Benefits of flexibility from smart electrified transportation and heating in the future UK electricity system

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Highlights

- The benefits of smart EVs/HPs on the carbon emission and renewable integration cost are quantified
- Advanced stochastic analytical framework is developed to assess the benefits of smart EVs/HPs
- Typical operating patterns and potential flexibility of EVs/HPs are sourced from recent UK trials
- A comprehensive range of case studies across several future UK scenarios are carried out

Abstract

This paper presents an advanced stochastic analytical framework to quantify the benefits of smart electric vehicles (EVs) and heat pumps (HPs) on the carbon emission and the integration cost of renewable energy sources (RES) in the future UK electricity system. The typical operating patterns of EVs/HPs as well as the potential flexibility to perform demand shifting and frequency response are sourced from recent UK trials. A comprehensive range of case studies across several future UK scenarios suggest that smart EVs/HPs could deliver measurable carbon reductions by enabling a more efficient operation of the electricity system, while at the same time making the integration of electrified transport and heating demand significantly less carbon intensive. The second set of case studies establish that smart EVs/HPs have significant potential to support cost-efficient RES integration by reducing: a) RES balancing cost, b) cost of required back-up generation capacity, and c) cost of additional low-carbon capacity required to offset lower fuel efficiency and curtailed RES output while achieving the same emission target. Frequency response provision from EVs/HPs could significantly enhance both the carbon benefit and the RES integration benefit of smart EVs/HPs.

1. Introduction

Rapid expansion of Renewable Energy Sources (RES) is expected to make a key contribution to electricity system decarbonisation. However, high penetration of intermittent RES will increase the requirements for various reserve and frequency response services, leading to reduced carbon benefit and increased balancing cost. Moreover, large amount of additional generation capacity is required to provide “RES firming” for system security reasons, which causes additional costs associated with RES integration.

At the same time, the electrification of transport through electric vehicles (EVs) and heating systems through heat pumps (HPs) is seen as another key policy measure to further reduce the use of fossil fuel in energy supply and hence reduce carbon emissions. However, as demonstrated in the Low Carbon London (LCL) trials [1] [2], this electrification may lead to an increase in peak demand that is disproportionately higher than the increase in energy consumption, which could increase the requirements for additional generation and network capacity with low utilisation levels [3]. Furthermore, as the demand associated with EVs/HPs concentrated during the periods of peak demand, it is going to be supplied by high-emission peaking plants, leading to a degradation of the system carbon performance.

On the other hand, there exists significant flexibility in temporal patterns of EVs [4] and HPs [5], providing an opportunity to utilising demand-side response (DSR) solutions facilitated by inherent storage capabilities present in EV batteries and thermal storage associated with buildings heated by HPs. Smart EVs and HPs could not only reduce the required generation/network capacity [3] and the incremental carbon emissions driven by EVs and HPs, but also facilitate the integration of RES through energy arbitrage [6] [7] and ancillary service provision [4] [8]. In this context, this paper focuses on analysing and quantifying the implications of deploying smart EVs and HPs for the carbon emissions and RES integration cost within the UK electricity system. Therefore, the key specific objectives of this paper can be summarized as:

1. Analyse the benefits of smart EVs/HPs trialled in LCL in reducing carbon emissions in a broader UK electricity system.
2. Quantify the economic benefits of carbon savings from smart EVs/HPs in terms of lower requirements to invest in zero-carbon generation capacity in order to achieve the same carbon emission target.
3. Analyse the benefits of smart EVs/HPs in reducing system integration cost of RES, including balancing cost associated with RES intermittency and investment cost associated with back-up capacity to ensure system security.

The impact of smart EVs/HPs is investigated for three future system development scenarios, with particular emphasis on different possible evolution trajectories of RES capacity. The key link between the technology-specific, bottom-up LCL trials and system-level studies presented in this paper is the effective shape of electricity demand seen by large-scale generation for different deployment levels of trialled EVs/HPs, as well as the potential to provide flexibility to the system, in particular load shifting and ancillary services. Unlike in previous published work [9] [10] where the operating patterns were inferred from those associated with conventional vehicles and heating systems, the uncontrolled charging and heating patterns assumed in this paper are based on measured populations, while modelling the ability of smart EVs/HPs to shift demand and provide frequency response has been updated based on insights from LCL trials.

Given that the uncertainty and limited inertia capability of RES are expected to be a major driver for escalating system emission and integration cost, the performance of the system is analysed using the Advanced Stochastic Unit Commitment (ASUC) model. One of the key advantages of ASUC when compared with deterministic generation scheduling models used in other studies [11] [12], is that it is able to dynamically allocate energy arbitrage and ancillary service provision by EVs and HPs depending on the conditions in the system. Moreover, unlike the simplified assumption on frequency response requirements typically used in other studies [4] [9] [13], the ASUC model is capable of explicitly quantifying the inertia-dependent frequency response requirements. Therefore, the impact of reduced system inertia driven by large-scale RES deployment on the benefits of frequency response provision from EVs/HPs is explicitly evaluated for the first time. The proposed model has been shown to be particularly suitable to analyse the benefits of flexibility provided by energy storage [14] and DSR [15] in systems with high penetration of RES.

2. Characteristics of EVs/HPs demand and their potential to provide flexibility

In this section we provide an overview of EVs/HPs investigated in LCL trials and specify their key characteristics with respect to the flexibility associated with them.

2.1 Electric vehicles

A detailed description of EV trials conducted in LCL is given in [16]. The trial included 72 residential and 54 commercial vehicles and monitored their charging at both home or office charging points, as well as around 400 public charging stations. The report quantified some of the key parameters of EV demand relevant for network planning and system analysis such as typical demand profiles and diversified peak demand for a given number of EVs.

As an illustration, the fully diversified average and peak day demand profiles for residential EV users are shown in Figure 1. The average profile represents the charging demand for an average day, while the peak profile has been obtained by extrapolating the diversity characteristic of EV peak demand towards a very large number of vehicles, where the trials have shown that coincidence factor[*] approaches 20% [16]. Given that the typical (non-diversified) charging power for a single residential charging point was around 3.5 kW, this resulted in a diversified peak EV demand of 0.7 kW. This information has been used to calibrate annual hourly demand profiles from [13] and use those profiles as an input into the ASUC model used for this study.

Reference [16] has further assessed the flexibility of EV demand, i.e. how much of EV charging demand may be shifted in time in order to support the electricity system but without compromising the ability of the EV users to make their intended journeys. The analysis of smart charging in [16] suggested that between 70% and 100% of EV demand can be shifted away from peak hours. This analysis included the driving patterns of EV users, so that the estimation of their flexibility ensured that all of the users' journeys can be completed despite temporal shifting of charging demand (i.e. the users' mobility requirements are not compromised as the result of smart charging). Based on this, we estimate that up to 80% of EV demand could be shifted away to other times of day while supporting the same journey patterns. This flexibility parameter is used as input into the ASUC model in order to allow it to make optimal scheduling decisions on when flexible EVs should be charged from the system operation perspective.

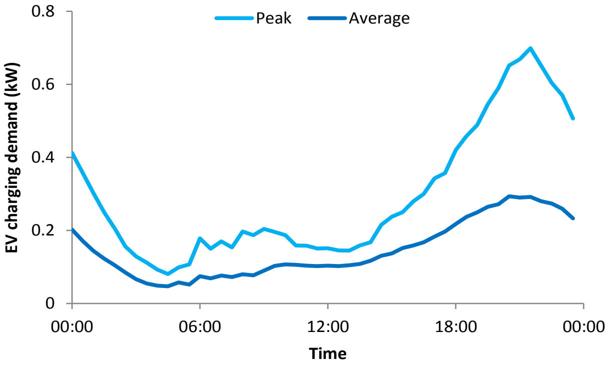

Figure 1 Average and peak EV charging demand profiles from LCL trials

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[*] The coincidence factor is defined as the ratio between the maximum instantaneous demand of a group of customers and the sum of their individual maximum demands. It is the inverse of the diversity factor.

The analysis has shown that the charging can typically be delayed by several hours when shifted away from the peak towards the night hours, as illustrated in Figure 2, which has been taken from [16].

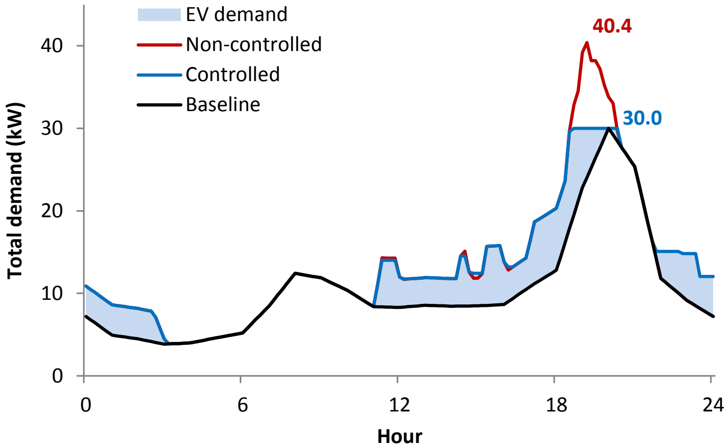


Figure 2 Uncontrolled and optimised charging profile for a residential EV sample superimposed on baseline residential demand

2.2 Heat pumps

LCL trials also involved the monitoring of residential heat pumps, as described in Report B4 [2], however due to a smaller sample size the trial results were only used to calibrate the likely non-diversified peak of residential heat pump load. In order to construct a fully diversified profile of national-level HP demand, we used inputs from previous studies [17] [18] [19]. All of these assumed a gradual improvement in building insulation levels, and estimated the hourly profiles based on representative temperature fluctuations for the UK. The diversified peak day demand for an average household with heat pump heating is shown in Figure 3 for illustration.

We further assumed that flexible HP operation would be possible if they were fitted together with heat storage. Based on the findings of [17] and [20], we assumed that for the heat storage size in the order of 10% of peak day heating energy demand, the peak HP demand can be reduced by 35% through using the storage and shifting HP demand into other times of day[†]. Although the potential flexibility of HP demand would generally vary among different customers depending on their consumption, heat storage size, insulation levels or temperature settings, in this paper the aggregate heat storage has been considered to be available to support system operation.

[†] In [19] this assumption resulted in a hot water tank of about 140 litres per average household.

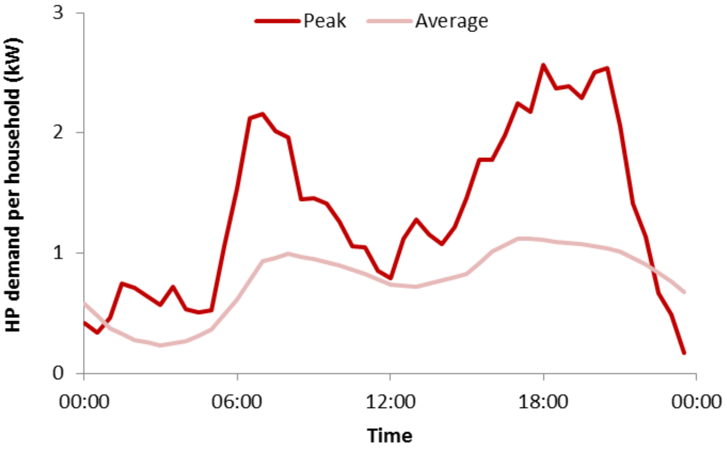


Figure 3 Peak (cold winter) day HP demand profile used in the analysis

3. Modelling approach and scenario assumptions

This section describes the modelling methodology applied to assess the impact of smart EVs/HPs on the carbon emission and RES integration cost in the future UK electricity system. It also presents the scenarios that are used in the case studies.

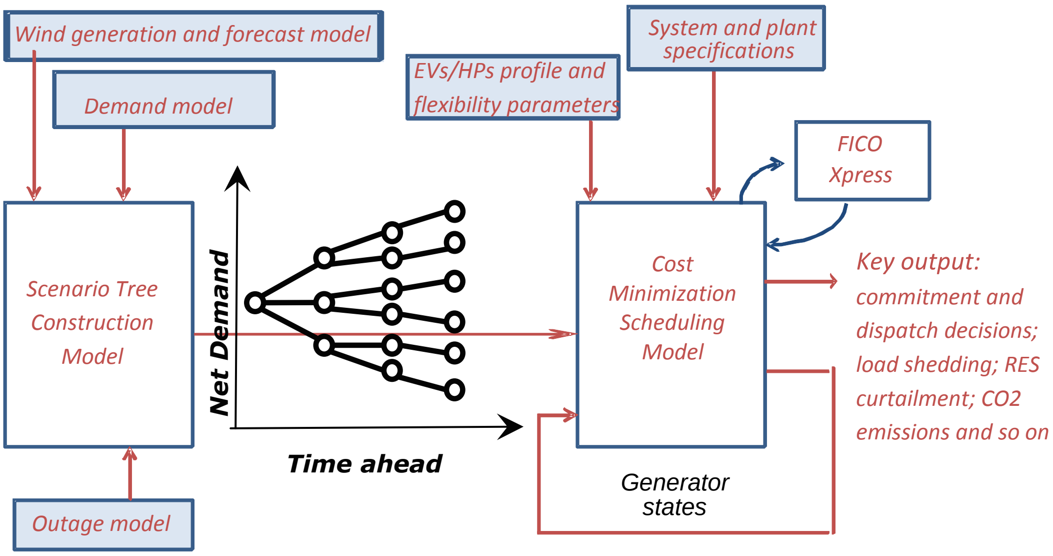


Figure 4 Schematic illustration of ASUC tool

3.1 Methodology

The Advanced Stochastic Unit Commitment (ASUC) model [21] with inertia-dependent frequency response requirements is implemented in order to assess the benefits of smart EVs/HPs. Figure 4 provides a schematic illustration of the key components of the tool. RES realisations, RES forecast errors, system demand and generator outages are synthesised from appropriate statistical models and used to generate scenario tree of the net demand. The scenario tree is then fed into the cost minimization scheduling model, and then a set of feasible control decisions is obtained for each node on the tree, such that the expected total operating cost is minimised. Because the actual realisation will differ from all the scenarios in the tree, the scheduling is performed using rolling planning, in which only the here-and-now decisions are fixed, and all subsequent decisions discarded. For this reason, the full tree, extending to 24 hours ahead, is solved at every time step. Key outputs of the model include the optimal commitment and dispatch decisions, volume of renewable output that needs to be curtailed as well as the corresponding emissions from the electricity system.

By performing two simulations that differ in only one aspect, for example with inflexible operation versa with smart operation of EVs/HPs, we analyse the changes in system operation and carbon emissions so that the benefits of smart operation of EVs/HPs can be quantified. The simulations are carried out over a year time horizon in order to capture the variations in system demand, RES generation as well as EVs/HPs demand.

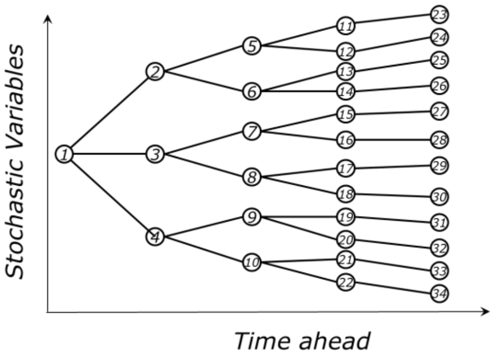


Figure 5 Schematic of a typical scenario tree in SUC

3.1.1 Scenario Tree

The unit commitment (UC) and economic dispatch (ED) are solved over a scenario tree (Figure 5). Quantile-based scenario selection method is adopted in the modelling framework. This method is developed in [22] by constructing and weighting scenario trees based on user-defined quantiles of the forecast error distribution. The normalized RES level is assumed to follow a Gaussian AR(2) process with half-hourly timestep, which is then transformed into a non-Gaussian RES output with a range from zero to the installed capacity of RES fleet [22]. The probability distribution of outages is derived by using the Capacity Outage Probability Table (COPT). The cumulative distribution function (CDF) $C(x;n)$ of the net demand is the total system demand minus the convolution of the probability distribution function (PDF) of realized RES production with the negative cumulative nodal COPT in each of the nodes of the scenario tree. The q^{th} quantile of the net demand distribution can be calculated as $x\colon C(x;n) = q$ by using a numerical root-finding algorithm. The nodal probability $\pi(n)$ is obtained using the trapezium rule [22]. More scenarios would lead to a better representation of system uncertainty and therefore more efficient operation of the system. However, large amount of scenarios would also cause a significant computational burden. Nine scenarios are selected in this study, which is shown to be a good balance between accuracy and computational time in [22].

3.1.2 Advanced Stochastic Unit Commitment (ASUC) model

The objective of the stochastic scheduling is to minimize the expected operation cost:

$$\sum_{n\in N}\pi(n)\left(\sum_{g\epsilon G}C_g(n)+\Delta\tau(n)\big(c^{LS}P^{LS}(n)\big)\right) \tag{1}$$

subject to the system-level constraints, including load balance constraint and frequency response constraints; local constraints for thermal units, such as minimum and maximum generation, commitment time, minimum up and down times, ramping rates, fast frequency response provision, as well as for storage units; details on these constraints and the equations describing generation costs are presented in [21].

A generic demand-side response model is adopted to describe smart EVs/HPs. Constraints associated with smart operation of EVs/HPs are modelled as: a) Total shifted energy (2); b) Maximum percentage of demand can be shifted in/out in each hour (3); c) Maximum/minimum amount of total shifted energy (4); d) Daily balancing of energy shifting (5); e) Maximum frequency response capability (6)-(7).

$$E(n)=E(a(n))+P^c(n)-H^{int}(n) \tag{2}$$

$$(1-\lambda)H^{int}(n)\le P^c(n)\le(1+\lambda)H^{int}(n) \tag{3}$$

$$E^{min}\le E(n)\le E^{max} \tag{4}$$

$$E(n)=0\ if\ t(n)=0 \tag{5}$$

$$0\le R(n)\le\beta^{max}\,H^{int}(n) \tag{6}$$

$$R_s(n)\le\Big(P^c(n)-(1-\lambda)H^{int}(n)\Big) \tag{7}$$

where $H^{int}(n)$ is defined as unmodified demand for EVs or HPs, $E(n)$ is total shifted demand, λ is the elasticity of EVs/HPs demand, E^{min}/E^{max} is the minimum/maximum amount of the shifted demand, $t(n)$ is the time corresponding to node *n*, $R(n)$ is frequency response provision from EVs/HPs, β^{max} is the maximum percentage of EVs/HPs demand that could contribute to frequency response.

3.1.3 Advantages of ASUC model in analysing the benefits of smart EVs and HPs

The ASUC model is capable of dynamically scheduling spinning and standing reserve in the system to ensure that a given level of security of supply is maintained at minimum cost. Therefore, operating reserve requirements are endogenously optimised within the model. Since smart EVs/HPs can contribute to reserve provision, optimal scheduling of various types of reserve is critical to understand the impact of smart EVs /HPs on the system operation. At the same time, stochastic scheduling also enables to optimally split the capacity of EVs and HPs between energy arbitrage and ancillary service provision under different system conditions.

Furthermore, the ASUC model considers the required level of frequency response in the system, taking into account the effect of reduced system inertia at high RES penetrations. Given that intermittent RES is expected to gradually replace conventional generation, the aggregated inertia in the system provided by rotating synchronous machines will decrease, requiring more frequency response to maintain the frequency within the statutory limits. If the required frequency response is provided only by part-loaded plants, this may lead to RES curtailment and lower operating efficiency of conventional plants, eventually increasing carbon emission and RES integration cost. It is therefore important to consider this effect when quantifying the benefits of frequency response provision from smart EVs/HPs. Figure 6 illustrates the frequency response requirements for varying levels of load and RES generation in the future UK system.

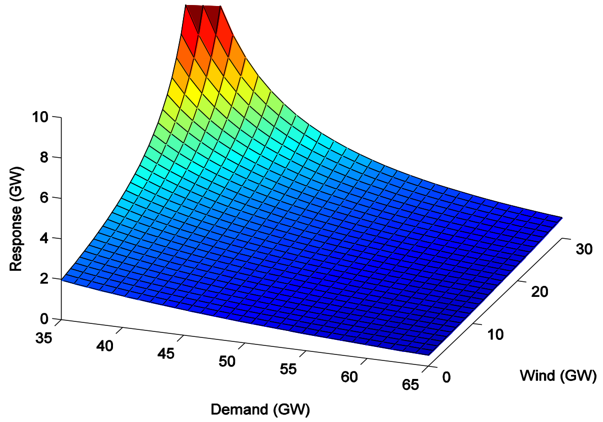
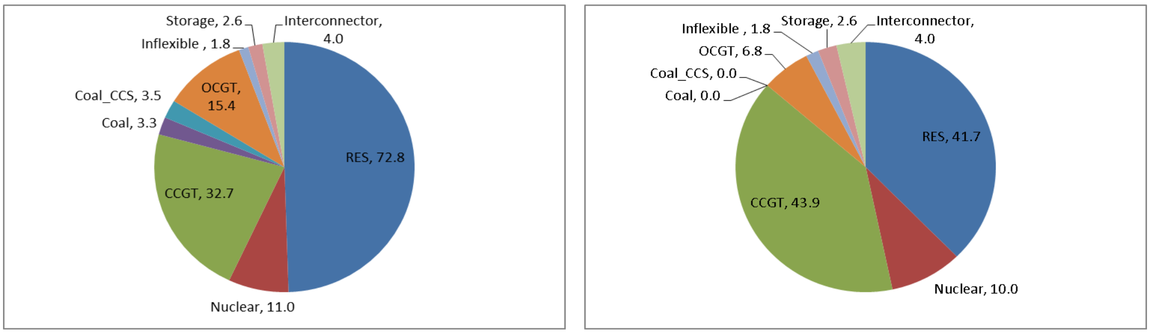


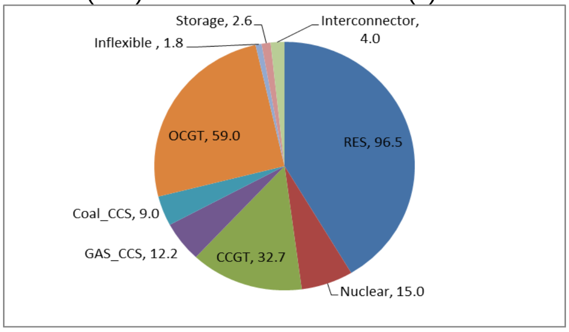
Figure 6 Inertia-dependent frequency response requirements

3.2 Scenarios for carbon impact assessment of future UK electricity system

In this paper we use two scenarios for 2030 from a recent report on synergies and conflicts in the use of DSR [23], Green World (GW) and Slow Progression (SP), including the associated generation capacities and demand profiles. Demand data also includes the assumptions on electrification of transport and heating demand, as specified in the following sections. The 2050 scenario used in the study is based on a High Renewable (HR) scenario from DECC Carbon Plan [24], with fluctuations of hourly demand constructed as in [14]. The assumed generation capacity in the UK system in 2030 and 2050 is presented in Figure 7.



(a) 2030 Green World (GW) (b) 2030 Slow Progression (SP)



(C) 2050 High Renewable (HR)

Figure 7 Generation capacity mix for different UK system scenarios in 2030 and 2050

Generation capacity in 2030 GW scenario is about 140 GW, of which 72.8 GW is RES generation (56.9 GW of wind and 15.8 GW of PV). Total installed capacity in 2030 SP scenario is around 104 GW, of which 41.7 GW is RES generation (34.4 GW of wind and 6.1 GW of PV). In the 2050 HR scenario there is 226 GW of installed generation, 42% of which is contributed by RES capacity. The penetration of RES with respect to meeting annual electricity demand is 31%, 47% and 54% in 2030 SP, 2030 GW and 2050 HR, respectively.

The demand assumptions are shown in Table 1. The base demand (excluding EVs and HPs demand) is the same for 2030 GW and 2030 SP scenarios, with the annual consumption of 344 TWh and peak demand of 59.1 GW. The EVs and HPs demand on the other hand is much higher in the GW scenario. The base demand increases moderately in 2050 HR scenario, however, the EVs and HPs demand increases more than twice compared with the 2030 GW scenario. Whereas Section 2 illustrated the typical EV and HP demand profiles for residential users, the EV and HP demand figures in Table 1 included both residential and commercial sectors.

Table 1 Demand Information for the UK system in 2030 and 2050

	Annual Demand	**Annual EV demand**	**Annual HP demand**
2030 Green World (GW)	344 TWh	18 TWh	53 TWh
2030 Slow Progression (SP)	344 TWh	6.6 TWh	24.9 TWh
2050 High Renewable (HR)	374 TWh	42.7 TWh	110 TWh

Representative annual EV and HP demand profiles for the UK are constructed based on peak demand profiles presented in Section 2, adjusted for the impact of typical annual temperature variations on EV and HP consumption, as elaborated in [19] and [20].

4. Quantitative assessment of carbon impact of smart EVs and HPs

In this section, the methodology described in Section 3 is applied to quantify the carbon impact of smart EVs/HPs in 2030 and 2050 UK systems.

4.1 Approach to quantifying the carbon impact of smart EVs/HPs

The carbon impact of smart EVs/HPs is assessed by comparing the annual system emissions with and without smart operation of EVs/HPs. Smart EVs/HPs operation can contribute to carbon emission reduction via three main drivers: (i) improved efficiency of conventional generation due to less variable net demand with lower peaks; (ii) reduced need to curtail RES output when there is excess energy in the system, as the surplus output can be absorbed by smart shifting EVs/HPs demand; and (iii) reduced need to run part-loaded conventional generation to provide frequency response, if this can be replaced by the same service provided by smart EVs/HPs.

In cases where it is assumed that EVs/HPs are capable of providing frequency response (FR), this was assumed to be implemented through rapid disconnection of a fraction of EVs/HPs demand. The disconnection would not compromise the end user requirements given the relatively short duration of interrupted charging or HPs operation and the availability of stored energy in the form of EVs batteries or heat storage as part of smart HP systems. The analysed cases are summarized in Table 2.

Table 2 Description of Case Studies

		Assumptions	λ	β^{max}
1	**Non-smart**	No smartness/flexibility from EVs and HPs	0	0
2	**Smart EV**	EVs are flexible with low frequency response capability	0	0.05
3	**Smart EV/ FR**	EVs are flexible with high frequency response capability	80%	0.8
4	**Smart HP**	HPs are flexible without response capability	0	0
5	**Smart HP/ FR**	HPs are flexible with high response capability	35%	0.8

Based on the carbon emissions obtained from the simulation of annual system operation, the results are presented through three different metrics. Firstly, average system emission rate is defined as the ratio of total system carbon emission over the total system demand:

$$\text{Average system emission rate} = \frac{\text{Total system carbon emission}}{\text{Total system demand}}$$

The second metric is the incremental carbon emission, which is the ratio of incremental carbon emissions driven by adding EVs/HPs demand to the existing electricity demand:

$$\text{Incremental carbon emission rate} = \frac{\text{Carbon emissions driven by EVs/HPs demand}}{\text{EVs/HPs demand}}$$

The third metric is the carbon emission reduction per unit of energy of “smart” demand, which is calculated as the ratio of total system emission reduction caused by smart EVs/HPs over the corresponding EVs/HPs demand:

$$\text{Carbon emission reduction per unit} = \frac{\text{Total system emission reduction}}{\text{EVs/HPs demand}}$$

4.2 Carbon benefits of smart EVs/HPs

4.2.1 Average system emissions

Carbon emissions from today’s UK electricity system are around 450 g/kWh.[‡] With the expansion of zero- and low-carbon technologies and retirement of high-emitting plants such as coal, the grid emissions are expected to reduce substantially. Scenarios analysed in this paper already reflect the decarbonisation of the electricity system, so the objective of case studies presented here is to estimate to which extent EVs/HPs can support an even more ambitious decarbonisation of electricity supply.

In the first step, the annual operation of the system is simulated without any flexibility contribution from EVs/HPs. As shown in the Non-smart cases in Figure 8, the average emission rate for the 2030 GW scenario is 115 g/kWh, while due to lower penetration of RES and Nuclear, the emission rate in 2030 SP scenario is around 150 g/kWh. The combination of high penetration of RES, Nuclear and CCS plants in the 2050 HR scenario leads to a highly decarbonised electricity system with the average emission rate at around 48 g/kWh.

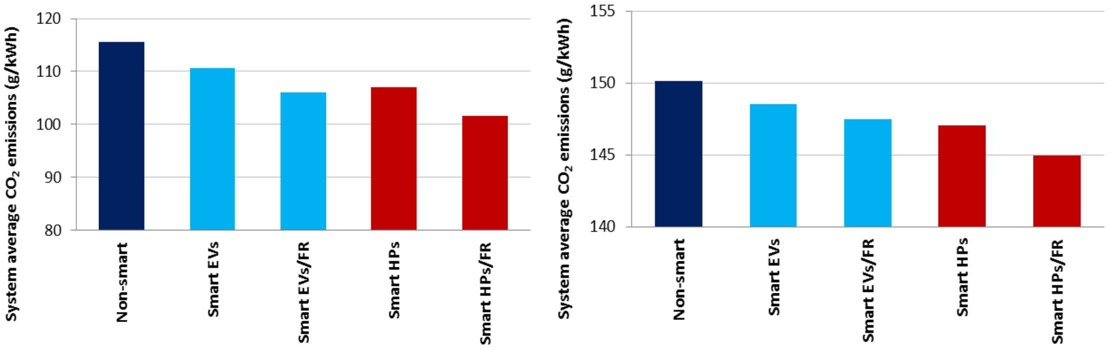
After establishing the baseline system carbon performance, we proceed to quantify the carbon benefits of smart EVs/HPs. The results for 2030 GW scenario are presented in Figure 8 (a). The average system emission rate is reduced by 5 and 8 g/kWh due to smart EVs and smart HPs, respectively, and this is further reduced by 4 g/kWh and 5 g/kWh if smart EVs/HPs can contribute to frequency response. Although smart EVs are in general more flexible than smart HPs, the reduction caused by HPs is higher due to higher volume of HPs demand.

As shown in Figure 8 (b), similar trends are observed in 2030 SP scenario, however the carbon impact of smart EVs/HPs is less significant, partly due to lower RES penetration, but also because the penetrations of EVs/HPs are also lower when compared with 2030 GW scenario.

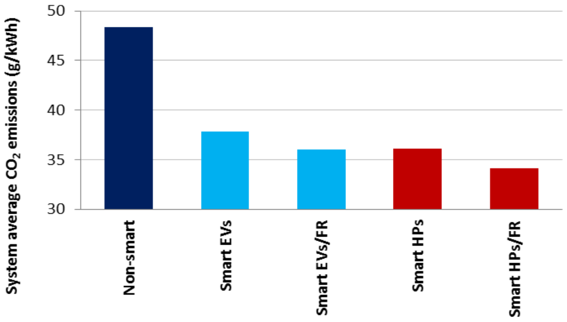
The carbon impact of smart EVs/HPs in the 2050 HR scenario is illustrated in Figure 8 (c). Although the electricity sector in this scenario is already largely decarbonised, smart EVs/HPs could effectively further reduce the average emission rate by up to 15 g/kWh. Because of a higher penetration of EVs and HPs than in the two 2030

[‡] DECC, “2014 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors”, July 2014.

scenarios, the average emission rate could be reduced from 48 g/kWh in the non-smart case to 38 g/kWh and 36 g/kWh by smart EVs and HPs, respectively. The provision of frequency response from smart EVs/HPs results in a very small additional carbon benefits due to the fact that the frequency response in the non-smart case is provided by low-emitting CCS plants, so the displacement of those, although economically beneficial, does not yield significant improvements in carbon performance.



(a) 2030 Green World (GW) (b) 2030 Slow Progression (SP)



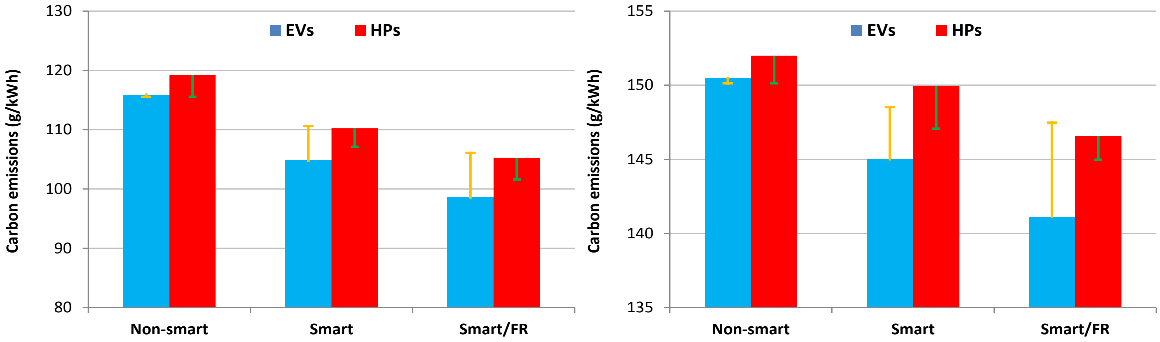
(C) 2050 High Renewable (HR)

Figure 8 Impact of smart EVs and HPs on average system carbon emissions

4.2.2 Carbon intensity of supplying electrified transport and heat demand

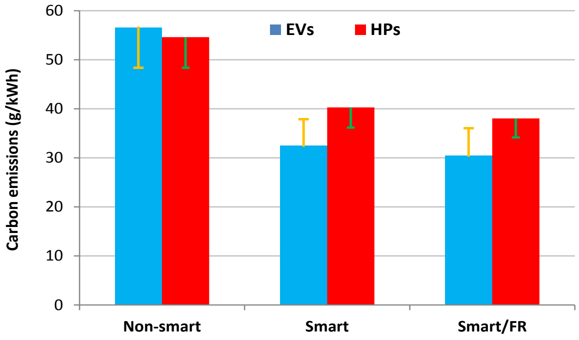
As the transport and heating sector become progressively electrified, additional electricity demand will need to be supplied by the power system, in particular during peak time, which may potentially increase the carbon intensity of electricity supply. For an effective decarbonisation of the overall economy, carbon increases in the electricity sector should be more than offset by carbon savings from the reduced use of fossil fuels in transport and heating. Note that in this paper we do not quantify the implications of reduced carbon emissions in those two sectors but rather focus on the impact on the electricity sector. Figure 9 shows the weighted average carbon intensity of the electricity consumed by EVs/HPs. The intensities of EVs/HPs demand have been found for non-smart, smart and smart/FR cases, by quantifying grid emissions in each hour during the year and averaging them over the volume of EVs/HPs demand while using hourly EVs/HPs demand levels as weighting factors. For each of the cases included in Figure 9, the average system emissions (as in Figure 8) as vertical error bars are also presented.

It is observed that the carbon intensity in the non-smart cases is significantly higher than that in smart operation cases. We further note that the carbon intensity of HPs demand is consistently higher than average emission rate of the whole system, regardless of the scenario and the level of smartness. This follows from the fact that HPs are mostly used during winter when demand is generally higher, requiring the use of more expensive and more carbon-intensive plants (such as e.g. CCGT and OCGT units). That is why even when HPs follow smart operation strategies and consequently reduce total system emissions; their average emission rate is still above the overall system average. Carbon intensity of EV demand in the non-smart cases is around or slightly above the average system emissions, but when smart EV charging strategies are implemented, the emissions associated with EV demand decline rapidly, also causing a decrease in the total system emissions.



(a) 2030 Green World (GW)

(b) 2030 Slow Progression (SP)



(C) 2050 High Renewable (HR)

Figure 9 Carbon emission intensity of supplying EV and HP demand

In particular, under the 2030 GW scenario the carbon emission rate of EV demand is reduced from 116 to 105 g/kWh by smart charging, and further reduced to around 99 g/kWh in the case with frequency response from EVs. Due to lower relative flexibility associated with smart HP operation, as well as its seasonal character, the decrease in the carbon emission rate driven by smart HP operation, when expressed per kWh of

HP demand, is slower than for smart EVs, but is still able to reduce the emission rate by 14 g/kWh in the case with frequency response provision.

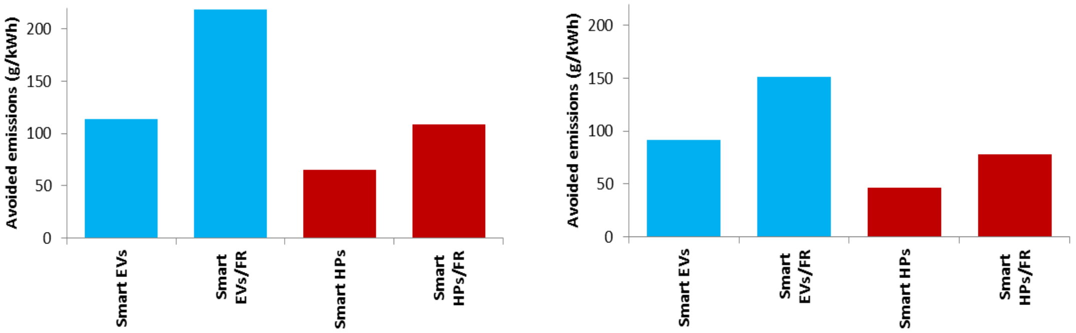
In the 2030 SP scenario, shown in Figure 9(b), similar trends for carbon emission rates of EVs/HPs demand are observed as in the 2030 GW scenario. However, due to the lower penetration of RES and nuclear capacity, the ability of smart EVs and HPs to reduce carbon emissions is not as pronounced as in the GW scenario. The emission rate, which already starts from a comparably higher level than in the 2030 GW scenario (over 150 g/kWh), reduces by only 9 and 5 g/kWh for EVs and HPs demand, respectively, when fully smart operation is accompanied by FR provision.

Finally, the results presented in Figure 9(c) demonstrate the carbon emission rate of EVs/HPs demand in 2050 HR scenario. In the non-smart case, the average emission rate of the whole system is rather low (48 g/kWh), although the carbon emission rate associated with EV and HP demand is slightly higher (57 and 55 g/kWh, respectively). Smart operation strategies reduce the carbon intensity to 30 g/kWh for EVs and 38 g/kWh for HPs; both of these figures represent a significant relative reduction from the non-smart cases. We again observe that smart EVs operation is more effective in reducing system carbon emissions than smart HPs operation due to the flexibility and seasonality of HPs demand.

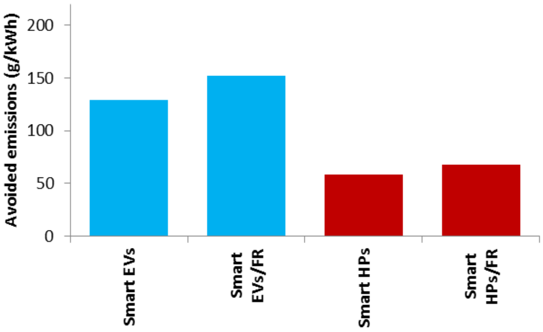
4.2.3 Avoided emissions per unit of smart EVs/HPs

This section estimates the carbon savings driven by the deployment of smart EVs/HPs expressed as annual carbon reduction per unit of “smart” demand. As shown in Figure 10, both EVs and HPs lead to a significant carbon emission reduction per unit demand. These carbon savings in many cases exceed the average system emissions, which means that in some cases the carbon impact of smart EVs/HPs is even better than carbon-neutral, i.e. they are able to create a net offset in carbon emissions per unit of smart demand.

In general, smart EVs show the most prominent reduction per unit demand, up to 220 g/kWh in the 2030 GW scenario, and 150 g/kWh in the 2030 SP and 2050 HR scenarios. Due to limited flexibility, smart HPs generate the lower carbon emission reduction per unit demand, but still could reduce the emissions by around 50-100 g/kWh under different scenarios.



(a) 2030 Green World (GW) (b) 2030 Slow Progression (SP)



(C) 2050 High Renewable (HR)

Figure 10 Carbon emission reduction per unit of "smart" demand

4.3 Summary of findings

Table 3 provides a summary of the carbon benefits per unit demand for smart EVs/HPs across proposed scenarios. Our studies on carbon impact of smart EVs/HPs suggest:

1. Carbon benefits of smart EVs/HPs expressed per unit of smart demand are driven by their flexibility to shift demand and provide frequency response.
2. Carbon benefits of smart EVs/HPs increase if they provide frequency response in addition to demand shifting. These additional benefits are significant in 2030 scenarios.
3. Carbon benefits are generally more pronounced with higher intermittent RES penetration, but can be limited if the non-renewable generation capacity on the system is mostly zero-carbon (as in the 2050 HR scenario).
4. Integration of electrified transport and heating demand is significantly less carbon intensive if smart operation strategies are adopted.

Table 3 Summary of carbon benefit per unit demand of smart EVs/HPs

(in gCO_2/kWh)	**2030 GW**	**2030 SP**	**2050 HR**
EV	92-151	114-218	129-152
HP	46-78	65-109	58-68

5. Impact of smart EVs and HPs on renewable integration cost

In this section we investigate the impact of EVs/HPs on the integration cost of RES. ASUC model is applied to quantify the cost reductions associated with lower back-up capacity requirements, reduced system balancing cost and reduced CAPEX due to avoided investment in low-carbon capacity to reach the CO_2 target.

5.1 Challenges of RES integration

UK has a very significant wind power resource with almost 12 GW of installed capacity at the end of 2014. Similarly, the UK system has recently seen a rapid increase in the number of solar PV installations. A key feature of wind as well as PV generation is the variability (intermittency) of the primary energy source.

These system integration impacts need to be assessed in order for the overall system cost of intermittent RES to be quantified. As indicated in Figure 11, the total Whole-System Cost (WSC) of intermittent RES consists of their Levelised Cost of Electricity (LCOE) and the system integration cost of RES. The latter is defined as the additional infrastructure and/or operating costs to the system as a result of integrating RES.

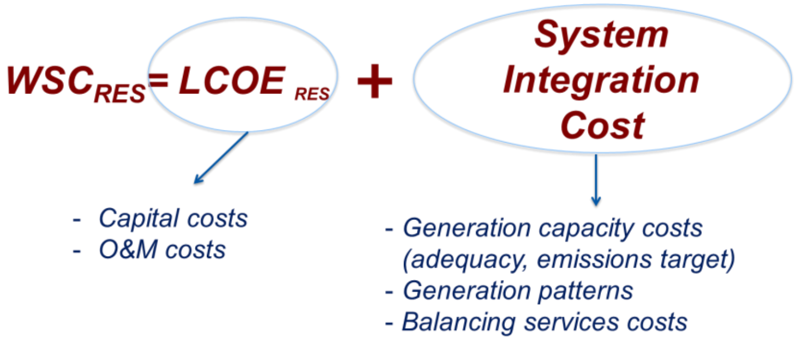


Figure 11 Whole-system cost of intermittent RES

LCOE considers the capital cost and O&M cost of RES technologies over their project life while the system integration cost of RES includes the system capacity costs associated with capacity needed for security, balancing costs and the impact of the RES output patterns.[§] Other components of system integration cost, not considered in this paper, may include transmission and distribution network costs, as well as the cost of network losses; these components would reflect any requirement to reinforce transmission and distribution networks in order to accommodate RES generation. In this paper we focus on the capability of smart EVs/HPs to reduce the system integration cost of RES.

As the system integration cost of RES due to increased requirements for back-up capacity and provision of ancillary services is significant, it is important to implement

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[§] For instance, a renewable technology generating the highest electricity output during system peak demand would have a lower integration cost than the alternative technology that produces the same output annually, but provides the highest output during off-peak conditions.

new operating approaches that can minimise the integration costs. In this context, we will quantify the benefits of smart EVs/HPs for reducing the system integration cost of RES. The benefits are assessed in the three categories discussed below:

1. Reduced backup capacity cost (Backup). Smart EVs/HPs have the capability of shifting demand i.e. modifying the effective (net) demand profile seen by conventional generators. If the smart EVs/HPs are operated so that they reduce the net peak demand, this will also reduce the requirement for generation capacity margin in the system while maintaining security of supply. In other words, smart EVs/HPs may improve the capacity value of RES. Reduction in backup capacity cost due to improved capacity value is quantified according to [25].
2. Reduced balancing operating cost (Balancing). This component of the RES integration cost reflects the increased need to provide ancillary services in the system with high RES penetration, as well as the occasional necessity to curtail RES output in order to balance the system (e.g. at times of low demand and high RES output). Smart EVs/HPs have the potential to absorb some of this output that would otherwise be curtailed, while at the same time provide ancillary services that would otherwise have to be provided by conventional plants at a considerable cost.
3. Reduced investment cost associated with balancing (Balancing (CAPEX)). In the context of a specific CO_2 target, reducing the curtailment of RES output by deploying smart EVs/HPs also means that less additional zero- or low-carbon generation capacity will need to be built in order to meet the carbon target. We quantify this component of RES integration cost savings by assuming reduced RES output required less CCS capacity to be built.[**]

5.2 Case studies

The studies are based on the future UK scenarios described in Section 3.2. Assumption for each case study remains the same as that in Section 4, which can be found in Table 2. The simulations are firstly carried out to characterise the annual operation of the system as well as necessary RES curtailment without any flexibility contribution from EVs/HPs (i.e. the non-smart case). After establishing the baseline RES balancing cost, benefits of EVs/HPs for RES integration are assessed by comparing the key characteristics of smart and non-smart cases: operating cost, backup capacity requirement and RES curtailment. The benefits are expressed as annual integration cost savings (with the three components defined in the previous section) divided by the volume of absorbed annual RES output. In all studies we treat

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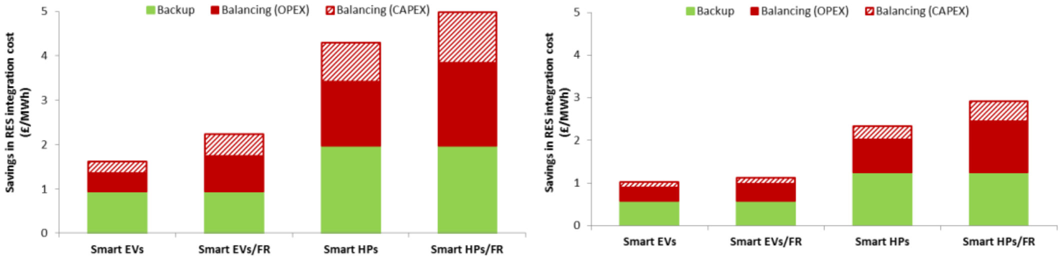
[**] In the studies presented here we assume the future investment cost of CCS capacity of £1,313.8/kW, lifetime of 25 years and the discount rate of 10%.

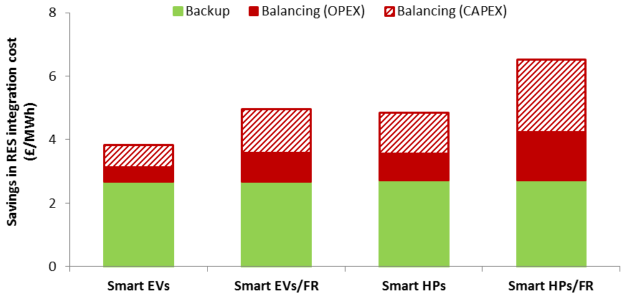
wind and solar PV collectively as intermittent RES, although in the model these two were disaggregated as illustrated at the end of this section.

Figure 12 (a) presents the benefit of smart EVs/HPs for reducing RES integration cost in 2030 GW scenario. Total integration cost savings for EVs/HPs vary between about £2 and £5/MW. The greatest integration cost savings are achieved with smart HP operation, mostly because of the large volume of flexible HP demand assumed in this scenario. Similar to the carbon impact, provision of frequency response could largely increase the value of smart EVs/HPs. It is also observed that the three components of RES integration benefits arise in broadly similar proportions.



(a) 2030 Green World (GW)

(b) 2030 Slow Progression (SP)



(C) 2050 High Renewable (HR)

Figure 12 Reduced RES integration cost from smart EVs and HPs

Results for the same set of case studies but for the 2030 SP scenario are presented in Figure 12 (b). Similar trends are observed as that in the 2030 GW scenario, although the benefits tend to be lower. Total integration cost savings for EVs/HPs vary between £1 and £3/MWh.

Finally, Figure 12 (c) shows the RES integration cost savings with smart EVs/HPs in the 2050 HR scenario. Total integration cost savings for EVs/HPs are now highest among all the scenarios, which lies between £3.8 and £6.5/MWh. The backup saving component for smart EVs/HPs increases significantly due to the large deployment of these technologies in 2050 HR scenario. The balancing CAPEX component in this scenario exceeds those seen in the other two scenarios, as the deployed volume of RES, and consequently also of the curtailment, is the greatest.

Finally, integration benefits are allocated separately to wind and solar generation, and the results suggest that the scale and the composition of benefits vary considerably between these two technologies. Figure 13 shows that while smart EVs/HPs reduce wind curtailment, they may lead to slightly higher PV curtailment as part of the overall cost-optimal solution (note that the total RES curtailment still reduces). This suggests that the model is able to identify certain trade-offs, where the flexibility of EVs/HPs is used to absorb wind output even at the expense of slightly increased PV curtailment, as it results in a more cost-efficient overall solution.

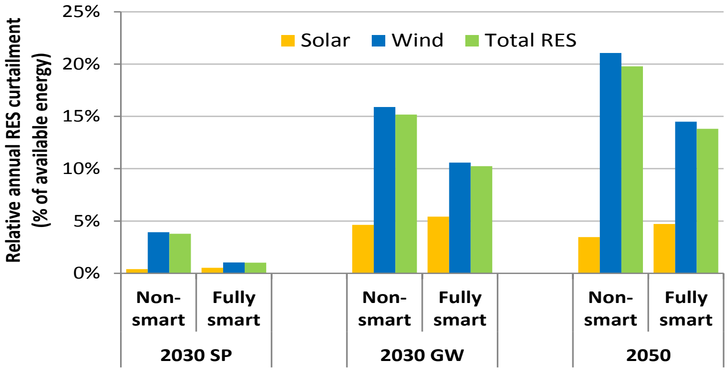


Figure 13 Wind and solar PV curtailment in non-smart and smart cases across scenarios

On the example of the 2030 GW scenario, Figure 14 further shows how different components of system integration benefits generated by smart EVs/HPs may arise in different proportions if these benefits are allocated to wind and solar capacity according to the integration cost driven by these two technologies. Wind capacity dominates the overall RES mix, therefore the integration benefits for wind and total intermittent RES portfolio differ very little. On the other hand, the benefits for PV integration consist almost exclusively of backup cost savings, with the balancing OPEX and CAPEX components almost negligible. As illustrated in the previous figure, this occurs because smart EVs/HPs are not utilised to reduce PV curtailment, but on the contrary rather allow the PV curtailment to increase slightly in order to use more attractive opportunities to save wind curtailment. Increase in PV curtailment is more than offset by balancing cost savings associated with more efficient system operation, which results in positive although small savings in balancing OPEX and CAPEX categories.

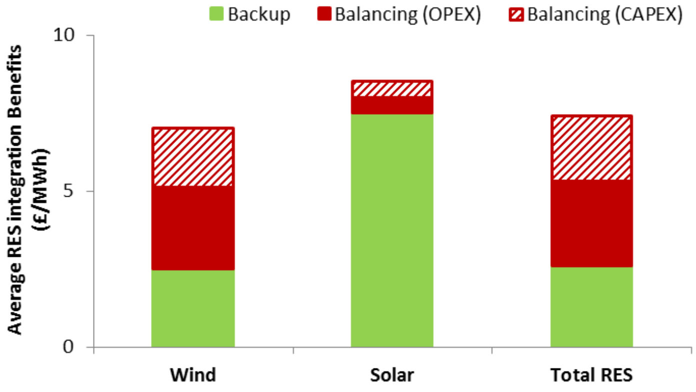


Figure 14 Average wind/solar integration benefits from smart EVs/HPs

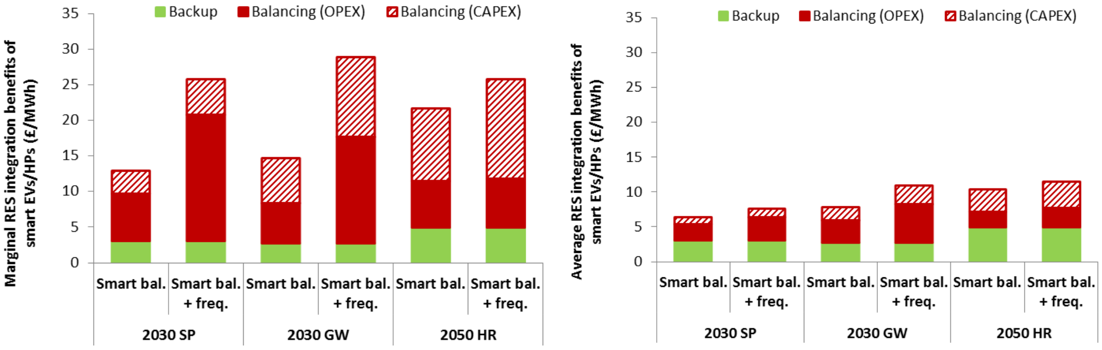
5.3 Average and marginal benefit of smart EVs/HPs

When analysing the benefit of smart EVs/HPs, their benefits are distributed in terms of reduced integration cost across the entire output of intermittent RES generators in a given scenario. It is obvious that if an additional unit of RES capacity is added onto a system that already has significant RES capacity, the additional integration cost of the added capacity is likely to be higher than the average integration cost of the entire RES portfolio. This is due to the fact that as more RES are added to the system, it becomes progressively more difficult to absorb their output without having to resort to curtailment. Therefore, in addition to average RES integration benefit described in Section 5.2, this section quantifies the marginal benefit of smart EVs/HPs, i.e. the reduction of RES integration cost if a small quantity of RES is added to the capacity already existing in each scenario.

Figure 15(a) shows the marginal benefits of smart EVs/HPs (with and without frequency response provision) when a small quantity of RES capacity is added to the system in 2030 SP, 2030 GW and 2050 HR scenarios. As a comparison, the average benefits for all three scenarios are presented in Figure 15(b). An immediate observation is that the marginal benefits exceed comparable average benefits by a factor of between 2 and 3. This suggests that the value of smart EVs/HPs for integrating additional RES capacity in a system that already contains a large share of intermittent renewables is significant. A further conclusion is that decarbonising the electricity system by integrating large amounts of RES can be much more cost-efficient if coupled with smart EVs/HPs.

In the two 2030 scenarios the marginal benefits double when frequency response is provided by EVs/HPs in addition to balancing, whereas in the 2050 HR scenario the difference between the two smart cases is much smaller. It is further noted that the dominant component of marginal benefits in the 2030 SP scenario is balancing cost

(OPEX); in the 2030 GW scenario balancing OPEX savings are commensurate with balancing-driven CAPEX savings. In the 2050 HR scenario the large volume of RES curtailment makes the balancing CAPEX benefits the dominant component.



(a) Marginal (b) Average

Figure 15 RES integration benefits from deployment of smart EVs/HPs

5.4 Key findings on renewable integration benefit of smart EVs and HPs

From the studies presented above, it is possible to draw the following conclusions:

1. Smart EVs/HPs have a significant potential to support RES integration by reducing: balancing cost, required back-up generation capacity and cost of replacing curtailed RES output with alternative low-carbon technology to achieve the same emission target.
2. The uptake of EVs/HPs is an important factor in the benefit of RES integration.
3. Average RES integration benefit of smart EVs/HPs varies between £1.5 and £7/MWh of absorbed RES output across the three scenarios.
4. Marginal RES integration benefit is 2-3 times higher than the average benefit, suggesting an increasingly important role for smart EVs/HPs in expanding RES capacity beyond the already high penetrations foreseen in the future.
5. Frequency response provision from EVs/HPs could significantly enhance the RES integration benefit of smart EVs/HPs. Particularly in the two 2030 scenarios, the marginal benefit doubles if smart EVs/HPs are also capable to provide frequency response.

6. Conclusions

This paper presents an advanced stochastic analytical framework and the results of a large number of case studies in order to quantify the benefits of smart EVs/HPs on the carbon performance and cost of RES integration in the future UK electricity system.

The results suggest that smart EVs/HPs are able to deliver measurable carbon reductions primarily by enabling the largely decarbonised electricity system to operate more efficiently. Carbon benefits of smart EVs/HPs, when expressed per unit of smart demand appear to be a function of the assumed flexibility of these two demand categories to shift demand and provide frequency response. Provision of frequency response in addition to smart balancing significantly increases carbon benefits, particularly for the systems without large amount of CCS plants.

Carbon benefits of smart EVs/HPs are generally more pronounced in systems with higher intermittent RES penetration, although there are limits to this trend where the non-renewable generation capacity on the system is also low- or zero-carbon. Furthermore, the integration of electrified transport and heating demand is shown to be significantly less carbon intensive if smart operation strategies are adopted, making a more positive impact on the overall carbon performance of the economy.

The second set of case studies established that smart EVs/HPs have a significant potential to support cost-efficient RES integration by reducing:

1. RES balancing cost
2. Cost of required back-up generation capacity
3. Cost of alternative low-carbon technology to offset poorer fuel efficiency and curtailed RES output while achieving the same emission target

The case studies show that smart EVs/HPs are capable of supporting cost-efficient decarbonisation of future electricity system by reducing RES integration cost. The results indicate that the uptake of EVs/HPs is an important factor in the value for RES integration, as it determines the volume of flexible services that can be provided.

Average RES integration benefit of smart EVs/HPs varies between £1.5 and £7/MWh of absorbed RES output across the three scenarios. Marginal RES integration benefit is 2-3 times higher than the average benefit, suggesting an important role for smart EVs/HPs in supporting the expansion of RES capacity even beyond the high shares foreseen in future scenarios. Moreover, the marginal benefit doubles in the two 2030 scenarios, if smart EVs/HPs are also capable to provide frequency response.

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