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Research Article

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Dispatch model for analysing the impacts of electric vehicles charging patterns on power system scheduling, grid emissions intensity, and emissions abatement costs

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ABSTRACT

Dispatching of generating resources at Power Stations is a complex task based on the balance of economics, contractual agreement, regulations, and environmental consciousness in terms of emissions produced in the course of electricity generation. The complexity of the task could be exacerbated with the integration of a large percentage of Electric Vehicles (EVs) in the quest to reduce CO_2 emissions in the transportation sector. In this paper, a dispatch model, which is suitable for analysing the impacts of charging patterns of EVs on grid emissions intensity and emissions abatement costs, is described and developed for dispatching generating resources/technologies. The dispatch model is based on the correlation between historical system load and capacity factors of generating units. The dispatch model is tested on data from the UK power system on a typical winter day in December 2015 with an assumed 50% integration of EVs on the system. Results show amongst others that charging of EVs in the off-peak period may affect the optimal deployment of generating technologies/resources with storage capacity and could produce a higher average grid emissions intensity.

KEYWORDS: CO_2 emissions; Electricity generation; Electric Vehicles; Load dispatch; Power System.

INTRODUCTION

Transportation accounts for about 14% of the global GHG emissions (Intergovernmental Panel on Climate Change (IPCC, 2014). Light-duty vehicles account for about two-thirds of the global GHG emissions from the transportation sector (Hawkins *et al.*, 2013). It is projected that the number of light-duty vehicles is expected to double in the next three decades (Crossin & Doherty, 2016). Already, about a quarter of the global demand for fossil fuel is for the consumption of light-duty vehicles (Ellingsen *et al.*, 2016). Thus, the projected increase in the number of light-duty vehicles means increasing demand and consumption of fossil fuel. This implies more GHG emissions from the transportation sector.

One solution to the heavy dependence of light-duty vehicles on fossil fuel is to change their traction engines from internal combustion types to electric types. Vehicles with electric traction engines are broadly called electric vehicles (EVs) (Eshani *et al.*, 2018). Unlike the conventional vehicles that use fossil fuel for traction, EVs use electricity stored in rechargeable batteries for traction. Therefore, EVs produce no direct emissions. For this reason, EVs are good alternatives to conventional vehicles in the quest to keep down emissions from the transportation sector.

Governments around the world are providing purchase subsidies and tax incentives to encourage the uptake of EVs (Zhou *et al.*, 2013; Helveston *et al.*, 2015; Office for Low Emission Vehicles (OLEV), 2018). In the United Kingdom (UK), the Government enacted a legally binding parliamentary act called the 'Climate Change Act 2008' to reduce UK's GHG emissions by 80% relative to the 1990 level by 2050 (Parliament of UK, 2008). To meet this target, the Government introduced different schemes to promote low-carbon and renewable electricity generation and usage. The UK Government also initiated an incentive scheme, Plug-in Car Grant (PICG), to encourage the uptake of EVs to replace ICE cars for road transport. Vehicles eligible for PICG, must amongst other things, have a zero-emission range of at least 70 miles and must emit less than 50g of CO2 per kilometre driven (Office for Low Emission Vehicles (OLEV), 2018).

Figure 1 is the statistical bar chart of the number of plug-in eligible cars registered for the first time in the UK between 2010 and 2017.

There was an almost 100% increase in the plug-in eligible cars registered for the first time between 2014 and 2015. Between 2015 and 2017 the annual uptake rate had been more than 25% reaching 46,058 plug-in eligible cars in 2017 that registered for the first time.

As the uptake of EVs increases, the impacts of their charging requirements and charging patterns on the generating infrastructure in terms of capacity, scheduling of resources, grid emission intensity, and emission abatement cost must be understood. The charging patterns and uptake level of EVs are likely to have significant impacts on electricity demand, affecting the technologies needed to meet the demand and grid performance (Mills & MacGill, 2014). To understand the worst-case scenario of the impacts of charging requirements of high penetration of EVs on the existing grid infrastructure, EVs must be considered as uncontrollable loads. As an uncontrollable load, the flow of power between the grid and the EV battery is unidirectional from the grid to the EV battery. With typical power charger ratings of 3kW (13A) for residential Mode 2 and 3.7kW (16A) for residential Mode 3 (British Standards Institution, 2011), high penetration of EVs as uncontrollable loads will increase the grid load demand during the charging process (Papadopoulos *et al.*, 2012).

This presents both technical challenges and business opportunities in the electricity industry. Technical challenges that may arise include increased peak load demand, violation of statutory voltage limits, harmonic problems, increased grid losses, and overloading of grid assets especially if the charging of EVs coincides with the peak load demand of the grid (Dharmakeerthi *et al.*, 2014). Business opportunities arising from the high penetration of EVs include increased electricity generation and a boost in economic activities for players in the electricity industry, as attention gradually shifts from the gas and oil industry (Grant *et al.*, 2015).

The dispatch of generating technologies to meet demand is a complex task based on the balance of economics, contractual agreement, regulations, and environmental consciousness. Many studies on the impacts of charging of EVs on power systems usually based the dispatch of generating technologies on optimisation techniques, aiming at least cost unit commitment Majidpour & Chen, 2012; Villar *et al.*, 2012; Zhang *et al.*, 2012; Foley *et al.*, 2013; Schill & Gerbaulet, 2015). In (Schill & Gerbaulet, 2015), a numerical optimisation model that simultaneously optimises power plant dispatch and charging of EVs on the German power system was performed. PLEXOS, a commercial optimisation software was used to investigate the impacts of charging of EVs on the Irish power system and electricity market in (Foley *et al.*, 2013).

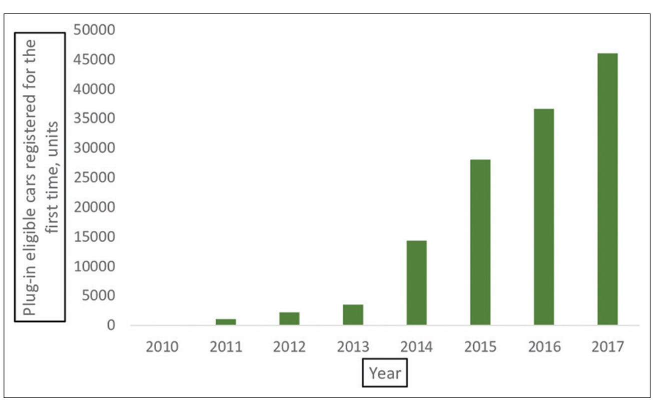

Figure 1: Plug-in eligible cars registered for the first time in the UK, 2010-2017 (Department for Transport (DfT), 2018)

In this paper, a model is described and developed for dispatching generating resources/technologies, which is suitable for analysing the impacts of charging patterns of EVs on grid emissions intensity and emissions abatement costs. The dispatch model is based on the correlation between historical system load and capacity factors of generating units as first described in (Jansen *et al.*, 2010). The dispatch model is tested on data from the UK power system on a typical winter day in December 2015 with an assumed 50% integration of EVs on the system under three scenarios. However, it must be noted that only generating resources/technologies with transmission entry capacities are considered in the study.

GENERATION MIX AND THE SYSTEM LOAD

Figure 2 shows the simplified diagram of the Transmission-Entry-Capacity generating resources/technologies that made up the electricity generation mix of the UK as of December 2015 and Table 1 gives their capacities (Department for Business, Energy, and Industrial Strategy, 2016; "G. B. National Grid status," 2016)

The baseline load indicated in Figure 2 is the usual conventional load on the system, consisting of domestic, commercial, and industrial loads before the EV load is added. From Table 1, it is seen that renewable energy resources (RES) accounts for 21% while low-carbon technologies account for 56% of the total generating technologies with transmission-entry capacity.

MODEL DESCRIPTION

Data on system load demand and generation output per technology for each day of December 2015 from (EirGrid Group,

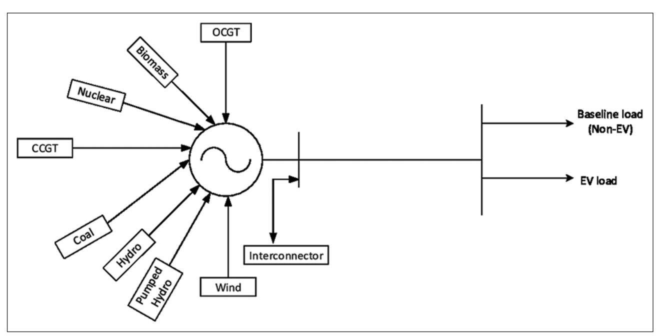

Figure 2: Simplified diagram of UK Power System showing Transmission-Entry-Capacity Generating Technologies as of Dec. 2015

2016; "G. B. National Grid status," 2016; System Operator for Northern Ireland (SONI), 2016) are processed. From the data, average half-hourly load demand and corresponding average half-hourly capacity factors of different generating technologies which met the demand were determined for an average day in December 2015. There were 48 data points each for load demand and capacity factor of each generating technology. Each data point is the average of data for each day of December 2015. Figure 3 is the average half-hourly load demand curve and average half-hourly output of generating technologies as processed from the data sources.

Figure 4 gives the summary of the average contributions of different generating technologies into the generation mix on a typical day in December 2015 as processed from historical data (EirGrid Group, 2016; "G. B. National Grid status," 2016; System Operator for Northern Ireland (SONI), 2016).

Scatter plots of average load demand and average capacity factor are presented for each generating technology to determine the correlation between them. Figures 5a-i show the correlations of average half-hourly capacity factors versus average half-hourly system load for all the generating technologies.

As seen in Figure 5a, the Nuclear generating unit shows no correlation between its capacity factor and the load demand. This can be explained as the Nuclear generating unit provides the baseload generation and its output is nearly constant at all times irrespective of the load demand.

Table 1: UK's Transmission-Entry-Capacity generating technologies as of

Technology	Transmission-Entry-Capacity (MW)	Percentage of Total (%)
CCGT	31,994	41.5
Coal	13,500	17.5
Hydro	3,836	5.0
Nuclear	9,937	12.9
OCGT	1,470	1.9
Pumped	2,828	3.7
Onshore wind	2,769	3.6
Offshore wind	4,333	5.6
Biomass	2,423	3.1
Interconnector	4,000	5.2
Total	77,090	100

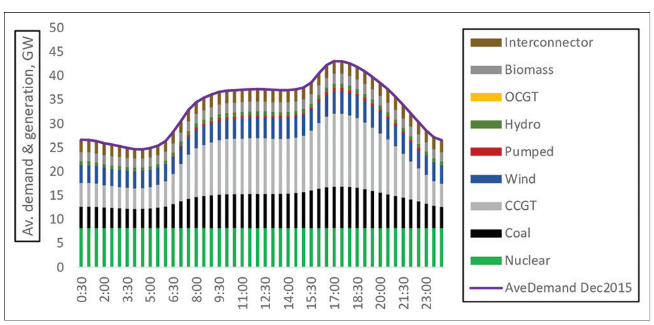

Figure 3: Average half-hourly system load demand and generation dispatch mix, Dec 2015 (Historical data (EirGrid Group, 2016; "G. B. National Grid status," 2016; System Operator for Northern Ireland (SONI), 2016))

The Coal, CCGT and Pumped hydro generating units show strong positive correlation between their capacity factors and the load demand as seen in Figures 5b, 5c, and 5e respectively. The coefficient of determination (R^2) of fitness to the regression line of Coal, CCGT and Pumped hydro generating units are 0.996, 0.997, and 0.931 respectively.

The Wind, Hydro, and Biomass generating units show fairly strong positive correlation between their capacity factors and the load demand as seen in Figures 5d, 5f, and 5h. Their coefficients of determination (R^2) are 0.888 for Wind, 0.892 for Hydro, and 0.837 for Biomass. However, it must be noted that the positive correlation shown by the Wind generating unit between its capacity factor and the load demand is weather-related. It has been shown that in Winter, high demand is driven by cold conditions which are due to the strengthening of the easterly winds, and thereby increases average wind power (Thornton *et al.*, 2017).

The OCGT and the Interconnector show weak correlation between their capacity factors and the load demand as seen in Figures 5g and 5i. The OCGT is a peaker generating unit which is operated only when the load demand is high. The net output of the Interconnector on the other hand is dependent not only on the conditions in the system but also on the conditions outside of the system.

MODEL FORMULATION

The total electricity generation from the different generating units/technologies to meet the load demand over a certain period is the sum product of the capacity factors and the Transmission-Entry-Capacities (TECs) of the generating units/technologies over the period as expressed in equation (1).

$$Gen_{Total} = \sum_{i=1}^{n}\sum_{t=1}^{T} g_i(t) = \sum_{i=1}^{n}\left[\left(\sum_{t=1}^{T} CF_i(t)\right) \times TEC_i\right] \tag{1}$$

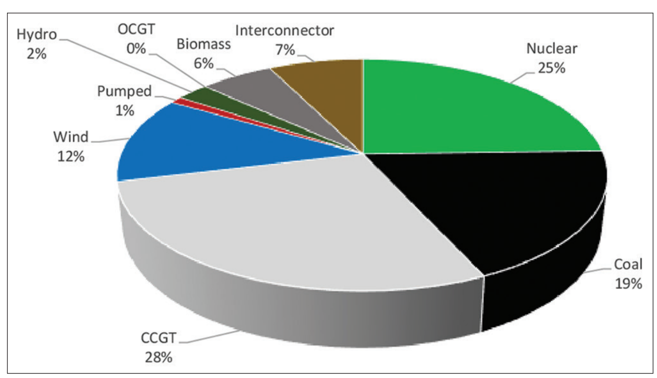

Figure 4: The average contribution of different generating technologies into the generation mix, Dec. 2015 (Historical data (EirGrid Group, 2016; "G. B. National Grid status," 2016; System Operator for Northern Ireland (SONI), 2016))

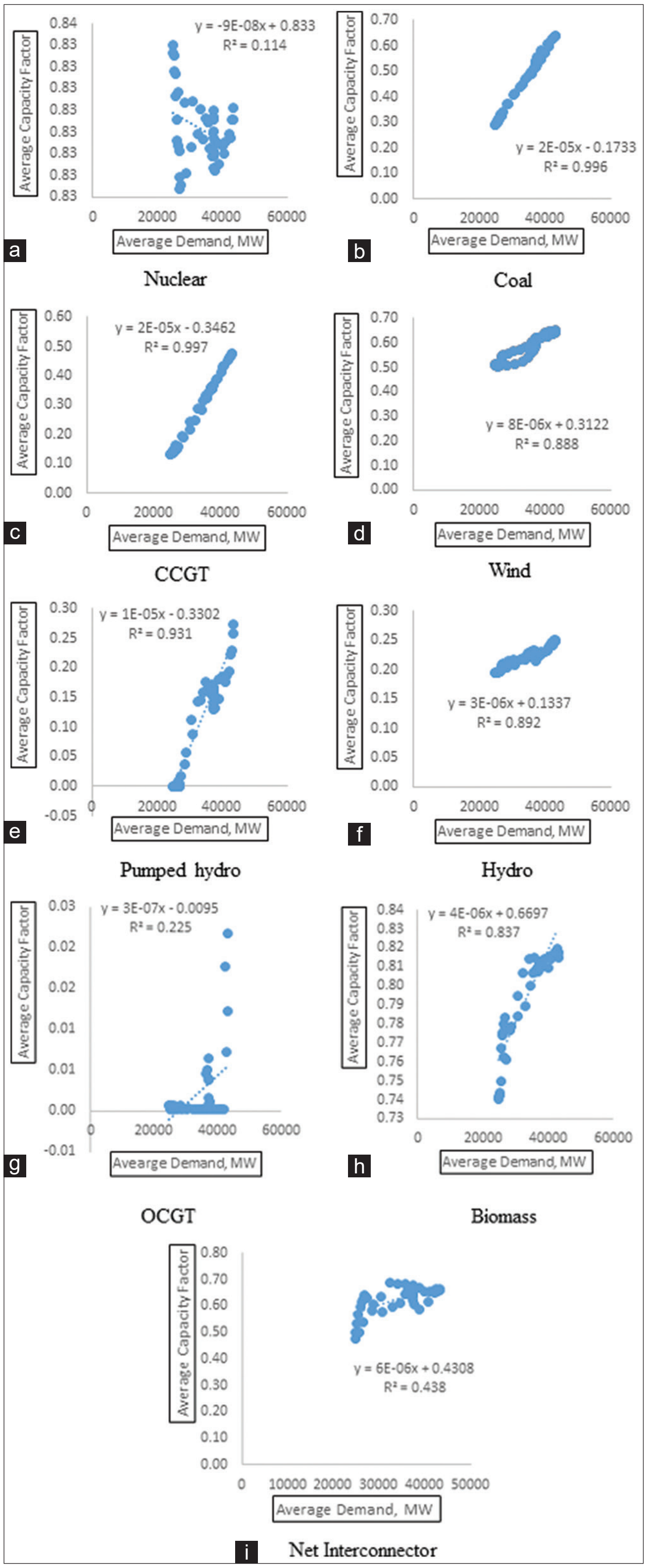

Figure 5: (a-i) Average half-hourly capacity factor versus average half-hourly system load

Where:

Gen_{Total} is the total electricity generation (MW) from all the different generating units/technologies,

i is the identifier index for generating unit/technology,

n is the total number of generating units/technologies,

t is the time interval,

T is the total number of the time intervals,

g_i is the electricity generation (MW) from a particular generating unit/technology,

CF_i is the capacity factor of a particular generating unit/technology,

TEC_i is the transmission-entry-capacity (MW) of a particular generating unit/technology.

The capacity factors of the generating units/technologies can be expressed in terms of their correlations with the load demand as previously established. Thus, equation (1) can be expressed in terms of the load demand as given in equation (2).

$$Gen_{Total} = \sum_{i=1}^{n}\sum_{t=1}^{T} g_i(t) = \sum_{i=1}^{n}\left[\sum_{t=1}^{T}\left(\left(a_i \times D(t)\right) \pm b_i\right) \times TEC_i\right] \quad (2)$$

Where:

a_i and b_i are constants of the equation of regression line of the correlation between the capacity factor of a particular generating unit/technology and the load demand,

D is the load demand (MW).

The total emissions produced by all the generating units/technologies over a period of time is expressed in equation (3).

$$Em_{Total} = \sum_{i=1}^{n}\sum_{t=1}^{T} Em_i(t) = \sum_{i=1}^{n}\left[\left(\frac{EmFac_i}{\eta_i}\right) \times \sum_{t=1}^{T} g_i(t)\right] \quad (3)$$

Where:

Em_{Total} is the total emissions (gCO_2e) produced by all the generating units/technologies,

Em_i is the emissions produced (gCO_2e) by a particular generating unit/technology,

$EmFac_i$ is the emission factor (g/kWh) of a particular generating unit/technology,

η_i is the thermal efficiency (%) of a particular generating unit/technology.

The average grid emissions intensity of the system due to electricity generation from all the generating units/technologies over a period of time can be determined as expressed in equation (4).

$$Grid_{Em_{Intensity}} = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{\sum_{i=1}^{n} Em_i(t)}{\sum_{i=1}^{n} g_i(t)}\right) \quad (4)$$

Where:
$Grid_{Em_{Intensity}}$ is the average grid emissions intensity of the power system (gCO_2e/kWh).

The total cost of generation by the system is given by equation (5).

$$GenCost_{Total} = \sum_{i=1}^{n}\sum_{t=1}^{T} gencost_i(t) = \sum_{i=1}^{n}\left[\sum_{t=1}^{T}\left(g_i(t)\right)\times £_i\right] \quad (5)$$

Where:
$GenCost_{Total}$ is the total cost of electricity generation of the power system over a period of time (£),

$gencost_i$ is the cost of electricity generation of a particular generating unit/technology (£),

$£_i$ is the variable cost or levelized cost (£/MW) (depending on the focus of the calculation) of operating a particular generating unit/technology to produce electricity.

Emissions savings/avoided on the road due to uptake of EVs can be expressed by equation (6).

$$Em_{savings} = EV_{uptake} \times n \times D_d \times CO_{2_{ICE}} \quad (6)$$

Where:
$Em_{savings}$ is the emissions savings on the road ($ktCO_2e$),

EV_{uptake} is the percent uptake of EVs (%),

n is the total number of licensed cars,

D_d is the average daily distance travelled by a car (km),

$CO_{2_{ICE}}$ is the average CO_2 emission intensity of ICE cars (g/km).

The net emissions reduction on the grand scheme is the difference between the emissions savings on the road and the marginal increase of the grid emissions (above the grid baseline emissions) due to EV charging load. The net emissions reduction can thus be expressed by equation (7).

$$Em_{Net_{reduction}} = Em_{savings} - Em_{grid_{incr}} \quad (7)$$

Where:
$Em_{Net_{reduction}}$ is the net emissions reduction ($ktCO_2e$),

$Em_{grid_{incr}}$ is the marginal increase of the grid emissions above the baseline grid emissions ($ktCO_2e$),

The marginal increase of the grid emissions above the baseline grid emissions is a function of the magnitude of the EV load, EV charging pattern and how the generating resources are dispatched to meet the load demand. These factors also contribute to the emission abatement cost, which is given by the ratio of the marginal increase in the electricity generation costs (above the baseline generation costs) to the net emissions reduction as expressed in equation (8).

$$Em_{abatement_{cost}} = \frac{GenCost_{incr}}{Em_{Net_{reduction}}} \quad (8)$$

Where:
$Em_{abatement_{cost}}$ is the emissions abatement cost (£/tCO_2e),

$GenCost_{incr}$ is the marginal increase in the electricity generation cost (£).

MODEL TESTING

The dispatch model is tested on data from the UK power system under three scenarios. Electricity generation cost, net emissions reduction, and emissions abatement cost are calculated in each scenario. The results of the calculations are compared to analyse how different charging patterns of EVs impact the power system in terms of dispatch of generating resources, grid emissions intensity, and emissions abatement cost. The three scenarios investigated are:

1) Baseline scenario: The generating units/technologies are dispatched to meet the average load demand on a typical day in December 2015. It is assumed the load demand contains no or insignificant EVs load because the uptake of EVs in the UK as at the end of 2015 was 0.9% (Department for Transport (DfT), 2016b).
2) Time-Of-Use-Charging scenario (TOUC): In this scenario, it is assumed that there is a 50% uptake of EVs and the EVs are charged based on the Time-Of-Use tariff. The generating units/technologies are thus dispatched to meet the average load demand, which is now augmented by the EVs load.
3) Without-Time-Of-Use-Charging scenario (WTOUC): As in TOUC, 50% uptake of EVs is assumed. But unlike TOUC, the EVs are charged without observing the Time-Of-Use tariff. The generating units/technologies are dispatched to meet the average load demand plus the EVs load.

In 2015, the number of licensed cars in the UK was 30.3 million (Department for Transport (DfT), 2016b)and annual road traffic made by cars/taxis was 398.6 billion kilometres (Department for Transport (DfT), 2016a). The average daily car travel is therefore estimated to be 36km. The average daily EV energy requirement for the charging of EVs on the national grid is thus estimated according to equation (9).

$$EV_{MWh_{grid}} = N_{EV} \times dist_{ave} \times \eta_{ave_{EV}} \quad (9)$$

Where:
$EV_{MWh_{grid}}$ is the average daily energy requirement of EVs on the grid (MWh),

N_{EV} is the total number of EVs,

$dist_{ave}$ is the daily average distance travelled by car (km),

$\eta_{ave_{EV}}$ is the average of the efficiencies of all the EVs (kWh/km).

Table 2 gives the list of the most popular electric cars in the UK in 2015 with their efficiencies and All-Electric-Range (Department for Transport (DfT), 2016c; DVLA/DVA/DfT, 2016).

The charging patterns for the TOUC and WTOUC scenarios are adapted from (National Grid, 2015). Figure 6 is the average half-hourly EV charging profiles for WTOUC and TOUC.

Substituting values into equation (9), the average daily EV charge requirement on the grid is estimated to be 104.72GWh. This is spread in time over the day according to the charging profile on top of the average load demand. Figure 7 shows the half-hourly system average load profiles for the baseline scenario, TOUC scenario, and WTOUC scenario.

Table 3 gives the system parameters in terms of the emission factors, thermal efficiencies, and operating costs of the different generating technologies with transmission-entry-capacity that made up the system as of December 2015.

RESULTS

The results of the model deployment are presented on scenario basis. Thereafter, comparison and analysis of the results are made.

Results for the Baseline Scenario

Figure 8 shows the half-hourly electricity generation from different generating technologies as dispatched in the Baseline scenario according to the model. Figure 9 is the detail of the daily average contributions of different generating technologies in the Baseline scenario.

Both Figures 8 and 9 respectively are very much comparable to Figures 3 and 4 which were produced from historical data. This comparability gives credence to the model. The marked observation between Figure 8 and Figure 3 is that whereas in Figure 3, there is no mismatch between the average load demand and the generation but in Figure 8 there is a mismatch of surplus generation of about 3% (total for a whole day) over the load demand.

In terms of contribution to the electricity mix, individual generating technology in Figure 9 compares well with Figure 4.

Results for TOUC Scenario

Figures 10 and 11 show the half-hourly electricity generation from different generating technologies as dispatched according to the model and the summary of the daily average contributions of different generating technologies respectively for the TOUC scenario. There is a surplus generation of about 3% (total for a whole day) over the load demand. The maximum average load demand is 44GGW with CCGT contributing 32% of the total electricity generation. Pumped hydro and OCGT contributed less than 1% at 5.55GW and 0.11GW respectively.

Results for WTOUC Scenario

Figures 12 and 13 show the half-hourly electricity generation from different generating technologies as dispatched according to the model and the summary of the daily average contributions of

Table 2: UK's most popular electric cars in 2015 (Department for Transport (DfT), 2016c; DVLA/DVA/DfT, 2016)

Brand (Department for Transport (DfT), 2016c; DVLA/DVA/DfT, 2016)	Model	Efficiency (kWh/km) (Office of Energy Efficiency & Renewable Energy, 2016)	All-Electric-Range (miles) (Office of Energy Efficiency & Renewable Energy, 2016)
Nissan Leaf (24-kWh)	2013/14/15/16	0.184	84
Nissan Leaf (30-kWh)	2016	0.191	107
BMWi	2014/16	0.172	81
Mitsubishi Outlander PHEV	2012/13/14/16	0.191	62
Tesla S (60-kWh)	2014/15/16	0.22	234
Average efficiency		0.192	

Table 3: Parameters of the generating technologies

Generating Technology	Emission factor (CO_2kg/kWh) (DECC, 2015), (Bates & Henry, 2009)*	Thermal efficiency (%) (DECC, 2015), (Biomass Availability and Sustainability Information System (BASIS), 2015)*	Variable Operating cost (£/MWh) (Mott MacDonald, 2010)	Levelised Operating cost (£MWh) (Mott MacDonald, 2010)
CCGT	0.23	47	64.30	80.00
Coal	0.39	36	62.40	104.00
Hydro	-	-	-	83.00
Nuclear	-	40	7.40	99.00
OCGT	0.18	42	80.30	90.50
Pumped hydro	-	-	-	118.00
Onshore wind	-	-	-	94.00
Offshore wind	-	-	-	161.00
Biomass	0.19*	29*	33.70	93.20
Interconnector	-	-	60.00	60.00

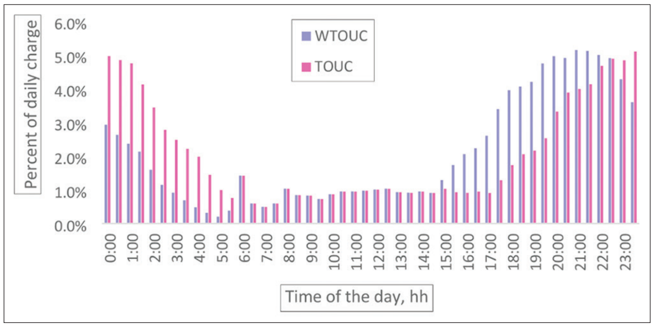

Figure 6: Average half-hourly EV charging profiles: WTOUC and TOUC (National Grid, 2015)

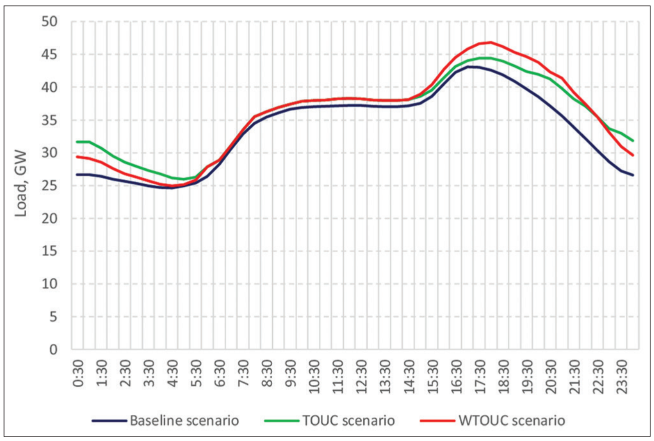

Figure 7: Half-hourly system average load demand

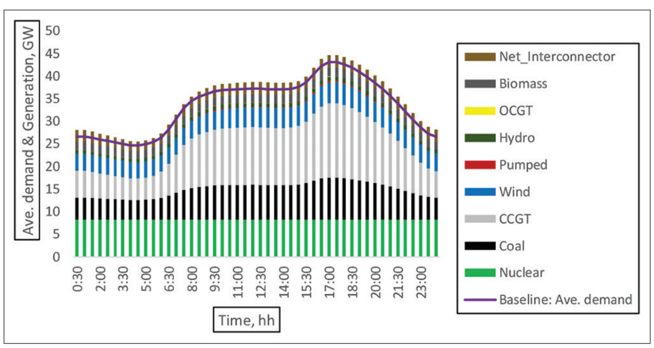

Figure 8: Baseline: Half-hourly generation from different generating technologies (modelled)

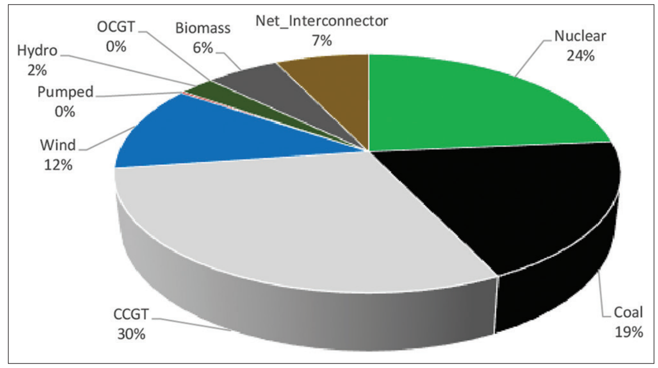

Figure 9: Baseline: Daily average contributions from different generating technologies (modelled)

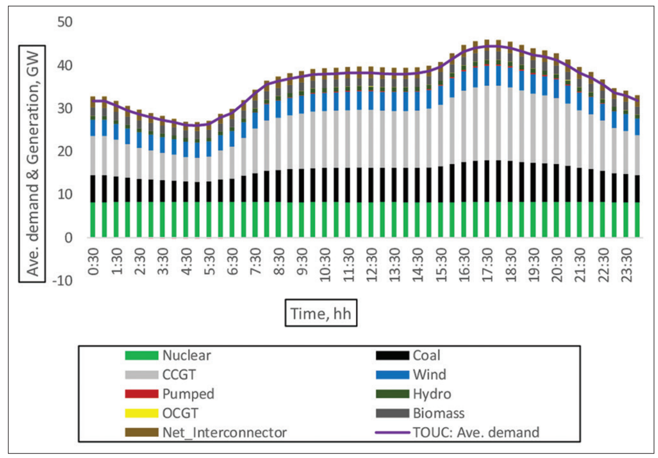

Figure 10: TOUC: Half-hourly generation from different generating technologies (modelled)

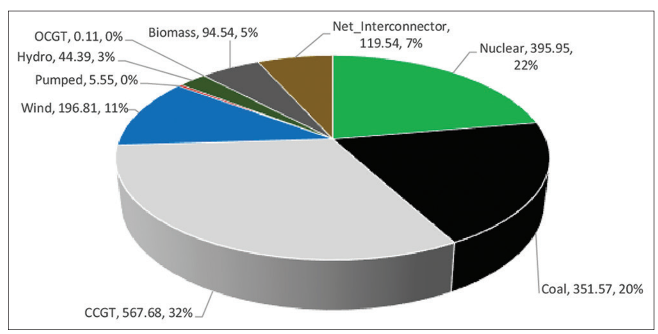

Figure 11: TOUC: Daily average contributions from different generating technologies (modelled)

different generating technologies respectively for the WTOUC scenario. There is also in this scenario a surplus generation of about 3% (total for a whole day) over the load demand.

The maximum average load demand is 47GW. The percentage contributions of the different generating technologies are almost the same as in the TOUC scenario. However, electricity generation from Pumped hydro and OCGT increased in this scenario to 6.18GW and 0.12GW respectively but is still less than 1% of the total electricity generation.

DISCUSSION

For each of the scenarios, the volume of emissions produced, average grid emissions intensity, and electricity generation costs (both levelised cost and variable cost) are calculated and are presented in Table 4.

The emissions produced in both TOUC and WTOUC scenarios are almost the same at a value of 354ktCO_2. This is because the contributions of the emissions-producing generating technologies to the electricity mix are almost the same in both TOUC and WTOUC scenarios except for OCGT which slightly contributed more (by 0.01GW) in WTOUC as seen in Figure 11 and Figure 13 respectively. The marginal increase in grid emissions above the baseline in both TOUC and WTOUC is therefore 32ktCO_2.

Table 4: Emissions, average grid emissions intensity, and generating costs for all scenarios

Scenario	Emissions produced ($ktCO_2$)	Average grid emissions intensity (gCO_2/kWh)	Variable generating cost (£M)	Levelised generating cost (£M)
Baseline	321.79	406	32.81	78.91
TOUC	353.64	422	35.87	83.25
WTOUC	353.65	419	35.87	83.29

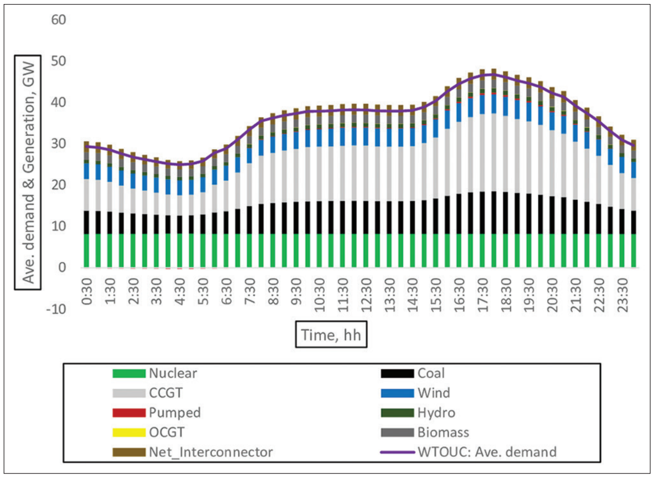

Figure 12: WTOUC: Daily average contributions from different generating technologies (modelled)

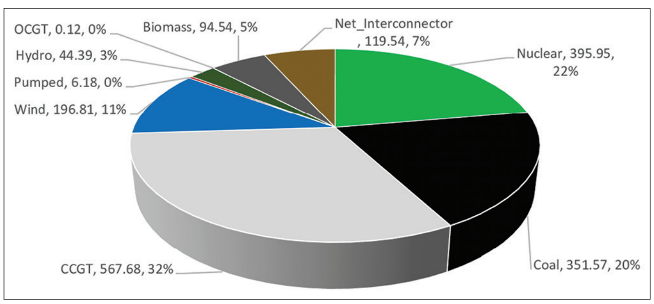

Figure 13: WTOUC: Daily average contributions from different generating technologies (modelled)

The Baseline average grid emissions intensity is 406gCO_2/kWh. However, although almost the same volume of emissions was produced in both TOUC and WTOUC scenarios, the average grid emissions intensities of the TOUC and WTOUC scenarios are 422gCO_2/kWh and 419gCO_2/kWh respectively. The disparity between the average grid emissions intensities of TOUC and WTOUC is because of the difference in aggregated mix outputs of the generating technologies at some instances. Figure 14 shows the grid emissions intensity profiles of all the scenarios over a 24-hour period. The average grid emissions intensity of the WTOUC is, however, lower than that of TOUC because the Pumped hydro technology slightly contributed more (by 0.63GW) in WTOUC than in TOUC, (Figures 11 & 13).

Using the reported 2015 average new car CO_2 emissions of 121.4g/km (Society of Motor Manufacturers and Traders, 2016), the emissions savings on the road, on a day in December 2015, due to 50% uptake of EVs is calculated according to equation (6) to be 66.29 $ktCO_2$. The net emissions reduction in both TOUC and WTOUC is therefore calculated to be 34.29 $ktCO_2$ according to equation (7).

The variable generating cost in the Baseline scenario is £32.81M. While the variable generating costs in both TOUC and WTOUC are the same at £35.87M. This is so because the contributions of the generating technologies in both TOUC and WTOUC are almost the same except for OCGT and Pumped hydro technologies which slightly contributed more in WTOUC. However, the extra contribution of OCGT in WTOUC is insignificant (0.01GW) to affect the total cost. Also, the extra contribution of the Pumped hydro in WTOUC is at no variable cost since the variable generating cost of the Pumped hydro is assumed to be zero in this work. Therefore, the marginal increase in the variable generating cost above the baseline is £3.06M in both TOUC and WTOUC. The emissions abatement cost in terms of the variable generating cost in both TOUC and WTOUC is calculated to be £89.24/tCO_2 according to equation (8).

The marginal increase in the levelised generating costs above the baseline in both TOUC and WTOUC are £4.34M and £4.38M respectively. This is because the levelised generating cost in WTOUC is higher due to the extra contributions of OCGT and the Pumped hydro technology. Therefore, the emissions abatement costs in terms of the levelised generating costs in both TOUC and WTOUC are £126.57/tCO_2 and £127.73/tCO_2 respectively. Table 5 summarises the comparison of the TOUC and WTOUC scenarios.

CONCLUSIONS

A dispatch model was developed based on the correlation identified from historical data between system load demand and capacity factors of generating units. A 50% uptake of EVs was assumed. Two types of EV charging patterns were used in the work. In one of the patterns, the charging of the EVs is based on the time of use tariff, designated as Time-Of-Use Charging (TOUC), which encourages charging of EVs during the off-peak period at night. In the other pattern, EV owners charge their cars without regard to time of use tariff, designated as Without-Time-Of-Use Charging (WTOUC). The model was then used to dispatch the generating resources to meet system load demand under the two charging patterns of EVs.

From the results the following conclusions can be made:

- Charging pattern that encourages charging of EVs in the off-peak period may affect the optimal use of generating technologies/resources with storage capability e.g. Pumped hydro unit.

Table 5: Comparison of TOUC and WTOUC scenarios

Scenario	Net emissions reduction ($ktCO_2$)	Marginal increase in generating cost (£M)		Emissions abatement cost (£/tCO_2)	
		Variable	Levelised	Variable	Levelised
TOUC	34.29	3.06	4.34	89.24	126.57
WTOUC	34.29	3.06	4.38	89.24	127.73

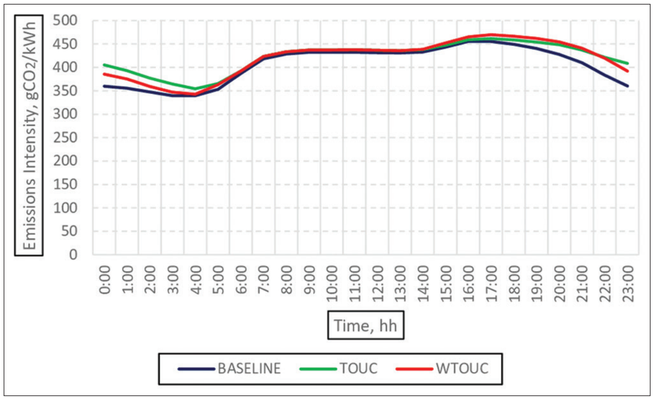

Figure 14: Grid emissions intensities of the scenarios

- Average grid emission intensity could be higher with the charging pattern of EVs based on a time-of-use tariff. This was the case in this work because there was less contribution from the Pumped hydro unit.
- Marginal increase in grid emissions and marginal increase in electricity generation costs are likely to be lower in the TOUC pattern than in the WTOUC pattern. Therefore, emissions abatement costs are likely to be higher in WTOUC than in the TOUC.

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