption for charging an EV with a mean of 7.03kWh per vehicle, the demand proportion rises significantly in all three scenarios. The forecasted figures for the participation of EVs in the 80% achieved objective comes out to be approximately 13.5 million, 8.4 million EVs for 50% and close to 5 million for 30% of V2G participating numbers. While the clean energy mix is expected to be dominated by solar and on-offshore wind energy assets, it becomes crucial to evaluate the extent of support the technology has been providing while matching the real-time half-hourly demand for grid-balancing. Based on the forecasted injecting potential of each supply source on a half-hourly basis a box and whisker plot has been obtained in figure 18 below.

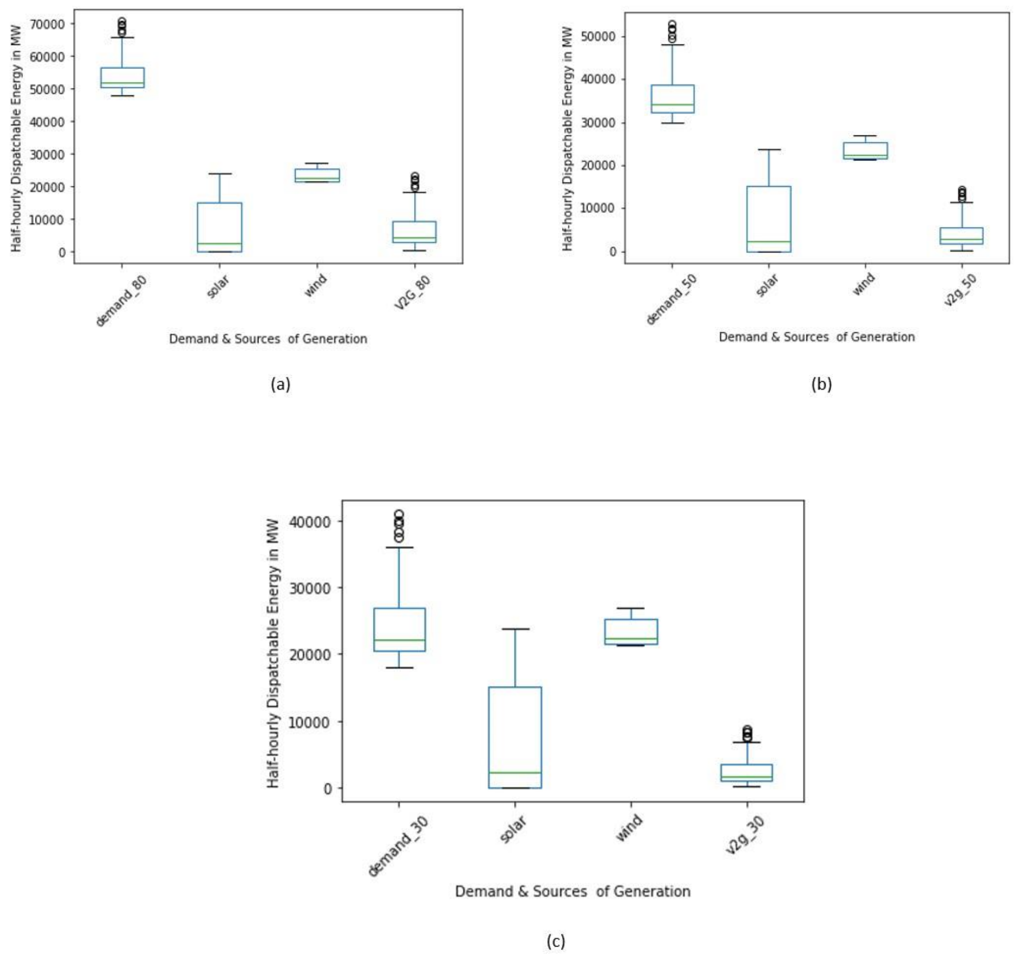


Figure 18: Boxplot of half hourly forecasted demand with respect to forecasted generation potential of all the three sources in each scenario (a) At 80% (b) At 50% (c) At 30%

While the randomness for demand and energy injected through EVs can be seen with the high number of outliers due to variation in consumption and the travel patterns affecting the idle dispatch conditions, the energy generation through wind and solar are negatively skewed with a median of 20.2GW and 5GW respectively. The interquartile range for solar tends to be higher due to the larger extent of intermittency as well as the restricted sunshine hour along with seasonality whereas the relatively stable capacity factor and limited impact of seasonality on annual halfhourly generation from the wind has restricted the quartile range of wind energy. The extent of the overall number of EVs participating in the V2G dispatch tends to remain relatively higher and thus bring consistency in overall energy dispatch.

To evaluate the degree of dependence upon generation from the solar, wind and forecasted V2G proportions with the forecasted demand, the multivariate regression was performed while considering forecasted demand depending upon the forecasted half-hourly generation from the three sources. However, to capture the uncertainty around the forecasted mix, the Monte-Carlo analysis has been used, based upon the forecasted generation data with the descriptive statistics feature of each independent variable as shown in table 4 below.

Table 4: Descriptive Statistics of independent variables

Source	Mean	Standard Deviation
Wind	23.37419	2.047248
Solar	7.344907	8.839062
V2G at 80%	7.309555	6.548191
V2G at 50%	4.564096	4.0887
V2G at 30%	2.737653	2.452498

Based on the mean and standard deviation obtained a total of 17,520 samples have been examined considering 365 days and 48 half-hourly data for each day upon 500 experiments to capture maximum uncertainty while considering the normal distribution of each variable as shown below in figure 19.

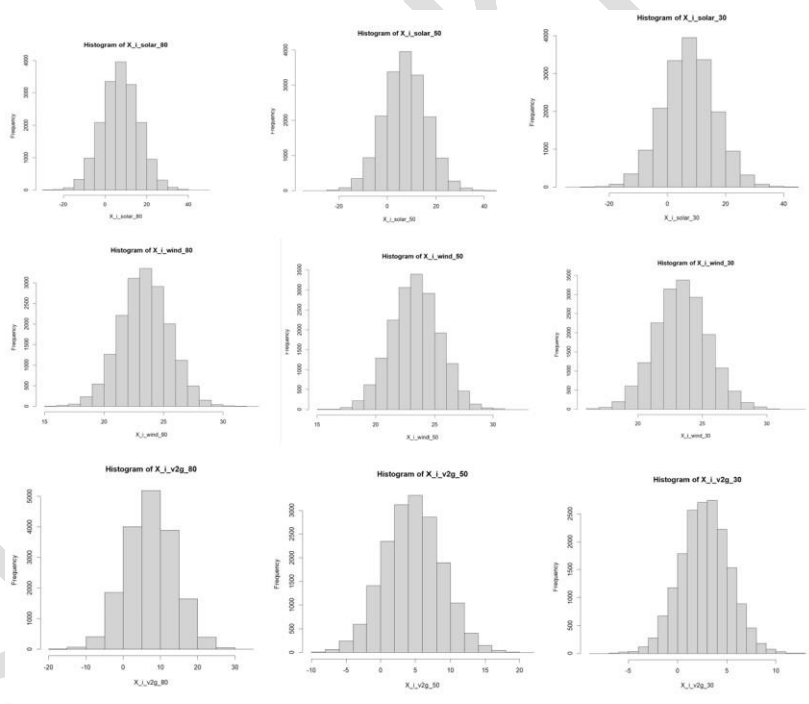


Figure 19: Extended sample size for all the variables

Considering the observations obtained from extending the sample space, the multivariate regression over 500 unique experiments has been performed with the equations defined below.

$$Y_{i,80} = \beta_0^{i,80} + \beta_{solari,80} * x_{isolar} + \beta_{windi,80} * x_{iwind} + \beta_{v2g}^{i,80} * x_i^{v2g\_80} \quad (14)$$

$$Y_{i,50} = \beta_0^{i,50} + \beta_{solari,50} * x_{isolar} + \beta_{windi,50} * x_{iwind} + \beta_{v2g}^{i,50} * x_i^{v2g\_50} \quad (15)$$

$$Y_{i,30} = \beta_0^{i,30} + \beta_{solari,30} * x_{isolar} + \beta_{windi,30} * x_{iwind} + \beta_{v2g}^{i,30} * x_i^{v2g\_30} \quad (16)$$

Were,

$j = \{ 30, 50, 80 \}$

$Y_{i,j}$ = Forecasted Demand in j[th] scenario

${\beta_0}^{i,j}$ = Intercept coefficient/ error term in j[th] scenario

${\beta_{solar}}^{i,j}$ = Coefficient of generation for solar energy

${\beta_{wind}}^{i,j}$ = Coefficient of generation for wind energy

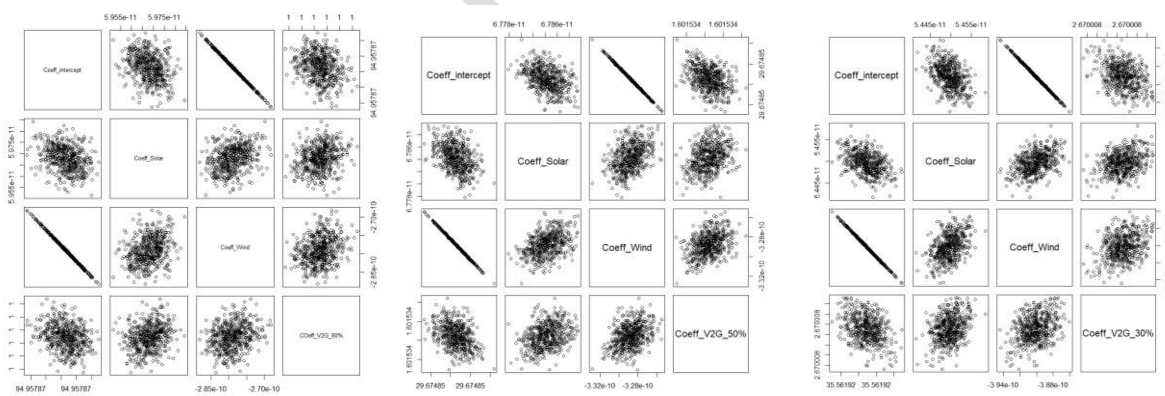
${\beta_{v^{i,}2^{j}g}}$ = Coefficient of generation for V2G dispatch

${x_i}^{solar}$ = Forecasted half-hourly generation from solar

${x_i}^{wind}$ = Forecasted half-hourly generation from wind

${x_i}^{v2g\_j}$ = Forecasted half-hourly generation from V2G in each of the j[th] scenario

With an assumption of normal distribution and varying margins, based upon the expanded sample space for the multi-variate regression five hundred experiments were performed and the coefficient variation can be seen below in figure 20.



(a) At 80% (b) At 50% (c) At 30%

Figure 20: Varying coefficients in five hundred simulations performed through Monte-Carlo

While the variability between the coefficients intends to capture all the probable scenarios for the net-generation efficiency, the mean of the coefficients obtained remains the same. The coefficients and estimates obtained through the summary of each model can be seen below in table 5.

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Table 5: Summary obtained from multi-variate regression of all the three scenarios

Scenario	Coefficients	Estimate	Std. Error	t-value
V2G feasibility at 80% of expected figures achieved	(Intercept)	4.747787e+01	1.017237e-08	4.667335e+09
	Solar	5.968020e-11	1.014309e-10	5.883827e-01
	Wind	-2.790746e-10	4.558951e-10	- 6.121466e01
	v2g_80	1.000000e+00	6.801387e11	1.470288e+10
V2G feasibility at 50% of expected figures achieved	(Intercept)	2.964525e+01	1.143772e-08	2.591884e+09
	Solar	6.784237e-11	1.140480e-10	5.948581e-01
	Wind	-3.288237e-10	5.126042e-10	-6.414768e-01
	v2g_50	1.601534e+00	1.224760e-10	1.307631e+10
V2G feasibility at 30% of expected figures achieved	(Intercept)	1.778192e+01	1.050270e-08	1.693080e+09
	Solar	5.449701e-11	1.047247e10	5.203834e-01
	Wind	-3.901845e-10	4.706995e10	-8.289461e-01
	v2g_30	2.670008e+00	1.874947e-10	1.424045e+10

The lower standard error for the coefficients is describing the good proportion of generation sample space. The error term stands relatively lower at 17.78 GW for the scenario evaluated with 30% of the expected figures achieved. However, the effect of size for the V2G contribution in this condition remains relatively high. Although the first scenario had a higher contribution during the discharge, the rise in demand impacts the dependence on excess generation reserves. The dependency on contingency reserves and the generation source during 80% of the V2G capable vehicle forecasted can be seen as high as 47.47GW.

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORKS

Overview

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In this chapter, the principal conclusion has been drawn based on the modelling parameters described and the analysis performed considering various scenarios and the forecasted demand–supply mix followed by the discussion on the limitations of the proposed model and the future recommendations that can be performed based upon the ground established by this research project through varying the parameters for making more complex and futureproof dispatch strategy models for the V2G scheme through EVs.

Conclusions

To conclude, this research work aimed to develop a smart aggregation charging-discharging strategy for the vehicle to grid technology varying based on the vehicle availability along with ensuring that sufficient energy has been injected back to the participating vehicles during the process to tackle social behavioural constraints such as range anxiety and mileage restriction issues. For equal participation opportunities and homogeneity in the discharge profile for the participants, the model assumes a similar energy discharge from all the involved EVs. Based on the forecasted total number of V2G capable EVs, the number of EVs participating at each instance for the charging in the 80% scenario had a higher similarity than the 50% of V2G capable scenario obtained through the agent-based modelling. Whereas the proportion of charging vehicles at 30% vs 80% and 30% vs 50% scenarios were found to be highly dynamic and could not be forecasted through a regression model.

The maximum energy injection potential into the grid through V2G was found to be during the late midnight and early morning hours between 12 AM-5 AM as high as 12GWh in the maximum occupancy case. On the other hand, the peak demand for charging tends to be higher at the same time requiring approximately 22GWh. To analyse the aggregation significance through V2G while relating to the forecasted energy mix of wind and solar, the aggregated energy obtained was found to have enough potential to overcome solar energy's intermittency during the night hours.

Based upon the highly dynamic idle vehicle condition, the charging-discharging scheme introduced and evaluated in the model can help develop a more predictive demand-supply balancing scheme in a net-zero energy grid. The forecasted demand was then evaluated with the generation from solar, wind and the injected energy through V2G followed by expanding the demand generation regression through Monte-Carlo helped in evaluating the dependency on other sources for all three scenarios, and the effect on coefficients of each generation source. Based upon all the three scenarios portrayed with a total of five hundred experiments to increase evaluation space, the dependency on other secondary sources tends to vary from a maximum of 17.78GW to 47.47GW for the half-hourly demand fulfilment across the three different scenarios. The model can be evaluated by varying the overall dispatchable vehicle participation and energy mix forecasting. While the scenarios evaluated reflect the potential of vehicle-to-grid technology to complement the forecasted solar and wind generation, the study above can be utilised to analyse the overall energy supplies and the planning of more spinning reserves for a decarbonized grid.

Limitations, Recommendations and Future Works

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The current model has been made with an assumption of homogeneity in allowed discharge energy for each V2G participant along with a limitation of considering all the parameters for a similar EV and an assumption that the participation of EVs strictly follows the idle vehicle function.

The variability in dispatch potential and participation can improvise the current aggregation model and can help in achieving the objectives more precisely. The generation efficiency and the net capacity factors for solar and wind energy have been obtained based on the half-hourly generation and net installed capacity in the year 2021. While these generation efficiencies are subject to variability in weather and technological advancements, the forecasted half-hourly generation may vary and so could the forecasted demand which only captures the additional demands of EVs in all the three different scenarios above the current demand. Considering the vehicle movement and optimising the model for geo-location priority dispatch on different days can lead to more precise results.

The model can be made more accurate and informative by including the social parameters capturing the uncertainty in EV participation for making the aggregation model more robust. For maximising the geo-location priority dispatch, a micro-level study of individual regions can be performed based on the compatible vehicle density and their discharging allowance potential along with a relative comparison to individual V2I/V2B (Vehicle to Infrastructure/Vehicle to Building) technologies in different scenarios. The aggregation thresholds can be varied and combined with life cycle assessment studies for evaluating profitability upon the investments for upgradation since the technology stands in its very early stage of diffusion.

Moreover, the model framed and evaluated considers solar and wind as separate independent generations and V2G as a separate generation source with reasonable supply potential. The study can be extended by assessing the utilisation of V2G along with a combination of solar and wind as an individual supply sources in decentralized infrastructure and it would be necessary to analyse the feasibility of such systems to ensure reliable supplies.

The agent-based model defined shows the promising result for the aggregation and implementation of a smart charging-discharging cycle for all three scenarios of V2G capable vehicles forecasted, however allowing heterogeneity in an environment with the charging vehicle proportion and schedules can help in delivering more interesting findings. The behavioural model can be developed to couple the process of incentivizing the participants for battery degradation as well as maintenance charges along with optimising the charging schedules on a day-ahead basis based upon the forecasted requirement for V2G generation with the forecasted distributed energy resources generation potential to overcome the stochastic uncertainty in balancing.

Future studies can focus on adding user preferences and consistency in an individual's participation in small environments and assessing the impact on power quality of the grid based upon the energy aggregation from each environment and the penetration of renewable energy in each environment ensuring the strategies support the consumer's convenience, minimum power losses and improved frequency regulation services. The bidirectional power flow in the grid still exists as one of the complex constraints in grid balancing, therefore more research studies of aggregation business models along with techno-economic analysis for the integration of V2G providing a substitute to current other conventional carbon-intensive generation sources can be done for extending the current study.

Overall, further work in optimising and allocating regional discharging strategy based upon the regional load profile for minimum losses and more in-depth research upon the same can help establish complex and practical models.

BIBLIOGRAPHY

Alam, M.M. and Lee, Y. (2021) *Cleaner Vehicles and Charging Infrastructure*, *Cleaner Vehicles and Charging Infrastructure*. Available at: https://doi.org/10.1596/36516.

Almehizia, Abdullah.A. and Snodgrass, J.M. (2018b) ‘Investigation of V2G economical viability’, in *2018 IEEE Texas Power and Energy Conference (TPEC)*. IEEE, pp. 1–6. Available at: https://doi.org/10.1109/TPEC.2018.8312048.

Anaya, K.L. and Pollitt, M.G. (2017) ‘Going smarter in the connection of distributed generation’, *Energy Policy*, 105, pp. 608–617. Available at: https://doi.org/10.1016/J.ENPOL.2017.01.036.

Andriosopoulos, K. and Nomikos, N. (2012) ‘Risk management in the energy markets and Value-at-Risk modelling: A Hybrid approach’, in *2012 9th International Conference on the European Energy Market*. IEEE, pp. 1–17. Available at: https://doi.org/10.1109/EEM.2012.6254649.

Antweiler, W. and Muesgens, F. (2021) ‘On the long-term merit order effect of renewable energies’, *Energy Economics*, 99, p. 105275. Available at: https://doi.org/10.1016/j.eneco.2021.105275.

Arent, D.J., Wise, A. and Gelman, R. (2011) ‘The status and prospects of renewable energy for combating global warming’, *Energy Economics*, 33(4), pp. 584–593. Available at: https://doi.org/10.1016/J.ENECO.2010.11.003.

Battistelli, C., Baringo, L. and Conejo, A.J. (2012) ‘Optimal energy management of small electric energy systems including V2G facilities and renewable energy sources’, *Electric Power Systems Research*, 92, pp. 50–59. Available at: https://doi.org/10.1016/j.epsr.2012.06.002.

Daim, T.U. *et al.* (2016) ‘Technology roadmap for smart electric vehicle-to-grid (V2G) of residential chargers’, *Journal of Innovation and Entrepreneurship*, 5(1), p. 15. Available at: https://doi.org/10.1186/s13731-016-0043-y.

Department for Transport and Office for Low Emission Vehicles (2021) *£30 Million Investment in Revolutionary V2G Technologies’. GOV.UK*.

EVDatabase (2018) *Nissan, L.E.A.F.* . Available at: https://ev-database.uk/car/1106/NissanLeaf
Galus, M.D., Wietor, F. and Andersson, G. (2012) ‘Incorporating valley filling and peak shaving in a utility function based management of an electric vehicle aggregator’, in *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*. IEEE, pp. 1–8. Available at: https://doi.org/10.1109/ISGTEurope.2012.6465894.

Globisch, J., Dütschke, E. and Wietschel, M. (2018) ‘Adoption of electric vehicles in commercial fleets: Why do car pool managers campaign for BEV procurement?’, *Transportation Research*

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Part D: Transport and Environment, 64, pp. 122–133. Available at: https://doi.org/10.1016/j.trd.2017.10.010.

Gowrisankaran, G., Reynolds, S.S. and Samano, M. (2016) ‘Intermittency and the Value of Renewable Energy’, *Journal of Political Economy*, 124(4), pp. 1187–1234. Available at: https://doi.org/10.1086/686733.

Guille, C. and Gross, G. (2009) ‘A conceptual framework for the vehicle-to-grid (V2G) implementation’, *Energy Policy*, 37(11), pp. 4379–4390. Available at: https://doi.org/10.1016/j.enpol.2009.05.053.

Guivarch, C. and Monjon, S. (2017) ‘Identifying the main uncertainty drivers of energy security in a low-carbon world: The case of Europe’, *Energy Economics*, 64, pp. 530–541. Available at: https://doi.org/10.1016/J.ENECO.2016.04.007.

Han, W. and Xiao, Y. (2016) ‘Privacy preservation for V2G networks in smart grid: A survey’, *Computer Communications*, 91–92, pp. 17–28. Available at: https://doi.org/10.1016/J.COMCOM.2016.06.006.

Hess, A. *et al.* (2012) ‘Optimal deployment of charging stations for electric vehicular networks’, in *Proceedings of the first workshop on Urban networking - UrbaNe ’12*. New York, New York, USA: ACM Press, p. 1. Available at: https://doi.org/10.1145/2413236.2413238.

Jin, Y. *et al.* (2020) ‘Optimal Aggregation Design for Massive V2G Participation in Energy Market’, *IEEE Access*, 8, pp. 211794–211808. Available at: https://doi.org/10.1109/ACCESS.2020.3039507.

van der Kam, M. *et al.* (2019) ‘Agent-Based Modelling of Charging Behaviour of Electric Vehicle Drivers’, *Journal of Artificial Societies and Social Simulation*, 22(4). Available at: https://doi.org/10.18564/jasss.4133.

Kaplan, S. *et al.* (2016) ‘Intentions to introduce electric vehicles in the commercial sector: A model based on the theory of planned behaviour’, *Research in Transportation Economics*, 55, pp. 12–19. Available at: https://doi.org/10.1016/j.retrec.2016.04.006.

Kempton, W. and Tomić, J. (2005a) ‘Vehicle-to-grid power fundamentals: Calculating capacity and net revenue’, *Journal of Power Sources*, 144(1), pp. 268–279. Available at: https://doi.org/10.1016/j.jpowsour.2004.12.025.

Kempton, W. and Tomić, J. (2005b) ‘Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy’, *Journal of Power Sources*, 144(1), pp. 280–294. Available at: https://doi.org/10.1016/j.jpowsour.2004.12.022.

Kumar, K.N. *et al.* (2014) ‘V2G Capacity Estimation Using Dynamic EV Scheduling’, *IEEE Transactions on Smart Grid*, 5(2), pp. 1051–1060. Available at: https://doi.org/10.1109/TSG.2013.2279681.

Lehtola, T. and Zahedi, A. (2019) ‘Solar energy and wind power supply supported by storage technology: A review’, *Sustainable Energy Technologies and Assessments*, 35, pp. 25–31. Available at: https://doi.org/10.1016/j.seta.2019.05.013.

G.S.KUKREJA

Loisel, R., Pasaoglu, G. and Thiel, C. (2014) ‘Large-scale deployment of electric vehicles in Germany by 2030: An analysis of grid-to-vehicle and vehicle-to-grid concepts’, *Energy Policy*, 65, pp. 432–443. Available at: https://doi.org/10.1016/J.ENPOL.2013.10.029.

Lund, H. and Kempton, W. (2008) ‘Integration of renewable energy into the transport and electricity sectors through V2G’, *Energy Policy*, 36(9), pp. 3578–3587. Available at: https://doi.org/10.1016/J.ENPOL.2008.06.007.

Ma, S.C., Yi, B.W. and Fan, Y. (2022) ‘Research on the valley-filling pricing for EV charging considering renewable power generation’, *Energy Economics*, 106, p. 105781. Available at: https://doi.org/10.1016/J.ENECO.2021.105781.

Mullan, J. *et al.* (2012) ‘The technical, economic and commercial viability of the vehicle-to-grid concept’, *Energy Policy*, 48, pp. 394–406. Available at: https://doi.org/10.1016/J.ENPOL.2012.05.042.

National statistics (2021) *Road traffic estimates in Great Britain: 2020*.

NationalgridESO (2022) *Future Energy Scenarios 2022 | National Grid ESO.* Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios#fullsuite. (Accessed: 12 August 2022).

NimbleFins (2022) ; Department of Transport Average Car Mileage UK 2022. 4 Sept. 2019, https://www.nimblefins.co.uk/cheap-car-insurance/average-car-mileage-uk.

Noel, L. *et al.* (2019) ‘Willingness to pay for electric vehicles and vehicle-to-grid applications: A Nordic choice experiment’, *Energy Economics*, 78, pp. 525–534. Available at: https://doi.org/10.1016/j.eneco.2018.12.014.

Pecas Lopes, J.A., Rocha Almeida, P.M. and Soares, F.J. (2009) ‘Using vehicle-to-grid to maximize the integration of intermittent renewable energy resources in islanded electric grids’, in *2009 International Conference on Clean Electrical Power*. IEEE, pp. 290–295. Available at: https://doi.org/10.1109/ICCEP.2009.5212041.

Pietzcker, R.C. *et al.* (2017) ‘System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches’, *Energy Economics*, 64, pp. 583–599. Available at: https://doi.org/10.1016/j.eneco.2016.11.018.

Richter, L.-L. and Pollitt, M.G. (2018) ‘Which smart electricity service contracts will consumers accept? The demand for compensation in a platform market’, *Energy Economics*, 72, pp. 436–450. Available at: https://doi.org/10.1016/j.eneco.2018.04.004.

SAHIN, I. (2006) ‘Detailed Review of Rogers’ Diffusion of Innovations Theory and Educational Technology-Related Studies Based on Rogers’ Theory’, *TOJET : The Turkish Online Journal of Educational Technology*, 5(2). Available at: https://www.proquest.com/scholarlyjournals/detailed-review-rogers-diffusion-innovations/docview/1288364916/se2?accountid=14511.

San Román, T.G. *et al.* (2011) ‘Regulatory framework and business models for charging plug-in electric vehicles: Infrastructure, agents, and commercial relationships’, *Energy Policy*, 39(10), pp. 6360–6375. Available at: https://doi.org/10.1016/j.enpol.2011.07.037.

G.S.KUKREJA

SHI, L., LV, T. and WANG, Y. (2019) ‘Vehicle-to-grid service development logic and management formulation’, *Journal of Modern Power Systems and Clean Energy*, 7(4), pp. 935– 947. Available at: https://doi.org/10.1007/s40565-018-0464-7.

‘Sixth Carbon Budget’. Climate Change Committee, (2020) *https://www.theccc.org.uk/publication/sixth-carbon-budget/. Accessed 16 Aug. 2022.* Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/. (Accessed: 16 August 2022).

Sovacool, B.K. *et al.* (2018) ‘The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review’, *Environmental Research Letters*, 13(1), p. 013001. Available at: https://doi.org/10.1088/1748-9326/aa9c6d.

Sovacool, B.K. *et al.* (2020) ‘Actors, business models, and innovation activity systems for vehicle-to-grid (V2G) technology: A comprehensive review’, *Renewable and Sustainable Energy Reviews*, 131, p. 109963. Available at: https://doi.org/10.1016/j.rser.2020.109963.

Statista 2021, ‘ Electric vehicle market in the United Kingdom - Statistics & Facts’ Available at: https://www.statista.com/topics/2298/the-uk-electric-vehicleindustry/#topicHeader__wrapper

Uddin, K. *et al.* (2017) ‘On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system’, *Energy*, 133, pp. 710–722. Available at: https://doi.org/10.1016/j.energy.2017.04.116.

Wang, N. *et al.* (2022) ‘Analysis of public acceptance of electric vehicle charging scheduling based on the technology acceptance model’, *Energy*, 258, p. 124804. Available at: https://doi.org/10.1016/j.energy.2022.124804.

Williams, B.D. and Kurani, K.S. (2007) ‘Commercializing light-duty plug-in/plug-out hydrogenfuel-cell vehicles: “Mobile Electricity” technologies and opportunities’, *Journal of Power Sources*, 166(2), pp. 549–566. Available at: https://doi.org/10.1016/j.jpowsour.2006.12.097.

Wolf, I. *et al.* (2015) ‘Changing minds about electric cars: An empirically grounded agent-based modeling approach’, *Technological Forecasting and Social Change*, 94, pp. 269–285. Available at: https://doi.org/10.1016/j.techfore.2014.10.010.

Zhou, C. *et al.* (2011) ‘Modeling of the Cost of EV Battery Wear Due to V2G Application in Power Systems’, *IEEE Transactions on Energy Conversion*, 26(4), pp. 1041–1050. Available at: https://doi.org/10.1109/TEC.2011.2159977.

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Step A6 – MSC ESDA Dissertation Ethics Declaration

Statement of Risk Assessment & Ethics Approval Requirements
Student Candidate Number [FILL IN]: [redacted]
Student Name: [FILL IN]: [redacted]
Student UCL Email Address: [FILL IN]: [redacted]
Supervisor Name: [FILL IN]: Dr Manos Chaniotakis
Supervisor UCL Email Address: [FILL IN]: m.chaniotakis@ucl.ac.uk
Dissertation Research Proposal [FILL IN]: • Title / Topic: Vehicle to Grid: exploring the potential following a data drive approach • Research Question(s) / Aims & Objectives: Assessing the feasibility of implementing V2G technology to support grid infrastructure in an emission free power sector • Data & source (specify all data to be used; if none, explain why): None. Dissertation dependent upon multiple mathematical modelling scenarios • Method(s) (specify all methods to be used): Optimization techniques to generate revenue models and relate to the practical world scenarios for the V2G integration.
I have read and understood **Step A1 'Does the research require a Risk Assessment?'** and: [DELETE ONE STATEMENT]: • ~~This planned research DOES require a risk assessment and appropriate approval will be secured before undertaking any of the activities covered by the risk assessment.~~ • This planned research does NOT require a risk assessment.
I have read and understood **Step A2 'Does the research require External research ethics approval?'** and: [DELETE ONE STATEMENT]: • ~~This planned research DOES require external ethics review and appropriate external ethics approval will be secured before the data collection starts.~~ • This planned research does NOT require external ethics review.
External ethics approval is *not required* and I have read and understood **Step A3 'Is the research Exempt from the need for ethics approval?'** and: [DELETE ONE STATEMENT]: • This planned research IS EXEMPT from the need for research ethics approval. • ~~This planned research is NOT EXEMPT from the need for research ethics approval.~~
The research is *not exempt* from the need for ethics approval and I have read and understood **Step A4 'Does the research require High Risk ethics approval?'** and: [DELETE ONE STATEMENT]: • This planned research IS deemed high risk and approval from the UCL Research Ethics Committee will be secured before the research starts. • This planned research is NOT deemed high risk.
The research is *not exempt* from the need for ethics approval, does not require high risk ethics approval and: I have read and understood **Step A5 'Does the research require ESDA low risk ethics review for questions-based methods OR BSEER low risk ethics review for other methods?'** and: [DELETE ONE STATEMENT]: • This planned research requires MSc ESDA Low Risk Ethics approval for questions-based methods and approval will be secured before data collection starts. • This planned research requires BSEER low risk ethics approval (for other methods), which will be secured before data collection starts.
I confirm that: • the information I have provided is accurate to the best of my knowledge. • if the answers to any of these questions changes, I will go through this protocol again.

NEXT STEPS:

- **STUDENT:** Copy the text of the *completed* statement above into an email and email it to your supervisor.
- **SUPERVISOR:** Reply to the email confirming your approval of the completed statement, attaching the form and copying in the Dissertation Tutor (Despina Manouseli).
- **STUDENT:**
  - Include this A6 Statement as a Dissertation Appendix after you have BLACKED OUT YOUR NAME & EMAIL ADDRESS so the second marker can mark anonymously.

The Dissertation mark sheet asks the second marker whether this form was filled out correctly and, if not, what % mark deduction they recommend.