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The integration of renewable energy sources, stationary batteries and vehicle-to-grid assets: A distributed energy case study for a municipal depot in the UK

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Summary

An integrated energy system for a municipal depot in the UK is modelled in this study. The model analyses the energy flows between the components of the system including the existing buildings of the depot, three proposed PV installations, potentially forty electric vehicles with vehicle-to-grid capabilities and a stationary battery. Based on that, the CO_2 emission savings are estimated and the potential reduction in electricity bill costs are calculated.

Keywords: battery, energy storage, EV (electric vehicle), modelling, V2G (vehicle to grid)

1 Introduction

The shift towards electric vehicles (EVs) and the adoption of renewable energy sources (RES) are important necessary steps towards mitigating climate change. EVs charged from grid mix electricity supplies already offer significant environmental advantages over conventional vehicles. It was shown in other studies that a 90% reduction of vehicle CO_2 emissions is feasible by 2050 in the UK [1], [2]; provided the current projections for decarbonisation of the electricity grid are achieved [3]. In addition, electricity as an energy source enables energy diversity. This ensures security of energy supply and a broad use of carbon-free energy sources [4].

It was shown in [5] that electrification is a viable strategy for more sustainable transportation, however, significant investment is needed in charging infrastructure. This imposes significant challenges for electricity supply networks which have to meet additional power demand whilst integrating increasing levels of intermittent energy sources.

The challenge is to design an integrated solution that resolves the mismatch between renewable energy production and consumption. Such a solution would minimise greenhouse gas emissions whilst making the business cases for electric operations and renewable energy (RE) generation more attractive.

Such a solution is explored by CleanMobilEnergy (CME), a €7 million Interreg North-West Europe funded project [6]. The project will integrate various RES, storage devices, EVs and optimisation of energy consumption through one unique smart energy management system. The development of this Interoperable Energy Management System (iEMS) will increase the economic value of RES and significantly reduce CO_2 emissions. The iEMS will assure the smart integration through interoperability based on open standards for data flows and analysis tools [6].

Among the operational pilots of the project, the Eastcroft municipality depot at Nottingham in the UK involves: i) forty battery-powered EVs (pool cars and maintenance vans) that are operated by Nottingham City Council (NCC) and are based at Eastcroft; ii) installation of an 89 kWp photovoltaic (PV) array; iii) installation of a stationary battery (the ideal size of the battery is determined in this study); and iv) installation of forty vehicle-to-grid (V2G) bi-directional charge points to enable the EVs to be used for energy storage and grid balancing [6].

An energy model for the Eastcroft Depot in Nottingham has been developed to analyse the energy flows between the components of the system (i.e. existing buildings of the depot and the CME equipment described in the previous paragraph). Real data about existing grid consumption and transport operations was obtained to determine baseline consumption and calculate the additional power demand from a shift to electrified transport operation. The results are combined with simulated generation profiles for the proposed PV installations. The impact from using the EV and stationary batteries for energy storage and peak shaving is then explored. Based on that, the CO_2 emission savings are estimated and the potential reduction in electricity bill costs are calculated due to the use of these additional technologies.

2 Modelling

The energy model for the Eastcroft depot is a spreadsheet-based model which includes real data about existing grid consumption and transport operations. This makes it possible to define the baseline and calculate the additional power demand from an electrified transport operation. The results are then combined with simulated generation profiles for the proposed PV installations. The impact on the energy profile from the adoption of smart charging, V2G assets and a stationary battery is also explored.

Metering systems monitor the energy consumption at Eastcroft on a half-hourly (HH) basis. The data is stored in an online database that is maintained by the monitoring company [7]. Energy consumption data for an entire year (July 2017 – June 2018) was obtained from the database and validated against electricity bills for the site. Electricity bills were also used for extracting important tariff and charge information as shown in Table 1.

In particular, a fixed rate of 13.964 p/kWh of energy imported from the grid is considered for consumption during the day hours and a fixed rate of 9.771 p/kWh for overnight use. Standing charge to account for the fixed costs of the electricity supplier of providing electricity is set at 34p per day and export rate at 5.03 p/kWh. The Climate Change Levy (CCL) which is an environmental tax to encourage business to operate in a more environmentally friendly way is set at 0.847 p/kWh.

Table 1: Model Assumptions

Assumption	Value (p/kWh)	Note
Day rate	13.964	Electricity import from grid during day hours
Night rate	9.771	Electricity import during night hours
Export rate	5.03	Electricity export to grid
Climate Change Levy	0.847	Extra charge for climate change
Standing Charge (p/ day)	34.0	Fixed costs of the electricity supplier

In addition, a CO_2 emission intensity of 335 gCO_2 per kWh was assumed for energy imported from the grid during the day hours and 265 gCO_2 per kWh during the night hours. These figures were calculated based on HH generation data by fuel type in the UK for 2018. The base data is provided by Elexon on [8].

2.1 Baseline

The average daily energy consumption at the depot for each month is shown in Figure 1. It can be seen in the figure that all months have similar energy profiles. The energy consumption during night is relatively low in comparison to the energy consumption during the day hours when energy is required for the offices and equipment of the depot. Overall, the annual consumption of electricity at the Eastcroft depot is calculated at 446.8 MWh per year and the peak HH power demand is 85.3 kW in February (see Table 2). Based on that, the load factor of the depot can be calculated at 60%. Load factor is defined as the average load (the annual consumption divided by the number of hours in a year) divided by the peak load (i.e. 85.3 kW). A high load factor means power usage is relatively constant. The electricity bill is calculated at £48.3k per year based on the assumptions listed in Table 1. Assuming the CO_2 emission intensity of 335 gCO_2 per kWh during the day hours and 265 gCO_2 per kWh during night as explained above, the Eastcroft depot is responsible for 141 tCO_2 per year. The results are summarised in the first column of Table 2.

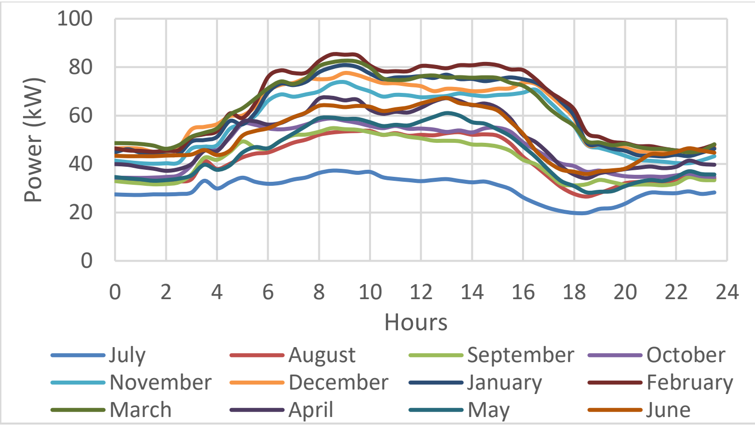

Figure 1: Daily energy consumption profile at the Eastcroft deport for each month

Table 2: Annual overview at the Eastcroft depot

	Baseline	PVs & EVs	PVs & EVs (smart charging)	PVs & EVs & V2G	PVs & EVs & V2G & Stationary
Annual Consumption (MWh)	446.8	451.6	451.6	522.9	534.0
Annual export (kWh)	-	612.4	294.1	-	-
Peak Demand (kW)	85.3	154.3	90.7	239.8	288.7
Load factor (%)	60	33	57	25	21
Peak Export (kW)	-	16.9	8.4	-	-
Electricity bill (£k)	53.8	54.5	53.1	49.4	47.8
Carbon Emissions (tCO_2)	141	121	119	121	120

2.2 Integration of PV and EV charging

The results from section 2.1 are combined with simulated generation profiles for the proposed PV installations. The combined PV system is rated at 89.2 kWp (two PV systems have been recently installed at Eastcroft). The generating energy was predicted at 101.1 MWh per year according to simulation exercises that were performed by the hardware provider and the energy office of the depot. As it was expected, most of the generation is available during summer. This, combined with relatively low energy consumption during summer (e.g. July as can be seen in Figure 1) results in surplus renewable energy at the site which would get exported (see Figure 2).

The charging energy requirements from shifting transport towards electric operations at the depot is also investigated in this section. Forty maintenance vehicles up to 3,500 kg gross mass were identified by NCC to be replaced with EVs. The current daily and annual mileage of the vehicles was obtained by the fleet manager of the depot. For the purposes of this study, it is assumed that the forty EVs will be performing the same operational function as the existing conventional vehicles. Consequently, it has been assumed that the current journey distances and profiles of the conventional vehicles will transfer to future EVs. In addition, it is assumed that all EVs would be Nissan e-NV200 since they are 3,500 kg vehicles and have V2G capabilities

[9]. An average energy consumption of 0.21 kWh/km (battery-to-wheel consumption) is considered for all operations out of the depot [9]. This is an average figure throughout the year.

Based on that, the daily energy requirements for each vehicle is calculated. Overall, electrification of forty EVs at Eastcroft will increase the energy consumption by 289.5 kWh per day which equals to an annual additional consumption of 105.7 MWh at the site. This corresponds to approximately 25% of the current energy consumption at the depot (105.7 MWh / 446.8 MWh = 0.24). A charging efficiency of 85% was included in the calculations to consider losses for storing AC grid energy into useful energy in the battery.

The forty vehicles that perform operations out of the depot belong to different teams and departments of NCC; including Workshop vehicles, Highways, Cleaning, Community Protection, Traffic Management, Parks and Open Spaces, Public Realm, etc. A list with the departments of the forty vehicles are summarised in Table 3. All operations can be divided into three main groups based on the start time and the duration of each usage away from site. This was achieved by analysing the log files of the vehicles which were obtained from the fleet manager of the depot. These groups are named as i) Working-Hours, ii) Early-Morning and iii) Random operations. For example, the Working-Hours group includes operations which are performed by the Workshop vehicles; the Early-Morning group includes operations like cleaning; and the category of Random operations covers operations like Community Protection. These assumptions are summarised in Table 3.

Table 3: Profile of vehicles at the Eastcroft Depot

Department	Number of Vehicles	Profile
Adult Services	1	Working hours
Cleaning	8	Early morning
Community Protection	2	Random
Domestic Waste	1	Early morning
Facilities Management	3	Working hours
Highways	3	Working hours
IT Services	1	Working hours
Parks & Open Spaces	1	Working hours
Planning Services	1	Working hours
Pool	4	Working hours
Public Realm Central	4	Working hours
Public Realm South	4	Working hours
Traffic Management	2	Working hours
Transport Projects	2	Working hours
Workshop/ Fleet	3	Working hours

It is assumed that the typical start time of a journey in the first group of operations (i.e. Working-Hours) is 10am. The typical start time for Early-Morning operations is 5am whereas the start time of Random operations is not defined; a journey can be performed anytime during the day. Working-Hours and Early-Morning operations follow a normal distribution profile [10]. A standard deviation of 1.5 hours and 1 hours is assumed for Working-Hours and Early-Morning operations respectively. This means that 95% of all Working-Hours journeys are performed within ±3 hours (two standard deviations) from the mean start time of Working-Hours journeys and within ±2 hour for Early-Morning operations. The probability to commence a Random journey is the same across the day. Working-Hours and Early-morning operations are assumed to last for 4 and 5 hours respectively. A journey duration of 2 hours is assumed for Random operations.

The possible departure time for each EV combined with the estimated journey duration create the charging profile for the depot throughout the day. The analysis shows that most vehicles return back to the depot in the afternoon, around 2-7pm. Assuming that the process of charging starts once an EV returns back to the base using a 7.2 kW charger, the energy consumption peaks in the afternoon as it can be seen in Figure 2. It is worth noting that the charging power profile for an e-NV200 tails off when the battery is almost full but a constant 7.2 kW average power is assumed in this study.

The daily modelled energy consumption for the Eastcroft depot is shown in Figure 2. This includes the energy consumed in the buildings, the predicted PV generation energy and the charging requirements for the forty

EVs. The annual consumption of the Eastcroft depot is not significantly changed based on the baseline calculations (see Table 2). This is due to the fact that the annual PV generation of 101.1 MWh is similar to the added load of 105.7 MWh for EV charging. Despite this, some generation from RES is not consumed within the depot and gets exported to the grid. Total surplus export is calculated to be 0.61 MWh per year (0.61% of total generation) at a maximum export rate of 54.5 kW. As it is shown in Figure 2, there is a peak of energy consumption in the afternoon when most EVs return back to the depot. The new peak power demand is calculated at 154.3 kW which is 80% higher than the baseline peak power demand of 85.3 kW. As a consequence of the higher peak power demand, the load factor of the site is reduced. This can be calculated at 33% which is 47% lower than the initial load factor of the system at 60%. There is increase in the electricity bill and carbon emissions of £0.7k and 2 t respectively due to the higher annual consumption at the depot. Yet, the impact from shifting towards electric operations at the depot will be to reduce vehicle related CO_2 emissions by 22 t per year; based on the fact that the forty depot vehicles perform 378,310 km per year in total, a conservative figure of 120 gCO_2/km for a conventional vehicle is assumed [11] and an EV is responsible or 57 gCO_2/km (the average energy consumption of 0.21 kWh/km is combined with the carbon inherent in electricity of approximately 300 gCO_2/ kWh in 2018 [3], [8]. Hence, the resulting CO_2 emissions at the depot are reduced by 20 t.

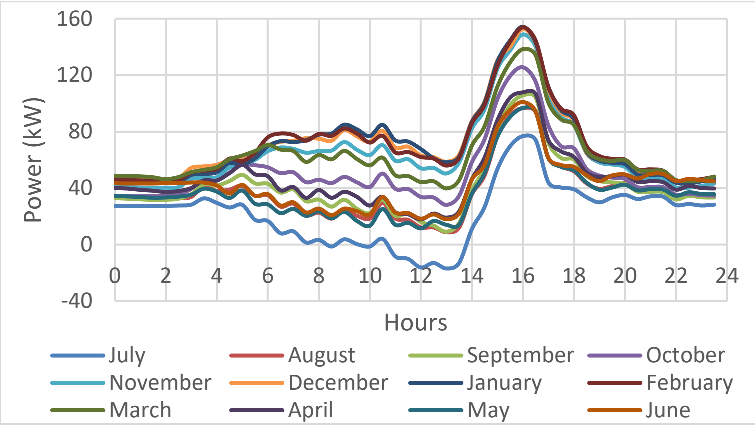

Figure 2: Daily energy consumption profile including predicted generating energy and EV charging requirements

2.3 Adoption of Smart Charging

One of the basic functions of the iEMS is the smarting charging of EVs to reduce peak power demands by evenly distributing the added load throughout the day. This approach is explored in this section and the resulting energy profiles for each month are shown in Figure 3. It can be seen that the peak power demand is reduced significantly reaching a lower value of 90.7 kW; instead of 154.3 kW when smart charging is not adopted (see section 2.2). As a result, the load factor is increased from 33% to 57%; which is similar to the initial load factor of the system according to the baseline calculations.

Export energy is also limited at less than 300 kWh per year (see Table 2) which corresponds to just 0.3% of the total PV generation (300 kWh / 101.1 MWh = 0.3%). Adoption of smart charging also offers some reduction in electricity bills and carbon emissions. The results are summarised in Table 2.

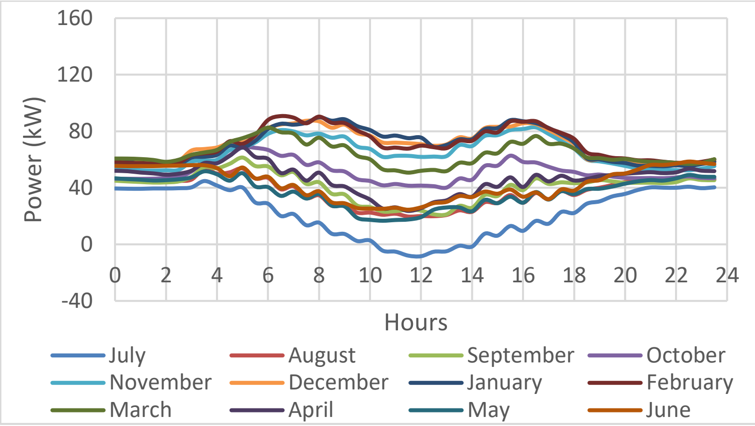

Figure 3: Daily energy consumption profile including predicted generating energy and EV charging requirements when smart charging is adopted

2.4 Introduction of V2G assets

The impact from introducing V2G assets at Easctroft is explored in this section. V2G enables EVs to charge, have managed charging (time shifted or slowed), or export electrical energy stored in the EV battery, back to the electrical system the EV is attached to. This means that grid consumption during peak times can be minimised to avoid high electricity tariffs whilst EVs batteries are recharged using electricity from RES and off-peak electricity. This strategy is explored in this study.

The following assumptions have been made: EVs can supply energy to the grid once they return back to the depot at a maximum discharging rate of 6.0 kW; this is a typical power transfer rate of a V2G charger [12]. Ten percent of the battery can be used for V2G services (i.e. 4 kWh) and none of the EVs is discharged below 20% SOC. It is believed that preserving at least 20% of the energy in Lithium-Ion batteries, predominantly used in EVs, does not intensify battery degradation [13]. A round trip charging/discharging efficiency of 75% was assumed for the calculations [12]; this includes losses incurred during the conversion of AC grid energy into useful energy in the battery and then converting battery energy back to AC for the grid.

The impact for introducing V2G assets at Easctroft is shown in Figure 4. The use of energy stored in the batteries of EVs significantly reduces the grid consumption during the daytime hours. The annual overview of the depot is summarised in the second column of Table 2. The annual energy consumption increases from 451.6 MWh (see second column of Table 2) to 522.9 MWh due to battery efficiency losses for charging/ discharging EVs. Peak power demand also increases because the recharging process occurs overnight and is not evenly distributed throughout the day. The vehicle charging process is also longer as it has to meet both travel and V2G energy requirements. As a result, the load factor of the system is reduced significantly to 25%.

However, a load factor of 75% is calculated when only off-peak times are considered in the analysis (i.e. 23:00 – 06:00). This is due to the fact that the annual overnight consumption at the depot is 459.9 MWh; (459.9 MWh / 365 days / 7.5 hours) / 239.8 kW peak power demand = 70%. This means that a relatively constant load is required overnight when there is substantial grid power availability.

The annual electricity costs are decreased by approximately £3.7k when compared to the smart charging only solution. This is due to the fact that grid energy (for travel requirements and building consumption) is mostly needed overnight when electricity prices are conventionally cheaper. By contrast, the CO_2 emissions are increased slightly by approximately 2 tCO_2 per year; since the annual consumption at the depot increases by 71 MWh due to charge/ discharge losses but this might improve in the future due to higher penetration of RES which would result in further CO_2 emission reductions. Nevertheless, there is a substantial annual reduction of 20 tCO2 when compared to the baseline and this is due to the fact that fossil fuel consumption diminishes with the uptake of EVs

Furthermore, Eastcroft could potentially consider participating in various grid services through V2G such as Firm Frequency Response (FFR), Short Term Operating Reserve (STOR), Imbalance, etc. This will create additional revenue streams and therefore, an opportunity for V2G to become financially more attractive. This is an area of further research.

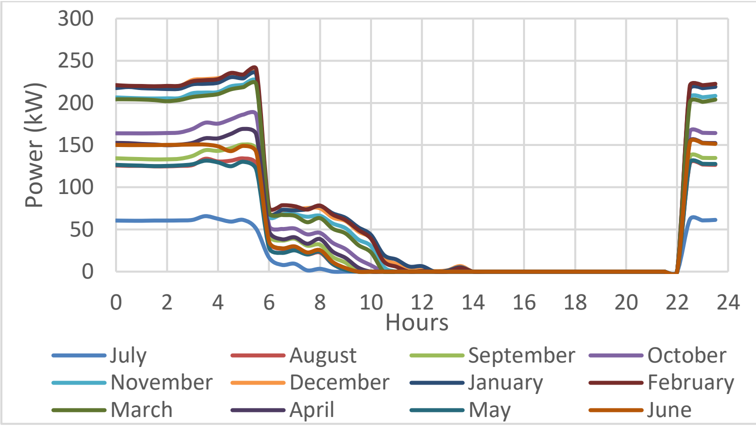

Figure 4: Daily energy consumption profile at Eastcroft depot with V2G assets

The results show that it is possible to minimise grid import during the daytime hours which results in lower electricity bills and CO_2 emissions. Yet, the additional usage of EV batteries might compromise the performance and life time of the batteries. The following approach has been followed to put into perspective the additional battery usage for V2G.

Lithium-ion batteries typically have a cycle life of approximately 1,500 full depth cycles [14]. This corresponds to 60,000 kWh of usable energy for the 40 kWh on-board battery of Nissan e-nV200 that is considered in the study. A total usable energy of 60,000 kWh is therefore assumed in this study. This, combined with a typical calendar life time of 15 years [14] means that the maximum recommended usage of the battery in a year is assumed to be 4,000 kWh.

The total energy consumption for all EVs at the depot was calculated at 105.7 MWh per year including charging losses (for travel only). The actual energy into EV batteries is calculated at 2,246 kWh per year on average (105.7 MWh X 85% efficiency / 40 EVs = 2,246 kWh). Assuming that each vehicle is discharged by 10% for V2G services (as explained above), an average energy of 4 kWh is used each day on top of the travel requirements. This corresponds to an annual additional usage of 1,460 kWh for V2G services. Hence, the total usage of the battery is 3,706 kWh per year; which is smaller than the maximum recommended usage of 4,000 kWh per year. Consequently, battery degradation might not be a major problem to consider for the case of Eastcroft Depot and is not considered further in this study. It is worth mentioning though that the average annual mileage of all depot vehicles is 9,280 km; a figure which is lower than the average annual mileage of 12,550 km for a passenger car in the UK [15].

2.5 Introduction of a Stationary Battery

The next stage on the study was to include a stationary battery in the system. Again, the aim is to minimise daytime consumption. The analysis shows that a capacity of 480 kWh is sufficient to i) to maximise usage of RES and ii) to avoid grid consumption during the day hours. A 20% safety margin is considered for the size of the stationary battery. The resulting energy profile for each month is shown in Figure 5. The annual overview is summarised in Table 2. As can be expected, the annual consumption increases slightly due to the inefficiencies of the stationary battery (a round trip efficiency of 75% is assumed). The total consumption of 534 MWh per year represents overnight consumption as no grid import is required during the day hours. The peak power demand increases as well reaching a new peak value of approximately 290 kW. The load factor of the system is calculated at 21% but again, a significantly higher load factor of 68% is achieved when the off-peak period is considered only in the analysis. The electricity bill is further reduced reaching a low value of £47.8k. This is the lowest among all the investigated options. The impact would be to reduce annual CO_2 emissions to 120 tCO_2 per year from 121 tCO_2 per year based on the previous case study (section 2.4).

It is worth stating that similar energy profiles could be achieved without the exploitation of V2G assets. However, to achieve this, the capacity of the stationary battery has to be significantly bigger (1,820 kWh calculated). Due to the size of the required stationary battery, this approach is assumed to be a non-viable solution and it is not considered further in this study.

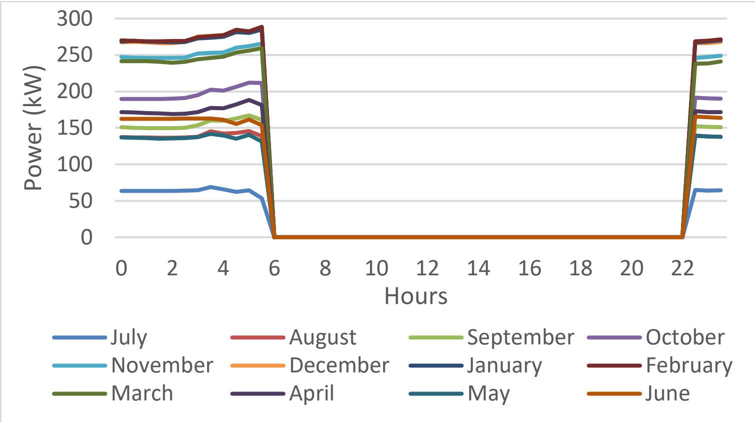

Figure 5: Daily energy consumption profile at Eastcroft depot with stationary battery and V2G assets

3 Conclusions

An integrated energy system for the Eastcroft Depot in Nottingham is modelled in this study. The model analyses the energy flows between the components of the system including the existing buildings of the depot, three proposed PV installations, potentially forty electric vehicles with vehicle-to-grid capabilities and a stationary battery. Real data about existing grid consumption and transport operations was obtained to define the baseline and calculate the additional power demand from a shift to electrified transport operation. The results are combined with simulated generating profiles for the proposed PV installations.

It was shown that the extra load for recharging the forty EVs is mostly compensated for by the energy generation of the proposed PV installations. This means that annual energy consumption at the depot remains about the same when compared to the baseline calculation. Yet, the new peak power demand increases by 80% as most EVs are charged simultaneously when they return back to the depot in the afternoon. The total impact is to reduce carbon emissions by 20 tCO_2 mainly due to the shift towards EVs.

Smart charging is particularly useful for peak shaving. The charging load is evenly distributed throughout the day and therefore, the peak power demand at the depot is preserved to similar levels compared to the baseline. Some reduction in electricity bills and carbon emissions is also possible as some energy consumption is shifted overnight when electricity prices are usually cheaper and the inherent CO_2 content of electricity is generally lower.

The energy stored in the EV batteries and the stationary battery can be used for balancing grid consumption at the depot during the day to avoid high electricity tariff prices. This approach shows it would be theoretically possible to bring grid consumption to zero during the day which results in substantial economic savings on energy bills and CO_2 emissions by £6.7k (12% reduction) and a 2 tCO_2 (2% reduction) per year when compared to the smart charging only solution.

The new peak power demand is increased by 235% in comparison to the baseline peak power demand, however this peak consumption now occurs during off-peak hours. The load factor of the system reaches a low value of 21%; but a load factor of 70% is achieved during the off-peak times.

Participation in various grid services such as frequency response could create additional revenue streams and make the case for V2G and stationary batteries more attractive. This is an area of further research.

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Authors

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