Optimal Charging Strategies of Electric Vehicles in the UK Power Market

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Abstract—In order to gain the most from their deployment, it is imperative for stakeholders to exploit the main benefits electric vehicles bring to utilities. Therefore, this paper focuses on the aspects required to model the management of electricity supply for electric vehicles. The framework presented details a time coordinated optimal power flow (TCOPF) tool to illustrate the tradeoffs distribution network operators (DNO) might encounter when implementing various load control approaches of electric vehicles. Within an UK context, a case study is performed where the TCOPF tool functions as the intermediary entity that coordinates cost-effective interactions between power markets, network operators, and the plugged vehicles. Results depict the stochastic but optimal charging patterns stakeholders might visualise from electric vehicles in local networks as they are operated to reduce energy and emission costs. Furthermore, results show current emission costs have a negligible weight in the optimisation process when compared to wholesale electricity costs.

Index Terms—Demand response services, distribution network operation, electric vehicles, fuel mix, load control, optimal power flow, storage modelling, wholesale electricity and carbon markets.

I. NOMENCLATURE

$EV_{B\alpha}^{soc}$	storage balance of PHEV fleet in node α
EV_{α}^{soc}	state of charge of PHEV fleet in node α
$EV_{\alpha\beta}^{soc}$	state of charge of PHEV fleet in node α at time β
$EV_{\alpha,max}^{soc}$	maximum state of charge of PHEV fleet in node α
$G2V_{\alpha}$	grid-to-vehicle power flow injections in node α
GW	giga-watt
hr^{total}	number of hours the energy system is assessed
kW	kilo-watt
kWh	kilo-watt hour
MW	mega-watt
MWh	mega-watt hour
$n\beta$	number of time periods
nS_e	number of grid supply points
P_n	number of electric nodes
$P_{D\alpha}$	active power demand in node α
$P_{G\alpha}$	active power generation in node α

$P_{T\alpha}$	active power transmission from node α
C_E	emission costs in the energy system
C_P	electricity costs in the energy system
C_{PE}	electricity and emission costs in the energy system
$P_{D\alpha}^{ev}$	EV power demand in node α
$P_{D\alpha,max}^{ev}$	upper EV power demand in node α
$P_{D\alpha,min}^{ev}$	lower EV power demand in node α
$P_{G\alpha}^{ev}$	EV power generation in node α
$P_{G\alpha,max}^{ev}$	upper EV power generation in node α
$P_{G\alpha,min}^{ev}$	lower EV power generation in node α
$Q_{D\alpha}$	reactive power demand from node α
$Q_{G\alpha}$	reactive power generation from node α
$Q_{T\alpha}$	reactive power transmission from node α
$ t _{\alpha}$	tap magnitude of OLTC unit α
$ t _{\alpha,max}$	upper tap magnitude limit of OLTC unit α
$ t _{\alpha,min}$	lower tap magnitude limit of OLTC unit α
V_{α}	voltage at node α
$V_{\alpha,max}$	upper limit voltage in node α
$V_{\alpha,min}$	lower limit voltage in node α
$V2G_{\alpha}$	vehicle-to-grid power flow injections in node α
α	index for unit
β	index for time
χ	spot market carbon price
ε	spot market electricity price
ω	weight index

II. INTRODUCTION

ELECTRIC vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) are set to be introduced into the mass market after extensive research and development from auto manufacturers [1], [2]. The introductions of these new types of vehicles, which obtain their fuel from the grid by charging a battery, signify that the electrification of the transport sector is imminent. If dealt with properly, PHEVs and EVs (used interchangeably in this text) provide a good opportunity to reduce CO₂ gases from transport activities. However, this assumption can be deceiving. This is because the emissions that might be saved from reducing the consumption of petrol could be off-set by the additional CO₂ generated by the power sector in providing for the load the vehicles represent. Therefore, EVs can only become a viable effective carbon mitigating option if the electricity they use to charge their batteries is generated through low carbon technologies [3].

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In addition to the environmental issue, these unique types of vehicles bring techno-economical challenges for utilities as well. This is because electric vehicles will have great load flexibility due to two key reasons. Firstly, they are idle 95% of their lifetime; making it easy for them to charge either at home, at work, or at parking facilities [4]. Secondly, most marketable batteries exceed the 40 mile per day average urban travel gathered in surveys; hence implying the time of day in which they charge can easily vary [5]. Thus, if set up correctly, the above conditions allow electric vehicles to adopt flexible tariff schemes permitting them to charge when electricity is more accessible and cheaper. Consequently, as renewable energy sources become prominent (e.g. wind power) and intelligent communication infrastructure more abundant (e.g. smartgrids), these mobile loads should seek to take advantage by charging whenever electricity is at its lowest cost and the generation fuel mix is less carbon intensive.

There are many fields of research that can be explored regarding the impacts of EV deployment on power systems. These topics range from the basic grid-to-vehicle (G2V) impact EVs can have on regional grids [6], [7]; continuing into ancillary services which consider the profitable aspects of having vehicle-to-grid (V2G) features [8], [9], [10]; and ultimately expands towards the integration of distributed energy resources (DERs) working in conjunction to meet the demand electric vehicles represent [11]. Nevertheless, so far no publications have explored the effects that an optimal coordination between energy networks, power markets, and electric vehicles can bring to stakeholders. As a consequence, this work follows the string of research which has stated that utilities need to focus on the integrated planning and operation of their assets in search of an enhanced grid [12], [13]. Therefore, this work expands and presents an integrated steady-state analytical framework: the TCOPF program. The TCOPF model portrays the interactions between the relevant parties in order to optimally integrate the presence of electric vehicles into daily operation of distribution networks. Appropriately, in this research the optimal power flow program can be viewed as a body that enables demand response strategies.

Fig. 1. Illustrates the interactions a global coordinator should consider in order to provide optimal load control signals to electric vehicle users.

Demand response refers to “deliberate load control during times of system need, such as periods of peak demand or high market prices, thus creating a balance between supply and demand” [14], [15]. Figure 1 illustrates the parties which are considered in this research study. As the figure shows, the TCOPF tool functions as a global coordinator that commands electric vehicle charging according to the conditions of the DNO, the power market, and the needs of the customers.

In order for the TCOPF to be effective and unbiased it is necessary to apply a holistic approach in assessing and quantifying the tradeoffs electric vehicles bring to energy flows at a distribution level. Although the optimisation formulations can be diverse, in this study the objective functions focus on minimising either energy or carbon emission costs. Modelling these interactions between the grid, the power market, and PHEVs stimulate questions of optimal system operation, such as:

- What form will EV load profiles have if vehicles are charged whenever electricity is at its lowest price?
- What differences can there be in EV charging profiles if priority is given to charge whenever there is low carbon electricity and not at moments of low cost electricity?
- How much influence can renewable generation in the UK fuel mix have on EV charging profiles?
- What effects does a high price on carbon emissions have on EV charging profiles?
- How will the different EV charging patterns affect the shape of the electric load profile the DNO will see from its supply point?
- In what manner will EV profiles affect key network operating variables such as losses and peak demand?
- If V2G power injections were possible, when would they occur and what profile could they take?

This work begins by explaining key concepts concerning an efficient integration of electric vehicles into the UK power industry. Then the paper continues by detailing the TCOPF formulation, hence explaining how to calculate the optimal charging profile electric vehicles can have in distribution networks. Finally, a case study under different scenarios is conducted and presented. Results from the case study demonstrate the relevance of the TCOPF tool in quantifying the tradeoffs stakeholders might face if they have the virtue of controlling or influencing when EV charging can take place based on what spot price and carbon markets dictate.

III. ELECTRIC VEHICLES AND THE UK POWER MARKET

Nowadays, light duty EVs and PHEVs are planning to be rolled out into the market after much work in developing prototypes that satisfy minimum battery range and capacity needs of the market [16], [17], and [18]. As a consequence, it is important to understand the potential effects that electric vehicles can have on energy and carbon efficiency when compared to conventional vehicles.

A. Electric Vehicle W2W Efficiency

No electric car is carbon free. This is because the electricity used to charge its battery is generated in power plants that produce CO₂ emissions. To begin addressing this concern, Table I allows us to compare the efficiency of different vehicle models by using the well-to-wheel equation (*W2W*) that quantifies the distance a car can provide per unit of energy used (measured in *km/kWh*). The *W2W* equation is popular within the literature and follows the energy content of the fuel from its original source up to its point of consumption. For a particular type of vehicle model; this can be described as [19]:

$$W2W = \eta_{W2V} \cdot \eta_{V2W} \quad (1)$$

where:

- η_{W2V} is the well-to-vehicle performance measured as %
- η_{V2W} is the vehicle-to-wheel performance measured in *km/kWh*

TABLE I
W2W ENERGY EFFICIENCY

Technology	Model	Fuel	η_{W2V}	η_{V2W}	W2W
ICE	Camry	Crude oil	0.82	1.23	1.09
ICE	Civic	Crude oil	0.82	2.27	1.86
HEV	Prius	Crude oil	0.82	2.47	2.03
PHEV	Volt	Coal	0.35	4.00	1.40
EV	Roadster	Coal	0.35	6.10	2.14
EV	Leaf	Coal	0.35	6.66	2.33

As Table I shows, even when coal is used as input fuel to power electric motors their *W2W* efficiency slightly surpasses those of leading ICE models, although this benefit is not as evident when compared to HEV models. It is safe to assume that as the input fuel efficiency for electric vehicles increases, the better their performance will be. Furthermore, similar to the *W2W* equation, it is possible to compute the *W2W* emissions of the automobile technologies. In this manner the environmental impact of replacing petrol with coal power generation can be estimated; this equation is presented as:

$$W2W_{CO_2} = \frac{CO_2}{W2W} \quad (2)$$

where:

- CO_2 is the carbon content of the fuel used measured in *kg/kWh*
- $W2W_{CO_2}$ is the carbon emitted per vehicle model measured in *kg/km*

TABLE II
W2W CARBON EFFICIENCY

Technology	Model	Fuel	CO ₂	W2W	W2WCO ₂
ICE	Camry	Petrol	0.292	1.09	0.268
ICE	Civic	Petrol	0.292	1.86	0.157
HEV	Prius	Petrol	0.292	2.03	0.144
PHEV	Volt	Coal	0.870	1.40	0.621
EV	Roadster	Coal	0.870	2.14	0.407
EV	Leaf	Coal	0.870	2.33	0.373

As it was expected, Table II confirms that charging electric vehicles with coal sources is in serious detriment to the environment. Coal was used in this example, as a worst case scenario, since it has the highest emission content from the current UK power portfolio. Therefore, it would be ideal for these new types of automobiles to fill up their batteries when the carbon emissions from power generation are at its lowest.

B. The UK Fuel Mix and Power Market

Although the UK is committed to have by 2020 a 15% of its power generation portfolio from renewable sources, currently its main sources (i.e. natural gas and coal) have a high carbon footprint which if not displaced soon will threaten its carbon mitigation targets [20]. Table III describes the range of carbon footprints for the technologies present in the UK fuel mix [21].

TABLE III
UK POWER GENERATION TECHNOLOGIES

Technology	Fuel Mix (%)	Carbon Emissions (kgCO ₂ /MWh)
Natural gas	47.7	450
Coal	25.8	980
Nuclear	18	6
Renewable	6.6	5.5
Other	1.9	630

As Table III illustrates, the current amount of renewable generation in the UK is quite small. If low carbon generation technologies are to be increased, mainly through an estimated planned 15 GW of combined on-shore and off-shore wind power facilities, these projects will naturally reduce the carbon footprint of the UK fuel mix [22]. Figure 2 illustrates the difference in carbon emissions the UK could have on a typical winter weekday if a prominent amount of wind penetration displaces coal generation in its fuel mix; indeed a preview of possible things to come, which power and environmental engineers will need to research further.

Fig. 2. Exemplifies the differences in the carbon emitted for each megawatt-hour of electricity generated during a day once wind power is prominent.

In addition to renewable energy sources affecting carbon emission variables, these generation technologies also have the potential to influence the wholesale market of electricity [23]. The reasoning behind this argument is because operating extra reserve capacity of marginal plants to meet peak demand is expensive and as a consequence it considerably elevates the spot price of electricity, which in turn raises energy costs for all consumers [24]. Therefore, as renewable generation capacity replaces fossil fuel generation capacity, the marginal cost of electricity can be reduced. By nature, the degree of influence these new technologies can have on prices will vary according to their stochastic generation profile and the demand required on that particular day. Nevertheless, studies have so far reported the greatest impacts on spot prices will likely occur either during daytime or when demand is very high [25].

Based on this assumption and serving as an analogy to the previous figure, Figure 3 depicts the variation in wholesale prices for the same winter day [26].

Fig. 3. The incursion of intermittent renewable energy sources in the UK fuel mix will have a strong influence in the bids and offers of the spot market.

Overall, due to its intermittency, a “greener” UK energy portfolio will bring many challenges to the wholesale and retail power markets which flexible loads, such as PHEVs, should try to exploit through price-responsive demand strategies [27]. Accordingly, the TCOPF model will be employed to characterise how grid operators and electric vehicles can make the most out of the variability and uncertainty the future UK power market is most likely to have.

IV. TCOPF FOR ENERGY SERVICE NETWORKS

The optimal power flow problem has many applications in power system studies. In this work, the TCOPF strictly focuses on operational issues; covering both optimal power delivery at a distribution level and the dispatch of electric vehicle fleets. Hence, the scope of the TCOPF tool presented here is to optimally coordinate the dispatch of EV units so they can have a seamless and more advantageous integration into the grid.

A. TCOPF Problem Outline

The TCOPF problems focus on minimising a nonlinear objective function over multiple period intervals which are restrained by a set of nonlinear constraints. By analysing the state of energy service networks for a daily load profile, it allows the TCOPF solver to devise throughout a day the best moments to dispatch its many control variables (e.g. EVs). Based on these characteristics, the TCOPF formulation can be categorised as a typical steady-state multi-period nonlinear constrained optimisation problem that possesses continuous and mixed-integer properties, while employing piecewise constant functions to regulate its control variables [28].

B. Problem Context and Objective Functions

For practical purposes, the TCOPF program can be seen as having an interesting and useful application for utilities. The reasoning behind this argument is because it can be anticipated that in the near future, one in which distributed energy resources are abundant in the grid, DNOs will not want to monitor and control every DER existent in the networks.

Instead, grid operators will just prefer to have partial control over the aggregate capacity these DERs represent. Thus, it would be very valuable for stakeholders if an independent entity, functioning as an aggregator and decision maker, would optimally coordinate the interactions between the different agents. Hence, the aggregator would therefore allow utilities to dispose of a predefined amount of controllable load, portrayed here by the TCOPF program (see Figure 1). Further details on the TCOPF framework can be gathered in [29], [30].

In this work, three objective function formulations which simulate various operating strategies have been developed. The optimisation solver is global and unbiased when solving the objective functions proposed, thus giving no preference to any particular stakeholder; these formulations are:

- Energy cost minimisation*: approaches the day ahead electricity spot market prices to reduce total energy costs incurred by the energy system while satisfying the technical demands of the infrastructure.
- Emission cost minimisation*: employs the cost from emitting carbon (set by the exchange market) in order to reduce the costs incurred from carbon emissions by the energy system while meeting all operational requirements of the assets.
- Combined minimisation*: reduces both energy and emission costs incurred by the energy system through a weighted linear optimisation combination of the individual objectives while assuring all operational constraints are satisfied.

C. TCOPF Problem Formulations

This section details the optimisation formulations by stating the problems described in the section above. According to the proposed operating strategies, the mathematical formulations for the TCOPF problems can be stated as:

For energy cost minimisation

$$\min C_p = \min \sum_{\beta=1}^{n\beta} \left[\sum_{\alpha=1}^{nSe} P_{D\alpha,\beta} \cdot \mathcal{E}_{p\beta} \right] \quad (3)$$

For emission cost minimisation

$$\min C_E = \min \sum_{\beta=1}^{n\beta} \left[\sum_{\alpha=1}^{nSe} P_{D\alpha,\beta} \cdot \mathcal{X}_{p\beta} \right] \quad (4)$$

For combined minimisation

$$\min C_{pE} = \min \left[(\omega \cdot C_p) + (1 - \omega) \cdot C_E \right] \quad (5)$$

Although the objective function formulations might differ, the equality and inequality constraints are the same for all TCOPF formulations. As expected, all of these constraints are directly responsible in defining the region of feasible solution for the energy system being analysed.

The TCOPF constraints can be classified into:

- Snapshot (i.e. for each time interval);
- Global (i.e. for the entire problem horizon).

Snapshot constraints are subject in each time period β to

$$P_{G\alpha} - P_{D\alpha} - P_{T\alpha} = 0 \quad \forall \alpha \in P_n \quad (6)$$

$$Q_{G\alpha} - Q_{D\alpha} - Q_{T\alpha} = 0 \quad \forall \alpha \in P_n \quad (7)$$

$$V_{\alpha,\min} \leq V_{\alpha} \leq V_{\alpha,\max} \quad \forall \alpha \in P_n \quad (8)$$

$$|t|_{\alpha,\min} \leq |t|_{\alpha} \leq |t|_{\alpha,\max} \quad \forall \alpha \in P_t \quad (9)$$

$$P_{D\alpha,\min}^{ev} \leq P_{D\alpha}^{ev} \leq P_{D\alpha,\max}^{ev} \quad \forall \alpha \in P_n \quad (10)$$

$$P_{G\alpha,\min}^{ev} \leq P_{G\alpha}^{ev} \leq P_{G\alpha,\max}^{ev} \quad \forall \alpha \in P_n \quad (11)$$

$$EV_{\alpha}^{soc} \geq 0 \quad \forall \alpha \in P_n \quad (12)$$

Global constraints are subject to the day being analysed

$$EV_{Ba}^{soc} = 0 \quad \forall \alpha \in P_n, \forall \beta \in n\beta \quad (13)$$

$$EV_{\alpha,\beta}^{soc} = EV_{\alpha,\max}^{soc} \quad \forall \alpha \in P_n, \forall \beta \in n\beta \quad (14)$$

$$G2V_{\alpha} - \left(P_{D\alpha,\beta}^{ev} \cdot \frac{hr^{total}}{n\beta} \right) = 0 \quad \forall \alpha \in P_n, \forall \beta \in n\beta \quad (15)$$

$$V2G_{\alpha} - \left(P_{G\alpha,\beta}^{ev} \cdot \frac{hr^{total}}{n\beta} \right) = 0 \quad \forall \alpha \in P_n, \forall \beta \in n\beta \quad (16)$$

Equations (6) and (7) refer, respectively, to the nodal balance for active and reactive power flow conservation that must be met in each node for each time interval. Expression (8) represents voltage limit at nodes, while (9) specifies the allowed range of operation for OLTC mechanisms. Terms (10) and (11) detail the EV demand and V2G injections permitted at each node. As a result, (12) states that all nodal battery storage systems must have at all times a state of charge equal to or greater than zero. Meanwhile, (13) guarantees a net zero storage balance is met for all battery systems, although if requested (14) specifies to fully charge the batteries for a specific time. Finally, (15) and (16) verify all the energy charged and discharged by EVs matches the sum of their individual power injection counterparts.

The TCOPF problem is programmed, executed, and solved by performing a multi-period nonlinear optimisation using the gPROMS^{TM} software [31]. Once the problem is solved, a summary report is provided; describing the following results:

- The time consumed during the optimisation process;
- The final value of the objective function;
- The values during each time interval for all variables which were constrained.

V. CASE STUDY AND RESULTS

A small 3 node radial network with reminiscent UK features was used to conduct the case study since its simplicity allows an easier analysis of EV operation. The generic distribution network features have been taken from specialised sources [32]. The base value of voltage is 11kV while the base power is 1 MVA. Meanwhile, the energy system is assessed for 24 hours in 48 time intervals. The domestic electric load profiles used are collected from an UK winter weekday [33].

A. Case Description and Assumptions

It is supposed there is a 30% EV penetration in the energy system (i.e. 270 units per node). The technical characteristics of all the plug-in vehicles considered in this study correspond to the Nissan Leaf. This car has a 24 kWh capacity that allows the driver to travel around 160 km, well over the daily average distance travelled by urban vehicles in the UK. Hence, it is assumed the vehicles travel 64 km per day and follow the driving patterns described in Figure 4. Concerning the charging rate of these mobile agents in a residential environment, a 3.12 kW capacity with 95% efficiency was adopted. In addition, for simplicity the simulation considers the EVs which are not on the road are parked and plugged to the grid. This condition allows EVs to provide a relatively small capacity for V2G services, conceding to the grid a 10% of their battery capacity, an amount equivalent to 2.4 kWh which they can comfortably discharge without risking their travelling priorities. Lastly, it is assumed for convenience of the drivers that all EVs must be fully charged by 7 a.m.; furthermore Table III illustrates the energy system parameters.

Fig. 4. Percent of journeys by time of day in an urban area of the UK [5].

TABLE III
CASE STUDY PARAMETERS

Element data	
Electric cables	Admittance = 205.3 - j38.2 p.u.
Slack bus	Voltage = 1∠0° p.u.
Electric vehicles	PHEV charge/discharge rate per unit = 3.12 kW Battery capacity per EV unit = 24 kWh
Constraints	
Electric nodes	0.95 p.u. ≤ V _α ≤ 1.05 p.u.
Tap changer	0.95 ≤ t _α ≤ 1.05
EV capacity	G2V ₁ = G2V ₂ = G2V ₃ = 3.410 p.u. V2G ₁ = V2G ₂ = V2G ₃ = 0.616 p.u.

Once the features and assumptions of the energy system have been determined, various scenarios can be simulated with the purpose of evaluating the different TCOPF formulations. The scenarios are classified based on the objective function, fuel mix (i.e. wind power penetration), and the value put on carbon emissions. The graphs showed in Figures 2 and 3 serve as input data to calculate the spot and carbon costs of energy; in this manner the information is taken as a sample of the current and possible future costs of electricity and carbon. Table IV summarises the simulation scenarios performed.

TABLE IV
DESCRIPTION OF CASE STUDY

Case	Formulation	Spot Price & Fuel Mix	Carbon Price
1a	Energy cost	Base case	£11 tCO ₂ /MWh
1b	Emission cost	Base case	£11 tCO ₂ /MWh
1c	Combined	Base case ($\omega = 0.5$)	£11 tCO ₂ /MWh
2a	Energy cost	Future case	£11 tCO ₂ /MWh
2b	Emission cost	Future case	£11 tCO ₂ /MWh
2c	Combined	Future case ($\omega = 0.5$)	£11 tCO ₂ /MWh
3c	Combined	Future case ($\omega = 0.5$)	£29 tCO ₂ /MWh

B. Techno-economical Results

The TCOPF solver is effective in finding and coordinating the optimal operation patterns of energy systems with a high penetration of EVs. Therefore, the simulations allow us to draw the following insights:

- Electricity is at its least expensive during the night, as the cost is driven by demand, thus if EVs follow price signals they will mainly charge during the early morning hours. Hence, utilities should be prepared to expect this considerable load increment.
- The presence of EVs on the 11 kV network have mild effects on key parameters such as energy losses. However, results from cases 2a, 2c, and 3c show a raise in the peak demand occurring around midnight, a condition that should draw attention from utilities.
- If V2G power injections were possible, they would be most beneficial at moments when electricity is at its most expensive, thus during the afternoon in winter.
- The current UK fuel mix, and even in a mix where considerable wind power has been introduced, are insufficient to influence EV load control strategies; thus EVs will not represent for the foreseeable future an advantageous environmental alternative in the UK.

Table V displays the techno-economical results from the different optimisation formulations. As the table clearly shows, the cost presently given to carbon emissions plays a negligible influence when a combined optimisation is performed. Furthermore, this asseveration still holds true even when the cost of carbon is priced at £29 tCO₂/MWh; the cost of emitting carbon during the peak in oil prices of summer 2008 (case 3c) [34]. In addition, results demonstrate the trade-off there is in cases 1b and 2b where emission costs are reduced and thus it considerably increases energy costs; this naturally means the criteria are conflicting. As a result, the value presently given to carbon has long ways to go in order to function as a driver which changes the way utilities supply power to its customers.

TABLE V
TECHNO-ECONOMICAL RESULTS

TCOPF Case	Losses (MWh)	Peak Load (MW)	C_P (£)	C_E (£)	C_{PE} (£)
1a	2.513	5.765	6326.59	542.60	6869.19
1b	2.359	5.734	6610.34	539.33	7149.67
1c	2.505	5.765	6327.46	542.46	6869.92
2a	2.522	6.013	5771.81	408.82	6180.63
2b	2.455	5.748	5929.47	404.33	6333.81
2c	2.521	6.013	5772.32	408.62	6180.94
3c	2.518	6.013	5773.63	1076.53	6850.16

Figures 5 to 7 describe “when and by how much” the fleet of EVs will charge power from the grid.

Fig. 5. The graph details the charging pattern of electric vehicles when they are coordinated to reduce energy costs. The variations are drastic and the potency of the TCOPF solver is proven by identifying that at 5.30 a.m. the cost of electricity rises and accordingly the charging EVs come to a halt.

Fig. 6. The graph details the charging pattern of electric vehicles when they are coordinated to reduce emission costs. The pronounced presence of wind power in case 2b gives some linearity to the charging profile, as opposed to the unpredictable charging behaviour seen for case 1b.

Fig. 7. The graph details the charging pattern of electric vehicles when they are coordinated to reduce both energy and emission costs. The variations in charging do not differ much from the stochastic patterns seen in Figure 5.

The above figures show how the charging of EVs is hardly influenced during the combined optimisation, although this condition should change as renewable generation becomes prominent and localised. Hence, optimal EV profiles should level out and become less stochastic; however so far the benefits for reducing emission costs are null.

Similar to the previous G2V figures, V2G results are heavily driven by the costs of electricity. Figure 8 illustrates that if vehicles could give power back to the grid this would occur in the early and late afternoon. This output is coherent with the winter weekday being assessed since these are the times at which the spot market has its peak value of electricity.

Fig. 8. The graph details the V2G injections electric vehicles have when they are coordinated to reduce both energy and emission costs.

By adding the results of the EV load profiles to the residential load required by the energy system; Figure 9 details how a DNO from its supply point would visualise the load. It is worth mentioning the drastic changes on the daily curve; from the obvious triple occurrence of peaks up to the considerable demand reduction when V2G injections occur.

Fig. 9. The graph showcases the effects EVs operating under different TCOPF formulations can have on residential load profiles.

VI. CONCLUSIONS AND FURTHER WORK

The challenge of seamlessly integrating a great presence of electric vehicles for an enhanced and reliable grid operation is paramount for power system, transport, and environmental engineers. By considering the influence power markets can have on demand response and load control strategies, this paper has expanded the TCOPF modelling framework for the optimal integration of EVs into the operation of distribution networks. As a result and within an UK context, new optimisation formulations have been introduced to address the economic issues spot energy and carbon markets will bring to future energy systems.

To deal with the integration issues of EVs, the TCOPF program functions as a global coordinating entity that manages cost-effective interactions by sending operating signals based on the conditions of the grid, the power market, and the requirements of the connected EVs. Thus, various operating strategies were assessed focusing on minimising the costs of energy and carbon emissions. The mathematical modelling was coded and solved by performing a piece-wise time non-linear optimisation using the gPROMS^{TM} software package.

Simulations demonstrate the efficiency and novelty with which the TCOPF tool coordinates EV technologies in order to improve the delivery of energy. Results are very encouraging at the level of detail in which EVs take and give power to the grid, while simultaneously showing the electrical infrastructure could easily cope with the additional load EVs represent. Nonetheless, the outputs from the simulation clearly show the cost currently given to emissions at the exchange market is insufficient to drive EV load control strategies when compared to spot prices of electricity. This condition is primarily due to the composition of the UK fuel mix which is dominated by natural gas and coal power plants. Therefore, stakeholders will have to think long term, and seriously push for a low carbon fuel mix in order to make EVs a viable environmental alternative to conventional ICE vehicles.

This work can expand by considering additional scenarios with seasonal variations and a higher presence of nuclear and renewable generation; thus displacing coal and natural gas. Further research which broadens the TCOPF program should cover the inclusion of agent based EV modelling, medium and low voltage assessment of commercial and industrial networks with congestion issues, and the inclusion of more DERs.

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