

## Article

# Practical Validation of nearZEB Residential Power Supply Model with Renewable Electricity Brought into the Building Using Electric Vehicles (via V2G) Instead of the Distribution Network

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**Abstract:** This article attempts to estimate the potential of supplying a residential building in Europe with energy exclusively from RESs during a whole year, including the heating period. The aim of the tests carried out was to minimize the purchase of energy required to achieve the thermal comfort (HVACR + DHW) of a residential building powered solely by electricity. During the tests carried out, the EVs were used by the residents as their daily means of transport, topped up during working hours, and the excess energy remaining in their batteries was discharged into the building when they returned home. Energy for the EVs/PHEVs was sourced from RESs (mostly for free) while they were parked at the workplace, and also on the way home. Two one-month tests in the spring and autumn resulted in a state where, instead of purchasing a significant volume of black energy from the grid, the building was mostly powered by green energy from roof-top PVs and RES energy brought in by the PHEVs/EVs. This study identified days when the building became a real nZEB, which was not possible in previous years. The results of economic gains and carbon footprint reduction were calculated. After a period of testing, the degree of degradation of traction batteries used to carry the energy of EVs/PHEVs was checked. A high potential for such an operation was identified, especially in areas where there are periodic shutdowns (due to a call from the grid operator) of local RESs situated near the residential areas. The proposed solution may be of interest to all countries where the use of grid energy is associated not only with a doubling of costs (grid charges), but also with significant emissions, particularly in the heating period (e.g., Poland).

**Keywords:** photovoltaics; electric cars; energy management; vehicle-to-grid; renewable energy; RES surplus; energy storage BESS



Received: 16 April 2025  
Revised: 14 May 2025  
Accepted: 23 May 2025  
Published: 27 May 2025

**Citation:** Biskupski, J.A. Practical Validation of nearZEB Residential Power Supply Model with Renewable Electricity Brought into the Building Using Electric Vehicles (via V2G) Instead of the Distribution Network. *Energies* **2025**, *18*, 2786. <https://doi.org/10.3390/en18112786>

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## 1. Introduction

In “the average” and even “the cold” climatic zones of Europe, nZEB residential houses are increasingly powered by electricity alone and have the potential to become energy self-sufficient thanks to the RESs installed in their surroundings [1]. Such houses do well in the summer (partly in autumn/spring) at obtaining the required energy from local rooftops and grid-tailed PVs. The energy yield from the sun and the energy storage system (BESS) in a correctly designed PV installation is sufficient to cover all the energy needs of a sustainable household during the warm part of the year [2]. This represents a very important aspect of reducing emissions both locally (by switching from fossil fuel DHW boilers to heat pumps) and regionally (by discontinuing inefficiently sourced and

pollution-emitting ‘black energy’). The real challenge remains to obtain energy (mainly for heating and hot water) during autumn and winter, so that the nZEB status of the building is also maintained during this time. The practice of PV installations in Poland shows that the amount of energy generated from a roof-top PV installation is sufficient to cover the building’s needs from May to October each year. However, from November to April, as the amount of energy from the sun reaching a mean household is NOT sufficient to ensure the energy independence of the building (nZEB) nor to ensure zero GHG emissions. Thus, during the 5–6 month heating season, even in buildings that achieve nZEB status during the previous part of the year, there is still a need to deliver black energy, most often from coal combustion, which in practice excludes them from the group of zero-energy (and zero-emissions) buildings throughout the year. For homes powered solely by electricity (in Poland), this means in practice that most of the energy consumed from the grid during the heating season is black energy generated from burning coal, which emits at least 800 kg of CO<sub>2</sub> for every single MWh of electricity (of final energy). On the other hand, during the summer, there is a natural surplus of energy from PVs in such households.

The national support system in Poland applied between 2015 and 2021, the so-called “Polish net-metering model”, allowed the excess energy from a domestic PV installation to be injected into the grid in the summer and redeemed in the winter in a ratio of 1:0.8 (given vs. redeemed), which partially solved the problem, allowing the distribution network to be treated (from the prosumer’s point of view) as a 12-month storage facility. This worked well because people learned how to expand their RES installations so that, with excess energy in summer, 80% of the energy regained in winter was enough for them to power heat pumps for the entire heating season. However, after passing the first million prosumer PV installations in Poland (there are in total about 7 million households in Poland), a problem arose on the part of utility energy suppliers, who were forced (by the aforementioned “Polish net-metering”) to increase their production (and thus their emissions) during the heating season in order to give back the energy transferred by the prosumers to the grid in summer. This has led to a very dynamic increase in PV capacity in Poland in just 6 years—up to 10 GW. On the other hand, it also turned out that all mid-size RES plants (50–1000 kWp) have had to periodically and unpredictably reduce their energy production in the summer period, due to the existing excess of rooftop RESs, even in periods like autumn or spring. In Poland, there are currently more than 21 GWp PVs installed, plus 12 GW in wind, with an energy system total demand of 25 GW. The net-metering system in Poland has, since 2022, been changed to a net-billing system, implemented as the necessity to sell surplus energy to the grid at fixed prices, practically always much lower than the price of energy purchased by prosumers. Such a system discourages prosumers from using PV electricity for heating purposes and currently causes a new trend towards a return to burning fossil fuels and biomass stoves in detached buildings. This problem will become particularly important after the implementation of ETS2 in Europe. On the other hand, the dynamic growth of PV power in Poland results in periodic calls to turn off (de-grid) midsize PV installations and consequent potential interest in P2P transactions and EV/PHEV charging as alternatives. This was also observed by researchers in other European countries claiming that V2G technology can help large-scale integration of RESs [3–6]. In Poland, in March 2024 alone, the reduction in production due to lack of grid capacity amounted to about 53 GWh of wasted, not generated green energy. The Polish definition states that a zero-emission building is a building that uses only energy and heat from renewable sources. Literature on the topic [2,7] and experience clearly indicate that this is not possible in Central Europe due to insufficient sunlight during the 6 colder months of the year. The question therefore remains as to which of the possible methods of supplying

energy from RESs, other than that generated in the vicinity of a given building, could meet this requirement and whether this would be possible at all.

This article considers a potential solution to this problem, in which instead of switching off PV sources, it would be possible to provide energy for free (or at a contractually attractive price on a B2P basis) to prosumers for charging electric cars, who could then highly efficiently auto-deliver the energy to residential buildings at the time it is needed there for living purposes. Analyzing the problem point-by-point, on 10 March 2024 alone, about 10 GWh of energy was wasted in Poland (by demanding mid-size PV turn-offs), which could have been used to drive about half a million kilometers in EVs/PHEVs, not to mention how much of this energy could be used to provide heat for households. For example, the use of heat pumps (26 GWh) could provide heat on that day for several hundred thousand households in an emission-free manner. In the author's opinion, this presents huge potential for reducing emissions, especially in small cities, on the outskirts of which PV farms are increasingly being installed. On the other hand, RESs and EVs/PHEVs have huge potential to stabilize the operation of the grid [6,8], but, already at this stage, it is apparent that the simplest solution of feeding energy from the RES farm directly to the end user (e.g., by V2G, V2H), could easily limit periodic problems with excess energy in the grid. Such potential concepts have already been discussed in the scientific literature [9].

This is a problem for all of Europe, as the dynamics of progressive switch-offs and negative prices in Europe are beginning to assume dangerous proportions, suggesting an emerging serious—and still unsolved—problem. The Financial Times summarized the 2024 press releases, and found that while 675 h of negative pricing occurred in Europe in 2019, for the first eight months of 2024, exchanges have already recorded 7841 h of negative pricing on our continent [10]. The idea of using electric vehicles topping up when renewable generation is high and discharging when peak demand is high was proposed by Kempton [3,11] as early as 1997 and it is surprising that it has still not been widely applied in European countries. However, charging EVs at home in the evening can pose a significant challenge to the local grid [3]. Most of the articles referring to this problem [3], try to solve it globally, by introducing different mechanisms like arbitrage, load shifting, emergency back-up, frequency regulation, and load shifting, managed by large, expensive and extensive cloud data applications [4,12–19]. The author is of the opinion that the potential solution lies much closer than it seems: allowing, for example, transactions between an energy producer who is threatened with shutdown and an end consumer who needs the energy and could bring it themselves, e.g., in their own EV/PHEV with V2G functionality. This solution was described in [7] for a small residential area of single-family houses. Most modern prosumer PV systems with energy storage (BESS) already have the option of connecting an external RES, such as CHP or EVs, to a household, almost as a 'plug and play' solution [20]. According to the author's interviews with PV mid-size farm (50–900 KW<sub>kp</sub>) owners, they would be willing to invest very quickly in EV/PHEV chargers with BESS at their farms, if only the option to release energy when the grid manager (that tells them to switch off their PV generators) would be allowed.

The main objective of the article is to test in practice the thesis of year-round zero emissions in a residential building that has NOT undergone deep thermal renovation. In Polish conditions (as probably in other European countries), the thermal modernization process, as described in a previous article [21], is a complex process and not always economically justified. In such a situation, will the majority of buildings in Poland (5 million) never be able to achieve nZEBs and zero emissions? In the article, the author set himself the goal of calculating how much energy from RESs would need to be supplied to such a building (during periods when own production from roof-top PVs cannot be counted on) and how

to do this so that the building could be considered nZEB or even zero-emission throughout the year.

In addition, the experiment posed three open research questions:

(1) Can EVs and PHEVs efficiently transfer electricity between local RESs temporarily in surplus (e.g., threatened with shutdown by the National Grid Operator or during negative price periods) to temporary under-supplied residential buildings? And, would this also be possible during the heating period (autumn–winter)? Does the capacity of modern EVs/PHEVs and the potential for energy transfer allow them to be considered as an alternative means of energy supply to the end user? Could such a model, in time, become an alternative to the grid for the distribution of RES energy between the RES generator and its end user?

(2) How can such a supply be organized? Would it be possible to charge cars, e.g., at a RES farm near the occupants' place of work or at a PV parking car-port where the car is parked during work, or at a city car park, and then unload it at home? Is this convenient for the users to do during regular working hours (8–10 h daily)? Does such an operation make economic sense for a household? Would it fulfil the model of local energy exchange (recommended, e.g., in the UE Directives) between producers and users (peer-to-peer)? Could such action be applied already today between consumers and energy producers through the use of EVs/PHEVs? How many such cars would have to circulate daily so as not to interfere with the normal use of cars as a means of transport?

(3) Is this use of EVs/PHEVs economically viable from the point of view of the wear and tear of the vehicles themselves? And, does it not degrade the traction batteries to such an extent that they would need to be replaced sooner and the energy savings thus made would be spent on overhauling the traction batteries?

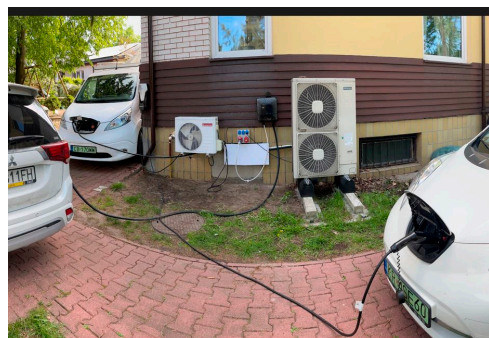
Following the research results an attempt to answer the research questions posed can be found in Appendix A.

## 2. Materials and Methods

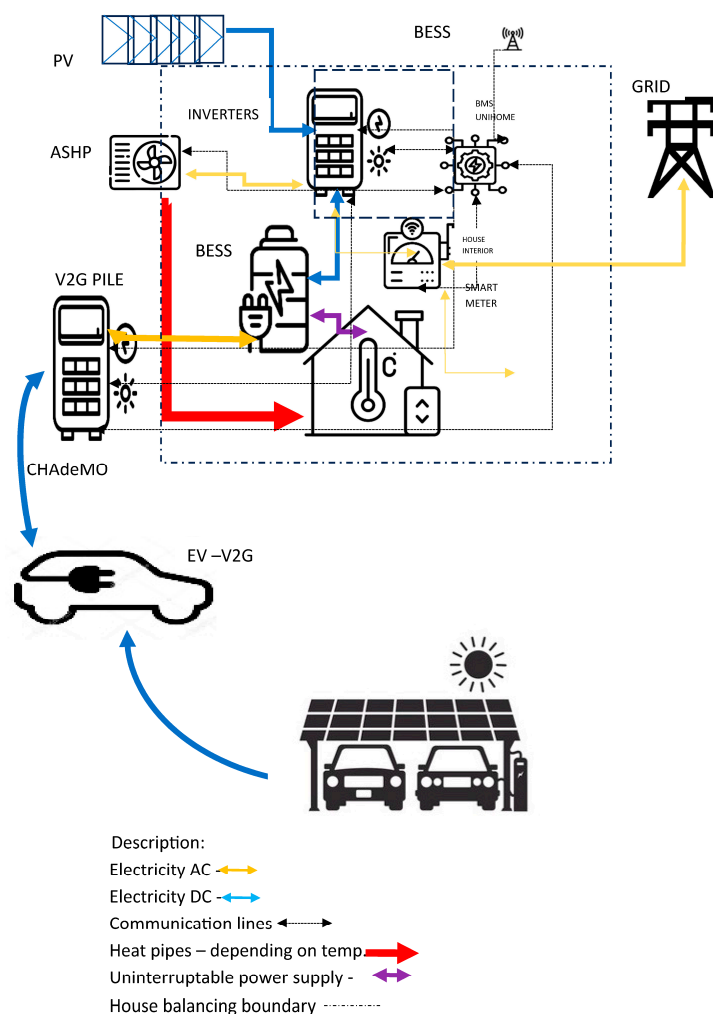
### 2.1. Test Laboratory

For the in situ test, we selected a single-family (Fot1) 1978 house with high energy consumption, located in central Poland, in the city of Legionowo, with a 20 kWp hybrid rooftop PV installation and a 14–54 kWh BESS. In the initial stage of the experiment, various possibilities for reducing energy consumption were analyzed, including different energy supply scenarios, inputs, and expected effects, making further approximations based on the author's previous nZEB projects [2,21]. As a preliminary step, some basic thermo-modernization work was undertaken on the test building (replacing the windows and doors, sealing the envelope to  $n_{50} = 1$ , installing a ventilation system with recuperation). These measures reduced the final energy demand from 250 kWh/m<sup>2</sup> year to ~160 kWh/m<sup>2</sup> year. Advanced building energy management systems (BMS/EMS Uni-home v.11) were introduced, but even the introduction of BESS and a significant increase in self-consumption could not solve the fundamental problem of having to buy significant amounts of gas in heating season (November to April). The primary objective became to eliminate natural gas (GHG emissions) and use RESs in this building so that they would be sufficient during heating periods. For heating purposes, two ASHP heat pumps were installed—a small one (3 kW) for hot water (DHW) and a large one (12 kW) for heating/cooling (as an alternative to the existing natural gas boiler)—as shown in Figure 1. Due to the high-temperature heating system (radiators) already present in this house, a Hitachi Ras 14 dual compressor high-temperature air source heat pump was selected. In addition, three BEVs/PHEVs—a Nissan Leaf (traction battery capacity of 42 kWh), a Nissan eNV200 Van (62 kWh), and a Mitsubishi Outlander PHEV car (20 kWh)—were also used for the ex-

periment in this household, all of which have a built-in two-way in-vehicle charger (V2G) with a CHAdeMO connector. Three EV chargers were installed in the building—one V2G (Octopus 6 kW) CHAdeMO Type 2 AC synchronized with the PV installation (as shown on Figure 1) and one V2H (Electway 6 kW) CHAdeMO (in House). Also 14–54 kWh BESS kit (gradually introduced during the experiment from 14 kWh to 54 kWh). The whole system was connected to and managed by the EBMS Unihome v 11 system (designed by the group of researchers led by the author), working together with the SEMS PV supervisory system delivered by GoodWe (that manages the PV inverters and the AC EV charger and some BESS). The final setup is shown on Figure 2.



**Figure 1.** System components connected to the test house (Photo J.A.Biskupski).



**Figure 2.** Brief description of test concept. 1st—BEV loaded at RES car-port, 2nd—home powered with V2G charger uses the remaining energy in car's battery.



## 2.2. Research Prerequisites

Prior to the experiment, it was observed that the test household's two BEVs (Nissan EVs) travel about  $30 \pm 10$  km per day, in urban conditions most of the time, which means that, once fully charged, most of their electrical capacity is not used during the day or even the week. It is theoretically stored for longer journeys, which, in the case of fixed, short local routes to-and-from work/school, turns out to be very infrequent in real life and practically this energy is never used. The role of the longer-route vehicle has been taken over by the PHEV car (Mitsubishi Outlander), offering much more convenient on-road energy performance (i.e., refueling also at petrol stations and much better total range), while allowing local driving in EV-only mode and discharging into a building. It has also been noted that a BEV with a nominal capacity of 62 kWh, discharged to 12 kWh, has the same traction utility as when it has a 100% of battery capacity, and it makes no difference to drivers whether they drive the car fully charged or at 20% capacity available (because fully charged traction batteries are no heavier than discharged batteries, so energy consumption is the same). In practice, therefore, the car is recharged most of the time at 80 or even 100% of battery capacity, and the energy remains 'locked up' and unused in the vehicle. Users of these vehicles have the option of recharging them for free while they are at work and, in addition, the experiment made use of the free charging stations of one of the supermarket chains, which allowed free charging while shopping with them, without limiting the amount of energy charged. In this way, free energy was obtained in vehicles for testing, which could reach up to 100 kWh per day.

At the same time, in Poland, PV farms and even independent generators (not utility scale plants, but midsize PV plants) with their own side installations (e.g., car ports for employee car parks), if only synchronized with the national grid, are forced to switch off by the grid operator (PSE) during times of excess energy in the grid (expected 24-h energy surplus). For or such a shutdown of a PV farm after a year of waiting for settlement, they receive less than 10% of the value of the energy that could have been produced during that time [22]. At one such PV installation (150 kWp car park), it has been proposed that employees, including residents of the test household, can periodically harness energy from the DC and AC chargers to BEVs. This proposal creates the opportunities described in research and was used by the residents of this house in the test.

Between November 2023 and November 2024, a series of tests was carried out using the free electric car chargers in the PV installation and the chargers of the discount network. The setup is shown in Figure 2. The results were obtained in March, April, and November 2024, when, due to the low production from the PVs and the high energy demand (the heating season), there was high demand for energy in the household. The tests were conducted every day (this was also when the discount store offered energy for free to the EVs, allowing two cars to be charged per day) in the test period. Two representative monthly periods were selected for analysis: autumn (November 2023) and spring (March–April 2024). The data came from records at DSO PGE and from the Quasar and Sems+ applications.

## 2.3. Theory Applied

As mentioned in the introduction, a building in which all energy consumption devices can be powered by electricity was selected for conducting tests. The final energy demand of such household  $E_{cons}$  (for 24 h test period) can be described by the following Formula (1)

$$E_{cons} = \sum_{i=0}^n P_i \times t_i \quad (1)$$

where

$E_{cons}$ —household total electricity consumption for given (24 h) day (in kWh);

$P_i$ —rated power of active appliance (in kW);

$t_i$ —daily usage time of appliance  $i$  (hours).

The energy will come from PVs and EVs. However, not all the energy charged by the EV/PHEV will be available to the building, as some of it will be used for traction purposes (vehicle travel) and climate control (vehicle heating and cooling). Daily energy brought (Edeb = real amount) to the household can be expressed as

$$E_{deb} = E_{chg} - E_{drive} \quad (2)$$

where:

Edeb—daily energy brought to the household;

Echg—energy acquired from chargers outside the household and available from EVs;

Edrive—energy used to drive home (and climate) from the workplace with the charging station.

Charging and discharging losses for the DC CHAdeMO connector can be assumed to be 6% for a single process and 10% for a round trip (empirically verified value), so we introduce the efficiency constant  $a$ .

The amount of energy remaining available for V2G will be

$$E_{drive} = aS_{daily}/\eta_{EV} - u \quad (3)$$

where:

$S_{daily}$ —the distance travelled by residents per day, here approx. 15 km to and 15 km from the workplace;

$\eta_{EV}$ —EV efficiency expressed in km/1 kWh. Empirically determined values were as follows:  $\eta_{EV}$  for Outlander = 5, for Nissan Leaf = 6.66, for Nissan eNV200 = 5.55;

$a = 0.9$ ;

$u$ —empirically determined constant, resulting from the need to use energy in BEV batteries to heat/cool the vehicle on the section used. For a section of 30 km per day, it was empirically determined to be approx. 1 kWh.

For example, one day, Nissan Leaf was able to use  $E_{drive} = 0.9 \times (30/6.66) - 1 = 3.05$  kWh and  $E_{deb} = 43.05 - 3.05 = 40$  kWh.

Energy balancing in the house balancing boundary is shown in Figure 2. The energy balance for the test period (24 h), described by Formula (4), is to be calculated (using data from the smart meter) by BMS/EMS to zero export and zero import.

$$E_{house, \pm BESS} = E_{pv} + E_{deb} + E_{grid} \quad (4)$$

If there is an unbalanced demand, energy should be automatically drawn from the grid, and if any surplus occurs, energy should be transferred to the grid.

$$E_{house, \pm BESS} - E_{pv} - E_{deb} < 0, \text{ then } E_{grid}(+) \quad (5)$$

$$E_{house, \pm BESS} - E_{pv} - E_{deb} > 0, \text{ then } E_{grid}(-)$$

Thus, the condition of complete nZEB power supply was met at all times when energy was supplied to the building by a photovoltaic source and/or EV/PHEV batteries. Very often, energy was automatically replenished from charged EVs/PHEVs, so it was impossible to determine which source was currently being used, as in daily mode.

$$E_{house, \pm BESS} = E_{pv} + E_{deb} = 0 \quad (6)$$

The EBMS was responsible for balancing the building so that it did not consume or (as far as possible) release energy, charging temporary surpluses from PVs to the BESS. As can be seen in the description of the results, with insufficient BESS capacity (14 kWh in the first period), this was not possible. Only in the second test period, where the optimal BESS capacity was empirically determined (increased to 54 kWh), could the EBMS automation ensure constant balancing according to Formula (6). However, during the coldest period, this required additional energy due to the very high daily demand of the building. In the entire experiment, the Unihome 11 BEMS system calculated the optimal amount of energy to be delivered for the next 24 h based on outdoor temperature measurements and historical data, which ranged between 10 and 50 kWh. If, for various reasons, it was not possible to deliver the energy required for a given day with one car, two cars were charged (one in the workplace car park and the other in a supermarket). The drivers (household members) agreed among themselves in the morning before leaving for work how much electricity each of them would bring on a given day, usually assuming an increase of about 15–20% due to winter conditions and leaving the necessary energy reserve for driving the next day. Nevertheless, charging too much energy meant that the EV had to be left at the charging station for too long (e.g., 50 kWh—7–8 h, but 64 kWh—approx. 10 h) in order not to exceed the 8-h working time. It would also not be possible to leave the car on a supermarket charger for 8 h, although CHAdeMO chargers with a minimum charging speed of 20 kWh/h (practically 1–2 h of charging) were most commonly used there. After being connected to home stations (Figure 1), the cars were automatically discharged to the BESS until they reached their target discharge level (usually 10–20% of capacity), so that they could be driven to work/the supermarket the next morning and recharged to the optimum level indicated in the morning by EBMS.

The energy stored in the BESS was empirically determined between the first test phase (March 2024) and the second test phase (November 2024), and a value of 55 kWh (gross) was indicated, i.e., 50 kWh of available net capacity as the peak daily energy demand for heat pumps and other household appliances during the day of heating season. The difference between the gross and net values results from the design of BESS, which usually requires leaving approximately 10% of the BESS capacity unused.

The operation of the Unihome EBMS automation was set so that  $E_{total}$  would tend towards zero every hour. While in the first test period (spring), this was not possible due to the insufficient capacity of the local BESS (and energy was fed back into the grid), in the second test season (autumn) it was fully successful.

#### *2.4. Attempt to Estimate the Amount of Energy Needed to Be Supplied to the Farm from RESs in Order to Result in a Zero-Emission Building*

The main objective of nearZEBs is to find the minimum of carbon dioxide emission function related to energy delivered to a household in time ( $t$ ):

$$\text{Min } \sum_t \text{CO}_2(t) \cdot [\text{Mg}] \quad (7)$$

The amount of local carbon dioxide emissions strongly depends on the fuel used to ensure thermal comfort in the household. In this case, it was decided to conduct tests in a building where all final energy is supplied exclusively by electricity, so that emissions from the mains electricity can be compared to emissions from local electricity (from local PVs) and, additionally, those imported from RESs by EVs/PHEVs. We presume that the amount of carbon dioxide is related only to imported black energy (as the generation of electricity from sun (PVs), generates no CO<sub>2</sub>) Let us also neglect for the calculation the



amount of CO<sub>2</sub> inbuilt in PVs and other RES equipment (also EVs/PHEVs). So, the grid related emissions can be described by Formula (7)

$$\text{CO}_2(t) = E_{\text{grid}}(t) \times C \quad (8)$$

where CO<sub>2</sub>(t) is the amount of carbon dioxide emitted to the atmosphere CO<sub>2</sub>/kWh, for every kWh of grid final energy delivered to the building balancing boundary, as shown in Figure 2, and C is the constant of carbon dioxide emission for final energy unit delivered to household (in Poland, C = 0.8 Mg of CO<sub>2</sub> for 1 MWhe).

As a result, the aim of the study (apart from answering the three research questions) was to indicate the extent to which carbon dioxide emissions from a household would be reduced if energy was imported during the transition period (autumn and spring) from RESs outside the building (using non-emitting EVs). The calculations and results are shown in Table 1.

**Table 1.** Calculation of potential CO<sub>2</sub> emission reductions resulting from the use of the proposed RES energy supply model by V2G.

| Action                   | Amount of Energy Consumed | Amount of CO <sub>2</sub> (Not Emitted) | 3 Months Warmer/Colder                        | For Entire Heating Season            |
|--------------------------|---------------------------|-----------------------------------------|-----------------------------------------------|--------------------------------------|
|                          |                           | 1 kWh = 0.800 kg                        |                                               | Heating Season 6 Months (est.)       |
| March–April 2024         | 400 kWh                   | 320 kg<br>(0.32 Mg)                     | Warmer<br>(Feb–April)<br>960 kg<br>(1200 kWh) |                                      |
| November 2024            | 750 kWh                   | 600 kg<br>(0.6 Mg)                      | Colder<br>(Nov–Jan)<br>1800 kg<br>(2250 kWh)  |                                      |
| Total for Heating season | 3450 kWh                  | Estimated<br>(960 + 1800)               |                                               | 2760 kg CO <sub>2</sub><br>(2.76 Mg) |

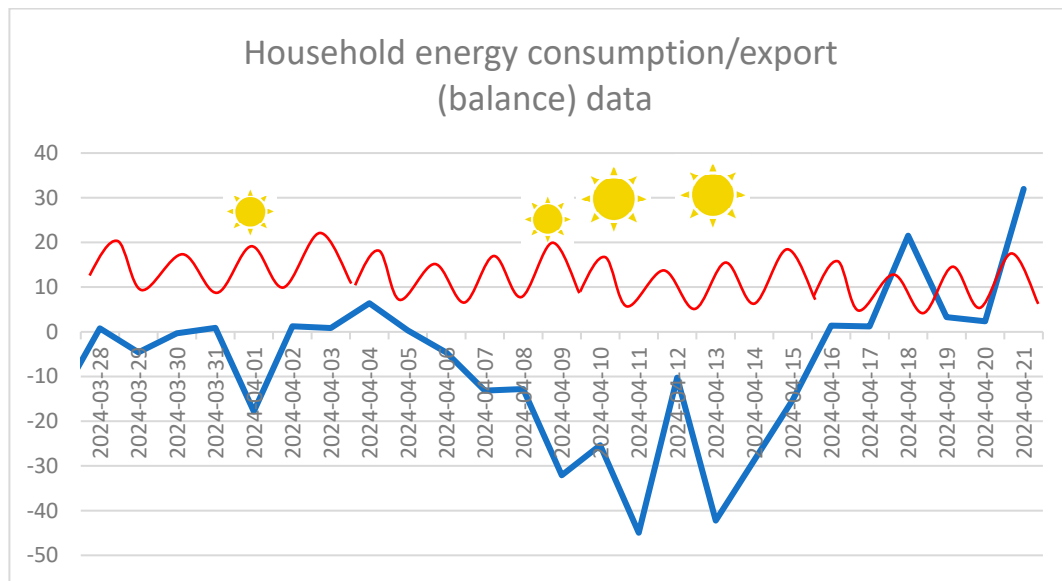
Comparative data were collected in Table 1.

### 3. Results of the Research

#### 3.1. First Period—March/April 2024

Tests of the first stage started on 24 March 2024 and lasted until 22 April 2024, and the course of the one-month test is shown in Figure 2. During this first test period, the EBMS was not yet coordinating all of the transferred energy as only the first stage BESS (14 kWh) was installed. The building's insufficient storage capacity meant that extension of PV energy had to be fed back into the grid, as the combined capacity of the BESS and connected EV was not sufficient to store the customs excess energy from the PV. As a result, on some sunny days (such as the 27 March and the 12 and 14 April), energy was being fed back into the grid, even though it was needed to power the building on the following days. From the perspective of the DSO grid, the energy fed into it has a negative sign, which is why negative energy can be seen in Figure 3 during this period. The system has not yet been optimized and, as a result, some energy was not stored locally and was drawn from storage (such as on 13.04, when there was an energy spike despite energy being returned to the grid the previous day). It is worth noting that in the test period, the building still required lot of black energy (E<sub>house</sub>, ±BESS from in Formula (4)) from the grid, while in

this same period, 372 kWh was transferred to the grid, according to Formula (5) (data from local DSO). EVs/PHEVs brought some 400 kWh of missing energy.

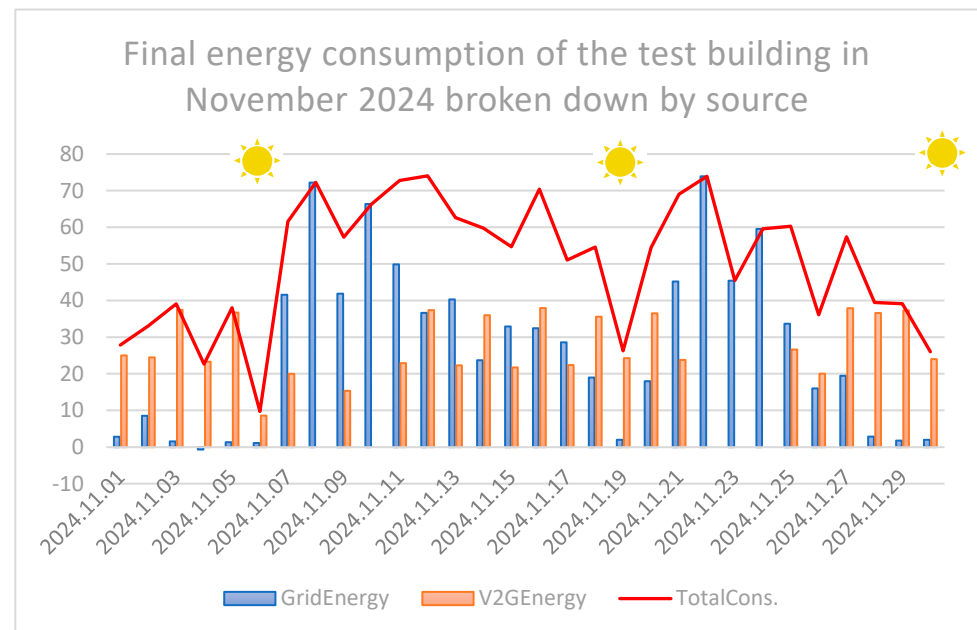


**Figure 3.** Energy balance of the test building in March/April 2024. Blue line = energy consumed or fed back into the grid, red line = expected consumption without V2G. Sunny days are marked with the Sun icon. Data acquired from DSO (OSD).

#### The Second Period (II)—November 2024

Stage 2 tests started on 1 November 2024 and lasted until 30 November 2024 and the course of the one-month test is shown in Figure 4. During this test period, the EBMS was already able to coordinate all of the transferred energy as an extended BESS with a total new capacity of 54 kWh was installed. Sufficient energy storage capacity no longer made it necessary to feed energy back into the grid, but on the other hand, an insufficient supply of PV energy resulted in a significant deficit up to (54% of needed volume), which had to be supplemented with energy delivered from outside RESs and delivered by vehicles using V2G (or purchased from the grid). Even on sunny days (e.g., 6, 19, and 30 November), the harnessed energy was insufficient to power the entire building. The lack of RES energy supply on several days (i.e., 8, 10, 22, 23, 24 November), showed clearly that the daily energy consumption for the two heat pumps and other domestic purposes (e.g., lighting, white staff, etc.), showed mean value of demand of 50 kWh/day to be purchased from the grid. On those days, energy could have been supplied to the building—provided that its residents were at home (they were away for those few days). With the help of V2G, it was possible to supply 46% of this demanded energy from outside RESs nearly every day of this period. It is worth noting the high energy conversion efficiency of the EV/PHEV batteries of more than 93% (ratio of energy disbursed from V2G to recorded energy in the building Figure 4), which, with an average heat pump coefficient of performance (SCOP) of approx. 2.8, resulted in very high savings on primary energy, which would have been obtained from coal and gas as an alternative means of energy supply. As a result, the CO<sub>2</sub> emission reduction described in Table 2 could be achieved. In the first test period (in March), sunny days provided an additional energy flow to the building (marked in Figure 3 as a Sun icon), which was enough to force the household to feed the surplus back into the grid. It is proved that energy balance is different in spring/autumn, and even very high (for November) solar energy yields would not be sufficient to cover the entire final energy demand in autumn in Poland (Figure 5). In this month, some 750 kWh was brought via V2G to the household and no energy was transferred to the grid. As a consequence, the proposed solution seems to be

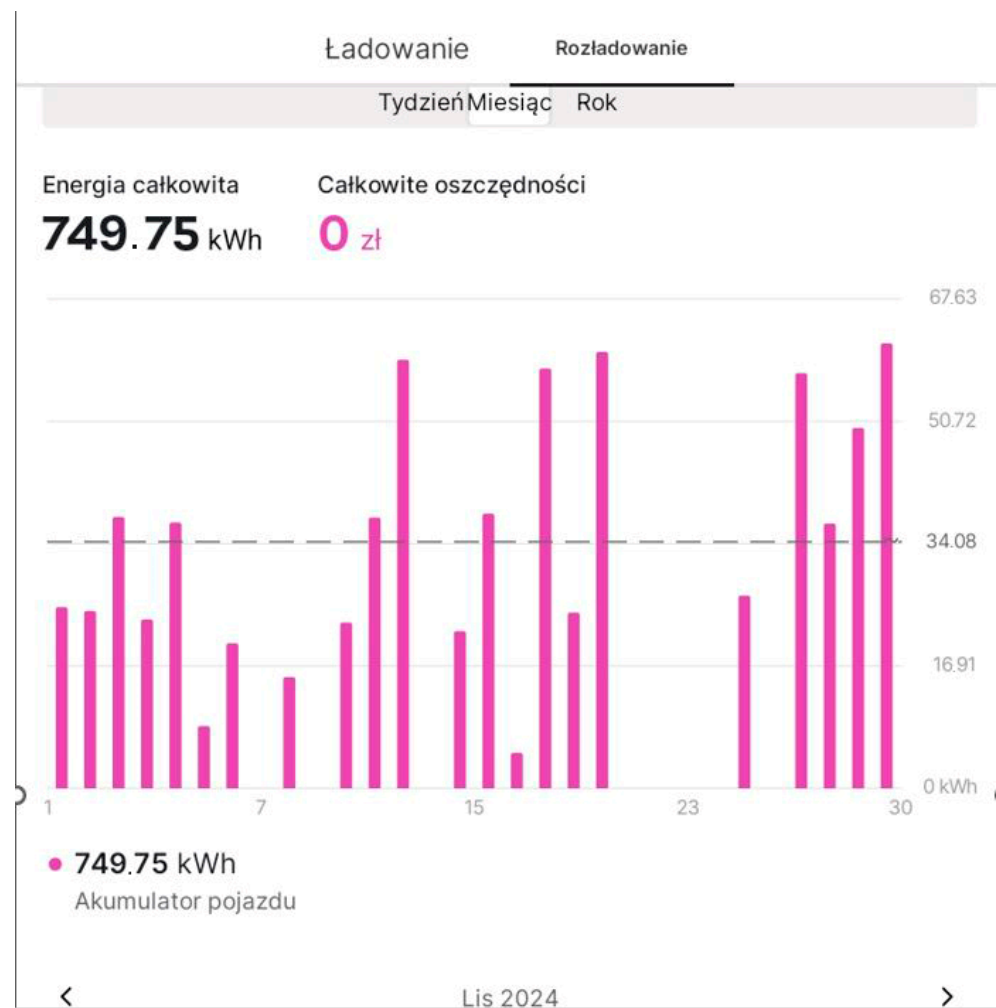
more important for autumn than for spring, under Central/East Europe climate “average” conditions.



**Figure 4.** Energy balance of the test building in November 2024. Blue bars—energy consumed from the grid, red line—expected consumption without V2G. Orange bars—energy from RESs. Sunny days are marked with the Sun icon. Data sourced from National DSO (OSD).

**Table 2.** SWOT analysis of discussed solution.

| Stakeholder/<br>Action                                                | Strengths                                                             | Weaknesses                                                                            | Opportunities                                                                                                                   | Threats                                                                                                                                    |
|-----------------------------------------------------------------------|-----------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| BEV/PHEV owner > discharge of BEV/PHEV at home via V2G/V2H.           | Easy, affordable non-disruptive energy source.                        | Limited amount of places with free top-up. High initial investment in infrastructure. | Potential reduction of cost of energy for home. Potential of more nZEBs. Reduction of CO <sub>2</sub> emissions from household. | Unstable system—no guarantee of availability of energy. May become costly in long term.                                                    |
| RES owner > charging of BEV/PHEV at RES plant.                        | Potential of extra income for RES plant owners.                       | Initial additional investment in infrastructure                                       | Potential of protecting stable income from RES plant (no more forced outage).                                                   | Potential of triggering “black energy market” of energy.                                                                                   |
| Local DSO > charging and discharging of BEV/PHEV as B2P (P2P) action. | No need for investment, limits the local problem of network capacity. | Loss of income& taxes on trading and distribution of electricity.                     | Less pollution and GHG emissions due to proximity heat generation. Quick solution to a problem of RES plant outage.             | Transfer of part of the responsibility for the grid performance to local RES owners.                                                       |
| Society/<br>National Energy Mix                                       | Less emissions/easy solution to some network capacity problems.       | Lack of wide acceptance of BEV and V2G/V2H. Lack of V2G stations                      | Reduction of GHG emissions and atmospheric pollutants/unlocking the connection of new RESs.                                     | Without a change in the authorities’ approach to a more liberal energy trade/exchange sales (of current monopolies), this may not succeed. |



**Figure 5.** Energy transfer data to the building (in Polish, “Rozładowanie” means “discharge”), showing that the cars transferred a total of 749.75 kWh of energy to the building in the month of “November 2024” (in Polish “Lis 2024”). Dashed line—average demand. Data sourced from V2G Wallbox Quasar desktop Android app.

### 3.2. The Results Summary

1. Although the experiments did not result in full satisfaction of energy needs in both transition periods analyzed, they demonstrated a method by which this could be possible.
2. Tests conducted for two representative 4-week periods of the heating season (the warmer half of February to the beginning of May) and the colder half (mid-November to mid-February) allow for preliminary calculations of CO<sub>2</sub> emission reductions during this period compared to obtaining electricity from the grid and using it to ensure comfort in the household with heat pumps (with SCOP = 2.8). It has been estimated that by importing approximately 3.5 MWh of energy via V2G, it would be possible to save approximately 2.78 tons of GHG (CO<sub>2</sub>) from being emitted into the atmosphere. It is worth noting that if the house were heated by electric heaters instead of a heat pump, the amount would be almost three times higher (7.8 tons). It can therefore be tentatively concluded that the minimum value of the function described by Formula (6) would be 0, assuming that the designed system would be technically and operationally capable of supplying this household with approximately 3.5 MWh ( $\pm 10\%$ ) of green energy from nearby RESs between ~7 November and ~7 May, using only

EVs/PHEVs. This would theoretically lead to nZEB status for this building, as all the energy used to achieve comfort in it would come from RESs.

#### 4. Discussion

A discussion must be conducted for at least two aspects: the possibility of bringing a significant amount of energy to the household and the GHG emissions avoided in this way.

The system designed by the author works very well from March to May, but while in the spring months (March–April), it was able to efficiently manage surplus energy, in the month of November (and the following months), its effectiveness strongly depends on the driver's ability to import energy into the building as well as local storage capacity BESS). In real conditions (as in the performed tests), the energy could be successfully transferred (via V2G) to households and, as shown in Figure 4, sometimes as little as 10–30 kWh per day could be sufficient to ensure 100% coverage of the RES energy needed to maintain the nZEB status of a residential building. In this case, the regularity of these activities is very important, including days off work (on these days, the test energy was supplied from a free charger at a supermarket). However, every day (as shown in Figure 4 showing data of 8, 10, 21, and 22 November) when residents were unable to bring energy to their home (e.g., due to illness or holidays), almost 100% of the energy had to be supplied from the grid. With regular vehicle use and a charging time (during work hours parking) of up to eight hours daily (using TYPE2 or CHAdeMO), in the months of September and October, all of the missing household energy can be brought into the building by a local PV generator. In the months of November and December, this could deliver only a fraction of the energy needed (the shorter the days, the less PV energy is available), effectively supplying 30–50% of the missing energy to the building (on the other hand, wind generators are potentially more frequently in operation). However, these amounts are very much dependent on the energy demands of the building, and for highly efficient buildings, up to 100% of their power requirements can be expected from V2G in the winter without additional stops for EV/PHEV charging outside the parking place. Nonetheless, in such a solution, several fundamental problems can be identified.

##### 4.1. Technical Problems

The V2G and V2H devices used were designed for relatively small powers (single phase—7 and 6 kW), which currently makes the whole process of reloading energy from the EV to the house insufficiently fast, as it usually took 8–10 h in winter conditions to top-up a vehicle. Due to charging the EVs in the experiment performed during the day (an 8-h working day) and discharging them at night, and having three cars available, this was possible. However, if the house did not have a BESS to buffer the energy, and if periodically the householders did not use all the three EVs, the energy stream from the EVs/PHEVs could prove periodically too slow for the system to work. Consequently, the EBMS would automatically select energy from the grid (or there would be compromises in terms of climatic comfort). Not every household has three EVs available, so this cannot be expected to be a standard solution in Europe. On the other hand, it was the low energies (currents) of the recharge operation by V2G and V2H that resulted in no apparent degradation of the traction battery performance of EVs and PHEVs in use. Three EVs/PHEVs with the specified battery capacities were selected as the optimal solution for this household.

##### 4.2. The Problem of Degradation of the Traction Batteries Used Instead of the Local Energy Distribution Network Was Found to Be Negligible

The use of AC chargers (7 to 22 kW power) for the project, as well as discharging energy to the home (via 6–7 kW DC connectors) at relatively low currents did not result in any visible degradation of the state of the traction batteries during the test period. Status



analysis of both the SOH (state of health) parameter of the battery as well as more advanced parameters indicative of battery degradation (such as the 'Hs' parameter for Nissan batteries) showed no deterioration in battery condition as a result of the experiment conducted over a total of nine months. The technical explanation for this could be quite simple—during the past winter of 2023/2024 (apart from a few days with extremely low temperatures outside), thanks to the warming of the climate, it was possible to run both the charging of the test cars and their discharge process in the environment (car park) at positive rather than negative temperatures. The strict control of charging currents, control of the range of usable battery capacity, as well as the charging/discharging process in relation to the battery's ambient temperature appear to be key battery hygiene parameters leading directly to the protection of the correct physicochemical structure of EV/PHEV traction batteries. By running these processes under the supervision of the EMS/BMS program Unihome 11—specifically adapted to this project—very good results were obtained.

#### 4.3. *The Problem of BEMS/V2G/Hybrid PV Systems Co-Working Together*

All of these systems need to be interconnected in the building, as shown in Figure 2. The ambition of the suppliers of PV hybrid systems (hybrid PV, i.e., PV + BESS), just like the V2G suppliers, is to enter the building energy management market, but in practice they want to manage energy at home alone and are reluctant to provide protocols for interoperability and management outside their closed applications. However, with as great a variety of solutions and combinations of heating systems as there are in Europe, it is not possible for a hybrid PV system to effectively manage a building's existing heating system. As a result, the interaction of a building-specific BEMS with a standard hybrid inverter management system (here SEMS system) becomes difficult. This can be clearly seen in Figure 3 as over-regulation, which should not occur in such a system (it should, however, store energy for the following days instead of transferring it to grid). Ideally, such a system should not have a complicated multi-performance BESS, but directly use the traction batteries of EV cars as if they were a BESS (e.g., direct DC connections of batteries to PV inverters).

#### 4.4. *GHG Emissions Reduction*

Undoubtedly, bringing green energy to the household by EV will reduce emissions from unused (not generated) electricity (as shown in Table 1) in utility scale [23]. This reduction will be greater the higher the share of hydrocarbon-based energy sources in a given country's energy system (in Poland, this share is over 70%). As a result, the environmental profitability of such a solution will strongly depend on the emissions of a given country's energy-mix, and while it may be an attractive solution in countries such as Poland, Bulgaria or Serbia, it is unlikely to be so in Scandinavia or Austria.

#### 4.5. *Economics of the Proposed Solution*

Energy from RESs that are switched off, like grid energy during periods of negative market prices, is worth zero on the market, but still has a value to households, so the main problem remains the development of a system in which the transfer of energy is free, or someone else covers the costs (purchase of EV cars and V2G devices). Another experiment conducted in Poland in this area (Energy Clusters 2016–2024) clearly showed that transferring free energy (or almost free) while leaving distribution charges in place discourages consumers from using such solutions. Perhaps the proposed bypassing of distribution networks could be the right solution to the local problem of how to deliver energy from RESs to households when it cannot be accommodated in the limited network resources of a given country at certain times. From an economic point of view, the choice to increase PVs, install BESS and use three EVs/PHEVs proved to be a lower investment for residents than the very expensive and difficult full thermal renovation of the entire building (with

a conversion of the heat distribution system to surface heating). This is mainly because vehicles have a huge advantage over building thermo-refurbishment—they can be used as convenient and environmentally friendly means of transport.

## 5. Conclusions

The most important achievements of the conducted experiment are:

a. The powering of an old non-insulated house (Figure 1) with a high final energy demand to the standard of a near-zero energy building level with a very low carbon footprint during part of the heating period (November and March–April). During two representative periods of ~30 days each, thanks to the proposed scheme, the test house did not require much fuel (usually hydrocarbons) for heating from outside and approached nZEB without any compromise in terms of climate comfort for the occupants. The local PV (rooftop) installation allows the nZEB status of this building to be achieved without external support for six ‘summer’ months of the year (May to October), but extending this potentially by a further 3–4 months offers the possibility of increasing energy independence from 50 to even 75% carbon-free energy (in relation to the annual energy flux required to cover losses). In the remaining 3 months (i.e., December, January, February), due to the very low solar radiation in Poland, there is no chance of obtaining locally enough energy from the sun to provide 100% of the needs in a representative household. So far, this period involves burning hydrocarbons or using black energy (via a heat pump) for heating. As a potential solution to this challenge, is bringing the energy from another RES by EV/PHEV or with filling this period with almost zero-carbon energy from the combustion (in a CHP unit) of locally obtained biogas/biopropane in the building (which author is also experimenting).

b. As a result, it was also possible to identify a way of obtaining green energy from RESs and transporting it almost free of charge to the test building without using overloaded and expensive distribution networks. On the other hand, it seems that limiting the amount of PV energy needed to be fed into the grid is one of the factors enabling further development of PVs (in Poland), while keeping investments in commercial PV cost-effective.

c. Assuming about 800 kg of saved carbon dioxide for each MWh of energy produced in the commercial power industry, considering a conversion factor (CC) for electricity of 2.5, bringing 1.5 MWh of energy into the building in this way would result in a reduction in emissions of 3.375 tons of carbon dioxide into the atmosphere, not to mention the avoidance of particulate low emission pollution.

d. According to residents who participated in the experiment, this solution is very promising because it can solve their major problem (high costs of climate comfort in winter) in a very simple and inexpensive way. The high declared satisfaction of the inhabitants with such a solution was a surprise to them “as it worked the same way as charging an electric car everyday”; it is a very simple operation that all EV/PHEV users have mastered perfectly. The whole process was automated, i.e., deciding whether the vehicle was currently being charged or discharged was taken care of by the EBMS (Unihome 11), for which a number of new algorithms have been developed and proved during these tests.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The author declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|                   |                                                                     |
|-------------------|---------------------------------------------------------------------|
| PV                | Photovoltaic                                                        |
| RES               | Renewable energy sources—such as PVs, wind turbines, etc.           |
| nZEB              | Net zero energy house                                               |
| HVACR             | Heating, ventilation, air conditioning, and (heat) recovery         |
| DHW               | Domestic hot water                                                  |
| V2H/V2G           | Vehicle-to-home, vehicle-to-grid                                    |
| BMS/EMS also EBMS | Building management system and energy management system             |
| EV/BEV/PHEV       | Electric vehicle, battery electric vehicle, PlugIn electric vehicle |
| BESS              | Battery energy storage system                                       |
| ASHP              | Air-sourced heat pump                                               |
| SCOP              | Seasonal coefficient of performance of a heat pump                  |
| CHP               | Combined heat and power production/generation                       |
| B2P               | Business-to-people business model                                   |

## Appendix A. Answers to the Research Questions

- a. As a result of the tests carried out in the winter and autumn of 2023–2024, the first of the research questions—‘Can EVs and PHEVs efficiently transfer electricity between RESs with a periodic surplus of energy to residential buildings with a local demand for energy, e.g., in the winter?’—can be positively answered. The transfer in practice of more than 2 MWh of energy between RES generators and a prosumer household proved to be sufficient to provide (through heat pumps) full thermal comfort sourced only from green energy brought in off the distribution grid. For the RES powered PV car park owner, in a situation where their installation is regularly forced to switch off, the transfer of RES energy had no significant monetary value, but for the prosumer, who was keen to minimize their carbon footprint, who thus bridged the gap in the production of green energy in winter for their needs, it was of crucial performance. From the prosumer’s point of view, this was also very important because no special tariffs for heat pumps have been introduced in Poland so far. As a result, the prosumer saved considerable financial resources. Therefore, it can be stated that EVs and PHEVs can effectively transfer electricity from RESs having an excess of electricity to residential buildings having a local and temporary shortage of electricity. In this solution, instead of building backyard BESS energy storage facilities (altogether much more expensive than the value of EV/PHEV batteries), the use of EVs offers the possibility of cheaper energy storage and the advantage of storage mobility is gained, in addition to the possibility of storing and transferring energy in terms of the local community. BESSs in the building were used in the experiment, but they did not have a fundamental impact on the efficiency of the process tested (they only improved timing).
- b. The second research question posed can also be answered in the affirmative. A peer-to-peer local energy exchange model implemented between consumers and businesses (recommended, e.g., in the RED Directives as C–C but also B–C arrangements) could have real application today. It seems that, at least in Europe, the additional costs associated with energy distribution, which are added to the energy bills of prosumers, are too heavy a load for the participants of the new prosumer energy sector (in Poland, about 50% of the value of energy bill paid). The RED II Directive encourages peer-to-peer transactions, but it has not yet been possible to develop (at least in Poland) a model which would reduce these charges in such relations between neighbors, whose buildings are several dozen or several hundred meters apart. The

solution may therefore be to provide electricity from the RES farm owner's chargers to virtually anyone who wants to charge their EV/PHEV, which would be a practical implementation of this postulate.

For the prosumer, this could solve the problem of the missing energy topping up the nearZEB balance during the winter period, without much damage to the profitability of the RES farm's owner.

- c. The researcher's third question could also be answered positively. The tests performed confirm that the use of EVs/PHEVs does not degrade the traction batteries to the extent that they would need to be replaced sooner. The operation of V2G is as far as possible covered by EV manufacturers' warranties, and the powers used in the process proposed do not threaten battery degradation in the long term. In practice, the powers that are transferable by V2G or V2H systems are 10 times less than the power of an EV's/PHEV's electric motor, but completely sufficient to cover the peak power of mean domestic consumers. As demonstrated, the solution also makes economic sense.

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