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# Using locally generated renewable energy to charge depot based electric freight fleets.

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**Abstract**

Waste collection and transportation is an essential public service which is sometimes perceived very negatively by the general population in residential and urban areas. The noise and emissions released from the tailpipe of conventional refuse collection vehicles (RCVs) are major concerns for local authorities in the United Kingdom (UK). Moreover, RCVs are one of the targets under Clean Air Zones (CAZ) policies that are encouraging waste management companies to start planning and implementing trials on electric RCVs. This study assesses the impact that different charging patterns have on energy management and consequently on grid dependency, total cost, and GHG emissions. Three charging patterns are analysed, viz., charging the fleet at 16:00h; at 21:00h; and finally splitting the fleet and charging over two different time slots: 11:00h and 23:00h. The results are assessed considering the installation of localised PV solar energy and battery storage. The results conclude that the most economical configuration corresponds to the scenario where the depot has PV solar panels installed, with a Battery Energy Storage System (BESS) and an eRCV fleet which is charged in two different time slots. For this configuration, the total cost can be reduced by up to £1m over the system lifetime.

*Keywords:* Electric refuse collection fleet; Energy management; charging pattern; Battery energy storage system; localised solar energy; decarbonisation, electric fleet, BESS, depot

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## 1. Introduction

Transport is the largest emitting sector, responsible for 24% of the UK's GHG emissions in 2020 (DfT, 2022b). Its impact on air quality, especially in urban areas, is a major concern driving global progress towards the decarbonisation of this sector. In particular, the UK has committed to achieving net-zero GHG emissions by 2050 (BEIS, 2021). Local authorities are also taking leadership in response to the Climate Crisis by introducing policies to establish Clean Air Zones (CAZ) and Low Emission Zones (LEZ) in major UK towns and cities (DEFRA, 2019). CAZ and LEZ policies encourage the adoption of lower emission vehicles to improve air quality and reduce health issues associated with air pollution. Road freight transport fleets are the main focus under those policies, many of which impose a fee to those vehicles entering the CAZ that does not meet emission standards.

RCVs must transit regularly throughout these zones to collect and transport the waste from households to disposal/recycling facilities. The distance travelled by an RCV to collect the waste depends on different factors, amongst others, the type of waste collected and the distance between collection points, disposal facilities and depots (Ramos *et al.*, 2018; Nilssen *et al.*, 2019). The latest data available from 2018 estimates a total waste generation of over 222 million tonnes in the UK, of which 27 million tonnes is household waste (DEFRA, 2022). The appropriate management and treatment of such quantities of waste is essential but relies heavily on heavy goods vehicles (HGVs), a sector within the road freight transport responsible for 13% NOx and 19% GHG emissions of the total road transport emissions (DfT, 2022b, 2022a).

Noise pollution is another major concern related to freight operations (Anderson *et al.*, 2005; Chowdhury *et al.*, 2022), with many urban areas banning heavy goods vehicles from operating between 22:00h and 06:00h due to issues associated with noise from traffic and delivery activities (Fu *et al.*, 2018). RCVs collections in residential areas are considered noisy and disturbing to those living close by, with noise complaints from RCV services becoming a regular problem for many councils in the UK (Steiger, 2021). Local authorities see the electrification of RCVs as a potential solution to diminish the noise created by conventional engines and to reduce the air pollution. Although there is not an official number on the share of electric RCV (eRCV) in the UK, there are many councils that have already replaced part of their fleet or are in trials to switch from conventional diesel power to eRCVs (DfT, 2022c). To name but a few, in the UK there are some eRCVs operating in London (Westminster City Council, 2023), Manchester (Manchester City Council, 2021), Brighton (Brighton & Hove City Council, 2022), York (City of York Council, 2020), Bournemouth (BCP Council, 2022), and Glasgow (Glasgow City Council, 2022).

Waste collection services could benefit the most from electrification within the road transport sector due to their well-structured and planned daily routes (Schmid *et al.*, 2021). Furthermore, the reduction of noise associated with using electric drivetrains creates the possibility of operating during off-peak hours. In turn, this would allow the charging of the fleet during daylight hours with solar energy. This could in fact amplify the benefits of electrification as the fleet would be fully or partly charged from solar energy sources. However, if wind generation is also available, this would further enhance the availability of electricity generation from renewable sources and create greater flexibility in potential route operating hours.

The energy sector is in a transition period shifting from centralised fossil fuel generation toward decentralised renewable energy generation (Kichou *et al.*, 2022). In fact, the overall reduction in emissions in the UK, in relation to 1990's levels, can be attributed to the decrease in electricity generation from coal and gas and the increased use of renewable energies in the power sector (BEIS, 2023). In the UK, renewables' share of electricity generation in the national grid was almost 39% in 2022 (BEIS, 2022a). Simultaneously, the market share of electric vehicles (EVs) continues to grow (IEA, 2022). The increase in the share of renewable sources in the grid network can contribute significantly to greening the road transport sector (Ensslen *et al.*, 2017). However, the potential for localised solar energy generation on waste services premises should be considered. These depots benefit from a large rooftop for PV panel installation and a relatively low energy consumption as the main activity of the site is carried out on the road.

As a consequence, energy storage becomes crucial to meet on-road demand (Haugen *et al.*, 2022). Battery Energy Storage Systems (BESS) are a key technology in the transition towards sustainable energy systems. They not only provide reliable regulation of active and reactive power and frequency, but also overcome problems related to interruptions of transmission or distribution systems (Das *et al.*, 2018). Additionally, BESS can enhance the self-sufficiency and self-consumption indicators, and increase the overall flexibility of the grid (Moghaddam *et al.*, 2019), reducing the energy bills by purchasing power from the grid during the off-peak hours and selling it back to the network during the peak demand hours. Due to the volatile nature of renewable energies, energy storage systems enhance their integration by levelling their output fluctuations and balancing the power flow (Das *et al.*, 2018). It also facilitates the incorporation of EV fleets as it allows for the charging throughout the day using renewable power. The availability of charging infrastructure and the capital investment required are major barriers for companies, especially when power connections do not meet EV fleet charging demand during the off-hours at the depot and companies are required to upgrade the utility grid connection (Quak *et al.*, 2016).

Currently, there is a lack of publications that discuss the impact of charging patterns when localised solar energy and battery storage is used to charge EV fleets at logistics companies depots. This information could be implemented into route planning (Ramos *et al.*, 2018; Nilssen *et al.*, 2019) and waste collection system design (Blazquez *et al.*, 2020) with the help of energy usage prediction (Zhao *et al.*, 2020) in order to have a full picture of the transition towards sustainable practices within the waste collection sector.

This paper aims are to provide information on the reduction of grid dependency, total cost and GHG emissions when implementing different charging patterns for an eRCV fleet and discuss the implications of installing localised PV energy generation and BESS for that purpose.

## 2. Methodology

### *2.1. Case study data*

For the purpose of this study, a local authority waste management depot in Nottinghamshire, UK, and its fleet of diesel RCVs has been examined. The site includes two different buildings, with a floor area of 2,445 m² and 2,361 m² respectively. Currently, the company is fully dependent on the grid to cover the electricity demand of these buildings. The local authority provided hourly energy consumption data from 1st of April 2021 to 31st of March 2022. The total electrical energy consumption for both depots was 234 MWh for this period. This equates the total energy consumption of the depot as in this case there is no grid connected gas infrastructure onsite.

The actual RCV fleet comprises 19 diesel RCVs with a total distance travelled and fuel consumed of approximately 23,000 miles and 19,500 litres respectively per month.

### *2.2. Scenarios studied*

Two different scenarios have been chosen to analyse the impact of using localised PV solar energy and BESS at this specific site. This has been done considering the grid dependency, total costs, and GHG emissions. The two scenarios modelled for this study are:

**Scenario 1 (Grid + eRCVs).** As seen in Fig 1., scenario 1 reflects the hypothetical scenario when the actual fleet is switched from conventionally fuelled to electric, and the demand from the depot and fleet is entirely covered by the grid. The fleet of 19 eRCVs is charged on site when vehicles return to the depot. The charging patterns assumed are introduced in section 2.3.

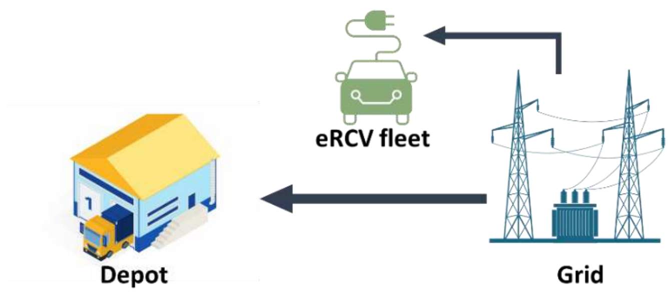


Fig. 1. Flow chart of scenario1.

**Scenario 2 (PV + BESS + eRCVs).** The fleet in this scenario is also electric (see Fig 2.), and comprises 19 eRCVs, with the same charging and operational times as per Scenario 1. When charging the eRCV fleet, solar energy will be used initially. However, if there is not enough solar energy available (e.g. at night when the BESS state of charge is at its minimum), the vehicles are charged from the grid. The depot is assumed to have rooftop PV panels installed and a BESS (with a round trip efficiency of 90%). The demand of the depot is covered, whenever possible, by the PV solar energy and the BESS, otherwise it is covered by the grid. If there is surplus solar energy after the total demand of the depot has been met, it is stored in the BESS for later use.

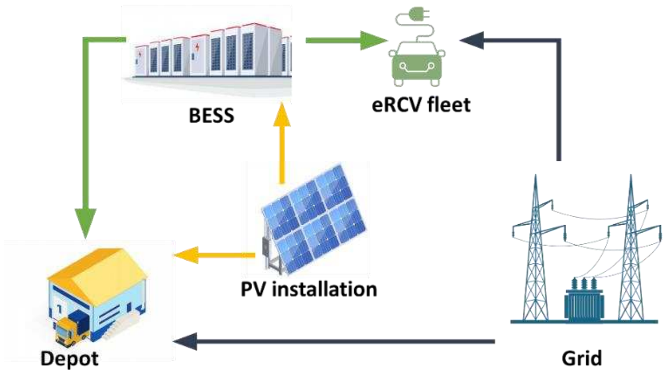


Fig. 2. Flow chart of scenario 2.

## *2.3. Charging pattern and operational times*

It is assumed that the entire RCV fleet is switched from diesel to electric. As the mileage of the conventional RCV fleet is available, the conversion factor used is 3.48 kWh/mile to give total energy requirement of the fleet. The conversion factor was obtained by using the energy consumption model for eRCVs proposed by Zhao *et al.* (2020). The maximum battery capacity of each eRCV is assumed to be 300 kWh, based on the average battery size of a number of eRCV manufacturer's prototypes. Each eRCV has its own charger and it's charged at the depot. The model assumes that the fleet operates Monday to Friday with a constant daily consumption of 185 kWh. It is also assumed that the vehicles depart from the depot with a fully charged battery.

Three different charging scenarios for the fleet have been studied with the aim of optimising depot charging, whilst also considering power connection, electricity cost and operational times. The charging scenarios are as follows:

**Charging at 16:00h with 22 kW chargers**. The eRCV fleet operates between 06:00h and 14:00h and returns to the depot to be charged from 16:00h for a maximum of 8.5 hours. This charging scenario provides a 2hr buffer for all vehicles to return to the depot prior to charging.

**Charging at 21:00h with 22 kW chargers**. The eRCV fleet operates between 06:00h and 14:00h and returns to the depot to be charged from 21:00h for a maximum of 8.5 hours. This scenario enables the vehicles to be charged at a lower electricity price (post 21:00h – no longer in peak hours).

**Charging at 11:00h and 23:00h with 50 kW chargers.** For this scenario, the fleet is charged in the morning and at night. In this configuration, 10 out of 19 eRCVs operate between 06:00h and 10:00h, then return to the depot to be charged at 11:00h for a maximum of 6 hours and return to the road from 18:00h until 22:00h. The other 9 eRCV operate between 06:00h and 14:00h continuously and are charged from 23:00h for a maximum of 6 hours.

*2.4. Modelled PV solar energy generation*

The PV solar energy generation for scenarios 1 and 2 has been modelled using MATLAB with empirical correlations developed by Nunez Munoz *et al.*, (2022). The input data used as hourly solar irradiation data for this study was obtained through the Centre for Environmental Data Analysis (CEDA) archive. The CEDA archive is the UK national data centre for atmospheric and earth observation research that ensures easy access to horizontal solar irradiation data from the open data version of Met Office Integrated Data Archive System (MIDAS) (CEDA, 2017; Met Office, 2020). The datasets correspond to hourly measurements of horizontal and diffuse global solar irradiation in kJ/m². The hourly data of horizontal global solar irradiation used for this specific study was measured in a weather station located in Walnatt (Nottinghamshire, UK) between 2009 and 2019. Values were averaged and transformed into kWh/m² to be used as input to the solar model.

It has been assumed that the PV installation has 946 PV panels in one of the buildings and 918 PV panels in the other, commensurate with the available roof size of the exiting depot buildings. The PV panels are assumed to be tilted at the existing roof inclination angle, 30° and orientated towards the south-east (140°) and the north-west (320°). From the arrangement, the modelled total PV solar energy generation from April 2021 until end of March 2022 was 328 MWh.

The modelled PV solar energy generation, and the hourly energy consumption corresponding to the local authority waste management buildings are plotted in Fig.3.

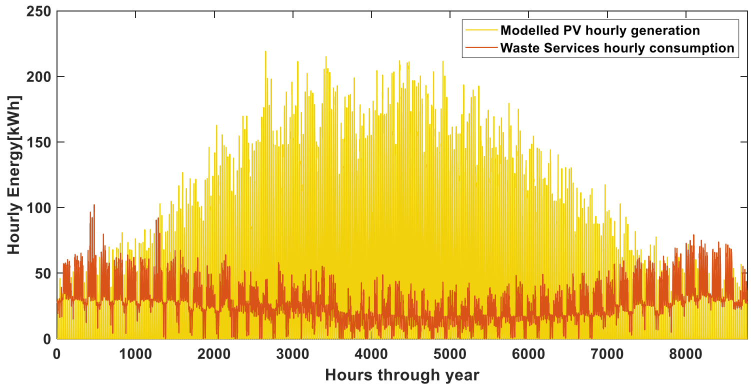


Fig. 3. Hourly electricity consumption and modelled PV solar energy generation for the depot under study.

As it can be seen in Fig.3, the modelled PV solar energy generation covers the demand across most of the year with a surplus that can be stored and used during night hours. During the winter months (i.e., November, December, and January), the premises rely on the grid network, as shown in Fig.4.

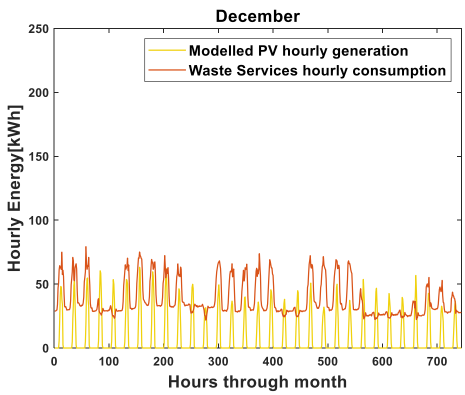


Fig. 4. Hourly electricity consumption and modelled PV solar energy generation during December.

### *2.5. Electricity price profile*

There has been a sharp increase in electricity prices since 2021, with global gas prices and wholesale electricity prices quadrupling in the last year. For this study, the cost of electricity has been estimated considering the average electricity price in the non-domestic sector published by BEIS (2022b). BEIS publishes average quarterly and annual electricity prices based on two surveys conducted for energy suppliers and non-domestic consumers. The depot under study is in the small consumption band, according to the classification from BEIS. For this band, the electricity price rose by 30% to 20.57p/kWh between Q1 2021 and Q1 2022.

Predictions point to a continuous price increase over winter. However, it is very difficult to estimate future energy prices as it is inherently challenging to predict the market dynamics, geopolitical factors or environmental concerns that shape the energy market landscape.

Since 2021, the Ofgem price cap has risen three times in the UK. Unfortunately, the available data for the non-domestic sector has not been updated since Q1 2022, when the second Ofgem price cap came into effect (1 April 2022). The percentage change for electricity prices for non-domestic consumers has been extrapolated from the price change for domestic consumers. In Fig 5(a), the percentage change in electricity prices between January 2021 and March 2022 can be seen. The proportional increase in electricity prices between domestic and non-domestic consumer was assumed to be the same between March and April 2022.

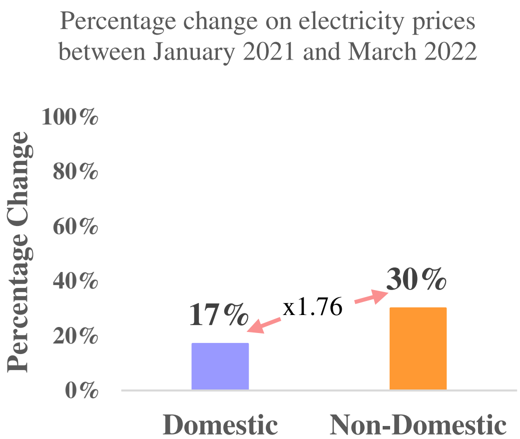


Fig. 5.(a) Percentage change in electricity prices for domestic and non-domestic consumers between January 2021 and March 2022 in the UK.

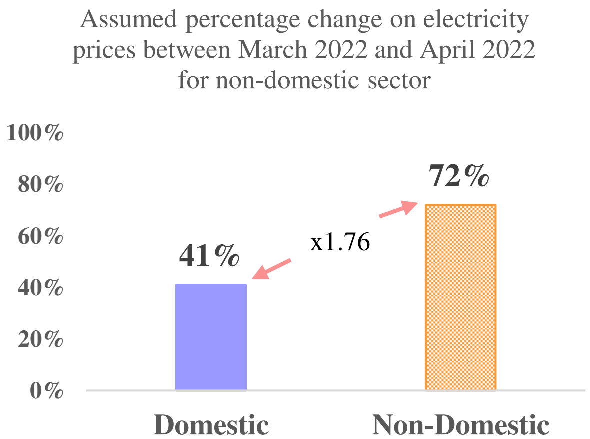


Fig. 5 (b) Assumed percentage change in electricity prices for non-domestic consumers between March 2022 and April 2022 in the UK.

The percentage change between March and April 2022 in the non-domestic sector was assumed to be 72% as seen in Fig 5(b). Based on the volatility of prices and continuous increases, an average price has been considered for this study of 35.38 p/kWh.

In order to show the differences in hourly electricity prices, the study has used wholesale electricity prices found on the Nord Pool website for the UK (Nord Pool, 2022) to create a price profile throughout a typical day. Nord Pool is in the framework of EU Regulation on Wholesale Energy Market Integrity and Transparency for power trading across Europe. As an example, Fig.6 shows the price profile for one day of the year. There are two peak times when the electricity cost is at its highest value (between 7am and 10am, and 6pm-8pm).

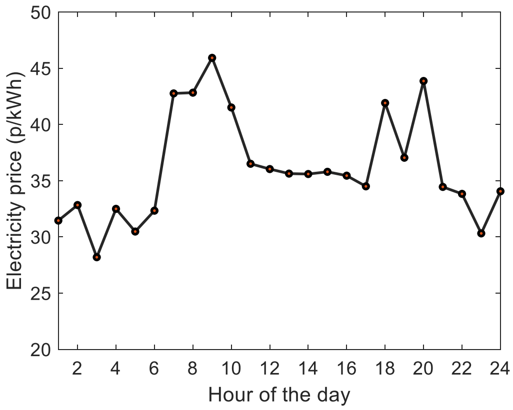


Fig. 6. Simulated electricity prices for one day of the year, considering a price profile pattern from Nord Pool with an average price of 35.38 p/kWh.

## *2.6. System cost analysis*

The economic impact of the two different scenarios has been quantified considering the following costs.

- **Cost of connection**: This refers to the contracted power capacity cost. It is charged by the energy supplier and corresponds to network costs. For this study, the cost of connection has been assumed to be 2.91 p/kVA/day based on the price from Western Power Distribution Network in the UK for a LV Site-Specific Band 1 (Western Power Distribution, 2022). When the fleet is switched to electric, the overall peak demand increases although the power connection is not always upgraded. Table 1 shows the annual power connection cost for the different charging patterns explored, when the power connection is not upgraded (i.e. 150 kW) and when the power connection is upgraded (i.e. 600 kW and 700 kW) for the two different scenarios studied. If the power connection is not upgraded, it will incur additional costs when the power capacity is exceeded. The exceeded capacity charge for a LV Site-Specific Band 1, according to Western Power Distribution Network in the UK is 5.73 p/kVA/day. The exceeded power capacity charge is different at each charging time and for each scenario under study. This is because the demand of the buildings from the waste management services changes every hour. For scenario 2 (PV+BESS+eRCV) the exceeded capacity charge is reduced for all the charging patterns because part of the demand is covered by PV solar energy. The more PV solar energy used, the higher the reduction of exceeded power capacity charge. The cost of upgrading the power connections are also included on Table 1 (Energy UK, 2020). When calculating the total cost over system lifetime, it has to be considered that the exceeded power capacity is charged annually whereas the grid connection cost is only paid once. It makes the upgrade of the power connection a more feasible option in terms of costs.

Table 1. Total cost of connection for the charging patterns studied.

| Charging pattern | Power capacity connection (kW) | Charger power (kW) | Grid connection upgrade cost (£) | Annual exceeded power capacity charge (£) | Annual power connection cost (£) |
|---|---|---|---|---|---|
| | | | *Scenario 1 (Grid+eRCV)* | | |
| **Charging at 16:00h** | 150 | 22 | 0 | 39,346 | 1,770 |
| | 600 | | 45,739 | 0 | 7,081 |
| **Charging at 21:00h** | 150 | 22 | 0 | 39,431 | 1,770 |
| | 600 | | 45,739 | 0 | 7,081 |

| | | | | | |
|---|---|---|---|---|---|
| **Charging at 11:00h & 23:00h** | 150 | 50 | 0 | 41,857 | 1,770 |
| | 700 | | 46,470 | 0 | 8,261 |

*Scenario 2 (PV+BESS+eRCV)*

| | | | | | |
|---|---|---|---|---|---|
| **Charging at 16:00h** | 150 | 22 | 0 | 35,351 | 1,770 |
| | 600 | | 45,739 | 0 | 7,081 |
| **Charging at 21:00h** | 150 | 22 | 0 | 36,423 | 1,770 |
| | 600 | | 45,739 | 0 | 7,081 |
| **Charging at 11:00h & 23:00h** | 150 | 50 | 0 | 31,824 | 1,770 |
| | 700 | | 46,470 | 0 | 8,261 |

- **Cost of energy**: It corresponds to the electricity unit cost from the grid. It has been estimated on an hourly basis for a year. An example of the unit cost can be seen in Fig 5. The cost is calculated following equation (1).

$$Cost\ of\ energy = Unit\ cost\ (p/kWh) \cdot Energy\ consumption\ (kWh) \quad (1)$$

  Additionally, a standing charge is added to the cost of energy. For this study, the standing charge cost has been assumed to be 294.57 p/day based on the price from Western Power Distribution Network in the UK for a LV Site-Specific Band 1 (Western Power Distribution, 2022).

- **Cost of BESS**: For the cost of the BESS, it has been considered a capital cost of £245/kWh (Cole *et al.*, 2021) and £2.5/kWh-year in Operation and Maintenance (O&M) costs (Kebede *et al.*, 2022). In Table 2, the total cost has been calculated for the lifetime of the BESS, assumed to be 15 years according to Cole *et al.*(2021).

Table 2. Total cost of BESS for a lifetime of 15 years

| BESS capacity (MWh) | Capital cost (£) | O&M cost (£) | Total cost (£) in 15 years |
|---|---|---|---|
| 0.5 | 127,000 | 18,750 | 145,750 |

- **Cost of PV panels**: The capital cost assumed for the PV panels is £1.25/$W_{DC}$ and the O&M cost is £17.92 / kWp-year (Vignesh Ramasamy *et al.*, 2021). Table 3 shows the total cost for the PV installation with a lifetime of 15 years.

Table 3. Total cost of PV installation for a lifetime of 15 years

| Number of PV panels installed in the depots | PV panel power output, STC (W) | PV system size (MW) | Capital cost (£) | O&M costs (£) | Total cost (£) in 15 years |
|---|---|---|---|---|---|
| 1,864 | 270 | 0.5 | 629,100 | 135,282 | 764,382 |

- **Revenue from the sale of solar surplus energy**: For scenario 2 (PV+BESS+eRCV), the PV solar surplus energy is sold back to the grid, and it generates an annual revenue that is considered in the calculations of total costs. For this study, it has been use a price of 5 pence per kWh of PV solar surplus sold to the grid (Reid *et al.*, 2015). Depending on the charging pattern used, the consumption of PV solar energy varies as can be seen on Table 4. When the fleet is charged at 11:00h and at 23:00h, the PV solar energy generated in the morning is used to charge the eRCV fleet and there is less PV solar surplus energy. However, when the eRCV fleet is charged at 16:00h or at 21:00h, the PV solar energy consumption in the morning is lower and so there is more PV solar surplus energy available to be sold to the grid.

Table 4. Annual revenue from the sale of solar surplus energy.

| Charging pattern | PV solar surplus energy sold to the grid (kWh) | Revenue from PV solar surplus energy per year(£) |
|---|---|---|
| **Charging at 16:00h** | 130,857 | 6,542 |
| **Charging at 21:00h** | 146,631 | 7,331 |
| **Charging at 11:00h & 23:00h** | 54,073 | 2,703 |

### *2.7. GHG Emissions analysis*

One of the main aims of switching from a diesel fleet to an electric fleet is to lower GHG emissions, in line with NetZero targets. Whilst eRCVs achieve zero emissions at the tailpipe, there remain GHG emissions associated with the electricity generation that need to be considered. The estimated annual GHG emissions vary for each scenario examined. The emission factors for electricity from the grid have been obtained from the UK Government GHG Conversion Factors for Company Reporting (BEIS, 2022c). The emission factor for electricity from the grid is 0.19338 kg $CO_2$ eq. per kWh. The conversion factor for emissions coming from the PV solar energy generation has been obtained from the software GaBi database, 0.0686 kg $CO_2$ eq. per kWh (Sphera, 2021). The PV emission factor is based on the global average of photovoltaic technologies installed: Mono-Silicon 42 %, Multi-Silicon 47 %, Cadmium-Telluride (CdTe) 7 % and Copper-Indium-Gallium-Diselenide 4 %.

## 3. Results

The grid dependency, total cost and GHG emissions results obtained for the two different scenarios at three different charging patterns are presented below. The results for each scenario are presented separately. Trends and comparisons between charging patterns are included in the discussion section.

### *3.1. Charging at 16:00h*

The grid dependency for scenario 1 (Grid+eRCVs) is 100% because all the energy demand from the depot and from the eRCV fleet is covered by the grid, no matter the charging pattern used. On the other hand, when analysing the grid dependency of scenario 2 (PV+BESS+eRCVs), the charging pattern affects the final outcome. As shown in Fig 7., when the fleet is charged at 16:00h for scenario 2 (PV+BESS+eRCVs), the dependency from the grid is reduced by 17% when compared to scenario 1 (Grid+eRCVs). This reduction arises from using the PV solar energy instantaneously (10%) and some of it being stored at the BESS (7%) to be used when needed. When the eRCV fleet is charged at 16:00h, the share of solar energy used for the fleet corresponds to 23%. 57% of the total PV solar energy generated is used to cover the demand from the depot. There is still a percentage of PV solar energy generated that has to be sold to the grid as surplus solar energy.

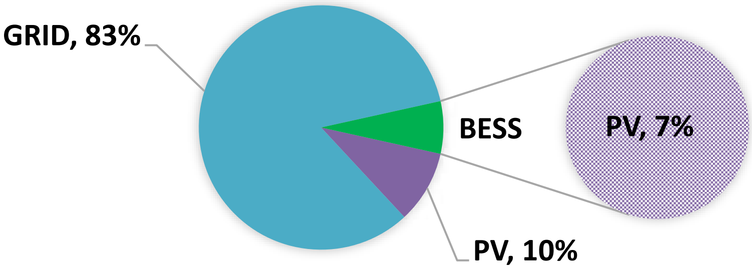


Fig. 7. Percentage of total demand covered by the grid and by the PV solar energy (instantaneous and stored energy at the BESS) when the fleet is charged at 16:00h.

In terms of costs, the charging pattern, the cost of connection and the assumed scenario all have an impact on the final cost. As shown in Fig 8b the installation of PV+BESS (i.e. scenario 2) reduces the total cost over system lifetime when compared to scenario 1 (Grid+eRCVs) (Fig 8 a). This is due to the reduction in the total cost of energy and the revenue from the sale of surplus solar energy over the system lifetime when the PV solar panels and BESS are introduced, minimising the impact of BESS and PV panels capital and O&M costs. On the other hand, for the size of the BESS explored, the results suggest that it is better economically speaking, to upgrade the power connection when charging the fleet at 16:00h, both if the demand is partly covered by PV (Scenario 2 (PV+BESS+eRCVs)) or if the grid covers the demand (Scenario 1 (Grid+eRCVs)).

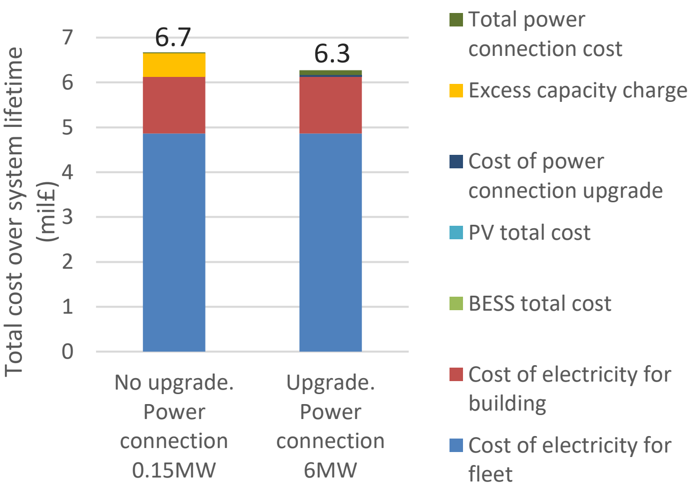


Fig. 8 (a) Total cost over system lifetime for scenario 1 (Grid+eRCVs) when the fleet is charged at 16:00h.

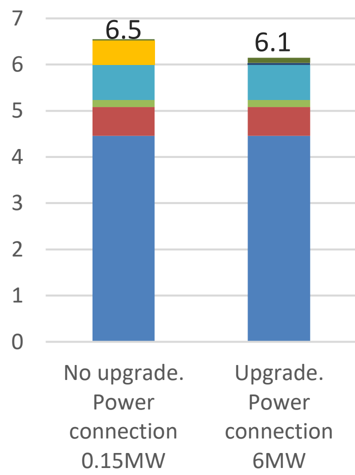


Fig. 8 (b) Total cost over system lifetime for scenario 2 (PV+BESS+eRCVs) when the fleet is charged at 16:00h

Regarding the GHG emissions, the results when the fleet is charged at 16:00h can be seen for Scenario 1 (Grid+eRCVs) and for Scenario 2 (PV+BESS+eRCVs) in Fig 9. Both the GHG emission coming from the electricity consumed at the depot, and the electricity consumed by the fleet, are reduced for Scenario 2 (PV+BESS+eRCVs) when compared with Scenario 1 (Grid+eRCVs). This is due to the use of PV solar energy.

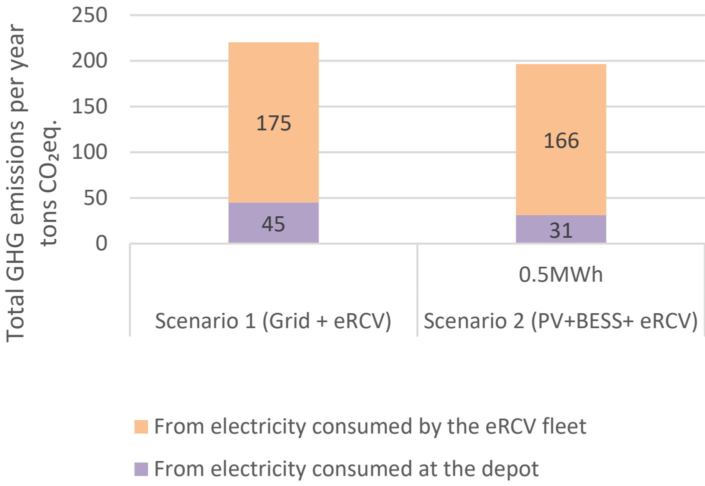


Fig. 9. Total GHG emissions per year for scenario 1 (Grid+eRCVs) and for scenario 2 (PV+BESS+eRCVs) when the fleet is charged at 16:00h.

### *3.2. Charging at 21:00h*

As it was previously stated, the grid dependency for Scenario 1 (Grid+eRCVs) is always 100%, irrespective of the charging pattern used. However, for Scenario 2 (PV+BESS+eRCVs), the dependency from the grid varies with the charging pattern. As can be seen in Fig 10., when the fleet is charged at 21:00h for scenario 2 (PV+BESS+eRCVs), the dependency from the grid is reduced by 15% if compared to scenario 1 (Grid+eRCVs). The percentage of energy covered by instantaneous solar energy (i.e., 8%) is reduced due to the peak in demand occurring at night when the eRCV fleet is charged. Therefore, the share of solar energy used for the fleet is reduced to 14%. The share of solar energy used for the depot decreases to 39%. For this scenario, most of the solar energy generated is sold back to the grid as surplus energy.

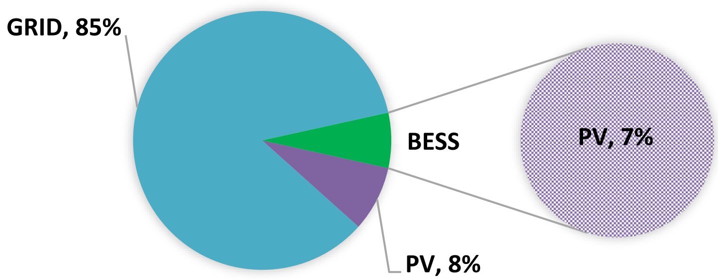


Fig. 10. Percentage of total demand covered by the grid and by the PV solar energy (instantaneous and stored energy at the BESS) when the fleet is charged at 21:00h.

Regarding the total cost, there is no difference between scenario 1 (Grid+eRCV) (Fig. 11 a) and scenario 2 (PV+BESS+eRCV) (Fig 11 b) when the fleet is charged at 21:00. In this case, the reduction on electricity cost does not compensate for the cost of PV+BESS (i.e. capital and O&M costs) and the final cost over system lifetime stays the same. When the fleet is charged at night, the potential of using PV solar energy is reduced for the system described and it minimises the benefits of using PV+BESS regarding costs.

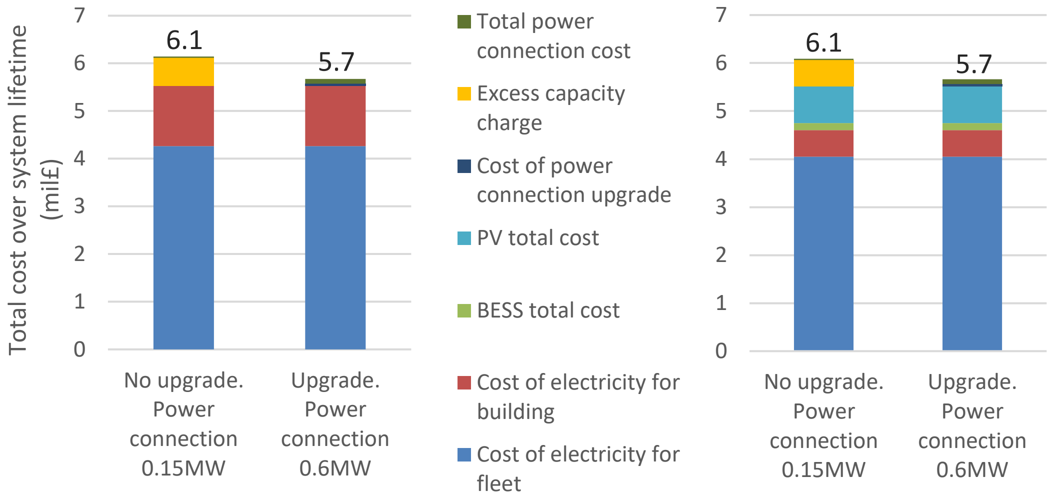


Fig. 11 (a) Total cost over system lifetime for scenario 1 (Grid+eRCVs)

Fig. 11 (b) Total cost over system lifetime for scenario 2 (PV+BESS+eRCVs) when the fleet is charged at 21:00h.

However, there is a difference when the total GHG emissions are analysed between scenario 1 (Grid+eRCVs) and scenario 2 (PV+BESS+eRCVs), as it can be seen in Fig 12. The installation of PV+BESS reduced the GHG emissions by 20 tons $CO_2$ eq. per year when the fleet is charged at 21:00h. Both, the impact from the electricity consumed by the fleet and the electricity consumed by the depot are reduced.

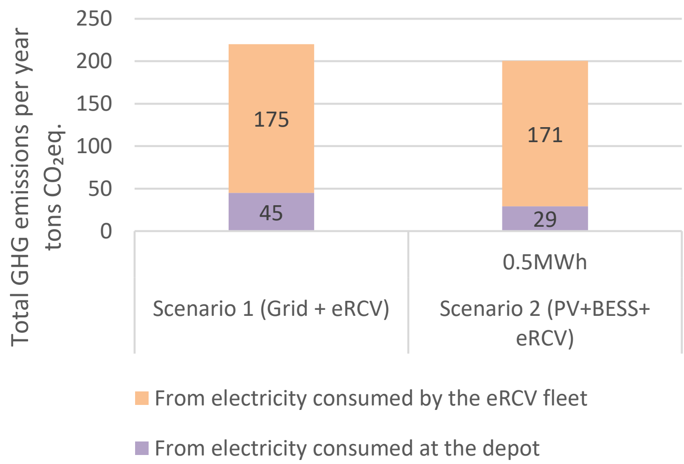


Fig. 12. Total GHG emissions per year for scenario 1 (Grid+eRCVs) and for scenario 2 (PV+BESS+eRCVs) when the fleet is charged at 21:00h.

### *3.3. Charging at 11:00h & 23:00h*

As it has been observed for previous charging patterns, the grid dependency is always reduced when the PV+BESS are used. In this case, the dependency from the grid can be reduced by up to 23%. Both the instantaneous and stored percentage of PV solar energy have increased if compared with charging the fleet at 16:00h and at 21:00h. Furthermore, this scenario presents the highest percentage of the share of solar energy used for the fleet, 43%. On the contrary, the share of solar energy used for the depot decreases to 37%. The percentage of instantaneous solar energy increases compared to the other charging patterns due to increased demand from 11:00h when part of the fleet is charged. This time of the day coincides with the peak in solar energy generation.

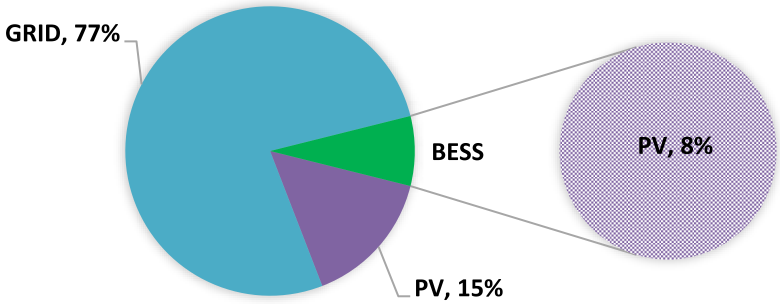


Fig. 13. Percentage of total demand covered by the grid and by the PV solar energy (instantaneous and stored energy at the BESS) when the fleet is charged at 11:00h & 23:00h.

As opposed to when the fleet is charged at 21:00, part of the fleet is charged during daylight hours and the use of PV solar energy is maximised so the reduction in costs is highest between scenario 1 (Grid+eRCVs) and (Fig 14 a) and scenario 2 (PV+BESS+eRCVs) (Fig 14 b).

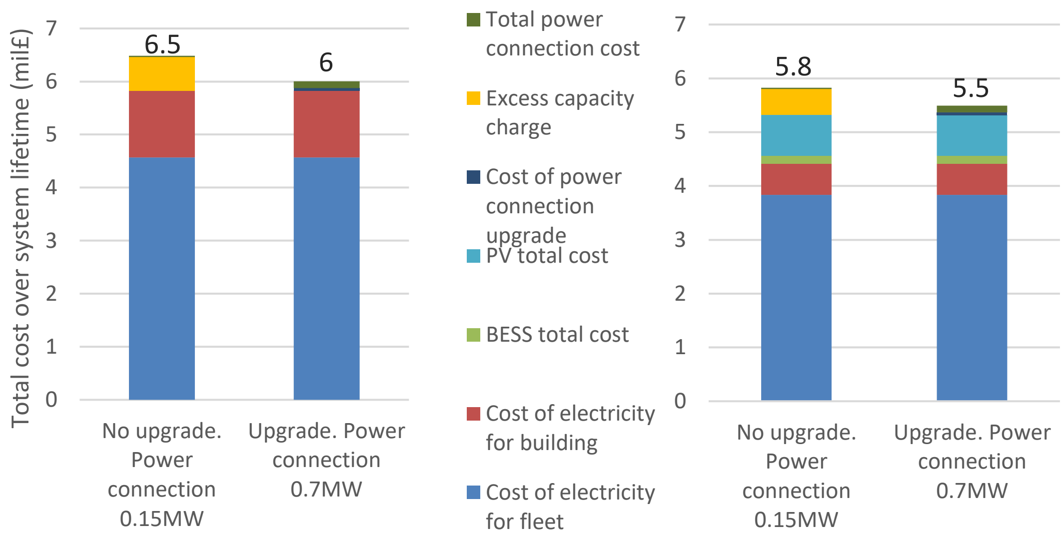


Fig. 14 (a) Total cost over system lifetime for scenario 1 (Grid+eRCVs) when the fleet is charged at 11:00h & 23:00h.

Fig. 14 (b) Total cost over system lifetime for scenario 2 (PV+BESS+eRCVs) when the fleet is charged at 11:00h & 23:00h.

For this particular charging pattern, the total GHG emissions per year are reduced by up to 31 tons $CO_2$ eq. for scenario 2 (PV+BESS+eRCVs) if compared with scenario 1 (Grid+eRCVs) (Fig 15).

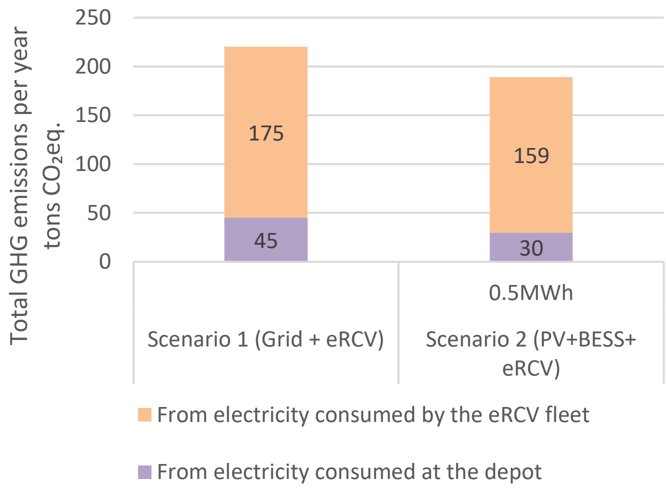


Fig. 15. Total GHG emissions per year for scenario 1 (Grid+eRCVs) and for scenario 2 (PV+BESS+eRCVs) when the fleet is charged at 11:00h & 23:00h.

## 4. Comparisons between different charging patterns

In this section, the results obtained are compared across the different charging patterns, considering the reduction on grid dependency, the total cost over system lifetime and the GHG emissions.

**Grid dependency reduction**: Scenario 2 (PV+BESS+eRCVs) reduces the dependency from the grid regardless of the charging pattern. However, the most favourable scenario for reducing grid dependency occurs when the eRCV fleet is charged at 11:00h and 23:00h for scenario 2 (PV+BESS+eRCVs). This configuration maximises the benefit of using PV solar energy at 11:00h, when the fleet is mainly charged directly from PV solar energy. Charging the eRCV fleet at night, reduced the potential of using PV solar energy and BESS, resulting in the system having greater grid dependency.

**Total cost**: For the system analysed for scenario 1 (Grid+eRCVs) and scenario 2 (PV+BESS+eRCVs), no matter the charging pattern, it is always favourable to upgrade the power connection of the site when a conventional fleet is switched to electric. The total cost over the system lifetime can be reduced further if the system uses PV+BESS when the fleet is charged at 16:00h, and at 11:00h & 23:00h. The charging pattern with the highest costs occurs when the fleet is charged at 16:00h, this is because the electricity price peaks around 16:00h. As for reducing the grid dependency, the most favourable configuration corresponds to charging at 11:00h and 23:00h for scenario 2 (PV+BESS+eRCVs).

**GHG emissions**: As it has been stated for grid dependency reduction and total cost, the introduction of PV+BESS (scenario 2) into the system improves the total GHG emissions for all the charging patterns. The fleet that emits lower quantities of GHG corresponds to the fleet charged at 11:00h and 23:00h for scenario 2. This is due to the portion of the fleet that is charged in the morning, increasing the potential to use PV solar energy. By contrast, when the fleet is charged at 21:00h (PV+BESS+eRCVs), the GHG emissions achieved their highest value for scenario 2 (PV+BESS+eRCVs).

## 5. Conclusions

This study has assessed the impact that different electric vehicle charging patterns have on energy management and consequently on total costs over the system lifetime, GHG emissions and grid dependency for an eRCV fleet. Three different charging patterns have been studied and implemented across two different scenarios. The scenarios considered were scenario 1 (Grid + eRCVs) and scenario 2 (PV + BESS + eRCVs). The charging patterns studied were selected based on operational requirements of the local authority waste collection vehicle fleet. The fleet of eRCVs operates from Monday to Friday for 8 hours, between 06:00h and 14:00h. The first charging pattern assumed that the fleet would be charged from 16:00h with a charger of 22 kW during up to 8.5 hours. The second option analysed charged the fleet at 21:00h using a charger of 22 kW for a maximum charging period of 8.5 hours to measure the impact of lower electricity prices available from 21:00h. Finally, the third charging pattern assumed that part of the fleet is charged at 11:00h and operates discontinuously from 06:00h to 10:00h and from 18:00h to 22:00h, whilst the other set of eRCVs operated from 06:00h to 14:00h and are charged at 23:00h. For the third charging pattern, it is assumed that the fleet uses a charger of 50 kW for a maximum charging period of 6 hours. As part of the future research, it is advisable to consider other charging patterns which allow higher use of the solar energy generation in line with the operational characteristics of the fleet.

The results presented here conclude that the use of PV solar energy generation and BESS (scenario 2) reduces the total cost of the system, the dependency on the grid and the GHG emission for all the charging patterns. The results demonstrate, for the system analysed, that:

1. Charging the eRCV fleet when the electricity price is at its lower values (21:00h) is the most advantageous option in terms of total cost, if the system is 100% dependent on electricity from the grid (i.e., scenario 1; *grid+eRCVs*). However, this charging pattern results in the highest values for grid dependency and GHG emissions.
2. Charging the eRCV fleet at 16:00h reduces the dependency from the grid and the GHG emissions of the eRCV fleet when compared to charging at 21:00h, but the total costs are increased due to charging time being concurrent with peak electricity prices.
3. Charging the eRCV fleet across two time periods, 11:00h & 23:00h for scenario 2 (PV+BESS+eRCVs) reduces the grid dependency, the total cost and the GHG emissions the most. It is also the most favorable configuration for the system analysed, although it requires modifications in the logistics operations and scheduling of vehicle use because it requires splitting the fleet across two charging time periods.
4. Under all of the scenarios covered by this paper, some degree of connection upgrade is advisable to minimize operation costs over the lifetime of the installation.
5. The grid dependency is always reduced when the PV+BESS are installed on the site.
6. Similarly, total cost is also reduced when the PV+BESS are installed on the site, except for when the eRCV fleet is charged at night, due to the reduction of PV solar energy usage. If charging the eRCV fleet at 21:00h is the selected charging pattern, it might be worth exploring the economies of installing different sizes of the BESS that increase the capacity to store more PV solar energy. The effects of potential variable pricing of the electricity supply will have an impact on the results of this study and a part of ongoing studies.
7. The GHG emissions associated with switching to and charging an eRCV fleet are always reduced when the PV+BESS are installed on the site. Until the grid mix is fully decarbonized, the use of on-site solar energy supported by BESS maximizes the benefits associated with the electrification of road freight transport, by reducing further the well-to-tank (WTT) emissions from EV freight fleets.

The results of the economic study suggest that the combination of an EV fleet and renewable energy, with the support of a BESS, is the most advantageous option with regards to total costs. The most economical configuration corresponds to scenario 2 where the depot has PV solar panels installed, with a BESS of 0.5 MWh and an eRCV fleet charged over two different time slots. For this configuration, the total cost can be reduced by up to £1m, the grid dependency can be reduced by 23%, and the GHG emissions reduced by up to 31 tons $CO_2$eq.

## References

Anderson, S., Allen, J. and Browne, M. (2005) ‘Urban logistics - How can it meet policy makers’ sustainability objectives?’, *Journal of Transport Geography*, 13(1 SPEC. ISS.), pp. 71–81. doi:10.1016/j.jtrangeo.2004.11.002.
BCP Council (2022) *Bournemouth: Climate actions and achievements*. Available at: https://www.bcpcouncil.gov.uk/environment/sustainability-and-carbon-reduction/our-climate-actions-and-achievements-so-far (Accessed: 6 December 2023).
BEIS (2021) *Net Zero Strategy: Build Back Greener*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/net-zero-strategy (Accessed: 7 June 2022).
BEIS (2022a) *Energy trends. UK, April to June 2022*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1107502/Energy_Trends_September_2022.pdf.
BEIS (2022b) *Gas and electricity prices in the non-domestic sector - GOV.UK*. Available at: https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector (Accessed: 1 June 2022).
BEIS (2022c) *Greenhouse gas reporting: conversion factors 2022 - GOV.UK*, *Conversion factors 2021: full set (for advanced users)*. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022 (Accessed: 20 November 2022).
BEIS (2023) *2021 UK Greenhouse Gas Emissions , Final Figures Statistical Release*. Available at: https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2021 (Accessed: 13 April 2023).
Blazquez, C. and Paredes-Belmar, G. (2020) ‘Network design of a household waste collection system: A case study of the commune of Renca in Santiago, Chile’, *Waste Management*, 116, pp. 179–189. doi:10.1016/j.wasman.2020.07.027.
Brighton & Hove City Council (2022) *New plans for electric refuse collection vehicles*. Available at: https://www.brighton-hove.gov.uk/news/2022/new-plans-electric-refuse-collection-vehicles (Accessed: 6 December 2023).
CEDA (2017) *CEDA Archive*. Available at: https://www.ceda.ac.uk/services/ceda-archive/ (Accessed: 16 March 2021).
Chowdhury, T. *et al.* (2022) ‘Modeling the Impacts of Off-Peak Delivery in the Greater Toronto and Hamilton Area’, *Transportation Research Record: Journal of the Transportation Research Board*, 2676(10), pp. 413–425. doi:10.1177/03611981221089552.
City of York Council (2020) *Waste management and the environment – City of York Council*. Available at: https://www.york.gov.uk/waste-management-environment/WasteManagementEnvironment/3 (Accessed: 6 December 2023).
Cole, W., Frazier, A.W. and Augistine, C. (2021) *Cost Projections for Utility-Scale Battery Storage: 2021 Update.*, *Golden,CO: National Renewable Energy Laboratory. NREL/TP-6A20-79236*. Available at: https://www.nrel.gov/docs/fy21osti/79236.pdf (Accessed: 10 May 2022).
Das, C.K. *et al.* (2018) ‘Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality’, *Renewable and Sustainable Energy Reviews*. Pergamon, pp. 1205–1230. doi:10.1016/j.rser.2018.03.068.
DEFRA (2019) *Clean Air Strategy 2019*. Available at: https://www.gov.uk/government/publications/clean-air-strategy-2019 (Accessed: 4 March 2020).
DEFRA (2022) *UK statistics on waste*. Available at: https://www.gov.uk/government/statistics/uk-waste-data (Accessed: 16 November 2022).
DfT (2022a) *Data on energy and environment from transport. Statistical data set: Energy and environment (TSGB0308)*. Available at: https://www.gov.uk/government/statistical-data-sets/tsgb03.
DfT (2022b) *Transport and environment statistics 2022*. Available at: https://www.gov.uk/government/statistics/transport-and-environment-statistics-2022/transport-and-environment-statistics-2022 (Accessed: 18 November 2022).
DfT (2022c) *Zero emission fleets: local authority toolkit*. Available at: https://www.gov.uk/government/publications/zero-emission-fleets-local-authority-toolkit/zero-emission-fleets-local-authority-toolkit (Accessed: 6 December 2023).
Energy UK (2020) *Connecting Your Fleet: A guide for businesses in Greater London*. Available at: https://www.energy-uk.org.uk/publication.html?task=file.download&id=7646 (Accessed: 20 November 2022).
Ensslen, A. *et al.* (2017) ‘Empirical carbon dioxide emissions of electric vehicles in a French-German commuter fleet test’, *Journal of Cleaner Production*, 142, pp. 263–278. doi:10.1016/j.jclepro.2016.06.087.
Fu, J. and Jenelius, E. (2018) ‘Transport efficiency of off-peak urban goods deliveries: A Stockholm pilot study’, *Case Studies on Transport Policy*, 6(1), pp. 156–166. doi:10.1016/j.cstp.2018.01.001.
Glasgow City Council (2022) *Fully electric bin lorry sees Glasgow driving ahead on zero emissions - Glasgow City Council*. Available at: https://www.glasgow.gov.uk/index.aspx?articleid=27592 (Accessed: 6 December 2023).
Haugen, M.J. *et al.* (2022) ‘Electrification versus hydrogen for UK road freight: Conclusions from a systems analysis of transport energy transitions’, *Energy for Sustainable Development*, 68, pp. 203–210. doi:10.1016/j.esd.2022.03.011.
IEA (2022) *Electric Vehicles*. Available at: https://www.iea.org/reports/electric-vehicles (Accessed: 19 November 2022).
Kebede, A.A. *et al.* (2022) ‘A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration’, *Renewable and Sustainable Energy Reviews*, 159. doi:10.1016/j.rser.2022.112213.
Kichou, S. *et al.* (2022) ‘A simple and effective methodology for sizing electrical energy storage (EES) systems based on energy balance’, *Journal of Energy Storage*, 49, p. 104085. doi:10.1016/j.est.2022.104085.
Manchester City Council (2021) *Climate Change Action Plan - Manchester City Council*. Available at: https://www.manchester.gov.uk/info/500002/council_policies_and_strategies/8238/climate_change_action_plan_-_work_plan_202122/3 (Accessed: 6 December 2023).
Met Office (2020) *MIDAS Open: UK hourly solar radiation data, v202007.*, *Centre for Environmental Data Analysis*. doi:10.5285/1dc8578eb7434a7d8a661744d53eedf9.
Moghaddam, Z. *et al.* (2019) ‘A coordinated dynamic pricing model for electric vehicle charging stations’, *IEEE Transactions on Transportation Electrification*, 5(1), pp. 226–238. doi:10.1109/TTE.2019.2897087.
Nilssen, J.E. *et al.* (2019) ‘Time calculation of waste collection routes: Case study from the City of Oslo’, *Waste Management and Research*, 37(7), pp. 667–673. doi:10.1177/0734242X19838612.
Nord Pool (2022) *Market Data | Nord Pool UK*. Available at: https://www.nordpoolgroup.com/en/ (Accessed: 1 June 2022).
Nunez Munoz, M., Ballantyne, E.E.F. and Stone, D.A. (2022) ‘Development and evaluation of empirical models for the estimation of hourly horizontal diffuse solar irradiance in the United Kingdom’, *Energy*, 241. doi:10.1016/j.energy.2021.122820.
Quak, H. *et al.* (2016) ‘Zero Emission City Logistics: Current Practices in Freight Electromobility and Feasibility in the Near Future’, in

*Transportation Research Procedia*. Elsevier B.V., pp. 1506–1515. doi:10.1016/j.trpro.2016.05.115.
Ramos, T.R.P., de Morais, C.S. and Barbosa-Póvoa, A.P. (2018) 'The smart waste collection routing problem: Alternative operational management approaches', *Expert Systems with Applications*, pp. 146–158. doi:10.1016/j.eswa.2018.03.001.
Reid, G. and Wynn, G. (2015) 'The future of solar power in the United Kingdom', *Energies*, 8(8), pp. 7818–7832. doi:10.3390/en8087818.
Schmid, F. *et al.* (2021) 'Electrification of Waste Collection Vehicles: Technoeconomic Analysis Based on an Energy Demand Simulation Using Real-Life Operational Data', *IEEE Transactions on Transportation Electrification*, 7(2), pp. 604–615. doi:10.1109/TTE.2020.3031072.
Sphera (2021) *GaBi LCA Database Documentation*, *GaBi Solutions*. Available at: https://gabi.sphera.com/support/gabi (Accessed: 30 November 2022).
Steiger, H. (2021) 'A London municipality's electric refuse collection vehicle–"The eRCV project"', *Cities and Health*, 5(1–2), pp. 56–60. doi:10.1080/23748834.2019.1603132.
Vignesh Ramasamy *et al.* (2021) *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021*. Available at: https://www.nrel.gov/docs/fy22osti/80694.pdf (Accessed: 25 May 2022).
Western Power Distribution (2022) *Western Power Distribution - Charging Statements*. Available at: https://www.westernpower.co.uk/our-network/use-of-system-charges/charging-statements (Accessed: 1 June 2022).
Westminster City Council (2023) *Westminster Council - electric waste collection fleets*. Available at: https://www.westminster.gov.uk/news/westminster-council-unveil-uks-largest-electric-waste-collection-fleet-powered-waste-they-collect (Accessed: 6 December 2023).
Zhao, R. *et al.* (2020) 'Sustainable city: Energy usage prediction method for electrified refuse collection vehicles', *Smart Cities*, 3(3), pp. 1100–1116. doi:10.3390/smartcities3030054.