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An approach for energy management of renewable energy sources using electric vehicles and heat pumps in an integrated electricity grid system

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ABSTRACT

The demand for electricity has been increasing worldwide and it is predicted that this trend will be particularly reinforced in developing countries by the gradual electrification of the transport sector and heat generation in buildings. The energy supply infrastructure required to meet the additional electricity demand should be carefully managed in light of the climate change carbon emission targets and commitments. A large proportion of the new electricity loads will be met from renewable sources. Therefore, means of power storage become vital to smooth out the intermittent nature of these energy supplies. The introduction of Electric Vehicles (EVs) could provide a viable and dynamic power storage solution through the concept of Vehicle-to-everything (V2X). This involves the storage of renewable energy (RE) in EV batteries during the charging cycle and restitution to the grid (V2G) or homes (V2H) when needed. In this context, this paper presents a methodology involving several strategies to stabilise the grid system and examines the impact of various types of EVs and heat pumps (HPs) for supplying heat in buildings. The results of this research approach show that the synergy of using V2H could reduce the carbon footprint of a typical domestic building in the United Kingdom (UK) by up to 87% and potentially recover up to 21.9 kWh/day of surplus renewable energy.

1. Introduction

Electricity generation from fossil fuels has long been of great concern for communities because of high carbon footprint and the effects of other harmful pollutants on the environment. An extreme amount of fossil fuels has been in use due to the increasing heating, electricity, and transportation needs around the globe. Electricity generation is an energy-intensive process which has contributed significantly to increasing greenhouse gases (GHGs) concentration in the atmosphere, including carbon dioxide (CO_2), water vapour (H_2O), methane (CH_4), nitrous oxide (N_2O), ozone, and chlorofluorocarbons (CFCs), leading to rising global warming. As part of the UK government's energy policy and climate change commitment, carbon emissions have decreased by 44% compared to since 1990 level with zero carbon targets being projected to be achieved by 2050 [1].

Currently, the United Kingdom (UK) transport sector accounts for 26% of the country's total emissions, the largest share of all other economic sectors [2]. It is followed by the energy generation sector which supplied buildings and industry. The residential sector, particularly, is responsible for 16% of the emission mainly for providing space heating and hot water needs of the residents. Transport and domestic buildings are the two hard-to-decarbonise sectors of the economy.

Therefore, current efforts are centred around promoting electric vehicles (EVs) for transport and heat pumps (HPs) for space heating and domestic hot water in buildings. Technically, the technology exists if the electricity that powers these systems can be sourced reliably and sustainably [3]. Hence, the share of electricity generation from renewable sources has been increasing and according to the Department for Business, Energy & Industrial Strategy (BEIS) [4], currently, renewable energy (RE) contributes around 40% of the country's overall energy supply, with wind energy accounting for 53% of the RE market. Despite significant advances, there is still a tremendous amount of work to be done in order to meet the country's zero-carbon goals. By 2050, it is predicted that 90% of the electricity generation would come from

Abbreviations: BEIS, Department for Business, Energy & Industrial Strategy; CO_2, Carbon Dioxide; COP, Coefficient of Performance; DfT, Department of Transport; DOD, Depth of Discharge; EST, Energy Saving Trust; EV, Electric Vehicle; GB, Great Britain; GHG, Greenhouse Gas; HP, Heat Pump; IEA, International Energy Agency; NST, National Travel Survey; PV, Photovoltaic; RE, Renewable Energy; RES, Renewable Energy Sources; RHPP, Renewable Heat Premium Payment; SoC, State of Charge; UK, United Kingdom; V1G, Smart Charging; V2G, Vehicle-to-Grid; V2H, Vehicle-to-Home; V2X, Vehicle-to-everything.

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renewable energy sources, with wind and solar photovoltaic (PV) power accounting for 70% of this REs supply [5]. Almost the bulk of the UK's 1,007,427 solar PV systems were installed on a small scale, with output capacities of less than 4 kW [6], primarily due to the feed-in tariff system that these installations receive. Another reason may be that the unpredictable and intermittent nature of renewable energy sources (RESs) in large-scale applications causes power challenges for the grid. Power stability, for instance, is one of the most frequently stated problems with electrical grids due to large variations in load and/or RES [7]. For a safe grid operation, the instantaneous energy demand and supply must be balanced otherwise, the grid may encounter overloading that can cause blackouts or overgeneration problems and lead to generation curtailment and energy waste.

The UK's net-zero emission strategy will require full decarbonisation of heat generation in domestic buildings by replacing combustion gas boilers with HPs and replacing combustion engine vehicles with EV fleets supported by the integration of large-scale RESs. Equally, to exploit fully RES, energy storage is important for smoothing out the renewable energy supply's unpredictable and intermittent nature [8]. Energy storage might create energy flexibility in the grid and, energy flexibility has an outstanding potential to improve and support the operation of the energy systems while contributing more RE integration into the grid [9]. Thanks to the mentioned importance of electricity storage, the Vehicle-to-everything (V2X) concept is being evaluated to offer the opportunity to store renewable energy in electric vehicle batteries and discharge this stored energy back to the grid (V2G) or homes (V2H) as necessary.

Electrical power storage technologies using stationary batteries offer many advantages including charging/discharging number of cycles, round trip efficiency, quick reaction times, flexibility and modular installation structures [10]. For mobile applications, however, battery technology still require suffers from low energy density and excessive cost. To overcome the cost issue of batteries in EVs is the dual use as the energy source for the car drivetrain and power storage for grid support. This is particularly important when combined with a holistic approach for zero-carbon targets [8]. For example, Kempton and Letendre [11] proposed V2G as a solution to managing grid peak power demand by transferring power stored in EV batteries to the grid. Similarly, the energy stored in an EV battery can be used directly to power the home in a V2H technology. A study examining the usability of V2H technology in meeting electricity demand in homes showed that a hybrid system including solar PVs, main battery and EV with V2H could reduce the electrical energy drawn from the grid by up to 68% [12]. Some studies also use V2H technologies as a backup system and investigate the feasibility of hybrid renewable energy systems [13]. On the other hand, V1G, smart charging methods are recommended to reduce the electricity demand in buildings. Li et al. [14] claimed that adopting smart charging in a sports hall powered by an on-grid PV and battery system could reduce the building load by 51.7%. Furthermore, according to Yao et al. [15], the V1G charging method combined with V2H technology minimises peak load in houses, and smart charging can also enhance the amount of usable wind energy.

Equally important is the UK government's policy to decarbonise heat generation in buildings for space heating and domestic hot water [16]. To fulfil this policy, it is proposed that the government will support the installation of 600,000 HPs a year by 2028 [17]. However, there is considerable risk that the current UK national grid generation capacity will not be able to meet any excess demand, particularly at peak hours of 07:00–08:00 and 17:00–18:00 during the heating season as space heating and domestic hot water needs are high [18]. Therefore, the introduction of HPs requires novel and sustainable grid energy management including performance improvement of the HPs and load-shifting strategies. For instance, solar-assisted heat pump systems have a higher coefficient of performance (COP) compared to air-source HPs [19]. For indirect solar-assisted heat pump operations, even for the same heat source temperatures, the COP of the solar-assisted heat pump would be higher due to the more favourable heat transfer properties of liquid compared to air [20,21]. A comprehensive review of solar-assisted HP technology was carried out by Buker and Riffat [22] who concluded that this combination can be a feasible solution to reduce power consumption for heating.

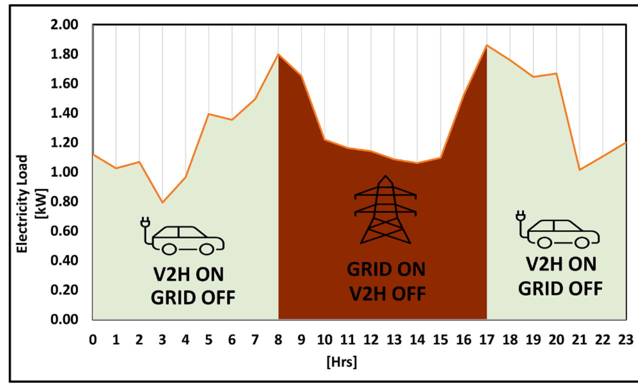

Fig. 1. The period targets for demand response.

In this context, increasing the share of RE in the power generation mix and managing the intermittency of these sources would require novel solutions such as bringing together EV technology, heat pumps and battery storage in a single integrated energy management approach to increase reliability and flexibility of the power grid. Current research in this field is still in progress and this paper attempts to assess a hybrid model in which EVs can be used to support heat generation (V2H) in domestic buildings using HPs. In this way, the study aims to present the emission reduction potential of the V2H system and, its combination with HPs in different scenarios and types of current EV technology. This will also have the added benefit of promoting RESs penetration and improving grid reliability.

2. Methodology

The UK government supports using HPs for heating and EVs for transport as part of the zero-carbon targets to reduce and end the use of fossil fuels. However, the rapid adoption of EVs and HPs without improving the share of RES in the UK energy market could unintentionally result in higher carbon emissions if new electrical power loads are fulfilled by the rising consumption of fossil-based resources. The key challenge with large-scale RES integration, nevertheless, is the stability and power quality issues in the grid imposed by the intermittent nature of renewable resources. Therefore, EVs with V2X technology may offer a sustainable solution and overcome large-scale RE integration challenges.

The study presents a comprehensive hybrid model that combines different HPs, different weather conditions and the most common EVs in the UK's EV market. This attempts to establish a synergistic interaction between EVs and HPs to enhance renewable energy integration by using V2H technologies and reduce the impact on the electricity grid. This takes into consideration both the conventional and heat pump loads using secondary data collection from several published research.

2.1. General research theory

This study is based on the RES-based charging scenario and investigates the potential of using EVs with V2H technology in demand response for a UK residential energy requirement for the heating and electrical loads. As per the general study hypothesis, an EV charged at work between 8 am and 5 pm using renewable energy is expected to meet a house's conventional power and heating needs via V2H technology when it returns home. Beyond this claim, the study analyses the impact of several EV models, HP types, and weather conditions on the

Table 1
The compared cases in the study.

Cases	Ambient Temperature	Type of Heat Pump
Case 1	Average	Air Source
Case 2	Average	Solar Assisted
Case 3	Cold	Air Source
Case 4	Cold	Solar Assisted

approach.

Considering the vehicle availability at home, the expected demand response times of the EV are shown in Fig. 1. In the paper, the grid will be used to supply all electrical needs of the house between 8 am and 5 pm. The EV would also meet its power demand, depart from work, and arrive at home throughout these periods.

In order to identify the house's total electricity demand, the power consumption of the heat pump compressor is calculated, and it is then added to the conventional electricity demand. Following the determination of the energy requirements, the research analyses UK EV statistics and examines the capability of various EVs to serve the house's load using V2H technology. Once the analysis is completed, the standard air-source HPs are replaced by solar-assisted HPs to explore the interaction of different HPs to the discussed approach, and the analysis is repeated. The cases performed to evaluate different types of HPs and different weather conditions are compared in Table 1.

2.2. Power consumption in the dwelling

The electric load of the house is investigated across two categories in the present research. The first category includes the use of conventional electricity to provide the base load, e.g., lighting, cooking, and any other electronics, while the second is based on electricity used by the heat pumps to heat the buildings.

For the conventional load, the data was taken from Energy Saving Trust's (EST) report [23]. The report presents the analysis of the energy load patterns of 26 UK residences and reveals an average yearly conventional power consumption of 3,638 kWh/year across the nation. The hourly electrical load pattern (excluding the heating load) given by the EST is utilised as a reference in this study.

The heating profiles were taken from the datasets of the Renewable Heat Premium Payment (RHPP) trial [24]. The RHPP scheme was administered by the UK Energy Savings Trust and Buildings Research Establishment to run the meter installation and data collection phases of the monitoring program. The collected data is based on 700 UK homes and includes both space heating and domestic hot water requirements. Monitored houses have different heating patterns, different building ages and fabrics even different locations, which reflects the general user profiles. In the paper, two profiles are presented: one for average weather conditions (in March), and the other for cold weather conditions (in January).

Fig. 2 displays the hourly demand profiles, electrical load pattern as $E_{conventional}$, the heating demand for average weather conditions as $Q_{average}$, and the heating demand for cold weather days as Q_{cold}. According to Fig. 2, the simulated home's daily conventional electricity use is around 9.75 kWh, with peak power demand occurring between 5 and 10 pm. However, the heating demand profile shows two peaks in the early morning and evening, regardless of the weather conditions. Under average weather conditions, the peak heating demand reaches 2 kW in the morning and 1.5 kW in the evening, with a daily total of 31.82 kWh. In cold weather conditions, the morning peak is 3.3 kW, evening peak is 3 kW, with a daily total of 52.37 kWh.

2.3. Analysis of solar-assisted heat pumps

The HP is a device that transfers heat from a low-temperature medium to a high-temperature medium. It consists of four main components, namely, a compressor, a condenser, an expansion valve, and an evaporator. Traditional HPs use ambient air as a heat source, and their performance is strongly influenced by the ambient temperature. The HP performance is defined in terms of a COP, which is the ratio of the delivered heat to the building and the electricity consumed by the compressor. This is expressed as follows:

$$COP = \frac{\dot{Q}_{heating}}{\dot{W}_{compressor}} \tag{1}$$

where $\dot{Q}_{heating}$ is delivered heat to the building, which is given hourly in Fig. 2. $\dot{W}_{compressor}$ is the electricity consumption rate of the compressor. This consumption changes with operating conditions such as pressure difference, related to operating conditions and refrigerant flow rate related to the heating load. Eq. (2) gives the isentropic efficiency of the compressor [25] to reflect the effect of operating conditions because suction pressure P_{suc} changes with the HP's evaporating temperature, which is related to heat source temperature. P_{dis} is also related to condensation pressure.

$$\eta_{is} = 0.874 - 0.0135 \bullet \frac{P_{dis}}{P_{suc}} \tag{2}$$

In order to carry out the heat pump simulation, the given assumptions are considered:

- The condensation and evaporation processes in the condenser and

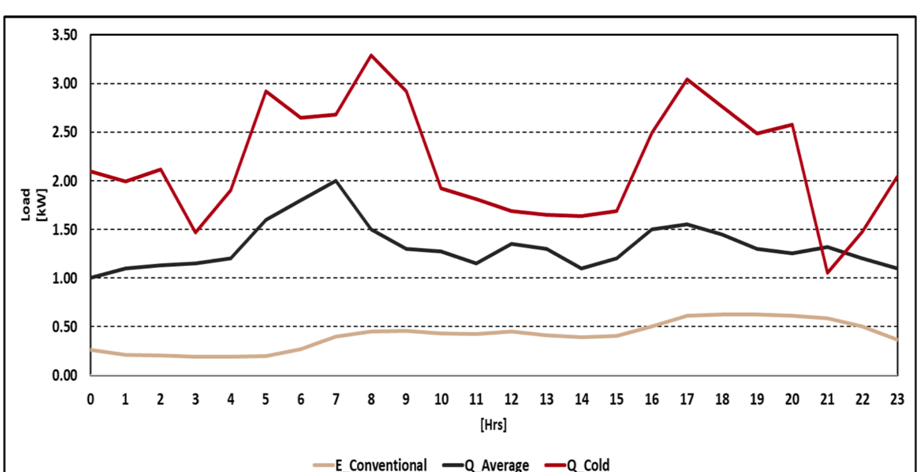

Fig. 2. The electricity and heat demand of a house.

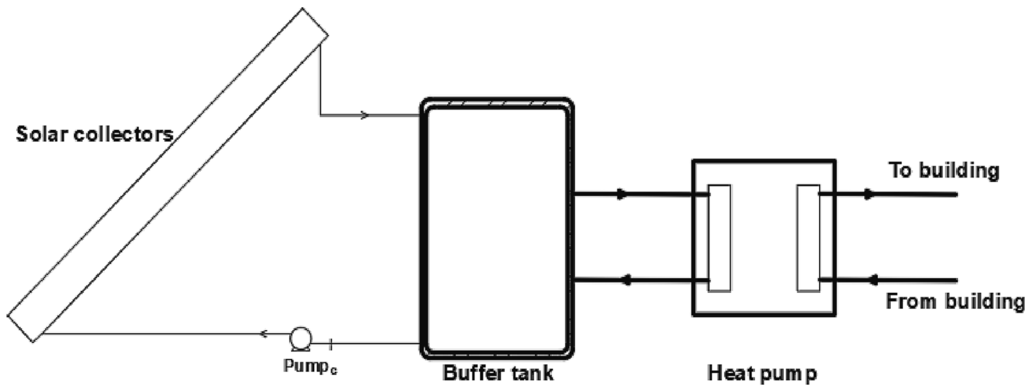

Fig. 3. Solar-assisted heat pump schematic.

evaporator are assumed to be at constant pressures.

• The subcooling and superheating temperatures are assumed as 5 °C [26].

• The air source evaporator's evaporation temperature is assumed as 10 °C lower than the ambient temperature. However, the condensation temperature is fixed at 70 °C.

Solar thermal collectors and a buffer tank should be integrated into the system for the solar-assisted HP unit. The solar collectors utilise the solar energy and store it in the buffer tank. The system schematic is given in Fig. 3.

Solar thermal collectors are modelled using the thermal efficiency equation. The general thermal efficiency equation of the solar collector is given by Eq. (3):

$$\eta_{col} = \eta_0 - c_1 \frac{\overline{T} - T_{am}}{G} - c_2 \frac{(\overline{T} - T_{am})^2}{G} \tag{3}$$

Thermomax HP-200 evacuated-tube heat pipe collectors [27] are used in the simulation. Heat loss coefficients and zero heat loss efficiency values are taken from Freeman et al. [28] as they applied incident angle modifier factors for London. η_0, c_1, and c_2 are 0.556, 0.888 and 0.006, respectively. $\overline{T}$ is the mean fluid temperature inside the collector, T_{am} is ambient temperature and G is solar irradiance.

After calculating the thermal efficiency, the collected useful solar energy can be found from Eq. (4).

$$\dot{Q}_{col} = \eta_{col} \bullet A_{col} \bullet G \tag{4}$$

A_{col} is collector area. The useful heat is transferred to the working fluid and it is calculated from Eq. (5).

$$\dot{Q}_{col} = \dot{m}_{wf} \bullet c_{p,wf} \bullet \left(T_{col,out} - T_{col,in}\right) \tag{5}$$

$\dot{m}_{wf}$ is the mass flow rate of the working fluid, it is given by the manufacturer as 0.033 kg/s. $T_{col,in}$ is working fluid temperature to the collector. It is assumed that there is no heat loss through the piping; thus, it is equal to the buffer tank temperature. $T_{col,out}$ is collector outlet temperature, the fluid at $T_{col,out}$ goes to the buffer tank.

Ethylene glycol water mixture is used as a working fluid in order to avoid freezing. The buffer tank model is built based on considering the transient performance of the tank and heat losses to the ambient [29]. The stored heat in the buffer tank is used by the heat pump. The evaporation temperature in the heat pump is decided by the buffer tank temperature. To ensure effective heat transfer, 8 K pinch temperature approach is assumed from the buffer tank and evaporator. The pinch temperature approach can be found in the reference [30].

By using the given equations and weather conditions, air-source HP and solar-assisted HP compressor consumptions will be calculated considering the demand profiles.

Table 2
The characteristic of the EVs selected for the study.

EVs	Type	Number [Unit]	Battery Capacity [kWh]	Consumption [kWh/mile]
TESLA MODEL 3	BEV	54,033	60	0.24
MITSUBISHI OUTLANDER	PHEV	45,956	12	0.27
NISSAN LEAF	BEV	42,174	40	0.26
VOLKSWAGEN GOLF	BEV/ PHEV	18,305	32/8.7	0.27
MERCEDES C CLASS	PHEV	10,518	25.4	0.22

*VW Golf's BEV model is used in the paper, and the PHEV model is for informational purposes only.

2.4. Power capacity of the electric vehicles

According to the International Energy Agency (IEA) [31], there were over 450 EV models at the end of 2021, with half of them SUV models, 23% medium and 10% small-size models. Moreover, the report remarks that the average EV battery range reached about 218 miles, an increase of 3.5% between 2020 and 2021. The usefulness of V2G/V2H to handle the load is strongly affected by the capacity of the EVs' batteries. As a result, EVs with a capacity below the required kWh of electrical energy (considering daily EV utilization and V2X efficiency) cannot manage the load successfully.

The most popular EVs in the UK were first investigated using data from the Department for Transport (DfT) [32] statistics to determine the different types of EVs to be used in this study. Examining the top 20 most used vehicles in the UK, it is observed that many EVs have similar capacity rates. Therefore, this study determined five different types of EVs, representing all of the small, medium and large capacity battery groups, to increase the variety of battery capacity. Based on their capacity and energy consumption rates, Tesla Model 3, Mitsubishi Outlander, and Nissan Leaf were selected as the top three EVs most frequently spotted on UK roads, along with the two top-20 most popular cars, Volkswagen e-Golf and Mercedes C Class. Table 2 provides an overview of these EVs' characteristics and their total numbers in the UK. The data presented in Table 2 are provided by DfT [32], EV-database [33] and Mercedes-benz's website [34].

To model daily automobiles driving profiles, a survey data from the Department of Transportation's National Travel Survey (NTS) [35] was used. NTS is a survey that analyses long-term internal travel patterns of British citizens, and it is participated annually by about 16,000 individuals from about 7000 households. The study collects information on the modes, reasons, times, and locations that people travel by considering travel-related factors such as driving licence and vehicle accessibility. According to NTS, a car on UK roads in 2020 travelled 6,700 miles annually, of which 200 miles were for business purposes,

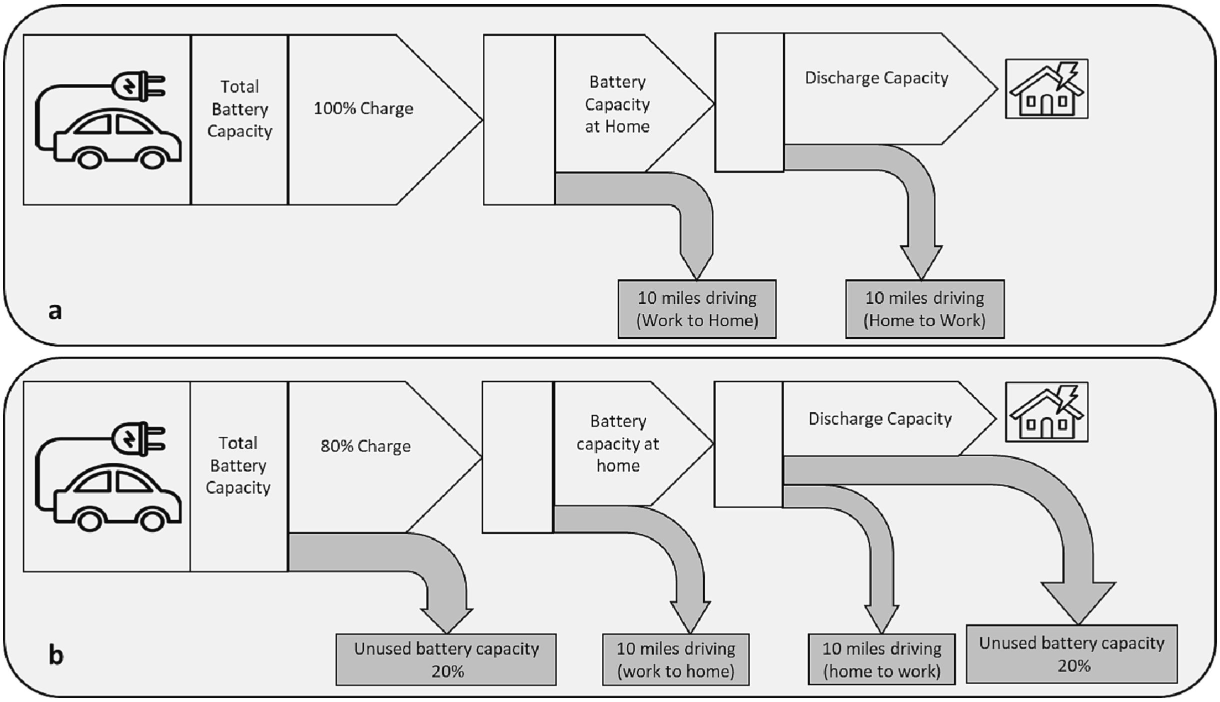

Fig. 4. EV battery power distribution, (a) the first charge/discharge scenario (b) the second charge discharge scenario.

2,400 miles were for commuting, and 4,100 miles were for personal usage. Here, the study makes the assumption that conventional vehicles and EVs have similar daily travel patterns. Considering 6,700 miles of an annual vehicle trip, an EV's daily travel distance ($D_{travel,total}$) is approximately 20 miles per day in the UK. For this reason, discharge operations in the present investigation are restricted to at least 20 miles of travel each day. The vehicle is considered to travel half of these 20 miles on the way home and the other half after stepping out of the house in the morning, so the distance the car driven before/after discharge operation (D_{travel}) is 10 miles per vehicle.

State of Charge (SoC) and Depth of Discharge (DoD) are two crucial parameters in battery charge and discharge modelling. SoC is the percentage of a battery's charged capacity. SoC can be calculated using Eq. (6) based on the coulomb counting method [36].

$$SoC_t = SoC_{t-1} - \frac{1}{P_{battery}} \int_0^t P_{supply}(t)dt \tag{6}$$

In the equations, $P_{battery}$ and P_{supply} represent the battery's initial power capacity, and the instantaneous power supply from the battery into the load at any given time, respectively. When P_{supply} is negative, it means an external energy source charges the battery.

On the other hand, DoD represents the proportion of the battery's total capacity that has been discharged and can be calculated by Eq. (7) or Eq. (8) [37]. In Eq. (7), 'Q_d' refers to the amount of charge extracted from the battery at the given state.

$$DoD_t = \frac{Q_d}{P_{battery}} \times 100\% \tag{7}$$

$$DoD_t = 100\% - SOC_t \tag{8}$$

Before starting the discharge operations, two potential charge/discharge scenarios were considered to assess the available power capacity of the EVs employed in the paper. In the first scenario, it is assumed that EVs are discharged with no DoD limits and are fully charged (100%) at a workplace charging station using renewable-based energy sources. The second scenario, a more practical strategy frequently advised to reduce battery degradation, calls for restricting up to 80% charge and 80% DoD. It is assumed that the EV used in this study is charged at a workplace charging station that is provided with RESs. A detail of these alternative scenarios is given in Fig. 4.

Table 3
EV parameters for discharge operations.

	TESLA MODEL 3	NISSAN LEAF	VW e-GOLF	MERCEDES C Class	MITSUBISHI OUTLANDER
Capacity [kWh]	60	40	32	25.4	12
Distance (Before Arriving Home) [mile]	10	10	10	10	10
Consumption Rate [kWh/mile]	0.25	0.26	0.28	0.22	0.27
Net Power (Before Discharging) [kWh]	57.55	37.36	29.22	23.20	9.3
SOC (Before Discharging) [%]	95.92	93.4	91.31	91.34	77.5
Needed Power (After discharging) [kWh]	2.45	2.64	2.78	2.2	2.7

After calculating the daily travel requirements (D_{travel}) for the EVs, the efficiency of their electric motors, μ_{EV} (kWh/mile), is taken into consideration, and the available power of the vehicles before starting the discharge operations (*NetPower*) and the required power to arrive at the workplace charging station (*NeededPower*) are computed by using Eq. (9) and Eq. (10), respectively.

$$NetPower = P_{battery} - (D_{travel} \times \mu_{EV}) \tag{9}$$

$$NeededPower = D_{travel} \times \mu_{EV} \tag{10}$$

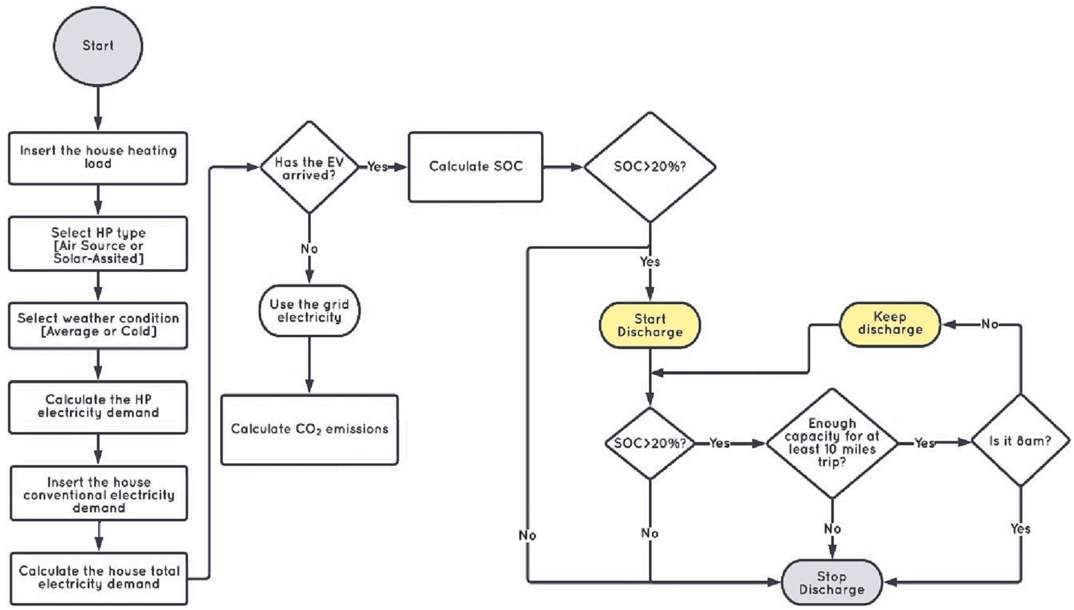

Fig. 5. The proposed model algorithm.

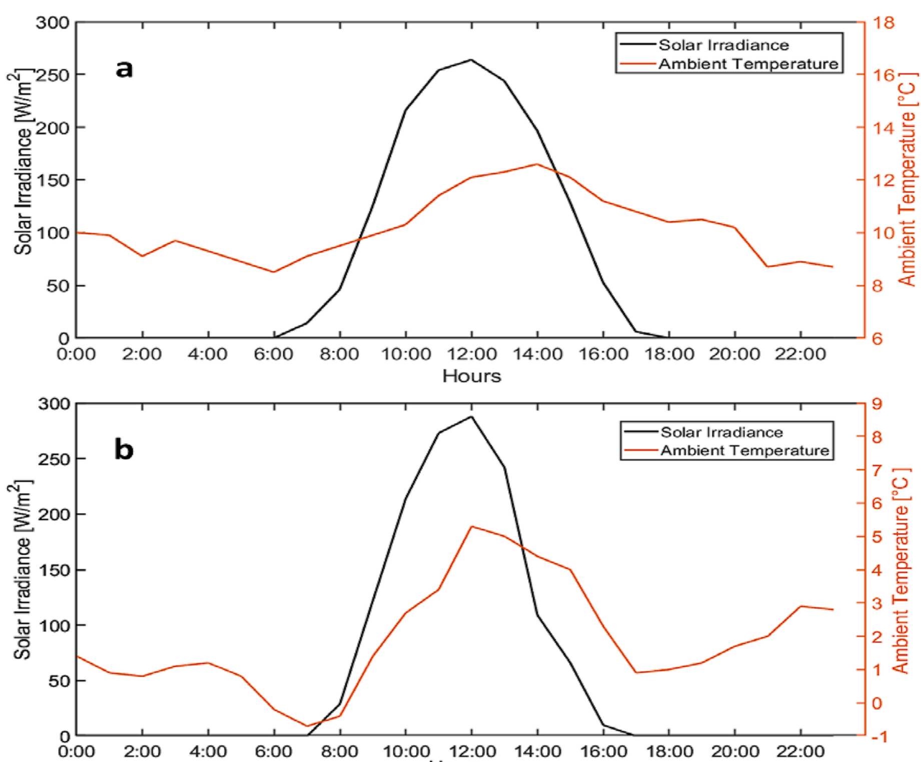

Fig. 6. EnergyPlus weather data for a) average day and b) cold day.

Table 3 provides a summary of all these computations. Some of the parameters shown in the table, such as the capacity and consumption rate of the EVs, are provided by EV-database [33] and Mercedes-benz's website [34]. Moreover, as previously discussed, the distance listed in the table is taken as 10 miles, and all other parameters result from the calculations.

The efficiency of V2H technology is also taken as 90% [38], and the EVs are assumed to be suitable for V2H technology in this study. The proposed model algorithm that manages the house electricity demand and responds to this demand using V2H is shown in Fig. 5.

Additionally, in order to carry out the EV simulation, the given assumptions are considered:

• The EVs are charged at a workplace charging station by renewable sources.

• The EVs are unavailable at home during UK working hours, 8 am and 5 pm. Additionally, the model considers only the working days of the week.

• The necessary technology is available at the grid operators and EVs, enabling V2G discharging.

• The EV user's home has the necessary infrastructure for allowing

Table 4
Solar-assisted heat pump system specifications.

Solar collector type	Evacuated tube collector	Heat pump condensation temperature	70 °C
Solar collector area	50 m^2	Pinch temperature in evaporator	8 K
Buffer tank volume	800 L	Tank heat loss coefficient	0.8 W/(m^2K)
Buffer tank fluid	Ethylene Glycol water mixture (30 %)	Collector pump flow rate	0.033 kg/s

discharging.

- The rate of V2H discharge is assumed to be constant.

3. Results and discussion

3.1. Power consumption in the house

One of the purposes of the study is to investigate the electricity requirement of air source and solar-assisted HPs under average and cold weather conditions. Fig. 6 shows solar irradiance and ambient temperature variations for the average and cold weather conditions. The meteorological data is taken from EnergyPlus software weather data [39]. Fig. 6 shows the average weather data for the 27th of February. The ambient temperature varied between 12.5 °C and 8.5 °C. For the cold day, on the 30th of January, the lowest temperature drops to −0.7 °C.

The solar-assisted HP uses the stored heat in the buffer tank; as long as the buffer tank temperature is higher than the ambient temperature, the HP's performance would be higher than the air source HP. Therefore, transient analysis is required to find the buffer tank temperature. This is performed by using the design conditions because the heat capacity of the tank, heat losses and useful heat input depends on the sizes of the components. The detail of the system components and specifications are summarised in Table 4.

Using average weather conditions and given specifications, Fig. 7 is obtained from the simulations. Fig. 7 shows the heating load to the building and the result of this, temperature change in the buffer tank and the ambient temperature because they have an influence on the heat pump performance. As solar energy is unavailable at night, the buffer tank temperature decreases with the heating load. Since the buffer tank is exposed to heat input and output during the day, the decrement becomes faster when the heating load is higher. Its temperature increases during solar hours, so the COP of the HP increases. Fig. 7b shows the compressor electricity consumption of both HPs. Compressor consumption changes parallel to heating demand as the required refrigerant flow rate increases with the heating load. Therefore, both consumption trends are similar, but the difference increases over time because the air source HP performance remains relatively stable; however, solar-assisted HP performance is improved with solar energy input. Fig. 7c shows COP variations of both systems. The solar-assisted HP COP decreases at night to a minimum of 3.5 and increases in the daytime to 6.6. It follows a similar trend of buffer tank temperature. The air source heat

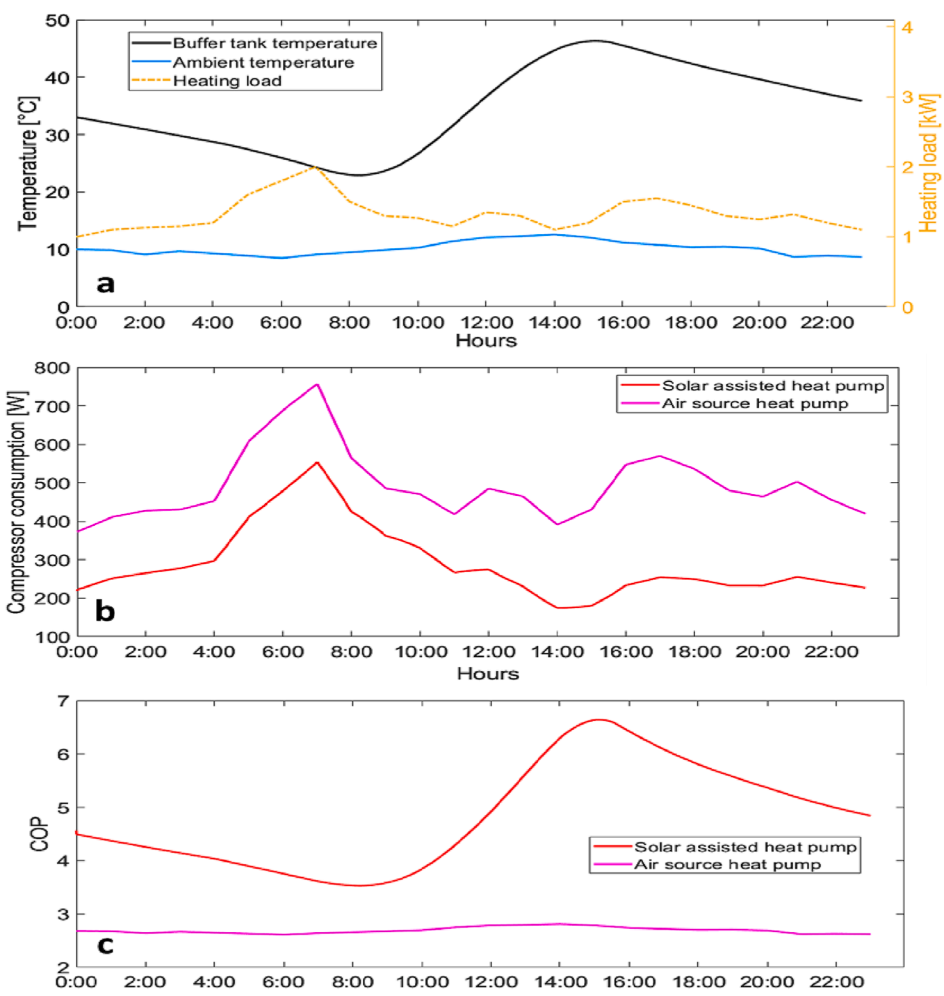

Fig. 7. Comparisons of air source and solar assisted heat pump on average day a) buffer tank temperature, b) compressor consumptions, c) COPs.

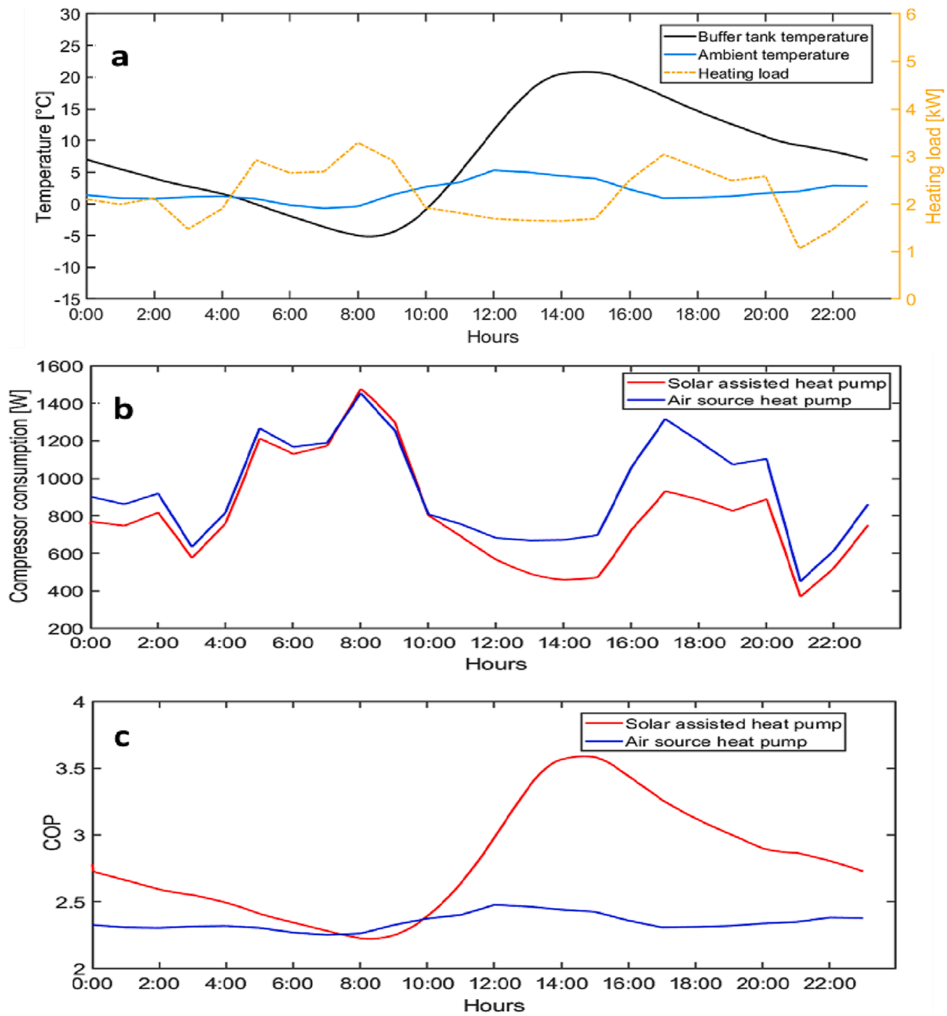

Fig. 8. Comparisons of air source and solar assisted heat pump daily variations on cold day a) buffer tank temperature, b) compressor consumptions, c) COPs.

Table 5
The designed heat pump's average COP and the daily electricity load of heat pumps for the heat needs of the house.

	COP	Electricity Consumption [kWh/day]
Case 1	2.69	11.8
Case 2	4.82	6.9
Case 3	2.34	21.9
Case 4	2.8	19

COP related to ambient temperature reaches a maximum of 2.8 during the day.

For cold weather conditions, Fig. 8 is given for a comparison of both heat pump performances. Fig. 8a shows the heating load, buffer tank and ambient temperatures. On a cold day, heating demand from the building is higher; thus, the HP supplies more heat, and the heat taken from the buffer tank is higher. Moreover, total solar hours are less than an average day, and solar heat input is less resulting in lower buffer tank temperature and lower HP performance. The interesting trend happened in the figure from 4 am to 10 am. During this period, the buffer tank temperature is lower than the ambient temperature, but later it increases by solar energy. Fig. 8b shows the compressor consumption of the HPs. The trends are parallel to each other, but the difference increases from 10:00 to 20:00 as the buffer tank temperature is higher. Regarding COP values, the solar-assisted HP's COP seems lower than the air source heat pump for a period, but it increases and reaches to 3.6 at 14:30.

Table 5 shows a summary of the findings related to the HP system of the house. The calculated average COP and daily electricity consumption for the air source HP on average weather day are 2.69 and 11.8 kWh, respectively. When the solar-assisted HP is used, the figures obtained are 4.82 and 6.9 kWh, respectively. On the other hand, average COP and daily electricity consumption are 2.34 and 21.9 kWh with an air-source HP and 2.8 and 19 kWh with solar assisted HP on a cold day, respectively.

The results show that electricity consumption can be reduced by 41.5% in average weather conditions and 13.2% in cold weather conditions by using solar-assisted HP unit instead of air-source HP unit. It should be noted that that these values were found for using 50 m^2 collector area, the figures would change with different solar collector areas.

Based on the calculated total hourly residential and heating-based electricity consumption of the house for all cases is shown in Fig. 9.

3.2. The first scenario: full capacity usage for discharging

The potential of EVs meeting the household electrical load in specific cases was the theme of the following section of this paper. The EV charge scenario in this section assumes that EVs will be fully charged (100%) at a workplace charging station using renewable energy sources before being discharged with no DoD limits. The study's methodology approach was used to construct each case's hourly EV discharge profiles.

Fig. 10 compares the change of SOCs of EVs during the discharge process in Case 3 and Case 4. The primary distinction between these two

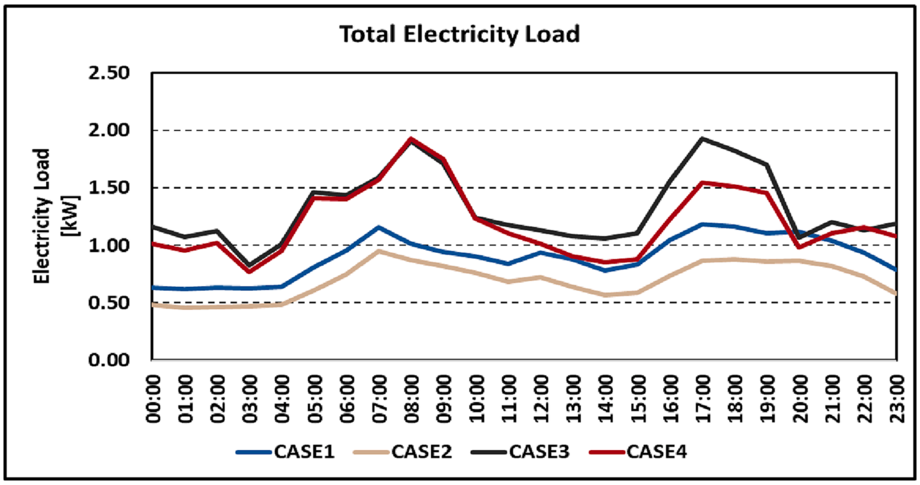

Fig. 9. Total electricity load profiles of the cases, including conventional electrical and heat demand.

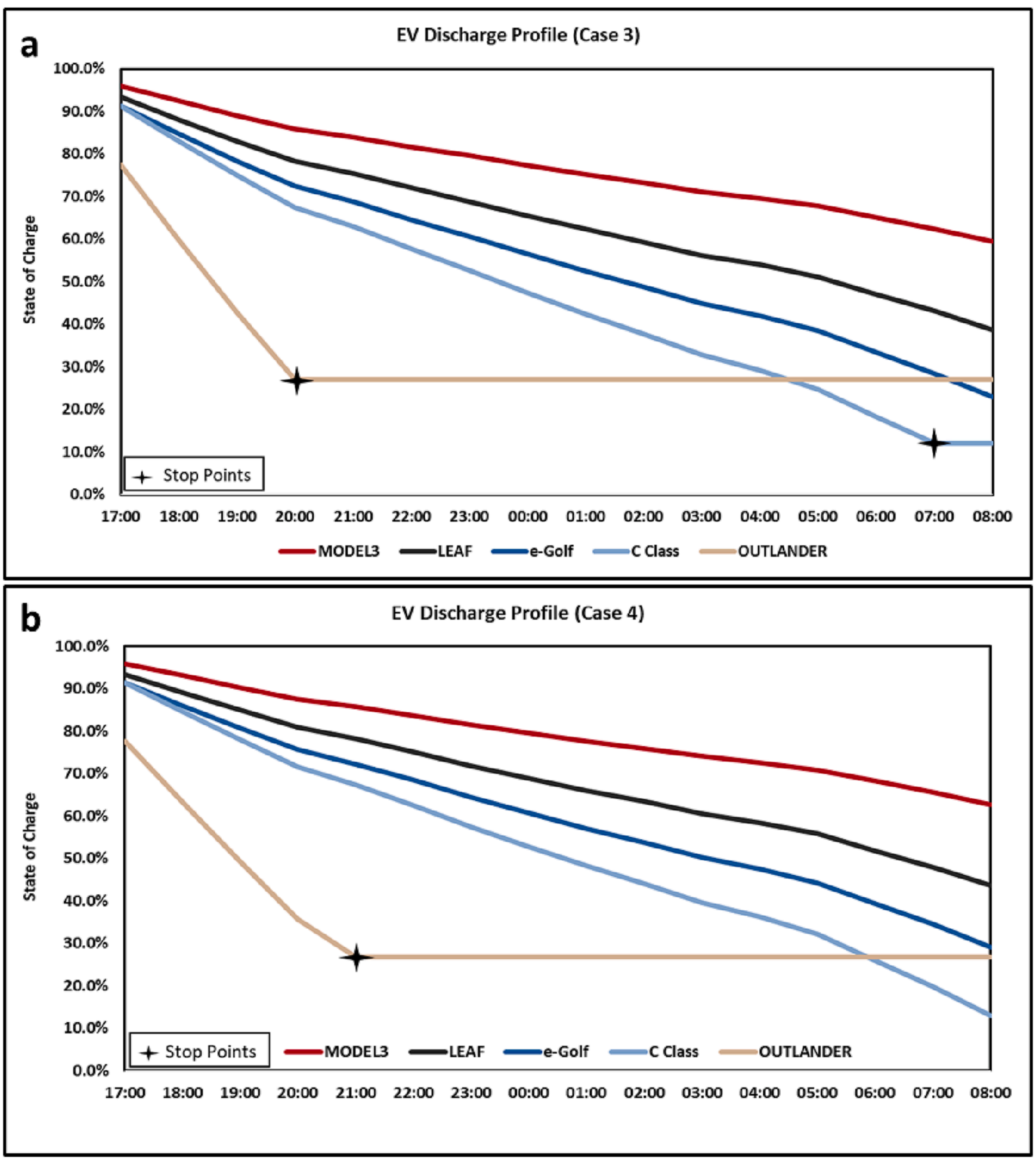

Fig. 10. EV discharge profiles for a. Case 3 and b. Case 4.

Table 6
The SOC of the EVs when arriving workplace.

EVs/Cases	Case 1	Case 2	Case 3	Case 4
Tesla Model 3	67.0%	72.8%	55.3%	58.6%
Nissan Leaf	49.6%	58.2%	32.0%	37.0%
VW e-Golf	36.1%	46.9%	14.1%	20.4%
Mercedes C Class	24.1%	37.7%	3.3%	4.28%
Mitsubishi Outlander	3.1%	3.1%	4.5%	4.1%

*Red indicates situations where the vehicle is unable to handle the entire one-day demand.

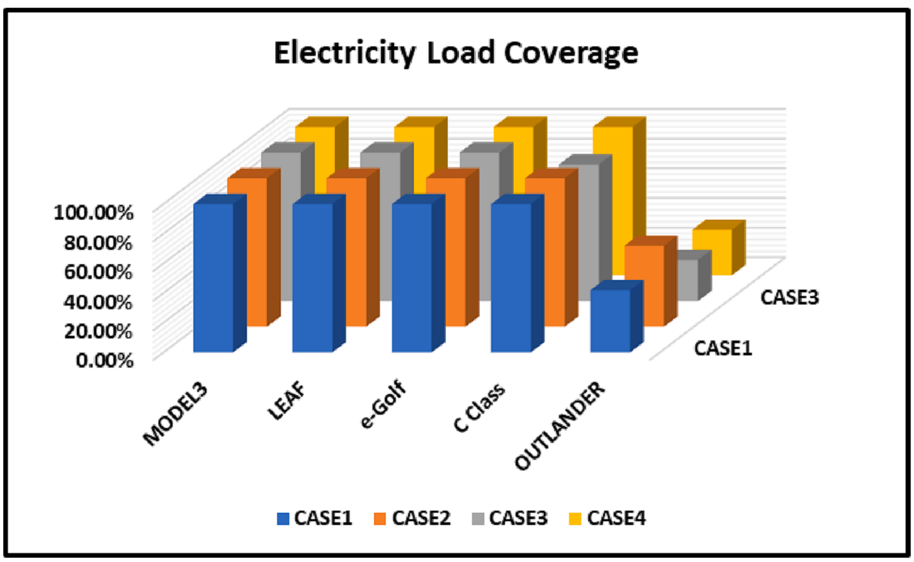

Fig. 11. The proportion of the house demand coverage.

scenarios is that Case 3 employs an air source HP to provide the heating load, while Case 4 utilizes a solar-assisted HP. The highest electricity demand for this study is for Case 3. Case 4 was chosen to show the effects of electricity load reduction. Tesla Model 3, Leaf and e-Golf provide the required electricity demand to the building for both cases. As the Mitsubishi Outlander plug-in hybrid has a small battery, its SoC level already falls under 80% when plugged in at home.

Findings for the Mercedes C Class highlight the benefit of using a solar-assisted HP unit. Fig. 10a depicts that in Case 3, the Mercedes' battery cannot cope with the residence load after 7 am. However, as can also be seen in Case 4 (Fig. 10b), if the building has a solar-assisted heat pump, this vehicle can provide the electricity demand of the building for a whole day. Fig. 10 also shows that using solar assisted heat pump can extend the benefit of V2H by one more hour for the given conditions and methodology adopted.

The results based on the four cases are compiled in Table 6, which indicates the battery level of the vehicles when they return to the charging station for recharging. Fig. 11 also depicts the success rates of the cars in supplying the required electrical energy in each case.

The results show that Tesla Model 3, Nisan Leaf and VW e-Golf (BEV) are suitable for all cases in the proposed methodology. Tesla Model 3 can achieve two days of operation without recharging in all cases, and Nissan Leaf can provide two days of service only in Case 2. However, in all cases, VW e-Golf can respond to the house load only for one day. It needs to be recharged for the following day.

Looking at Table 6, it is apparent that vehicles such as Mitsubishi Outlander PHEV with a small battery are unsuitable for the proposed methodology in all cases. Even after accounting for travel needs, Mitsubishi's battery still has 6.6 kWh of power. This amount of electricity can be used to satisfy the peak evening electricity demand using a smart charging algorithm. This may smooth out the peak stress on the supply mechanism. This is an indication of the importance of using V2X technology with the smart charging approach.

Fig. 11 shows that the entire electrical load is always covered by the Tesla Model 3, Nissan Leaf, and Volkswagen e-Golf. Mercedes supported 100% of the total load of the house in Cases 1, 2, and 4 but only 92% of the load in Case 3. An additional 3.36 kWh of electrical load is required from the grid as a result of this circumstance. The most successful Outlander scenario, on the other hand, is Case 2, which has the lowest load requirement. The Outlander can carry roughly 55% of the load that should be carried by EVs in this case.

3.3. The second charge scenario: limited capacity usage for discharging

In the second scenario of the study, it is assumed that automobiles are charged up to 80% and that SOC cannot fall below 20%. In practice,

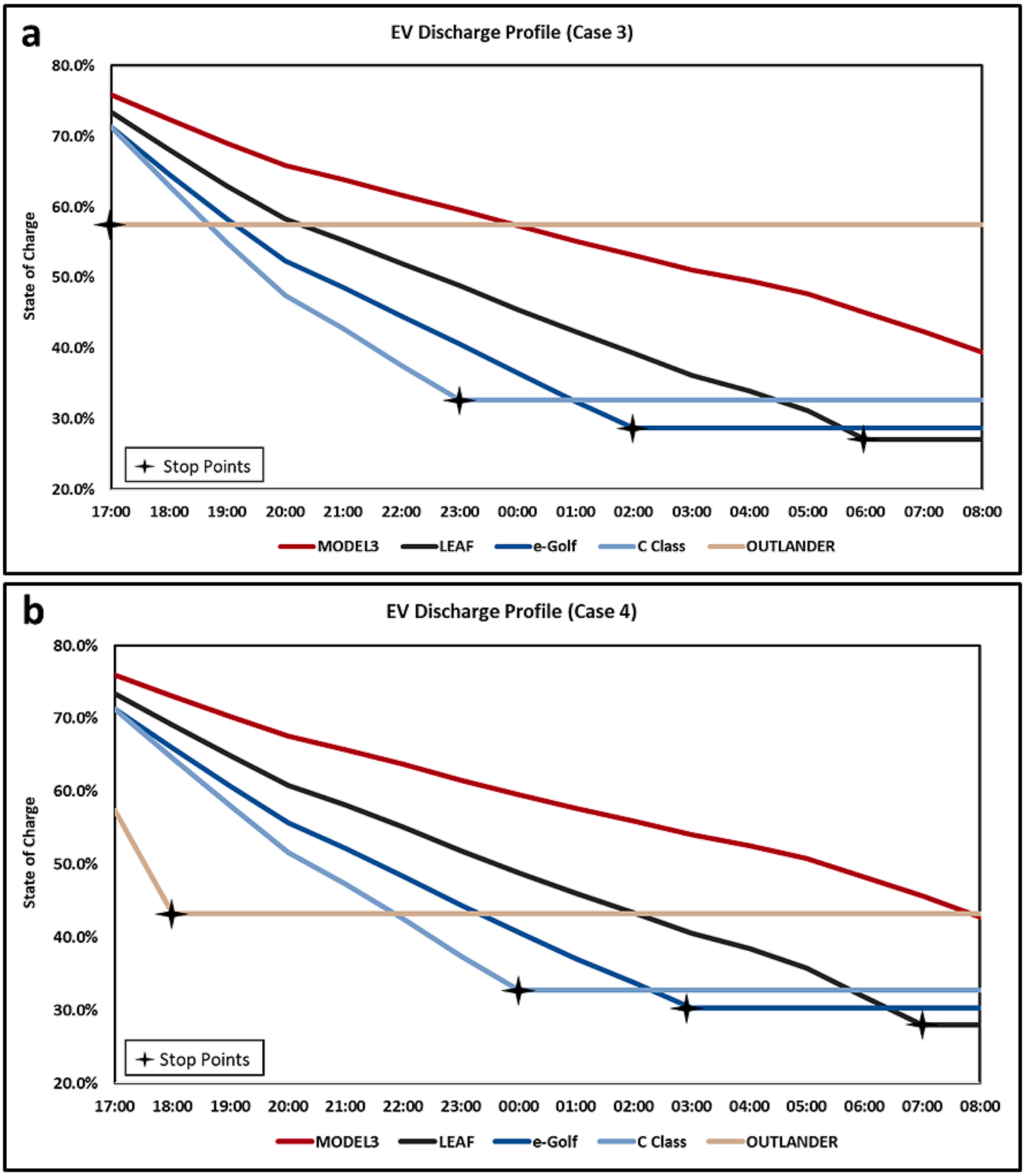

Fig. 12. EV discharge profiles for a. Case 3 and b. Case 4.

this charge/discharge model is usually advised. There have been numerous numbers of research recommending a charge range between 20% and 80% or a maximum of 90% to mitigate battery degradation and electricity loss throughout the charge/discharge operations [40,41].

For the second charging scenario, the graphs created for the first charging scenario—showing the EV discharge profiles and demand response rates—were updated, and displayed in Figs. 12 and 13, respectively.

Most vehicles cannot provide the required daily load of the house compared to the prior charging scenario. The only car that can handle the entire demand in any situation is the Model 3, which has a high-capacity battery. Mitsubishi Outlander cannot provide even one-hour electricity to the building in Case 3 as its SoC is lower than 60% because of the distance from the charging station to the home. However, it can provide one-hour electricity in Case 4.

Regarding to the average weather scenarios in Cases 1 and 2, Tesla and Leaf can achieve 100% of the demand response in both cases. However, e-golf is another EV that may contribute to the entire electricity load of the house only in Case 2 because of the lower demand.

As seen in Fig. 13, even in the worst case, vehicles still contribute significantly to the total load of the building, even when their battery level does not fall below 20%. In the worst-case situation, the Nissan Leaf, VW e-Golf, and Mercedes C class could cover 84.66%, 62.25%, and 44.88% of the household's total electrical load (conventional and heating), respectively.

This scenario shows the importance of battery capacity (kWh) and range (miles/charge). At least, they have been climbing thanks to advancements in battery technology [8]. Given the success of Tesla in this charging scenario, it is almost likely that more EVs will be joining it in the near future.

3.4. *Environmental analyse*

If the total electricity demand of the house is met through V2H, as mentioned above, the excess renewable electricity generation could be fed into the grid. In addition, with this method, the stress to be created on the grid by HPs, which will increase in number in the future, may be reduced through EVs and renewables. More importantly, zero-carbon

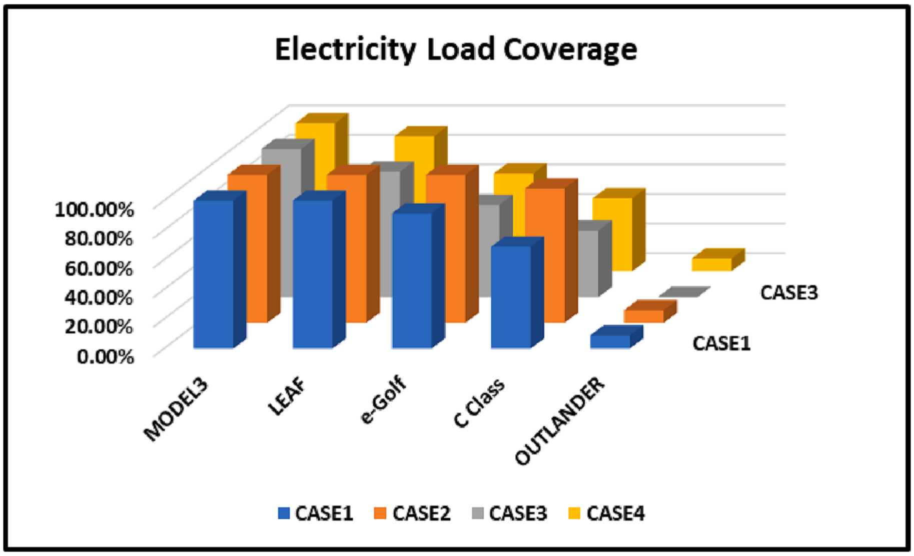

Fig. 13. Proportion of the house demand coverage.

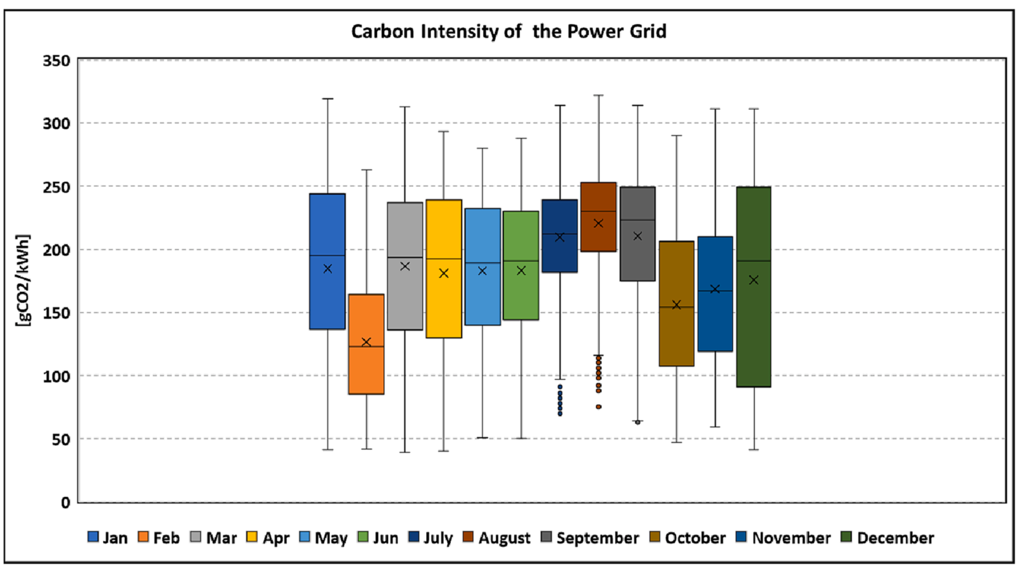

Fig. 14. CO_2 emission of the GB's electricity networks.

targets can be supported by reducing carbon emissions through the cooperation of RESs, EVs and HPs.

An environmental analysis was conducted to investigate the approach's effects in mitigating carbon emissions. Data on half-hour carbon emissions provided by the Electricity System Operator of Great Britain (GB) (National Grid ESO) [42] was gathered and examined. The results showed that in 2022, the lowest monthly carbon density of the GB network occurred in February, with 126.57 gCO_2 per kWh of electricity, and the highest carbon density in August, with 220.59 gCO_2/kWh. This discrepancy can be attributed to the fact that electrical energy produced from renewable sources climbed by about 50% in February compared to August, while output from fossil fuels declined by around 50%, according to National Grid ESO's history of the carbon intensity of generation statistics [42]. Additionally, a basic average calculation showed that the GB network emitted 182.11 gCO_2/kWh of carbon dioxide annually on average in 2022, according to calculations. This average value was also used for CO_2 emission calculations of HPs and the proposed V2H system. The detailed monthly change in carbon emission amount can be seen in Fig. 14.

A comparison of three scenarios in which the electrical and heating demand of the home is supplied by various technologies was done in order to better understand the impact of the suggested approach on cutting carbon emissions. The first two scenarios discuss situations in which the entire home's electrical demand is fulfilled by the grid and the heating demand is met by the boiler or a heat pump, respectively. The last depicts the situation in which, using the methodology of this study, V2H would provide all of the electrical energy for the property. Regarding gas boiler emissions, it is reported that new gas boilers should have an efficiency rating of A and B, which emits between 210 and 230

Table 7
The amount of daily GHG emissions from the house electricity usage.

	Boiler + Grid [$kgCO_2$]	HP + Grid [$kgCO_2$]	V2H [$kgCO_2$]
Case 1	9.09	3.92	1.49
Case 2	9.09	3.03	1.16
Case 3	13.82	5.76	2.18
Case 4	13.82	5.24	1.98

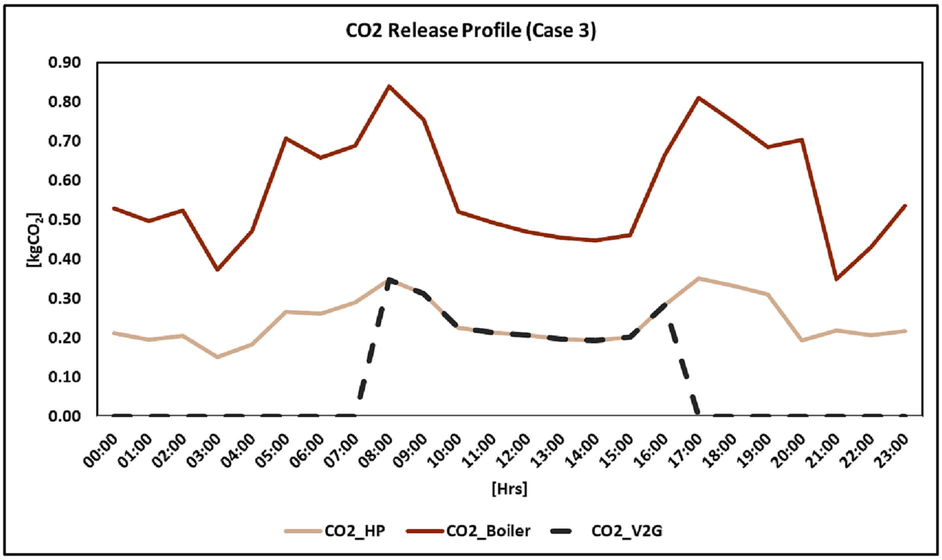

Fig. 15. CO2 release for the three mentioned systems.

gCO_2eq/kWh. Also, it is known that in 2014, 53% of boilers in the UK complied with this criterion [43]. Therefore, 230 gCO_2eq/kWh carbon footprint has been used in gas boiler carbon emission calculations. Table 7 lists the total carbon emissions emitted by the home based on the three scenarios. Moreover, Fig. 15 represents the hourly CO_2 release curve for Case 3, which has the highest electricity demand.

In summary, it has been observed that the proposed methodology can provide a serious reduction in the carbon footprint of the house. Compared to the boiler system, the introduced V2H project in the paper can achieve up to 85.6% reduction in carbon emissions under cold weather conditions. This rate is also 87% under average weather conditions because the contribution of the solar-assisted HP was higher in average weather conditions due to a better solar irradiance profile. Moreover, it has been concluded that the proposed V2H system might recover up to 21.9 kWh/day of excess renewable energy on cold days and 14.87 kWh/day under average weather conditions. However, it should be noted that this study only analyses one house and one vehicle. Therefore, considering the national models in which future scenarios are included, a considerable amount of RESs may be integrated into the grid system, and the high amount of emissions from residential loads can be minimised.

3.5. Further discussions

The paper's findings provide an essential contribution to the larger discussion on energy efficiency, renewable energy, and the development of smart buildings. The results of this investigation illustrate how V2H technology may enhance energy flexibility by minimising dependency on power from the grid during shortage periods. This supports the conclusions of researchers like Li et al. [9], who claim that the efficiency and sustainability of the energy system may be improved with the usage of flexible energy.

The presented research findings are consistent with and expand upon existing knowledge compared to similar research that looked at relevant technology or objectives. García-Vázquez et al. [13] noted the potential of Vehicle-to-Grid (V2H) technology in providing an outstanding self-consumption by avoiding grid stress. Similarly, Slama [44] showed that V2H technology in homes whose electricity demand is met by solar PV has a high potential to meet the required power of the grid during peak hours. Based on this, the investigation analyses the yet-to-be-explored potential of V2H technology in managing electrical demand as well as powering household heat pumps, a subject that has received less attention in the literature recently.

This research has many possible real-world applications and has the potential to have an impact on many different stakeholders. Homeowners, for instance, may better understand the potential benefits of V2H technology. This is supported by studies like Garca-Vázquez et al. [13], which demonstrated how V2H technologies could potentially save money for homeowners or EV owners. Furthermore, our results underscore the benefits of V2H to balancing grid load, echoing Amani et al. [45] emphasis on the potential of V2H in keeping the grid voltage within the acceptable range by enhancing grid stability. This could motivate energy providers and decision-makers to make supportive regulations and incentives to advance the adoption of such technologies.

4. Conclusions

This paper reports the findings of a research investigating the maximum interaction between EVs, RESs and HPs. The paper also has evaluated the effectiveness of different EVs with V2G/V2H technology for demand response, by considering the heating loads of the UK buildings under cold and average weather conditions. Five different EVs in the market have been examined, and two different charging-discharging scenarios were adapted. A comprehensive heat pump model was built, and air-sourced and solar-assisted heat pump cases were compared. Based on the analysis, the conclusions are drawn as follows.

- Air source HPs can operate at a daily COP of 2.69 on average and 2.34 on cold days. While solar-assisted HPs would operate at COPs as high as 4.82 and 2.8, respectively. Compared to the air source HPs, the improved COP in solar-assisted HPs results in a lower electricity consumption amounting to 41.5% and 13.2% for average and cold days, respectively.
- Switching the air source HP to solar-assisted HP units will offer up to one hour more EV discharging service for the house's electrical load.
- In the first charging scenario (to 100% SoC), Tesla Model 3, Nissan Leaf, and VW e-Golf provided all daily required electricity to the building in each condition.
- In the second charge scenario (to 80% SoC), Tesla is the only vehicle that covers 100% of the electricity requirement in all cases. Nissan Leaf can also cope with the demand in Cases 1 and 2. However, e-Golf may contribute to the entire electricity load of the house only in Case 2.
- It has been concluded that EVs, with a battery capacity of as high as 40 kWh (i.e., Nissan Leaf), could not provide the whole day's

required electricity in cold weather conditions (Case 3) due to charge/discharge restrictions, battery efficiency and daily travel needs.

- Another finding shows that EVs, with a battery capacity of as high as 60 kWh (i.e., Tesla Model 3), can supply the whole day electricity load of the residence in average weather conditions (Case 2).
- It has been found that the proposed methods can significantly reduce the house's carbon footprint. Compared to the boiler system, the introduced V2H project in the paper can achieve up to 87% reduction in carbon emissions under average weather conditions.
- The proposed V2H system could reduce the carbon footprint of a conventional residential build by up to 87% and recover up to 21.9 kWh/day of excess renewable energy on cold days and 14.87 kWh/day on average days.

This approach will also prove helpful in expanding the understanding of how EVs and HPs might be used as solutions to minimise carbon emissions and the impact of the large-scale RES integration into the grid instead of a challenge that adds additional electricity load into the system.

On the other hand, more research would help us to establish a greater degree of understanding of the effectiveness of EVs with V2X technologies on demand response by improving the RE integration. Although the current study is based on a small scale of applications such as a house, the findings suggest that the present approach should be assessed on a community scale. Additionally, in this future study, it will be important to consider all essential parameters together such as energy generation, consumption, and EVs' charging and discharging events by stochastically modelling all uncertainties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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