

Vehicle to grid: driver plug-in patterns, their impact on the cost and carbon of charging, and implications for system flexibility

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ABSTRACT

Vehicle-to-grid (V2G) from electric vehicles (EVs) represents an opportunity to provide transitioning electricity systems with battery storage as they face increasing shares of variable renewable generation. However, whilst the availability of V2G as dispatchable storage depends on the travel and charging habits of drivers, there is scarce experience of managing portfolios of EVs in this way. This paper investigates the impact of plug-in frequency – given real-life travel data – on the potential of V2G to reduce i) consumer bills and ii) carbon emissions of charging. In doing so, we investigate the extent to which consumers are incentivised to participate in V2G, how this might change based on different charging behaviours, and what the implications are for V2G as a storage asset. Two models of plug-in behaviour are input into a time-coupled optimisation that schedules EV (dis)charging to minimise the net cost of an EV's required energy gain within network constraints, simulating how V2G could be dispatched by a 'load controller' in a liberalised electricity market. The cost minimisation is based on the Octopus Agile V2G tariff in January 2021, which is matched to GB grid carbon intensity data from National Grid ESO for the same period. It was found that, on the basis of the time range studied, V2G can reduce the average price paid for EV-charging electricity by 28–67% versus a flat tariff – with the lower end of that range representing a case where consumers only plug in when they 'need' to, and the higher end representing the case where consumers plug in whenever their cars are at home. It was also found that due to the weak positive correlation between price and carbon during the time range studied, optimising for price also resulted in slight reductions in carbon intensity of the EV-charging electricity by 5–6% compared to uncontrolled charging, with the range representing the same cases as before. Taking into account a review of battery degradation costs from V2G, using an EV's battery in this manner only makes financial sense to the owner if they maximise their plug-in frequency; this, alongside the increased savings, should provide an incentive to owners to plug in as much as possible – thereby maximising storage resource for a low carbon electricity system.

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1. Introduction

The UK is one of an expanding set of major economies that has committed to end the sale of internal combustion vehicles (ICVs) – in this case by 2030/2035¹ at the time of writing [1] – as part of its legally-binding commitment to reach Net Zero greenhouse gas emissions by 2050 [2]. Even if private car ownership and use in the

UK reduces as per wider decarbonisation strategies [3], the market dominance of battery electric vehicles (EVs) over other low carbon powertrains [4] means that it is likely that tens of millions of EVs will be bought in the UK in the next two decades.

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¹ 2030 is the current phase-out date for purely internal combustion powered vehicles; the sale of plug-in hybrids is due to be banned in 2035.

Nomenclature			
Sets			
\mathcal{B}	Buses, indexed by b	$p_{e,t}^{\text{imp}}$	Active power imported by an EV in charge event e during time period $[t, t + 1]$
\mathcal{D}	Domestic loads, indexed by d	$p_{e,t}^{\text{exp}}$	Active power exported by an EV in charge event e during time period $[t, t + 1]$
\mathcal{E}	Electric vehicle charging events, indexed by e	$p_{g,t}^G$	Active power from grid supply point g during time period $[t, t + 1]$
\mathcal{G}	Grid supply points, indexed by g	$p_{l,t}^L$	Active power flow on line l during time period $[t, t + 1]$
\mathcal{L}	Lines, indexed by l	t_e^{in}	Plug-in time of EV for charge event e
\mathcal{T}	Time horizon comprised of ten-minutely timesteps, indexed by t	t_e^{out}	Plug-out time of EV for charge event e
Parameters		t_e^s	Original plug-in time of EV for charge event e
E_e^{max}	Battery capacity in EV for charge event e	t_e^d	Original plug-out time of EV for charge event e
E_e^{start}	Energy storage content of EV at start of charge event e	$t_e^{\gamma}, t_e^{\infty}, t_e^{\text{min}}$	Time at which the EV's SoC reaches γ in charge event e , time at which the charging power reaches 1% of the maximum rated power in charge event e , minimum of t_e^d and t_e^{∞}
E_e^{end}	Energy storage content of EV at end of charge event e	$\beta_{e,t}$	Binary variable used for constraint to ensure no energy dumping for charge event e at timestep t
M	Upper limit of constraint to ensure no energy dumping	$\sigma_{e,t}$	State of charge (per unit) of EV in charge event e at timestep t
P_e^{max}	Max. charging power for EV in charge event e	Abbreviations	
S_l^{max}	Active power capacity of a line l	CC-CV	Constant current-constant voltage
γ	SoC at which the charging profile transitions from the constant current to the constant voltage region in charge event e	CCGT	Combined cycle gas turbine
Δt	Difference between adjacent timesteps $[t, t + 1]$	CDF	Cumulative distribution function
η	One-way charger efficiency	ESA	Energy smart appliance
Variables		ESO	Electricity system operator
$c_t^{\text{CO}_2}$	Carbon intensity of grid electricity at timestep t	EV	Electric vehicle
c_t^{imp}	Export tariff at timestep t	GB	Great Britain (referring to the largest island of the UK)
c_t^{exp}	Import tariff at timestep t	ICV	Internal combustion vehicle
dE_e^{LHS}	Energy to be trimmed from beginning of charge event e	NTS	National Travel Survey
dE_e^{RHS}	Energy to be trimmed from end of charge event e	SoC	State of charge (of an EV's battery)
$E_{e,t}$	Energy storage content of EV in charge event e at timestep t	V2G	Vehicle to grid
$p_{d,t}^D$	Active power delivered to domestic demand d during time period $[t, t + 1]$	WTP	Willingness to pay

Bi-directional charging, or *vehicle to grid* (V2G), represents a technological opportunity for decarbonisation at the transport-electricity nexus. Firstly, by providing a revenue stream for EV (or charge point) owners, V2G can encourage EV uptake (or charge point installation) and hasten the transition from ICVs [5]. Secondly, V2G enables the provision of fast-responding electricity storage from vehicles that are otherwise idle: there is the potential for a significant proportion of the UK's required electricity storage² as it adopts increasing levels of variable renewables to be met by the control of EV batteries.

Similarly to stationary battery storage, V2G can provide several services of benefit to the electricity system, including frequency [8] and voltage [9] regulation, peak shaving [10] and spinning reserve [11]. However, unlike stationary battery storage, the availability of

V2G depends on how often the EV is plugged in and what the travel requirements of the EV are. Emerging business models for V2G in the UK context are centred on a 'load controller' (an entity such as an aggregator or supplier) sending requests and incentives to a charge point, facilitating power flow to and from the vehicle's battery in line with consumer wishes and offering that flexibility into a series of markets which, in the GB context, include the balancing mechanism and dynamic containment [12]. Due to the infancy of V2G there is very little experience of managing portfolios of EV batteries as dispatchable battery storage. Therefore, the level of resource at an aggregated level is difficult to estimate.

Whereas V2G depends on customers plugging in their vehicles as much as possible, it has been shown that drivers tend to plug their vehicles in less often than every time they arrive home, particularly for vehicles with larger batteries: in the 2016–2019 trial *Electric Nation*, drivers of larger battery (40–60 kWh) EVs were found to plug in half as frequently (2.2 times per week vs. 4.4 times per week, on average) as drivers of smaller battery (10–25 kWh) EVs [13].

This paper presents a study of the impact of drivers' plug-in patterns on the potential of V2G to reduce i) consumer bills and ii) carbon intensity of charging. Implicit in V2G doing these things is the provision of much-needed flexibility in demand, reducing the need to reinforce distribution networks and therefore alleviating

² In their 2019-published Net Zero pathway *Innovating to Net Zero* [6], the Energy Systems Catapult estimates that the UK would need 29–35 GWh of electricity storage for a Net Zero-compliant generation mix to meet demand and maintain grid stability. If there are 20–30 million EVs on the UK's roads by 2050 as in National Grid Electricity System Operator (ESO)'s *Future Energy Scenarios 2020* [7], and the average EV battery capacity is 40–60 kWh, then there would be 800–1800 GWh of battery storage distributed amongst the UK's private cars. Even for low rates of V2G uptake, there is clearly potential for in-vehicle battery storage to support the integration of variable renewable generation in the electricity system.

the difficulty of recovering investments in networks with low load factors and peaky demands.

Two models of plug-in behaviour are presented based on a charging schedule heuristic developed in previous work [14]: a Minimal charging model, in which drivers schedule their charge events with the goal of minimising the number of plug-ins (in the aim of maximising the ‘convenience’ of EV use), and a Routine charging model, in which drivers always plug in upon arrival at home regardless of their battery’s state of charge (SoC) or upcoming journey requirements. The charging models generate week-long charging schedules that satisfy the energy requirements for week-long travel diaries from the UK National Travel Survey (NTS). The charging schedules output from these models and the travel data are used with a new V2G formulation that seeks to minimise cost according to two variable tariffs, an import (buy) price and an export (sell) price, taken from the Octopus *Agile* V2G tariff as available at [15]. Due to the positive correlation between the price of electricity and its carbon intensity (as explored in section 4.1), the study also quantifies the potential reduction in carbon intensity from V2G when optimising on cost. This is done by linking the tariff data with carbon intensity data from National Grid ESO [16] for the same time period in January 2021.

The optimisation in this study is carried out on the basis of minimising the cost of electricity to consumers with time-varying tariffs. This is generally cited as a major motivation for the adoption of smart electrical appliances. For instance, in BSI PAS 1878 [17], a UK Government-sponsored specification for the operation of ‘energy smart appliances’ (ESAs) – including smart EV chargers – in providing system flexibility, it is stated that “consumers with ESAs can reduce their electricity costs... and can earn revenues by allowing domestic appliances to be controlled flexibly”. However, as consumers are increasingly concerned with the carbon emissions of their electricity use (as exemplified by the recent growth in green domestic tariffs [18]), the effect of minimising cost on the carbon emissions associated with electricity use is investigated.

The rest of the paper is organised as follows: section 2 provides a literature review on the state of the art of V2G modelling and trials; section 3 describes the methodologies used in this study; section 4 presents the results, which are discussed in section 5; section 6 presents conclusions and suggests pieces of future work based on this paper.

2. Literature review

2.1. Establishing value in vehicle to grid

For consumers to adopt V2G, there must be some retrievable value in it for them. The authors in Ref. [19] present results from a choice experiment across Nordic countries, in which respondents choose between EVs with V2G capability, EVs without V2G capability and ICVs. The authors present the willingness to pay (WTP) for various characteristics of EVs, including V2G capability. It is concluded that while WTP for V2G capability was strongly positive in some regions (including Norway, whose vehicle-purchasing population is likely to have significant familiarity with EVs due to the country’s high uptake [20]), it is zero in others (an outcome which, as argued by the authors, is strongly influenced by the fact that 90% of survey respondents had not heard of V2G before the experiment). It is recommended in Ref. [19] that awareness-raising policies should be pursued in order to increase the visibility – and desirability – of V2G capability in a vehicle.

There have been several works in the literature on establishing different revenue streams available for consumers for EVs participating in V2G, looking to maximise the revenue for individual vehicle owners or fleet operators. An investigation into different

business cases available to a fleet operator through participating in V2G is presented in Ref. [21], in which it was found that participation in the balancing mechanism offers the most reward compared to other accessible parts of the electricity market in 2017 when the paper was published. In Ref. [22], the authors analyse the potential for EV fleet aggregators’ participation in frequency support in both Denmark and Japan, based on the export price per unit power within the frequency response markets. It is established that profitability is only achieved when V2G is done on an ‘industrial’ scale. A rule-based optimisation for V2G is presented in Ref. [23], where each EV in a set seeks to minimise its cost based on GB wholesale electricity prices – in which the process is found to be economically feasible based on the changes in wholesale electricity prices. Analysis of the potential for V2G to participate in a set of regulating power services is presented in Ref. [24], where the results indicate that while V2G is profitable in Germany, it is not in Sweden. Optimisation of V2G within a UK science park (with adjacent behind-the-meter demand, solar generation and a grid connection) is presented in Ref. [25], in which it is found that net present values of £8,400 per vehicle are achievable over a 10-year time frame.

There have also been works on the system-wide benefits from V2G, on the premise that the value of V2G should be unlocked for operators of electricity systems, generators and/or distribution networks. In Ref. [26], the authors present analysis into the potential reduction in curtailment of wind generation in Denmark by a ‘nationwide battery’ approach where half a million EVs are aggregated into one virtual power plant – concluding that curtailment can be reduced by up to 21% over a year from using the aggregated EV fleet in V2G. In Ref. [10], the extent to which V2G can reduce peak demand – and therefore distribution network losses and the need for reinforcements – is analysed across exemplar GB and Texas networks: it was found that peak demand could be reduced by up to 35% and 20% in the British and Texan networks respectively. In Ref. [27], the authors evaluate the potential for V2G to maximise the self-consumption of solar generation within an export-constrained network in Italy. In Ref. [28], the authors present analysis of the potential for V2G to support the Moroccan national grid. Through various scenarios of future EV adoption and electricity demand, the authors conclude that V2G could provide several GW of controllable load by 2030 and a potential source of ancillary services for support of a high penetration of asynchronous renewable generation. In Ref. [29], authors use techno-economic analysis to establish the potential of ancillary services from V2G contributing to strengthening security of supply in the Indonesian power system. According to Ref. [29], V2G can contribute to significant reductions in cost of charging (up to 60%) and reductions in the use of coal (up to 3%) and gas (up to 9%) to supply peak demand.

2.2. Plug-in behaviour modelling

The biggest difference between stationary battery storage and using V2G as battery storage is the variable availability of the latter. While the data governing the availability of the vehicles in Refs. [10,21–27,29] varies between travel data or simpler, fixed assumptions (such as in Refs. [22,29], where scenarios are used to represent the availability of EVs – for example, all vehicles being assumed connected between 17:15 and 06:00³), all of them are predicated on the assumption that if a vehicle can charge when it

³ While this is a fairly common assumption in the literature, it is shown through analysis of travel data in Ref. [30] that under half of UK cars are driven according to the ‘commuter’ stereotype of leaving in the morning and arriving back home in the evening.

arrives at a charger, it will do so regardless of its SoC or future travel demand. Conversely, both Philipsen [31] and Schauble [32] show that EV charging behaviour is diverse between drivers and it is apparent that EVs are plugged in less often than every time they arrive home – as already stated, drivers in the 2016–2019 trial *Electric Nation* [13] plugged in half as frequently if they had access to a vehicle with a larger battery capacity.

There have been works to model EV charging behaviour and examine the resulting impact on networks. In Ref. [33], the authors propose a probabilistic model that combines NTS trip data with charging data from the *My Electric Avenue* EV trial and, using an aggregation at a scale of 50 vehicles, assign peak demand and energy demand values to 50-household networks across GB based on the distribution of car ownership across the country. Several studies present probabilistic models based on EV trial data alone and apply the resulting charge events to models of real distribution networks. These include [34], in which probabilistic analysis is used to combine data from the English *SwitchEV* trial with smart meter data [35], in which EV trial data from a trial on the island of Bornholm, Denmark, is used to simulate challenges faced by the power network following 100% penetration of EVs, and [36], in which data from the *My Electric Avenue* EV trial is statistically analysed and applied to a model of a distribution network to explore the potential challenges to the network from adoption. Furthermore, several studies use travel data to simulate charge events on distribution network models. These include [37], which uses a heuristic algorithm to produce charging schedules from UK NTS travel data and applies them to a distribution network model [38], which employs an inhomogeneous Markov chain model to derive charging schedules from a German national mobility dataset to deduce characteristic distribution network load curves from EV charging, and [39], which uses statistical analysis of results from a French travel survey to derive potential EV charging loads on both rural and urban distribution networks.

2.3. Research gaps and contributions of this paper

While there have been a significant number of works in evaluating the value of V2G [10,21–27] and also a significant number of works modelling plug-in behaviour [33–39], there is not – to the authors' knowledge – anything in the literature that seeks to quantify the effect of plug-in behaviour on the value of V2G. Nor has any literature been found that explicitly examines the potential for V2G using real-world tariffs, as the Octopus *Agile* tariff data is used in this paper. While many of the V2G studies discussed use price profiles to assess value in V2G, none of them used tariff data that would be directly available to a domestic consumer. This is an important gap, as the savings made by a household on charging their EV's battery is an important motivator in encouraging V2G uptake (and therefore higher levels of flexible resource for a low carbon electricity system).

This paper represents a novel contribution in linking vehicle trip data to potential V2G resource – and how it affects consumer bills and the carbon intensity of the electricity used to charge the EVs – for different modes of charging plug-in frequency.

3. Method

3.1. Summary and previous work

This paper presents analysis of the potential impact of varying plug-in frequency (resulting from different charging behaviours) on V2G, in its ability to reduce the price paid for charging, and examine whether that has an influence on the carbon emissions associated. This study is carried out over the course of 10 consecutive days,

based on real tariff data, from 6th–15th January 2021 inclusive. The optimisation of charging and discharging of EVs is carried out in discrete, 24 h windows. This was chosen on the basis that the *Agile* tariff displays import and export prices for the 00:00 – 23:30 period for the 'next day' from approx. 16:00 on a given day: therefore, a load controller would have a 24 h window of optimising the return on the charging and discharging of the EVs' batteries.

This paper builds on a heuristic model to generate credible charging schedules given travel data originally presented in Ref. [14] and a time-coupled linearised optimal power flow formulation for a smart (one-way) charging study originally presented in Ref. [40]. In the interest of conciseness, the methodologies used to derive i) charging schedules given travel data based on EV fleets instantiated in distribution networks and ii) flexible charging events (in which the time in, time out, energy required and power rating are prescribed), are only briefly described in this paper. For full details of the methods, the reader is referred to Refs. [14,40] where relevant in this section.

The complete set of data, models and methods in this work is shown in Fig. 1 as three modules labelled 1, 2 and 3.

In Fig. 1, modules 1 and 2 are both described in detail in Ref. [40]. The justification for the sociotechnical approach outlined in module 1 – by which NTS diaries are disaggregated by employment and means of travel to work – is presented in Ref. [37]. The Minimal charging model shown in module 2 is detailed in Ref. [14].

While this paper builds on a large foundation of previous work, key parts of modules 1 and 2 in Fig. 1 are briefly summarised in sections 3.3 and 3.4 respectively, so that this paper can be read as a standalone work.

3.2. Data sources

3.2.1. UK National Travel Survey

The UK NTS is an annual survey in which around 15,000 UK residents fill out a week-long travel diary, providing details such as the mode, distance, time and duration of all trips made over a 7-day period [41]. The 7-day period recorded differs between the individuals, hence minimising any bias from seasonal variation/holidays. The resulting dataset for the years 2002–2018 as used in this study contains details of over 2 million car-based trips split between over 100,000 vehicles, which have been aligned such that they all take place from 00:00 on Monday to 23:59 on Sunday. An example NTS travel diary, showing only car-based trips, is shown in Table 1.

Because the 7 day period is recorded at different times for different respondents to minimise bias from seasonal variations, no seasonal variation can be ascertained from the data. Therefore no typical 'winter' EV charging behaviour can be simulated to match the winter tariffs in this study. This is identified as a limitation in this method.

3.2.2. Octopus *Agile* tariff data

Octopus' *Agile* electricity tariff [42] is designed for consumers who can shift their demand in time to make use of lower wholesale prices. The tariff rate changes by the half-hour, and is communicated through the GB smart metering system. There are two tariffs as part of *Agile*: an import tariff that is limited to maximum of £0.35/kWh, but that can go negative in times of low demand and high supply from variable renewables, and an export tariff that consumers are paid per unit of electrical energy that they send to the grid: either from local generation, or from a V2G-capable EV charge point.

Historical data for the Octopus *Agile* tariff is available from Energy-stats UK [15]. The 10-day period in this study is the 6th–15th January 2021 inclusive; in that period, both import and export

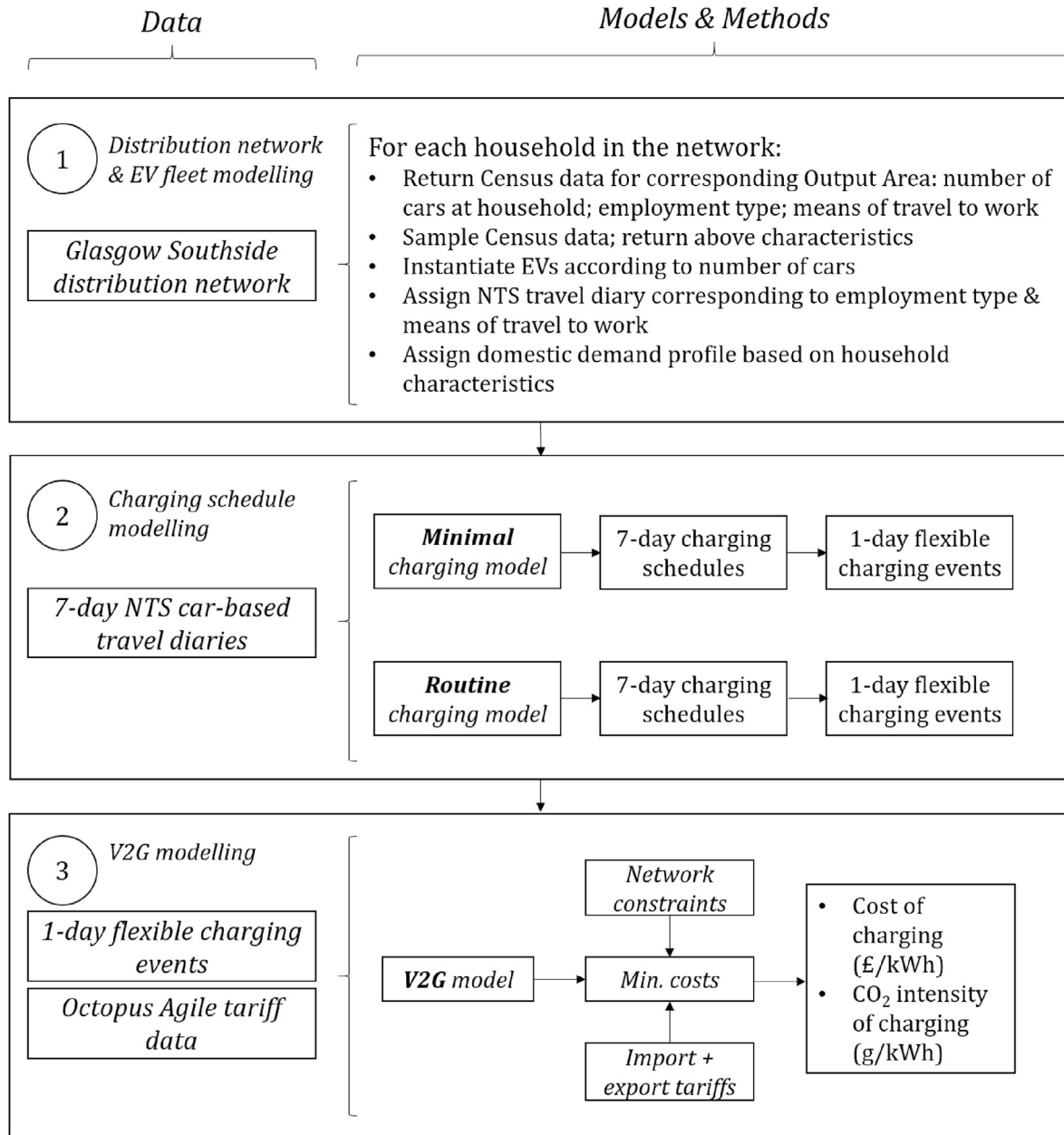


Fig. 1. Data, models and methods used in this work, including those referenced in previous outputs and those new to this paper.

Table 1

Example UK NTS travel diary (car-based trips).

Trip #	Origin	Destination	Trip Start	Trip End	Distance (miles)
1	Home	Food shop	Tu 09:30	Tu 09:50	3
2	Food shop	Home	Tu 10:40	Tu 11:00	3
3	Home	Other escort	Tu 18:15	Tu 18:20	0.25
4	Other escort	Home	Tu 18:20	Tu 18:25	0.25
5	Home	Other escort	Tu 19:40	Tu 19:45	0.25
6	Other escort	Home	Tu 19:50	Tu 19:55	0.25
7	Home	Food shop	W 09:30	W 09:50	3
8	Food shop	Home	W 10:30	W 10:45	3
9	Home	Work	Su 07:40	Su 08:00	7
10	Work	Home	Su 17:00	Su 17:20	7

tariffs are shown to vary significantly (Fig. 2). The tariff differs according to GB region; the data shown in Fig. 2 corresponds to South Scotland as to be of most relevance to the Glasgow Southside

distribution network (Fig. 3) from which the EV fleet is instantiated. As shown in Fig. 2, the export tariff exceeds the import tariff – times during which a charge point would generate revenue by exporting to the grid – on 7 out of 10 days.

As typical of the British midwinter, the tariffs are higher than the year-round average for this tariff as demand is naturally higher than at other times of year. For the 10-day period under study, the average import tariff and export tariff values were £0.18 and £0.12 respectively. The averages of the historical data from Ref. [15] (February 2018–January 2021 for the import tariff and May 2019–January 2021 for the export tariff) are £0.14 for the import tariff and £0.06 for the export tariff.

3.2.3. National grid ESO grid carbon intensity data

Grid carbon intensity is the measure of grams of CO₂ emitted per kWh of electrical energy generated. As per National Grid ESO's



Fig. 2. Time series of Octopus Agile tariff and National Grid ESO carbon intensity data, 10 days in January 2021.



Fig. 3. Glasgow Southside network used for instantiation of EV fleet (left) and rendered 3D image of area in question (right).

methodology [43], the emissions are not inclusive of life cycle emissions associated with fuel processing or installations. Therefore, low carbon sources including wind, solar and nuclear are all labelled 0 gCO₂/kWh. The carbon intensity of combined cycle gas turbines (CCGT) – the dominant fossil-based generation method in GB – is taken to be 394 gCO₂/kWh.

Half-hourly GB grid carbon intensity (gCO₂/kWh) was obtained for the same 10-day period as for the Agile data from National Grid ESO's carbon intensity API [16]. Fig. 2 shows the variation in carbon intensity over the period; it varies from a low of 98 gCO₂/kWh at 23:30 on 10th January to a high of 330 gCO₂/kWh at 06:30 on 15th January. The average carbon intensity during the period was 248 gCO₂/kWh, which is 25% higher than the year-round average carbon intensity (198 gCO₂/kWh in 2019, which is the most recent value available [44]). This is also typical during the winter, during which time demand is higher and higher-carbon generation sources such as CCGT plants and sometimes coal-fired power stations are dispatched.

3.3. Distribution network and EV fleet modelling

The network model used to instantiate a fleet of EVs and to set constraints on their charging is derived from a real

distribution network in the residential-dominated Southside area of Glasgow, UK. The network consists of a secondary (11/0.4 kV) substation and three 0.4 kV distribution feeders. The network serves 157 households, spread amongst 47 endpoints (i.e. there are some address points that are apartment blocks with multiple households). It is assumed that the different households are equally divided among the three phases and that those phases are balanced. Fig. 3 shows a plot of the network topology with the location of the grid connection highlighted (left) and a rendered 3D image of the area in question (right) – imagery from Google Maps [45].

EVs are instantiated according to the method summarised in Fig. 1 and described in detail in Ref. [40]. The approach is a Monte-Carlo based method, in the way that the 2011 UK Census (the most recent available) distributions relating to each household served by the network are sampled each time the model is run. The model is run 10 times to produce 10 separate fleets of EVs with a corresponding set of NTS travel diaries, linked to the employment type and means of travel to work as the individuals served by the network. Each time an EV is instantiated, its battery capacity is sampled randomly from a set of capacities found on the EV market:

Table 2

Minimal charging schedule derived from NTS travel diary in Table 1 for an EV with a battery capacity of 24 kWh and a home charger rated at 3.7 kW AC

Trip #	Charge Type	t^{in} (Plug-in)	t^{out} (Plug-out)	E^{start} (kWh)	E^{end} (kWh)	P^{max} (kW)
8	home	W 10:45	Su 07:40	8.44	24	3.7

24, 30, 40, 60 and 75 kWh. All EVs were assumed to have 7.4 kW charging capability, to reflect the trend towards higher power home chargers.⁴ All EVs have access to parked charging at home only. For more details on the effect of changing battery size, charger power and the set of locations at which the EV can charge on the resulting plug-in frequency, the reader is referred to Ref. [37].

3.4. Modelling charging schedules from travel data

Two models are used to derive charging schedules from the NTS travel diaries (e.g. Table 1), designed to represent the spectrum of likely charging behaviours. These models, denoted the Minimal and Routine models, are described in sections 3.4.1 and 3.4.2 respectively. These 7 day charging schedules are then transformed into 24 h sets of 'flexibility windows' as per the method described in section 3.4.3.

3.4.1. Minimal charging model

The Minimal charging model represents a scenario in which plugging in an EV is seen as an inconvenience, and therefore something to be minimised. This model uses a heuristic originally presented in Ref. [14]. In summary, the model returns the minimum number of charge events required to satisfy the energy requirements of an NTS travel diary (Table 1), choosing parked charging events first and resorting to en route charging events only when parked charging opportunities are insufficient in meeting the travel diary's energy requirement. This is done by ensuring that the vehicle's SoC is always greater than or equal to a prescribed minimum; that which would give 25 km of remaining range on a 'combined' energy consumption rate, based on how far a prudent driver would be willing to drive before charging. While the EV will minimise the time spent en route charging, gaining only enough energy it needs to arrive at the end of the trip with the minimum permitted SoC, it will seek to gain the maximum energy transaction it can from any parked charging event – subject to the charger power and a standard Lithium-ion battery charging curve [14].

A detailed explanation of how this heuristic works is given in Ref. [14]. Table 2 shows a Minimal charging schedule that meets the energy requirements of the NTS travel diary shown in Table 1. The SoC with which the vehicle starts the travel diary is randomised between the prescribed minimum (i.e. to give a range of 25 km at a 'combined' consumption rate) and 100%. In this example case, it was randomised as 74%.

In Table 2, t^{in} and t^{out} are the plug-in and plug-out times respectively; E^{start} and E^{end} are the energy storage contents of the EV at the start and end of the charge events respectively. P^{max} is the maximum rated AC (grid-side) power the EV can be charged at.

Table 2 shows that the EV was able to charge sufficiently to meet the energy requirements of its travel diary with one parked charging event taken at home at the end of trip 8. Note that although they could have charged after trips 2, 4 and 6, the driver chose not to as they could defer their charging until later in the week, thus finishing the week's travel diary with the maximum possible SoC.

⁴ in the UK, there is generally no difference in price between 'slow' and 'fast' home chargers – e.g. the WallPod EV charger retails at £320 in the UK for either 3.7 or 7.4 kW configuration [46] – thus it is likely that 7.4 kW chargers will soon become the norm.

To validate that the plug-in frequency produced from the Minimal charging model is representative of real-life EV driver behaviour, Fig. 4 (originally presented in Ref. [40]) shows the resultant charging frequency (plug-ins per week) for sets of simulated charging schedules based on fleets of 10,000 EVs for two battery sizes, 24 kWh and 64 kWh. On the same axis is data from the *Electric Nation* EV trial [13]; note that the battery sizes used for the latter are the midpoints of the intervals reported, e.g. where the project reported that EVs with batteries of 10–25 kWh charged on average 0.63 times per day, the corresponding value used for the figure is 17.5 kWh.

Fig. 4 shows that the pattern of a reduction in charging frequency for increasing battery size holds true for the simulation in this study when using the Minimal charging scenario. Note that when using the Routine charging method, the frequency of home plug-ins will not change as drivers will always plug-in at home; their charging frequency will be equal to the average number of times they arrive at home in a day.

3.4.2. Routine charging model

The Routine charging model represents a scenario in which EV charging at home is seen to carry negligible inconvenience (i.e. it has become 'routine') such that vehicles are always plugged in on arrival at home regardless of their remaining range or upcoming trips. Table 3 shows a schedule of charge events produced using the Routine charging model for the same NTS travel diary in Table 1.

In Table 3, the EV charges at all the home-based opportunities it gets: in this example, whereas it did not charge after trips 4, 6 and 8 under the Minimal scenario, it did charge after these trips in the Routine scenario. As a result, its energy requirements for these charge events tends to be less. Given that the total charging time is dictated by the duration of the parking event, charging under the Routine model of charge event scheduling is typically more flexible than charging under the Minimal model.

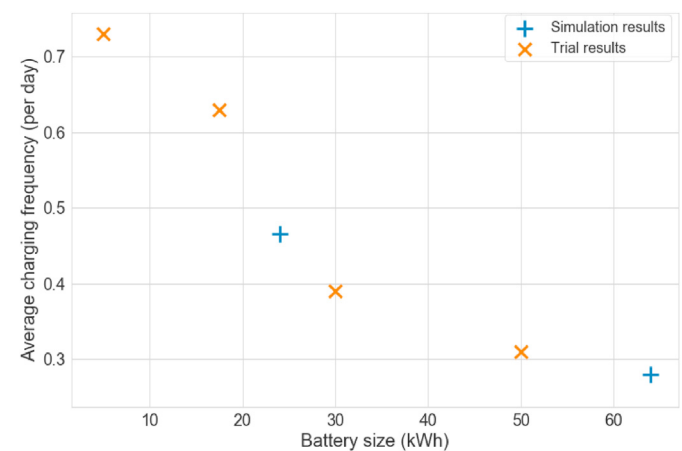


Fig. 4. Scatter plot showing average charging frequency (events per day) against vehicle battery size for *Electric Nation* trial data and results from the simulation (Minimal charging) in this study – figure originally presented in author's previous work [40].

Table 3

Routine charging schedule derived from NTS travel diary in Table 1 for an EV with a battery capacity of 24 kWh and a home charger rated at 3.7 kW AC

Trip #	Charge Type	t^{in} (Plug-in)	t^{out} (Plug-out)	E^{start} (kWh)	E^{end} (kWh)	P^{max} (kW)
2	home	Tu 11:00	Tu 18:15	10.36	24	3.7
4	home	Tu 18:25	Tu 19:40	23.86	24	3.7
6	home	Tu 19:55	W 09:30	23.86	24	3.7
8	home	W 10:45	Su 07:40	22.36	24	3.7

3.4.3. Flexibility windows

As explained in section 3.3, each 24 h period in which EV (dis)charging is scheduled is associated with a new fleet of EVs instantiated in the network based on the output of a Monte Carlo-based method. As these charging schedules are 7 days long and the period over which the optimisation is conducted is 24 h long, the week-long charge schedules are trimmed accordingly to establish a ‘flexibility window’ for each charging event that fits into the 24 h window of the optimisation study. The process by which this is done is illustrated in Fig. 5.

Fig. 5 illustrates how charge events are modified to fit the 24 h time period over which the optimisation is carried out. Firstly, any charge events that are completely outside of the 24 h window are discarded. Secondly, any that overlap the beginning and/or the end of the 24 h window (e.g. Charge Events 1 and 3 in Fig. 5) are trimmed accordingly as per (1), such that only the energy that would ordinarily have been delivered during the 24 h window – under a ‘dumb’ charging schedule – is accounted for.

$$dE_e = dE_e^T - (dE_e^{\text{LHS}} + dE_e^{\text{RHS}}) \quad (1)$$

where dE_e^T is the total energy received by the vehicle during charging event e , dE_e is the trimmed energy, dE_e^{LHS} is the energy to be trimmed from the charge event e overlapping the start of the 24 h window and dE_e^{RHS} is the energy to be trimmed from the charge event e overlapping the end of the 24 h window.

The energy that is to be trimmed from these charge events is calculated according to the CC-CV lithium ion charging profile used in this study. The resulting expressions for the calculation of dE_e^{LHS} and dE_e^{RHS} are given in (2). For the derivation of these expressions, the reader is referred to Ref. [14].

$$dE_e^{\text{LHS}} = \frac{\max\{0, (t_e^{\gamma} - t_e^s)\}}{(t_e^{\gamma} - t_e^s)} \int_{t_e^s}^{t_e^{\gamma}} P_e^{\text{max}} dt + \frac{\max\{0, (t_e^{\text{in}} - t_e^{\gamma})\}}{(t_e^{\text{in}} - t_e^{\gamma})} \int_{t_e^{\gamma}}^{t_e^{\text{in}}} P_e^{\text{max}} e^{-\lambda_e t} dt \quad (2a)$$

$$dE_e^{\text{RHS}} = \frac{\max\{0, (t_e^{\gamma} - t_e^d)\}}{(t_e^{\gamma} - t_e^d)} \int_{t_e^d}^{t_e^{\gamma}} P_e^{\text{max}} dt + \frac{\max\{0, (t_e^{\text{out}} - t_e^{\gamma})\}}{(t_e^{\text{out}} - t_e^{\gamma})} \int_{t_e^{\gamma}}^{t_e^{\text{out}}} P_e^{\text{max}} e^{-\lambda_e t} dt \quad (2b)$$

where t_e^s is the original start time of the charge event e , t_e^{in} is the adjusted start time of the charge event e (i.e. the start of the 24 h window), t_e^d is the original departure time of charge event e and

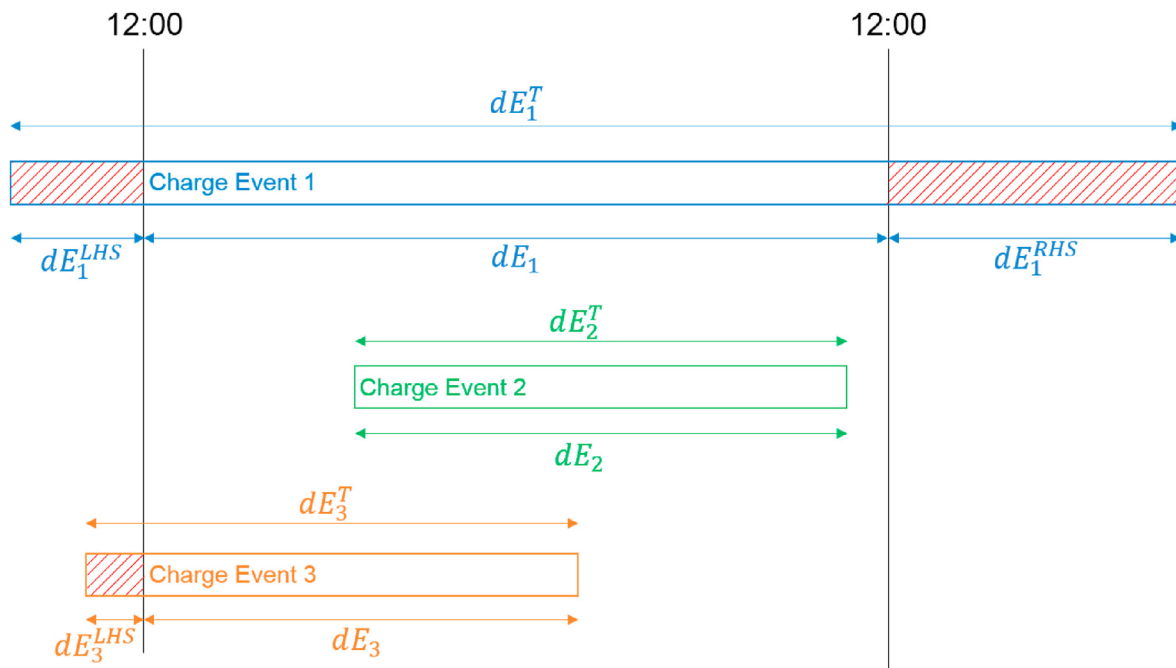


Fig. 5. Illustrative example of charging flexibility window concept, showing how 7-day charging schedules are trimmed to 1-day charging flexibility windows for optimisation: figure originally presented in author's previous work [40].

t_e^{out} is the adjusted departure time of the parking event following trip e (i.e. the end of the 24 h window). t_e^γ is the time at which the EV's SoC reaches γ , the point at which the charging profile transitions from the CC to the CV region for charge event e . λ_e is the decay constant associated with the CV region. t_e^∞ is the time at which the charging power reaches a value close to zero (taken as 1% of the maximum rated power) and the charger switches off on account of the vehicle's battery being full. t_e^{\min} is the minimum of t_e^d and t_e^∞ (3).

$$t_e^{\min} = \min\{t_e^d, t_e^\infty\} \quad (3)$$

3.5. Vehicle to grid optimisation

3.5.1. Introduction to optimisation method

The problem formulation used in this paper is designed to represent how EV chargers could be remote controlled by 'load controllers' – electricity market actors such as aggregators and suppliers – when faced by changing market conditions (this is of increasing relevance when the supply of electricity becomes increasingly variable). The value passed onto the customer – in the form of a set of variable import and export tariffs – is the cost to be minimised in the optimisation.

The V2G model presented in this paper takes charging schedules from a fleet of EVs (i.e. aggregated sets of data as shown in Tables 2 and 3) to return a solution in which EVs schedule their charging and discharging subject to an import and export tariff in seeking the minimum possible cost of charging, while meeting the same energy gain as it would have under uncontrolled charging at minimum cost. Firstly, the charging schedules are transformed into flexible charging events that cover a 24-h period in 10 min timesteps. The 24-h period chosen represents the period from 12 noon on Tuesday to 12 noon on Wednesday in the 7-day long NTS diaries; the resulting 10 days of flexible charging events are matched randomly to aligned 24-h datasets of tariffs and carbon intensity (which were both linearly interpolated to produce 10-minutely data).

The optimisation is based on a time-coupled linearised optimal power flow formulation, in which EVs schedule their charging and discharging subject to an import and export tariff in seeking the minimum possible cost of charging. The formulation of this problem is described in sections 3.5.3–3.5.5, and was solved with the CPLEX solver using OATS [47].

3.5.2. Limitation of simplified optimal power flow formulation in this paper

Traditionally, the non-linear AC optimal power flow problem is employed for the case of distribution networks due to their high line impedances and consequential variation in voltages [48]. However, the time-coupled modelling that is required to assess charging and discharging of EVs in a network results in a very large-scale optimisation problem: in this case, too large to be solved using an AC formulation on a standard PC. While it is acknowledged that there have been advancements in the literature on the subject of linearisation of nonlinear AC power flow equations to model voltages and reactive power [49–52], this paper uses a simplified transport model (sections 3.5.3–3.5.6) to represent power flows in the distribution network resulting from controlled charging and discharging of EVs. As a result, a limitation of this study is that the accuracy of power flow modelling in this paper is compromised. Based on the findings in this paper, the accurate model of power flow is an area that future work (section 6) is recommended to focus on.

3.5.3. Objective function

The objective function to be minimised is the sum of the costs of importing or exporting power in each timestep over the sum of charge events (4).

$$\min \sum_{t \in \mathcal{T}} \sum_{e \in \mathcal{E}} (c_t^{\text{imp}} p_{e,t}^{\text{imp}} - c_t^{\text{exp}} p_{e,t}^{\text{exp}}) \Delta t \quad (4)$$

where \mathcal{T} is the time horizon (the set of 10 min timesteps indexed by t); \mathcal{E} is the set of charge events across all EVs in the fleet; c_t^{imp} and c_t^{exp} are the import and export tariffs respectively at timestep t ; $p_{e,t}^{\text{imp}}$ and $p_{e,t}^{\text{exp}}$ are the grid-side active power imports and exports to and from an EV in charge event e respectively to charge or discharge its battery in the time period $[t, t + 1]$ (note that both $p_{e,t}^{\text{imp}}$ and $p_{e,t}^{\text{exp}}$ are strictly positive); Δt is the length of the time period $[t, t + 1]$ (10 min).

The objective function in (4) is minimised subject to the constraints in (5–12).

3.5.4. Power flow

The power balance equation is given as (5), $\forall b \in \mathcal{B}, t \in \mathcal{T}$:

$$\sum_{g \in \mathcal{G}} p_{g,t}^G = \sum_{e \in \mathcal{E}} (p_{e,t}^{\text{imp}} - p_{e,t}^{\text{exp}}) + \sum_{d \in \mathcal{D}} p_{d,t}^D + \sum_{l \in \mathcal{L}} p_{l,t}^L \quad (5)$$

where \mathcal{B} is the set of busbars in the network; \mathcal{D} is the set of domestic demands (i.e. one per household); \mathcal{L} is the set of lines in the network; $p_{g,t}^G$ is the active power contribution from the grid supply point g in the time period $[t, t + 1]$; $p_{d,t}^D$ is the active power drawn by domestic demand d in the time period $[t, t + 1]$; $p_{l,t}^L$ is the active power flow on line l in the time period $[t, t + 1]$.

The power flow equation is given as (6), $\forall l \in \mathcal{L}, t \in \mathcal{T}$:

$$-S_l^{\max} \leq p_{l,t}^L \leq S_l^{\max} \quad (6)$$

where S_l^{\max} is the power rating of line l .

3.5.5. EV charging model

The energy storage content $E_{e,t}$ of an EV during charge event e at timestep t is related to that in the previous timestep and the energy gained or lost in Δt by (7).

$$E_{e,t} = \left(\eta p_{e,t}^{\text{imp}} - \frac{1}{\eta} p_{e,t}^{\text{exp}} \right) \Delta t + E_{e,t-1} \quad (7)$$

where the one-way charger efficiency η (for both charging and discharging) is taken as 90%, in common with values for home charging observed in Ref. [53] – and as cited in Ref. [10].

The EV's battery energy content upon plug-out must be greater than or equal to what it would have received under an uncontrolled charging event (i.e. from Table 2 or 3) (8)⁵; furthermore, the energy content is constrained between 0 and the battery capacity E_e^{\max} of the EV in charge event e , $\forall t \in \mathcal{T}$ (9).

$$E_{e,t^{\text{out}}} \geq E_e^{\text{end}} \quad (8)$$

⁵ It should be noted that the driver may be able to manage on substantially less than this energy content without it impacting their travel diary, and a relaxation of this constraint could bring benefits to the driver through increased revenue resulting from increased flexibility.

$$0 \leq E_{e,t} \leq E_e^{\max} \quad (9)$$

The power imported to an EV is constrained by a constant current – constant voltage (CC-CV) charging profile typical of lithium ion batteries [54–56], in which the maximum charging power is equal to the rated power P_e^{\max} for a battery SoC up to γ , after which it linearly decreases to zero at an SoC of 1. In this work, γ is set to 0.8 in accordance with battery charging protocols used for lithium ion batteries [57]. The charging power constraint is stated formally in (10), $\forall t \in \mathcal{T}$.

$$p_{e,t}^{\text{imp}} \leq \begin{cases} P_e^{\max}, & \sigma_{e,t} \leq \gamma \\ \left(\frac{1 - \sigma_{e,t}}{1 - \gamma} \right) P_e^{\max}, & \sigma_{e,t} > \gamma \end{cases} \quad (10)$$

where $\sigma_{e,t}$ is the state of charge of an EV during charge event e at timestep t , calculated as in (11).

$$\sigma_{e,t} = \frac{E_{e,t}}{E_e^{\max}} \quad (11)$$

The power exported from an EV is constrained by (12).

$$p_{e,t}^{\text{exp}} \leq P_e^{\max} \quad (12)$$

To ensure that no energy dumping can occur (i.e. charging and discharging at the same time), a final set of constraints is added to ensure that if an EV's import power at a given time step is greater than zero, then its export power is zero (and vice versa). This is done using a binary variable $\beta_{e,t} \in \{0, 1\}$ and a fixed value M , that is greater than the maximum import and export power. When $\beta_{e,t} = 0$, $p_{e,t}^{\text{imp}}$ is forced to take the value of zero and $p_{e,t}^{\text{exp}}$ is relaxed to take any value within its bounds (12). Similarly, when $\beta_e = 1$, $p_{e,t}^{\text{imp}}$ is free to take any value within its bounds (10) and $p_{e,t}^{\text{exp}}$ is forced to zero. This is expressed mathematically as (13a–13b).

$$p_{e,t}^{\text{exp}} \leq M\beta_{e,t} \quad (13a)$$

$$p_{e,t}^{\text{imp}} \leq M(1 - \beta_{e,t}) \quad (13b)$$

3.5.6. Calculation of cost and carbon intensity

The cost C_e^c of each charge event e is obtained using (14) with a solution obtained after solving the V2G model.

$$C_e^c = \frac{\sum_{t \in \mathcal{T}} (c_t^{\text{imp}} p_{e,t}^{\text{imp}} - c_t^{\text{exp}} p_{e,t}^{\text{exp}}) \Delta t}{E_e^{\text{end}} - E_e^{\text{start}}} \quad (14)$$

The carbon intensity $C_e^{\text{CO}_2}$ of each charge event e is given by (15).

$$C_e^{\text{CO}_2} = \frac{\sum_{t \in \mathcal{T}} c_t^{\text{CO}_2} (p_{e,t}^{\text{imp}} - p_{e,t}^{\text{exp}}) \Delta t}{E_e^{\text{end}} - E_e^{\text{start}}} \quad (15)$$

where $c_t^{\text{CO}_2}$ is the carbon intensity of the grid at timestep t . A negative cost value implies that the EV made revenue over the course of a charging event, by exporting in times of high export price and importing in times of low import price. Likewise, a negative carbon intensity value implies that the vehicle exported during times of high carbon intensity (of which, the carbon intensity would be equal to the imports minus exports multiplied by the carbon intensity at the relevant times (15)) and imported

during times of low carbon intensity. In this way, the provision of power from the EV's battery can be seen as reducing the need for the dispatch of high-carbon generation elsewhere in the system.

4. Results

4.1. Correlation between price and carbon intensity

Fig. 6 shows the level of correlation observed between grid carbon intensity and tariff, shaded by time of day (00:00–23:50) for 6th–15th January 2021 inclusive. The left-hand plot shows both import and export tariffs; the right-hand plot shows the difference between import and export to highlight the conditions in which consumers will be paid a higher price to export than they would pay for import.

Two patterns are observable from Fig. 6. Firstly, there is a weak non-linear positive correlation between carbon intensity and both import & export tariffs. There are two spikes visible on both plots, corresponding to times when the price of electricity rose far above the nominal range. The cluster of points to the right of the CO₂ intensity axis in the left-hand plot shows that electricity tends to be more expensive when the source is high carbon. Secondly, there is a visible affect of time of day on both tariff and CO₂ intensity. The vast majority of points during times of high price correspond to the peak demand time of 16:00–20:00; on the other hand, the vast majority of points corresponding to a CO₂ intensity of under 150 g/kWh are at night, between 22:00 and 06:00. These two patterns are advantageous for a V2G scheme, as EVs are more likely to be plugged in overnight.

4.2. Demand profiles

Figs. 7 and 9 shows the baseline (uncontrolled) EV charging profiles alongside domestic demand and grid carbon intensity for all 10 days under study in January 2021 for the Minimal and Routine charging models respectively. Figs. 8 and 10 show the same data for the results of the V2G optimisation.

While the profiles in Figs. 8 and 10 are the result of the optimisation in section 3.5, the baseline profiles (Figs. 7 and 9) are the results of load flow analyses, given the uncontrolled charging schedules resulting from the Minimal charging model (e.g. Tables 2 and 3). As such, the latter do not respect network limits and clearly violate them in several instances (where the total demand is higher than the 'plateaus' clearly visible on Figs. 8 and 10).

4.2.1. Minimal charging

Fig. 7 highlights the level of diversity that can be expected in uncontrolled EV charging. While there is clearly some variation day to day with the peak magnitude varying by as much as 50% between days, the peak always occurs within 19:00–22:00; when combined with the domestic demand which tends to peak earlier at 18:00–20:00, the total net peak occurs at 19:00–20:00. In all 10 days under study, the minimum CO₂ intensity occurs during the night, within the window 22:00–06:00.

Fig. 8 shows the extent to which EV charging could be controlled in a V2G scheme if EVs were plugged in only when they 'need' to (section 3.4.1). The total EV demand goes negative (export) on all but 1 day under study, due to either i) a higher export tariff than import at that specific moment in time or ii) a chance to sell (via the export tariff) and buy at a cheaper price at a different moment in time (subject to the constraints in (5–12)). The export always occurs in the time period 17:00–19:00, where the export price is highest (Fig. 2). In all 10 days under study, the peak EV charging demand occurs in the dead of night (02:00–05:00) – representing the time when the maximum resource (number of EVs) is plugged in and the

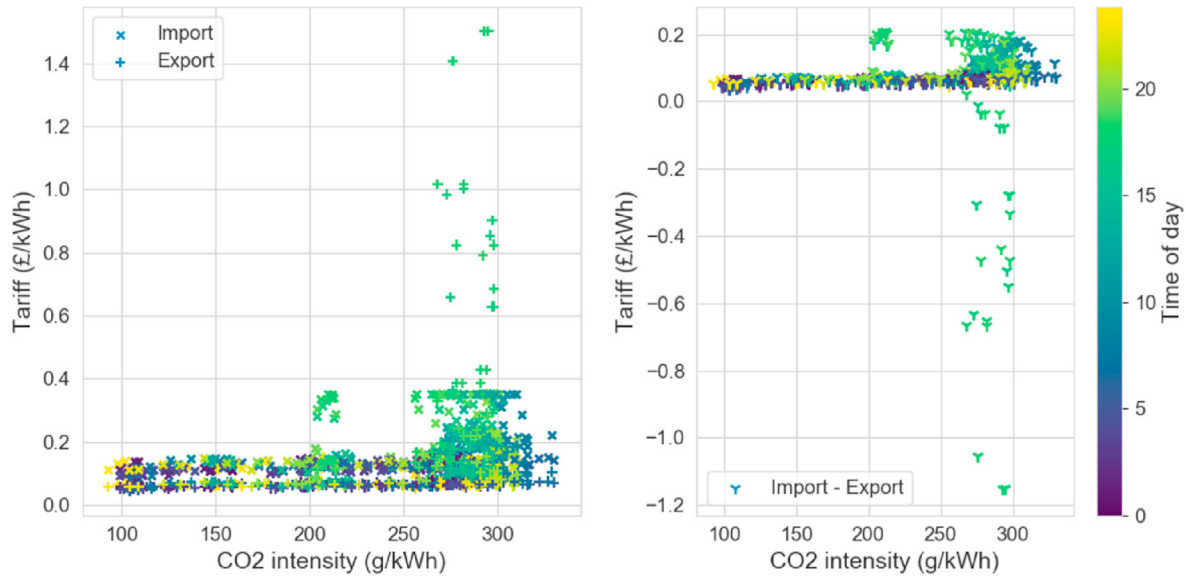


Fig. 6. Scatter plots showing (left) import & export prices vs. carbon intensity and (right) the relative difference between import & export price vs. carbon intensity for 6th–15th January 2021 inclusive – both plots coloured by time of day.

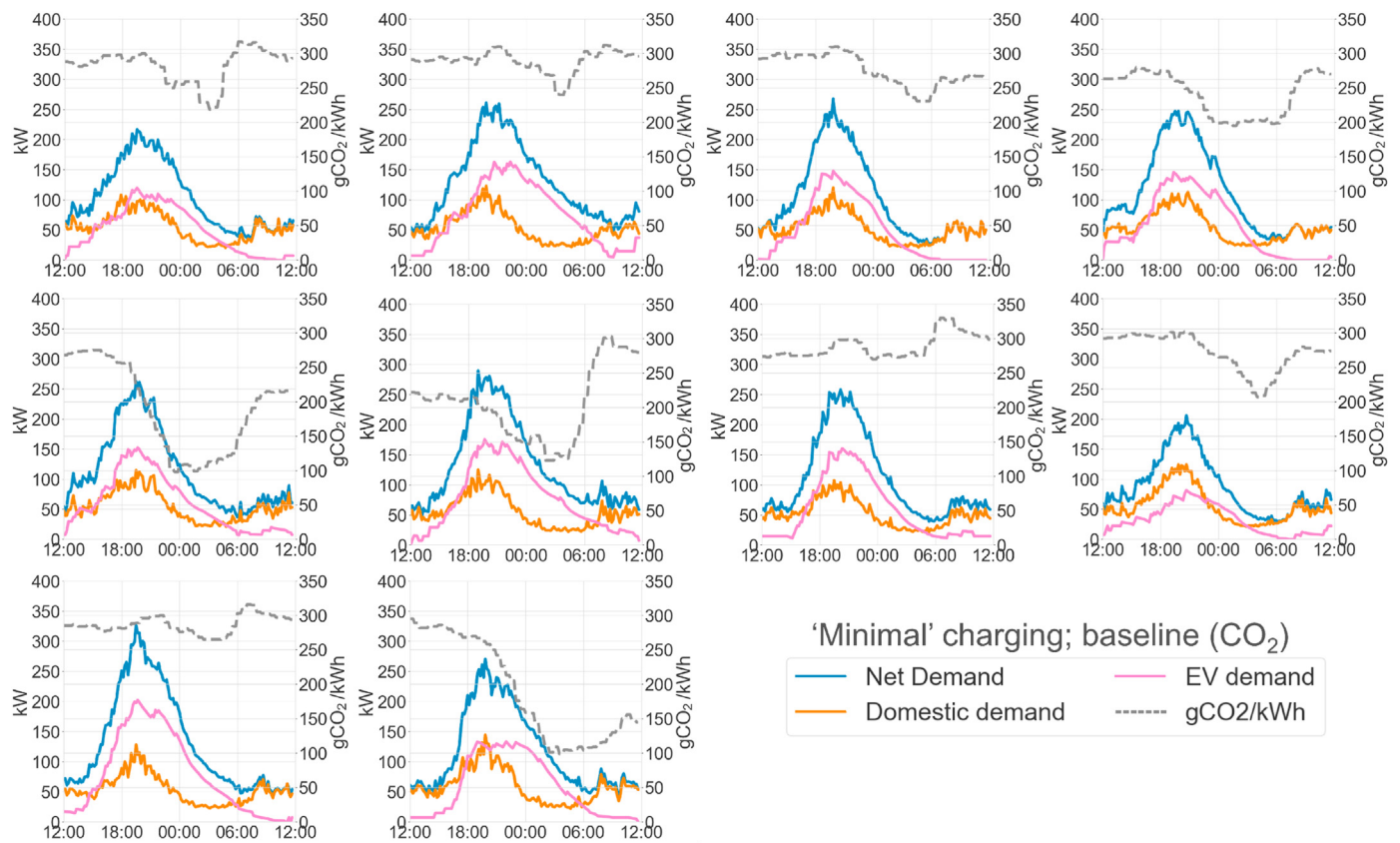


Fig. 7. Baseline (uncontrolled) EV charging, domestic demand and grid carbon intensity for 10 days under study in January 2021 – Minimal charging model.

import tariff is generally lowest. As shown, this often corresponds with troughs in grid CO₂ intensity.

4.2.2. Routine charging

Compared to the baseline charging demand for the Minimal case (Fig. 7), Fig. 9 shows the trend toward less diversity in

uncontrolled EV charging. This is to be expected, as every EV is plugged in on every arrival at home. The result is that the peak magnitude varies by only approx. 30% across the days, compared to approx. 50% in Fig. 7. The peak is also shown to be generally higher for the Routine case, but with a sharper decline during the night. This is because while more EVs plug in and begin charging in the

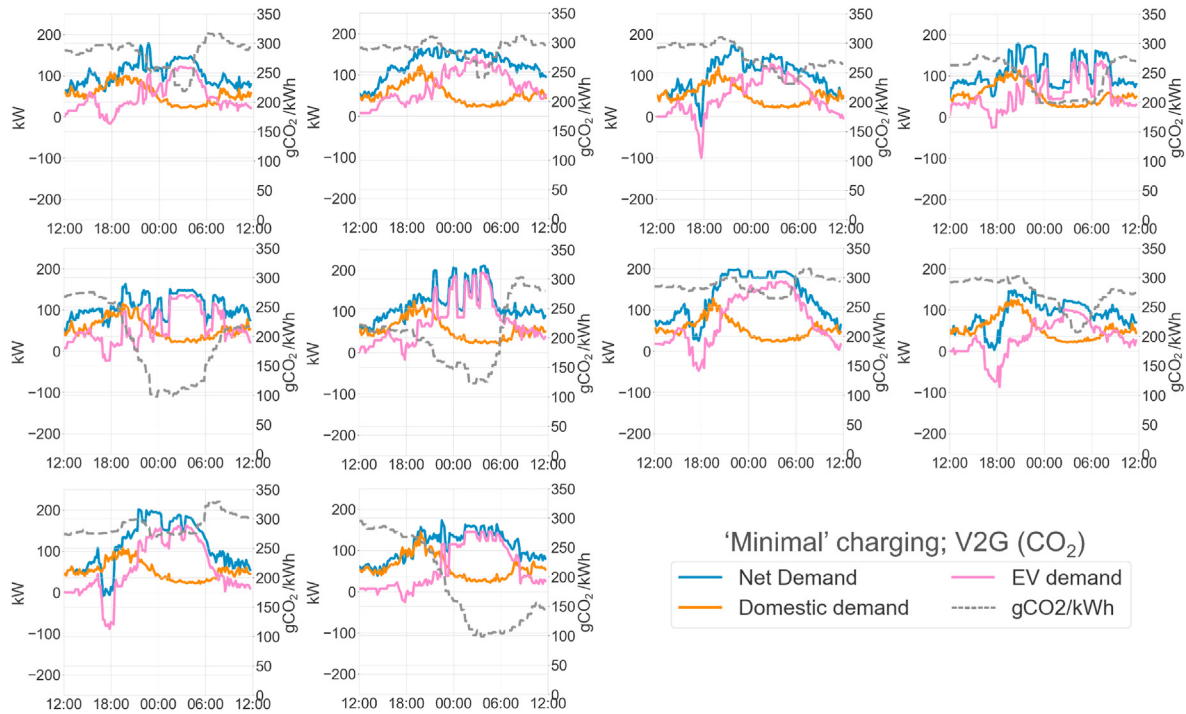


Fig. 8. V2G-controlled EV charging, domestic demand and grid carbon intensity for 10 days under study in January 2021 – Minimal charging model.

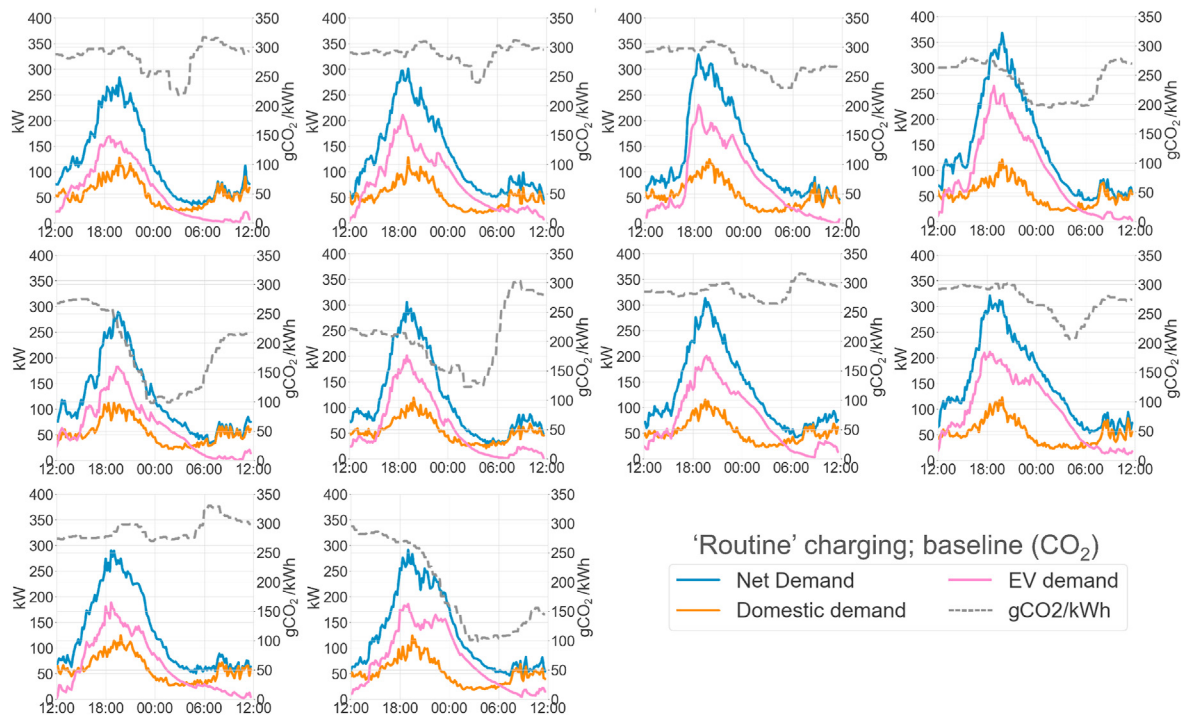


Fig. 9. Baseline (uncontrolled) EV charging, domestic demand and grid carbon intensity for 10 days under study in January 2021 – Routine charging model.

evening, their energy requirement tends to be lower and so they reach 100% SoC faster than in the minimum case. As already discussed, this shows that the Routine charging model produces more flexible EV charging: any controller has a longer time to achieve a given energy increase.

In comparison to the V2G-controlled Minimal charging case (Figs. 8), Fig. 10 shows a much higher degree of export from the EV

fleet: the combined demand from EVs goes negative on all 10 days, and the average peak export magnitude is over twice as great. The net demand profile in both Figs. 8 and 10 are clearly constrained by the network, resulting in the flat plateau-style traces visible in many of the plots.

It should be noted that whilst the sudden swings visible in Fig. 8 and (especially) Fig. 10 are advantageous for reducing the price paid

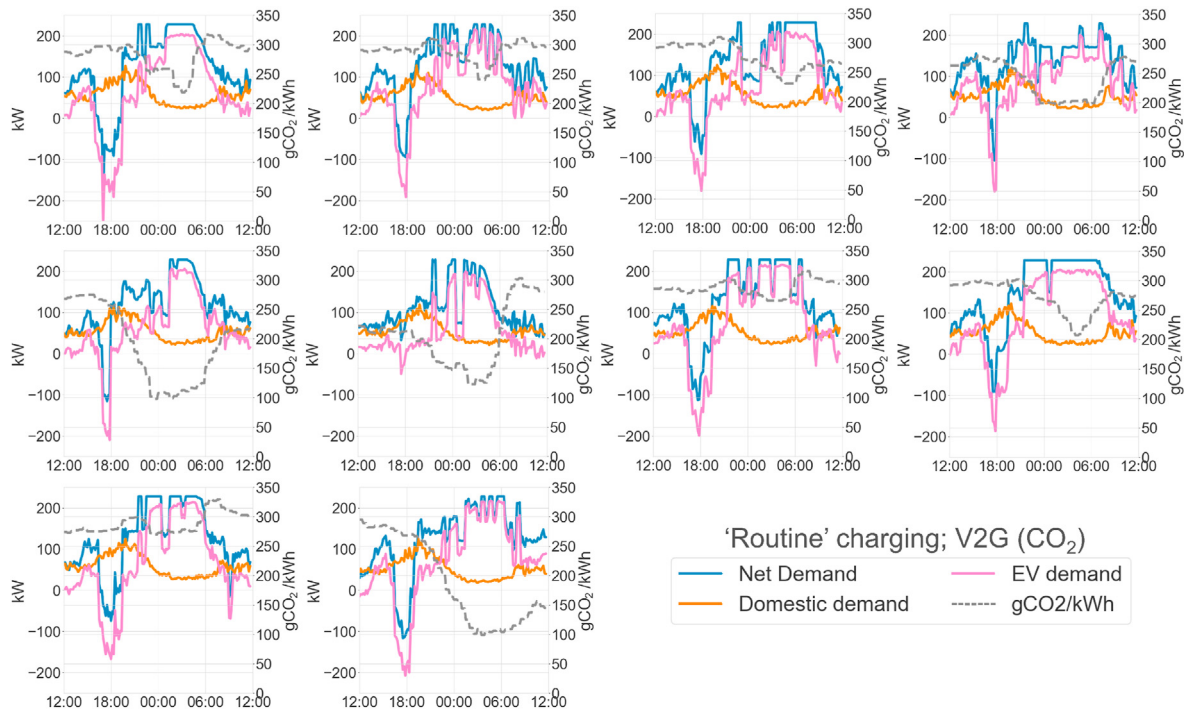


Fig. 10. V2G-controlled EV charging, domestic demand and grid carbon intensity for 10 days under study in January 2021 – Routine charging model.

for electricity, they are potentially more difficult for an ESO to predict and could lead to degradation in grid stability, including sudden swings in grid frequency. To remedy this, flexible demand (such as V2G-controlled EV chargers) could be subject to randomised offsets in its response to changes in dynamic tariffs such as the Octopus *Agile* tariffs used in this study. This approach, favoured in BSI PAS 1878 [17], would have some effect on the ability to minimise cost of charging as per the method in this study. A valuable piece of further work would be to investigate the impact of mandating such standards on the potential flexibility of responsive demand such as V2G.

4.3. Price paid and carbon content

Fig. 11 shows cumulative distribution functions (CDFs) of the average price paid by an EV (left) and the average carbon intensity (right) of the EV's net energy import during a given charge event.

Fig. 11 shows the ability of V2G to reduce the price paid and carbon intensity of electricity used to charge an EV's battery for both the Minimal and Routine modes of charging. It is shown on the left-hand plot of Fig. 11 that virtually every EV across all the trials paid less using V2G than when charging according to the baseline. On the other hand, around 60% of EVs were able to reduce the carbon intensity of the electricity they receive versus the baseline case. The horizontal axes on both plots is shown to extend into the negative of their dimensions. The left-hand plot shows that approx. 10% of EVs were able to make a profit under the Minimal charging model, rising to 17% of EVs under the Routine charging model. A negative carbon intensity value on the right-hand plot implies that the vehicle exported during times of high carbon intensity (of which, the carbon intensity would be equal to the imports minus exports multiplied by the carbon intensity at the relevant times (15)) and imported during times of low carbon intensity. Fig. 11 shows that, although price and carbon intensity are correlated (Fig. 6), the potential for V2G to reduce the carbon intensity of electricity used to charge an EV is not as great as its ability to reduce

cost: only 7% of EVs were able to achieve a negative carbon intensity using V2G under the Routine charging model; this was a negligible amount under the Minimal charging model.

The mean values of the distributions in Fig. 11 are shown on Fig. 12 alongside horizontal lines representing the mean import tariffs and carbon intensities for different time periods, to highlight how V2G can reduce the price paid for electricity and support decarbonisation of the electricity system by importing low carbon electricity and exporting it back at times of high carbon intensity.

Comparing the baseline (dark 'Xs') in Fig. 12, it can be seen that the price paid and the carbon intensity are higher for the Routine case than for the Minimal case. This is because, under the Routine case, EVs are more likely to have completed their charging in the high-priced and typically high-carbon evening peak, whereas if EVs have a larger energy requirement as per the Minimal case they are more likely to be charging later in the night when the price and carbon intensity are lower.

Fig. 12 shows that, when optimised for minimum cost, V2G can reduce the price paid for electricity by significantly more when the EV is plugged in every time it arrives home compared to if it is plugged in according to the Minimal charging model. Of course, a customer who was not having their EV controlled would be unwise to opt for a dynamic tariff such as Octopus *Agile*; they would be more likely to opt for a flat tariff. Comparing the values in Fig. 12 to Octopus' flat tariff for South Scotland of £0.157/kWh for January 2021 [58], and the average CO₂ intensity for the period, it was found that:

- V2G charging, if optimised for monetary cost, was found to reduce the price paid for electricity by 28% on average if EVs are only plugged in when they 'need' to (i.e. in accordance with the Minimal charging model) and 67% on average if EVs are plugged in every time they arrive home.
- V2G charging, if optimised for monetary cost, was found to reduce the carbon intensity of electricity supplied by 5% on average if EVs are only plugged in when they 'need' to (i.e. in

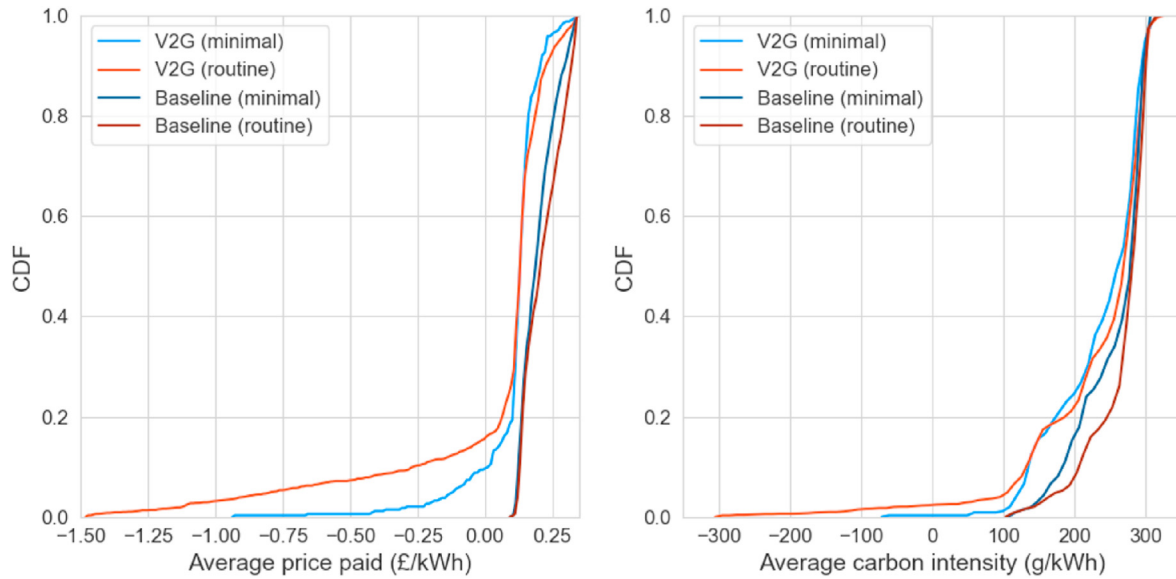


Fig. 11. Cumulative density functions (CDFs) showing the price paid (£/kWh) and carbon intensity (g/kWh) for baseline (uncontrolled) and V2G-controlled EV charging for 10 days under study in January 2021.

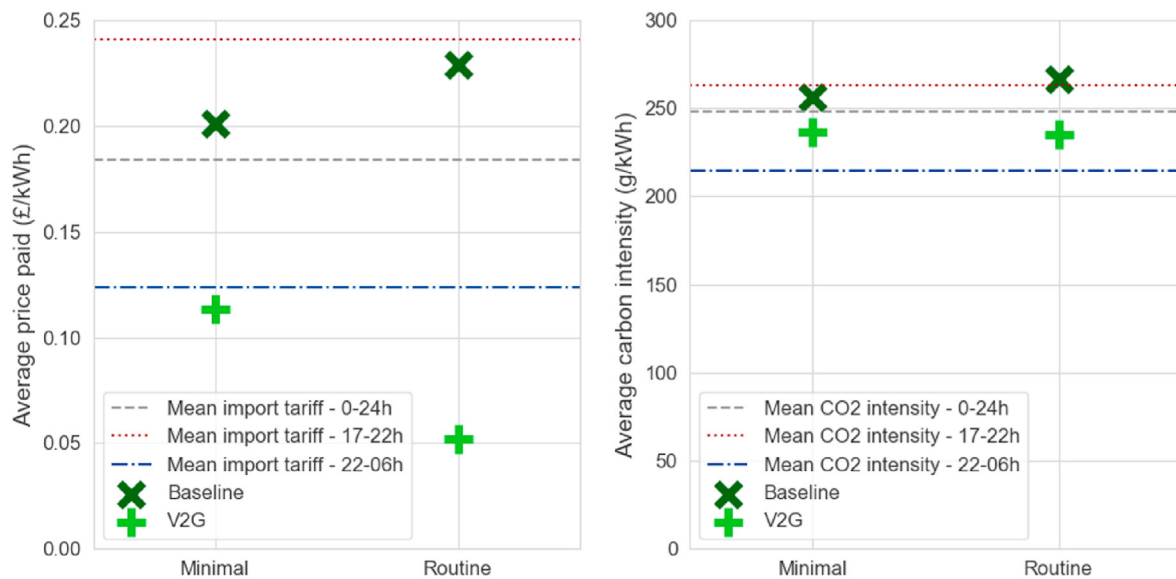


Fig. 12. Comparison of average price paid (£/kWh) for baseline (uncontrolled) and V2G-controlled EV charging for 10 days under study in January 2021 – with average tariffs shown for reference.

accordance with the Minimal charging model) and 6% on average if EVs are plugged in every time they arrive home.

5. Discussion

The results presented in section 4 show how the potential flexibility of EV charging changes depending on how often drivers plug their vehicles in. Clearly, when drivers plug their vehicles in 'routinely' (whenever they arrive home), there is greater potential to shift demand in time and respond to system-wide requests. Aside from reducing consumer bills and the carbon emissions associated with charging, it increases the level of storage resource available to the system. The approach demonstrated in this paper can be used by aforementioned load controllers (aggregators or suppliers) to predict the level of resource they can offer as part of

balancing services. The total storage resource from V2G is a function of the number of EVs plugged in, their SoC and network constraints (the latter related to the spatial distribution of the EVs). While increasing plug-in frequency will lead to an increasing storage resource, the relationship will not be linear: as cars are plugged in more often, they are more likely to be plugged in with a higher SoC (for a given set of travel requirements) – and hence more likely to be charging in the constant voltage (CV) region of the CC-CV charging profile as typical for lithium-ion batteries. The network constraints are also clearly curtailing some of the contribution from V2G in this example, visible through the flat plateau-style traces visible in Figs. 8 and 10.

The results in section 4 are based on the premise that every V2G-controlled charge event must enable the same energy transfer as would have been possible in a 'dumb' charging event: in most

cases, one that takes them to 100% SoC. However, as exemplified by Table 1, the majority of trips taken by drivers are not sufficient to totally deplete even a modestly-sized EV battery of charge; it would be reasonable to expect, therefore, that drivers could seek a lower energy transfer in return for increasing revenues/reduced costs – so long as it would be sufficient to meet the energy demand of their next journey away from home.

The results in section 4 show a modest reduction in CO₂ emissions associated with charging. However, the main contribution to decarbonisation from V2G is by providing balancing services to the electricity system – these will be increasingly valuable as the proportion of converter-interfaced generation increases [59]. Therefore, by incentivising drivers to plug their vehicles in every time they arrive home, load controllers can offer a greater amount of flexible resource to the electricity system.

Of course, use of the battery in V2G is not free: charging and discharging the battery for V2G ultimately uses up the cycles within a battery's useful life. While this matter has been a subject of much debate, including some evidence that there is potential to actually increase useful battery life through V2G [60,61], a review in Ref. [62] puts the cost of V2G associated with battery degradation in the range £0.03–0.09/kWh. In comparison to the average savings made from V2G as found in this study versus the comparable flat tariff (£0.04/kWh and £0.11/kWh from the Minimal and Routine charging models respectively (Fig. 12)), it is shown that V2G is likely to be commercially viable under existing tariff arrangements if vehicles are plugged in every time they arrive home. However, if the cost of battery degradation due to V2G is towards the high end of this range, then the case for V2G to consumers is slim.

Further to battery degradation cost, the upfront cost of V2G hardware must also be discussed. As of 2022, all UK-based V2G trials (including the 2020 trial *Scirius* [63]) have been carried out using DC charging, which requires the installation of a comparatively expensive DC charger (including an AC/DC converter) where the car is to charge and discharge. Whilst consideration of the hardware cost of V2G is outside the scope of this study [63], reports falling hardware costs and payback times of 2 years against the initial investment. Furthermore, if vehicle manufacturers provided on-board converters with the ability to pass power bidirectionally, then this additional investment in hardware (versus a smart AC charger) would not be necessary.

6. Conclusion and further work

This paper has presented an assessment of the potential for V2G to reduce consumer bills and the carbon emissions associated with charging by linking travel data to a time-coupled linearised V2G optimisation model via two separate charging behaviour models: a Minimal model in which drivers seek to minimise their number of plug-ins, and a Routine model in which drivers plug in every time they arrive at home. It was found that, on the basis of the time range studied and the prices used, V2G can reduce the average price paid for EV-charging electricity by 28–67% versus a flat tariff – with the lower end of that range representing a case where consumers only plug in when they 'need' to, and the higher end representing the case where consumers plug in whenever their cars are at home. It was also found that due to the positive correlation between price and carbon in the period from which data for this study was used, optimising for price also resulted in reductions in carbon intensity of the EV-charging electricity by 5–6%, with the range representing the same cases as before. Furthermore: approximately 10% of drivers were able to make a profit under the Minimal charging model; approximately 17% of drivers were able to make a profit under the Routine charging model.

Taking into account a review of battery degradation costs from V2G, using an EV's battery in this manner only makes financial sense to the owner if they maximise their plug-in frequency; this, alongside the increased savings, should provide an incentive to owners to plug in as much as possible – thereby maximising storage resource for a low carbon electricity system. However, it should be noted that real-time price variations in future will be influenced by further investment in the capacity of variable renewables and may be significantly different from those experienced to date.

A key result presented in this paper is that drivers who plug in every time they arrive home pay less on average for their EV charging electricity than those who plug in only when they need to. Therefore, there exists an incentive for drivers to plug-in as often as they can and help to increase the level of electricity system flexibility offered by EV charging. These plug-in 'good habits' could be encouraged by public information campaigns and information publicised by electricity suppliers. It is made clear in PAS 1878 that "actors providing these revenue opportunities to consumers are encouraged to make these benefits clear to encourage the uptake of domestic appliances able to support network operation" [17].

The 10 days under study in this paper are in January 2021, which (as typical of the winter) represents generally high electricity prices and high carbon intensity. V2G operation would be expected to vary around the year as both electricity demand and renewable resource available change. Furthermore, these patterns would be expected to change in the future as the UK continues to install greater capacities of variable renewable generation. Therefore, the first piece of recommended further work from this paper would be to apply the model to different times of the year to build up a more complete picture of how consumers would (financially) interact with V2G.

The second piece of recommended further work is to investigate the effect of slackening the constraint in (8), that every EV must finish charging with the energy content that they would have received under uncontrolled charging. An alternative constraint could be that if the baseline (uncontrolled) energy content upon plug-out is greater than 80%, then the energy content required upon plug-out in this V2G scheme could be revised down to 80%. Due to the non-linear charging profile (10), this could significantly increase the flexibility of the V2G scheme when applied to a fleet of vehicles.

The third piece of recommended further work is to investigate the effect of the forecasting window for optimisation. In this study, the optimisation period is 24 h. This was done on the basis that the Agile tariff is released for the 00:00–23:30 period at 16:00 the previous day, so any load controller using this data would receive 24 h worth of price data on which to optimise EVs' bi-directional energy exchange with the grid. However, there could potentially be significant benefits from using longer horizons, owing in part to the fact that variable renewable resources can change over time (for example, low wind periods can last several days [64]).

The fourth piece of recommended further work is to research methods of improving the accuracy of power flow modelling for this problem. As already mentioned in section 3.5.2, the simplified linear model employed in this study introduces limitations to the level of accuracy of power flow modelling. There should be future research in this area to focus on improving the accuracy of power flow modelling for this problem, taking into account the various linearisation methods that have been published in the literature.

The fifth piece of recommended further work is to develop an optimisation framed around reductions of both carbon emissions and the cost of electricity. To aid this, it is suggested that research be carried out as to the relative importance of low carbon vs. low cost electricity for consumers. This could aid the design of effective

optimisation solutions for future energy smart appliances, with implications beyond EV charging.

The final piece of recommended further work is to examine the influence of changing travel patterns on the results of this study. While the NTS data used in this study is a useful resource for current car-based travel habits, the potential for this to change in conjunction with the electrification of private vehicles (and the decarbonisation of the wider economy) is undeniable. Firstly, significant changes in travel behaviour from the ongoing COVID-19 recovery may last into the long term [65]. Secondly, a reliance on a switch to EVs without any reduction in car use would be likely to result in the UK missing its 2050 Net Zero target [66], and therefore increases in public [67,68] and active [69] transport are equally vital parts of the transport system decarbonisation strategy as electrification of private vehicles. Therefore, potential futures of car ownership and travel behaviours should be included in the analysis for the potential of EV/power system integration and the role of V2G to support electricity system decarbonisation.

CRediT authorship contribution statement

James Dixon: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **Waqquas Bukhsh:** Methodology, Software, Writing – review & editing. **Keith Bell:** Funding acquisition, Supervision. **Christian Brand:** Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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