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Are Commercial EV Chargers Ready to Aid with Household Power Consumption?

Leila Shams Ashkezari [1,*], Marco Succetti [1], Rémi Jabœuf [2], Paolo Tosco [2] and Morris Brenna [1]

[1] Department of Energy, Politecnico di Milano University, 20156 Milan, Italy; marco.succetti@mail.polimi.it (M.S.); morris.brenna@polimi.it (M.B.)
[2] Edison Spa, 20158 Milan, Italy; remi.jaboeuf@edison.it (R.J.); paolo.tosco@edison.it (P.T.)
* Correspondence: leila.shams@polimi.it

Abstract: The transportation industry now accounts for approximately a quarter of worldwide energy-related direct CO_2 emissions, and governments all around the globe have committed to converting their fossil-fuel vehicles to zero-emission ones by adopting electric vehicles. Current electric vehicles (EV) can store approximately 18 to 100 kWh of energy, which may be employed not only for commuting but also for other purposes such as delivering energy to households (V2H) or buildings (V2B), as well as offering ancillary services to the power grid (V2G). In this study, a real test setting including a trending bidirectional charger, an EV, a PV simulator, and household appliances are utilized to evaluate the performance of various V2H components and to learn about the concerns that may arise during V2H operation. The results of the tests on the bidirectional EV charger are presented in this paper. Although the results of the tests on the charger installed in the house are not satisfactory and consistent to the project's goal, they are released in order to aid future studies in better understanding the true challenges of commercial bidirectional chargers.

Keywords: bidirectional charger; constant tariff; electric vehicle (EV); energy management system (EMS); nearly zero energy building (NZEB); time varying tariff; vehicle to home (V2H)

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1. Introduction

Smart cities have significant challenges in reducing greenhouse gas emissions and energy use. According to recent studies, the transportation industry is one of the major contributors to air pollution, and the trajectory has been growing in the last few years. EVs have gained a lot of attention in recent years as a solution to this problem and they are becoming increasingly popular due to their environmental and economic benefits. The government's tax incentives and lower fuel costs per mile are the main driving forces for growing the number of EVs on the road [1–3]. In just three years, the number of EVs on the road tripled to over 16.5 million in 2021. Figure 1 shows the registrations and sales share of electric vehicles from 2016 to 2021 [4].

In order to mitigate the mileage concern, EVs with larger battery capacities, such as the Tesla Model S with 85 kWh or the Nissan Leaf with 60 kWh, are receiving more and more attention. In the majority of situations, a vehicle's daily trip energy requirement is less than the energy available on vehicle's battery. As a result, in addition to offering the energy required for driving, EV batteries bring a great amount of unused capacity. EV as a distributed energy storage system can become an essential element of the smart grid if the idle battery is used to store and feed power to the grid or consumers [5]. EVs as a short-term energy storage system can supply electricity to household appliances throughout blackouts (vehicle-to-home (V2H)), provide quick charging to other EVs (vehicle-to-vehicle (V2V)), or feed energy to the transmission network (vehicle-to-grid (V2G)) [1,5].

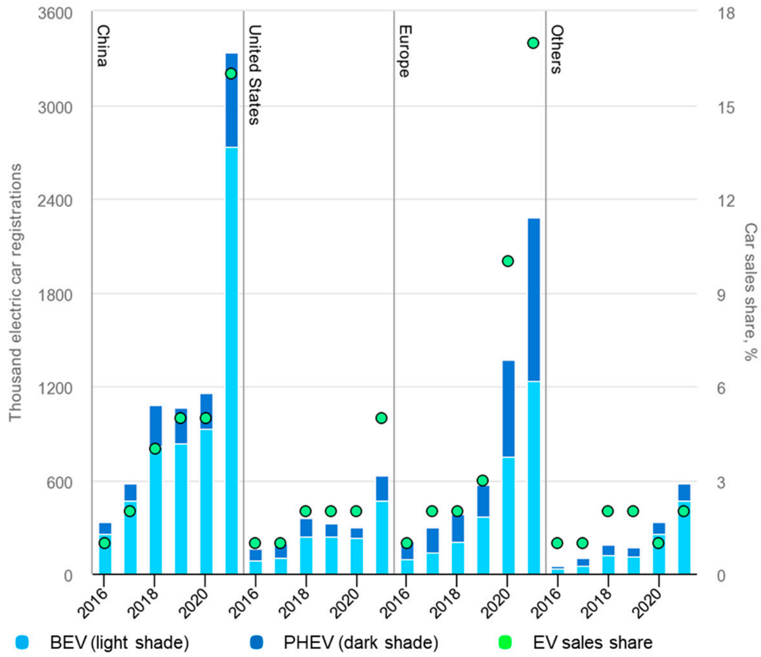


Figure 1. Electric car registrations and sales share 2016–2021 [4].

V2H allows an EV to operate as a backup power supply, providing electricity to a home throughout short-term power cuts, helping to reduce peak demand, regulating residential energy usage, and reducing electricity purchases from the grid [6]. It can theoretically be utilized to meet nearly zero energy building (NZEB) goals by merging EV and renewable energy sources (RES), e.g., solar, wind, or biomass. An NZEB, according to the US Department of Energy, is an energy-efficient building that meets its energy requirements by its own energy generation [3]. According to authors of [7], the PV and V2H combination can fully meet the energy demand of a household on sunny and cloudy days without the need for grid power purchase. The energy flow between the grid, RES, EV, and loads in the house is governed by the home energy management system (EMS). Figure 2 depicts a generic schematic of a V2H structure and data and power transfer between different players in V2H performance.

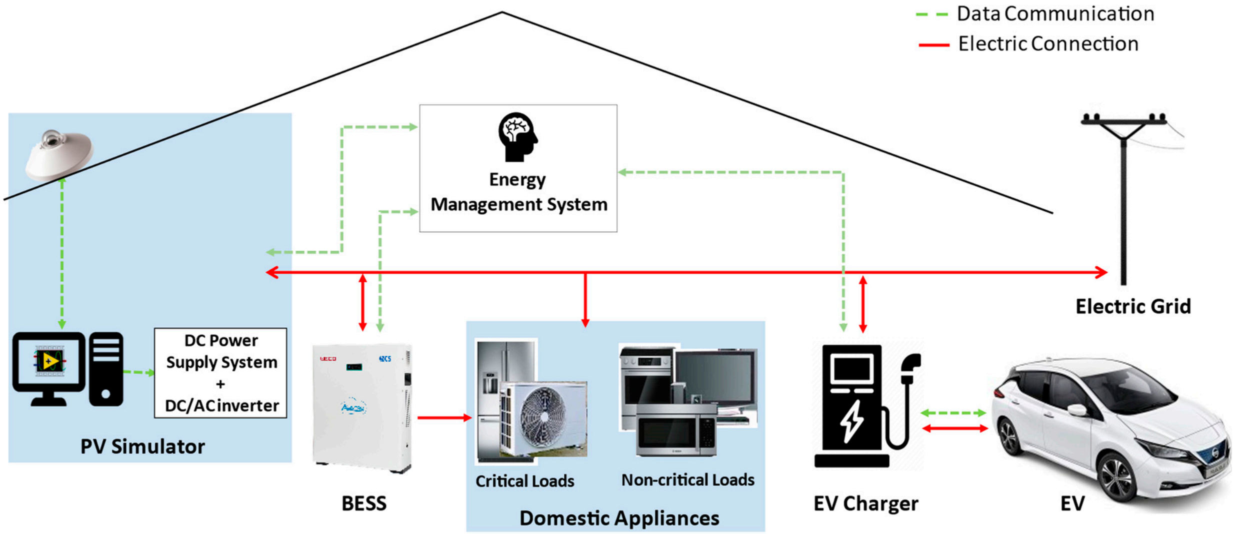


Figure 2. General schematic of the building under study.

There is a rich literature on V2H technology and numerous researchers have looked into it from different perspectives. Authors of [6] simulate a V2H prototype to reduce peak power in the house and tests the model with three different vehicle usage rates. Ref. [8] claimed that the V2H system can construct an off-grid microgrid with enough voltage control, energy storage, and safety to supply backup power by having an EV-based storage node. According to the study's findings, a home V2H system with rooftop PV may supply backup power for 19 to 600 h, depending on the time of year and vehicle design. The authors of [9] created a mixed integer linear programming (MILP) model to optimize the PV and stationary battery capacity for a residential area with an EV and V2H. Refs. [7,10] investigated the economic benefits of establishing PV and V2H facilities for EV customers and discovered that the combination of PV and V2H technologies offers considerable savings. They came to the conclusion that V2H technology boosts PV utilization rate and grid power reliability. According to the authors in [10], the total power cost with the suggested Semidefinite programming (SDP) optimum control for Tesla Model S (85 kWh battery pack) and Nissan Leaf (24 kWh battery pack) is 493.6% and 175.89% less than without the optimal control. The roles of EVs and RES as potential features in an NZEB was investigated in [11–13]. Ref. [11] used the new concept of "building to vehicle to building" (B2V2B) to analyze the energy flow between a residential building and an office building that included EV and RES. The suggested EMS enhances grid reliability and reduces grid power consumption by up to 77%, according to its simulation results.

Table 1 gives an overview of some of the real-world initiatives that are being carried out in this field. It also contains the services examined in those initiatives. To the best of the authors' knowledge, no articles have been published which present V2H test findings derived from real setups. The goal of this project is to fill this research gap by analyzing the V2H idea with real-world equipment and achieving NZEB by integrating PV panels and V2H.

Table 1. Overview of some V2H pilots around the world.

Name of Project	Lead Partner	Time Span	Services	Notes	Ref.
Lab4V2H (Italy)	Edison spa	2021–now	• Time shifting • Emergency back-up	An energy management system is defined to make the house self-sufficient based on the forecasted data of house consumption and PV power production	Current paper
Vehicle-to-coffee The Mobility House (Germany)	Endesa	2015–now	• Time shifting	Electricity from the EV's battery is fed directly into the office building's power grid, and the classic connection to the electricity grid is no longer required.	[14]
Piha V2H trial (Australia)	Auckland energy company	2019–now	• Emergency back-up • Time shifting	In remote and sparsely populated areas, residents are often reliant on a single feeder cable. The goal is to make residents reliant on their own backup electricity supply with the help of EV batteries.	[15]

Table 1. *Cont.*

Name of Project	Lead Partner	Time Span	Services	Notes	Ref.
Smart MAUI (Hawaii)	Hitachi	2012–2015	• Time shifting	The goal is to enable the efficient use of RESs and contribute to the implementation of a low-carbon social infrastructure system. It has been designed to respond to rapidly changing demands in the renewable energy market through the use of EV and other technologies.	[16]
Dendo Drive House (Japan)	Mitsubishi Motors Corporation	2019–now	• Emergency back-up	The goal is to store electricity generated from solar panels in either the EV battery or a stationary battery at the home.	[17]
IREQ (Canada)	Hydro-Quebec /IREQ	2012–2014	• Grid Services • Time shifting • Emergency back-up	It would allow plug-in EV owners to use the energy stored in their batteries as a temporary home power source.	[18]
Amsterdam Vehicle2Grid (Netherlands)	Engie	2014–2017	• Time shifting	The following results are obtained in this project: (1) the household increased the energy independence or, zero Emission energy autonomy (from 34 to 65%); (2) decline in energy exchange with the electricity network, 45% less compared to situation without V2G; (3) the degradation of the battery after 2 years is quite limited (6–7%).	[19]

The remainder of this paper is organized as follows: Section 2 provides an overview of V2H concepts and benefits, as well as the limits that must be considered when performing V2H. The overall design of the system and the equipment used in the experiments are described in Section 3. The tests and results are found in Section 4. Finally, Section 5 contains final observations.

2. V2H Principles

In an energy-sufficient building project, the key aims are to maintain efficient utilization of RESs, increase the maximum power available to the house, and minimize the impact of the residential appliances especially EV chargers on the grid. To reach these objectives, V2H technique is utilized, which deploys EV as an energy storage system that allows the introduction of a substantial quantity of electrical storage into the home with no further expenditure. In the following section, we will go over some of the most notable V2H benefits.

2.1. V2H Advantages

- Time shifting: by taking advantage of charging the EV at night (at cheaper periods) and injecting the energy stored in the batteries into the house during peak hours (at more expensive periods), the house peak energy demand and the associated cost is reduced. In this mode, the energy demand is transferred from expensive hours to cheap hours (Figure 3). According to the findings of research conducted by the authors of [20], controlled charging decreases energy costs, battery degradation, carbon dioxide emission, and grid use by 88.2%, 67%, 34%, and 90%, respectively, compared to uncontrolled charging;

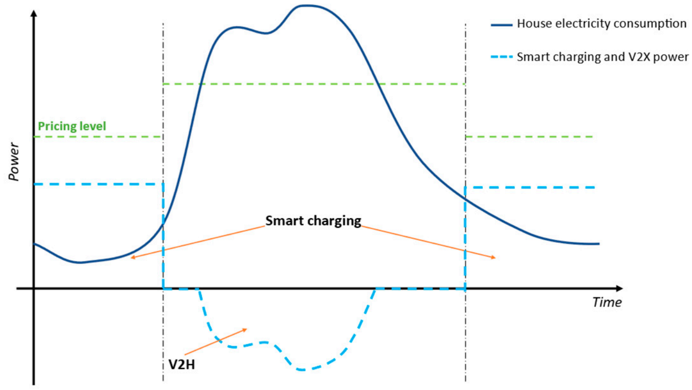


Figure 3. Time shifting and peak shaving by V2H.

- Emergency back-up system: the EVs can act as a temporary backup in short power outage periods. During those situations, the fleet could continue to supply the building with the most important services until the operating condition returns to normal;
- Increased RES utilization rate and reduction of associated CO_2 emissions: EV batteries may be used to store energy generated by RES in the house. Furthermore, by shifting EV charging periods to the times when there is excess energy generated by the RESs at home, the EV's consumed energy will become completely green with almost zero cost (Figure 4);

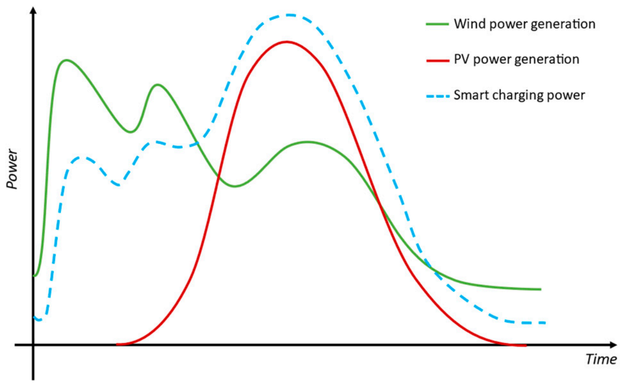


Figure 4. Charging EV according to the available RES's production.

- Possibility to use large capacity home appliances contemporarily: Many modern houses in old cities do not have the possibility to grid upgrade and are thus limited to use small capacity home appliances. Even if they buy large ones, they will not be able to use them at the same time. Furthermore, in most nations, using more electricity than the contract limit is not feasible. EVs with V2H can act as a buffer in these cases to provide the extra capacity, without going for a need to upgrade the grid connection or contract limits for the power provided by the external grid.

The combination of aforementioned factors can contribute to reducing emission factors, improve energy performance of houses, and have economic benefits to both EV users and households.

2.2. V2H Constraints

To maximize the use of on-site generated power, the usage of the EV battery should be optimized, and a number of limitations are taken into account to guarantee that the EV battery undergoes the least amount of deterioration and no V2H-related equipment is harmed. The limits that must be adhered to when doing V2H are listed hereunder.

- Voltage limits: During the charging/discharging, the voltage of each node should be within the specified limits as shown in Equation (1). The voltage will start dropping if the load is too high, and the voltage starts rising if we decrease the load; the voltage must not violate the voltage standard;
- Line capacity: The current flowing in each electric line of the domestic installation should not exceed the maximum current capacity of the conductors. The flow of current in a line depends on the load connected to it. The load should be within the limits to avoid the capacity issues of the line and any other damage to the line;
- Limits of state of charge (SoC) of EV Battery: The main purpose of an EV is to provide easiness in traveling. In order to not affect the main purpose of EVs, a minimum SoC is defined in an energy management system which is called minimum battery percentage (MBP) in this article. MBP is the minimum SoC, above which V2H can be activated and below its value, V2H services will not be performed. A simple representation of the MBP idea is shown in Figure 5.

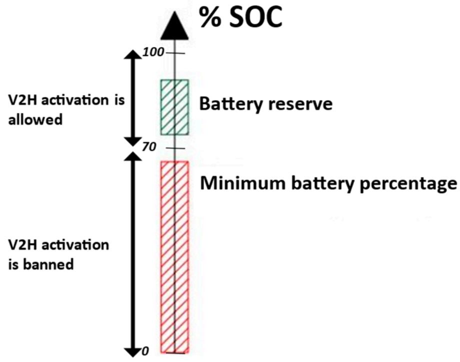


Figure 5. MBP representation.

As well as the above-mentioned limitation, there is another constraint applied by EV producers with the aim of avoiding degradation of the EV battery. The battery management system of EV modifies the charging behavior at the extremes of battery's SoC. Therefore, because of the nonlinear relation between the power setpoint and the real charging power in this region, it is avoided in our experiments.

- Island Size: To supply the continued power to the island within the disconnected region of the distribution system, the size of the island should be within the limits so that the load does not exceed the available energy and power of EV. The term "island" refers to the critical loads that must be powered by the EV in the event of blackout. The mathematical expression is as follows (Equation (1)), where P_{Li} represents the load at any node and E_{aPL} is the available energy to utilize during the fault:

$$\sum_{i=j}^{k} P_{Li}(t) \leq E_{aPL} \quad (1)$$

2.3. Common EMSs Used in V2H Studies

EMS has evolved as an efficient control of household devices such as EV charger and BESS to offer services to a household. Different approaches of EMS are investigated in various articles; the main ones are outlined as follows. The smart home structure considered in the following articles includes BESSs with peak shaving and valley filling potential, bidirectional EV charging stations, and a small-scale RES that enables energy sell back to grid. Refs. [9,21,22] provide evaluation of smart homes using the MILP architecture. An effective stochastic dynamic programming approach is presented in [10,23] to charge an EV as efficiently as possible while taking into account the inherent unpredictability of its use. In order to achieve this goal, driving patterns are represented using a Markov model using data acquired from the use of an electric car. Ref. [24] proposes an EMS for determining the best day-ahead appliance scheduling of a smart home using hourly price and peak power-limiting demand response algorithms. Ref. [25] investigates nonlinear predictive EMS for a residential building with a rooftop PV system and second-life lithium-ion BESS. The EMS described in [26] is separated into two parts: a local control and a global control. The local control is based on the base load profile of the home, the availability of their EVs, their arrival and departure timings, and their initial SoC, while the global one is based on the power requirements of the individual residence, the combined power requirements of the neighbors, and the availability of neighbors' EVs. In this work, the charging station operation is controlled by the internal EMS of the charger in accordance with measured values of the household appliances consumption and PV generation. The primary aims of this EMS are to optimize PV energy local consumption, decrease the share of energy purchased from the grid, and prevent exceeding the contractual power limit. The theoretical model of the power balance at every hour inside the house is represented by the power balance Equation (2). The variables P_{IMP}, P_{PV}, and P_{EV+} in this equation reflect imported, solar, and EV discharging power. While the exported, house consumption, and EV charging power are represented by P_{EXP}, P_L, and P_{EV-}, respectively. In this equation, A indicates if the EV is available at home (A = 0 (away) or 1 (at home)).

$$P_{PV}(t) + P_{IMP}(t) + A.P_{EV+}(t) = P_L(t) + P_{EXP}(t) + A.P_{EV-}(t)\ \forall t \in T \tag{2}$$

The power balance equation is verified when limitations described in previous subsection are taken into account.

3. Materials and Methods

The purpose of this research is to design an HEMS in Edison's laboratory in Milan, Italy, to reach a NZEB. In order to accomplish this task, in addition to RES, V2H is also taken into account. Therefore, several tests on the bidirectional charger installed in the laboratory are carried out to verify if the EV charger is performing effectively in terms of V2H performance. The testing setups and findings of this investigation are provided in the following sections.

3.1. EV Charger

In this study, a 6 kW bidirectional charging station for charging EVs at home is used. It uses a CHAdeMO connection to charge in Mode 4 (currently the only connector suited for bidirectional functions). Table 2 contains important technical information regarding the charger.

Table 2. Technical specifications of EV charger.

Max. Charging/Discharging Power	6 kW (Bidirectional)
DC Output Voltage Range	50–500 V
Maximum DC Output Current	15 A
Connector	Mode 4 (IEC 61851-1/23/24), CHAdeMO V2X 2.0
Power connection type	Single-phase
Maximum power	6.5 Kva
Nominal AC Input Voltage	230 VRMS (±10%)
Maximum AC Input Current	26 ARMS
Nominal frequency	50 Hz (±2%)
EMC/Electrical safety	IEC 61851-1, IEC61851-23, IEC 62196

According to the charger's datasheet, the user may select the period that they require the car to be used for so the charger will automatically charge the EV using either free RES installations in the house or grid electricity during off-peak hours when the cost is lower. By using this feature, it can also forecast when the user is not using the car, allowing it to harvest the surplus energy and transfer it to home or back to the grid. As a result, the EV serves as a source of energy for their home. Thanks to the charger's user app (iOS/Android/Web), the user can control the charging process at any time and from anywhere. The app allows the user to set charging plan, configure different charging modes and monitor the energy flow of your home.

The system should be configured the first time in order to make use of its V2H and smart charging capabilities. Several critical factors are provided by the user in the configuration file, including grid code, power distributor rates, type of internet connection, presence of RES in the house, maximum power permitted by the energy contract, the possibility to define variable tariff energy or constant tariff, and whether or not smart charging (V1G) is authorized. The charging device is accompanied by two measurement devices that measure the power drawn from the grid by the home as well as the electricity generated by the RES. One of the key goals of this research is to interface the device with a HEMS. Consequently, understanding the behavior of the charger becomes a major concern of the research activities.

3.2. EV

A NISSAN LEAF 2018 (Figure 6) is used in the test, which has two types of batteries that can deliver high and low voltages. A traditional lead-acid 12 V battery and a Li-ion high-voltage battery pack are available. The traction motor is powered by a high-voltage battery pack that stores energy at around 360 V DC. This car is designed to perform bidirectionally (in our study for V2H); in charging mode, the high voltage battery stores energy drawn from the charging station. Conversely, in discharging mode, it acts as an electricity source, releasing its stored energy to supply energy either to the car electric engine or to the home to balance its load partially or fully. Two ports are available on the NISSAN LEAF for Normal charge and Quick charge. Type 2 inlet is used when charging at home or at public slow and fast AC points. While the CHAdeMO inlet is used to carry high power during rapid DC charging. In order to have V2X services, the CHAdeMO inlet should be used [27].

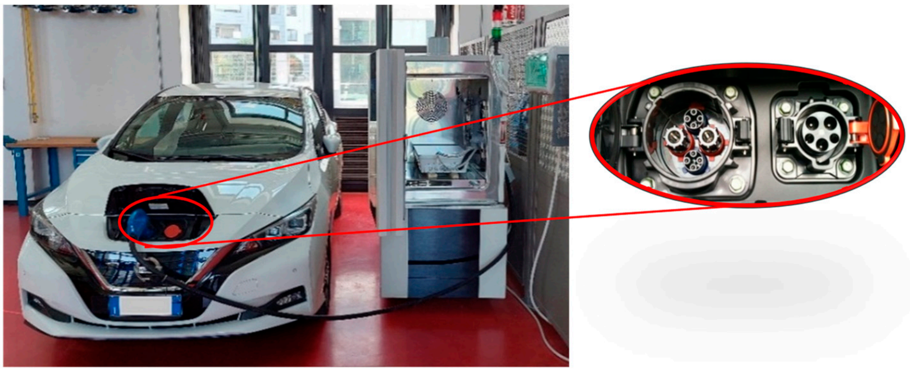


Figure 6. Nissan Leaf used in V2H tests and its charging inlets.

3.3. Household Appliances

The charging device is connected to both a programable load and real domestic appliances. Domestic appliances offer the possibility to observe their electric interactions with the charger. On the other hand, the manipulation of the house consumption by a programmable load is more convenient and faster in the tests, so later on it is used to simulate the domestic load. Figure 7 presents the real house appliances present in the laboratory environment and Table 3 lists various important properties of the programmable electric load employed in this work.

Figure 7. The real house appliances present in the laboratory.

Table 3. Programmable load's technical specification.

Number of phases	1
Frequency	DC, 40–1000 HZ
Maximum AC input voltage	280 V
Maximum DC input voltage	400 V
Power	4.2 kW
Rise/fall time	15 µs

3.4. PV Panels and Stationary Battery Storage System

A pyranometer, a computer, and a programmable DC supply system are used for PV production simulation; then, this system is connected to a battery energy storage system (BESS) through a unidirectional DC/AC converter. The pyranometer detects sun irradiance on the laboratory ceiling first then sends the data to a computer. In this study, LabVIEW interface is used to modify the data so that they can be read by the power supply system. The power supply system generates the necessary DC power, which is then pumped into the inverter. The real testing equipment is shown in Figure 8.

Figure 8. The BESS and part of the installation used for simulating PV generation.

The system is designed to resemble a solar plant with 9 modules, each having peak output of 327 W, dimensions of 1.046 × 1.559 m, efficiency of 20.5%, and temperature coefficient of −0.35 percent per Celsius. The total power generated is computed using the formula below (3), which varies according to the installation circumstances. In this formula, N is the number of PV modules, S is the single module's surface, E is the efficiency, I_{rr} is the solar radiation in W/m^2, γ is the temperature coefficient, and T is the ambient temperature in °C.

$$P_{tot} = N * S * \eta * I_{rr} * [1 + \gamma*(T - 25)] \quad (3)$$

In addition, a BESS is integrated into the house to store surplus power generated by the PV emulator and return it to the house appliances whenever it is needed. Furthermore, in the event of a blackout, this BESS temporarily backs up critical loads in the house. The tests were conducted using a li-ion battery, which has the properties shown in Table 4. Following the BESS, there is a bidirectional converter that allows electricity to flow from the BESS to the home or from the power supply system to the BESS.

Table 4. Technical specification of BESS.

Nominal voltage	48 V
battery capacity	100–500 Ah
storage capacity	9.6 kWh
Maximum charging/discharging current	60 A
Depth of discharge	0–80%
Maximum input power	3500 W
Maximum output power	3000 W
Charging/discharging efficiency	94.6%
Number of MPPT	2

3.5. Measurement and Monitoring Devices

The measurement devices employed in this study are categorized into two groups: (1) EV charger's measurement devices supplied by the manufacturer, whose findings are delivered to the charger's EMS in order to perform V2X services; and (2) measurement devices used for additional testing and research in Edison's laboratory. One of the first sets of measurement devices is put at the connection point to the grid in order to measure the house's total power consumption, and the second one is positioned after the PV inverter to measure the PV power production at the time. Through an RS-485 cable and Modbus protocol, these meters are directly connected to the bidirectional charger. The second set of measuring devices is placed in key locations throughout the testing facility to measure and gather data for additional exploration and analysis.

4. Tests and Results

To achieve the goal of energy sufficiency in a home, an energy management system must be defined based on the facilities present, but to do so, it is critical to understand the working principles of all devices and their behaviour in the presence of other devices in the house. Although the final goal of this project is energy sufficiency, because of inconsistent behaviour of the EV charger in the tests, this goal could not be achieved, and another EV charger will be used for this purpose. Most of the issues noticed were so commonplace and unpredictable that no researcher would give them any thought while modelling the EV charger. As a result, we decided to describe some of these concerns here in order to inform researchers about real-world problems in an EV charger. Each test in this work has been repeated numerous times under almost identical conditions to ensure that the results are not influenced by transients and each test adheres to all aforementioned constraints.

The first test is carried out to see how the bidirectional charger behaves when a house consumption is present and changes over time. The result of this test is shown in Figure 9. According to the charger's datasheet, it should be able to adjust its power consumption according to the house consumption from the grid, i.e., the capability of smart charging. PV production is excluded from this test to assess the charger's fundamental performance. The household consumption is first set to 0 W, and then it is increased by 200 W per minute until a power value higher than the contract power limit is reached. The contract limit is defined 6 kW in the configuration file, and the tariff of electricity is assumed to be constant. The results illustrated in Figure 7 indicate that the charger appropriately adjusts its power based on the home load value and tries to keep total power within the contract limit. The charger's power reduction is continued till the charger's minimum power (190 W) is attained. After this point, even when the contractual restriction is exceeded, the charger does not modify its power.

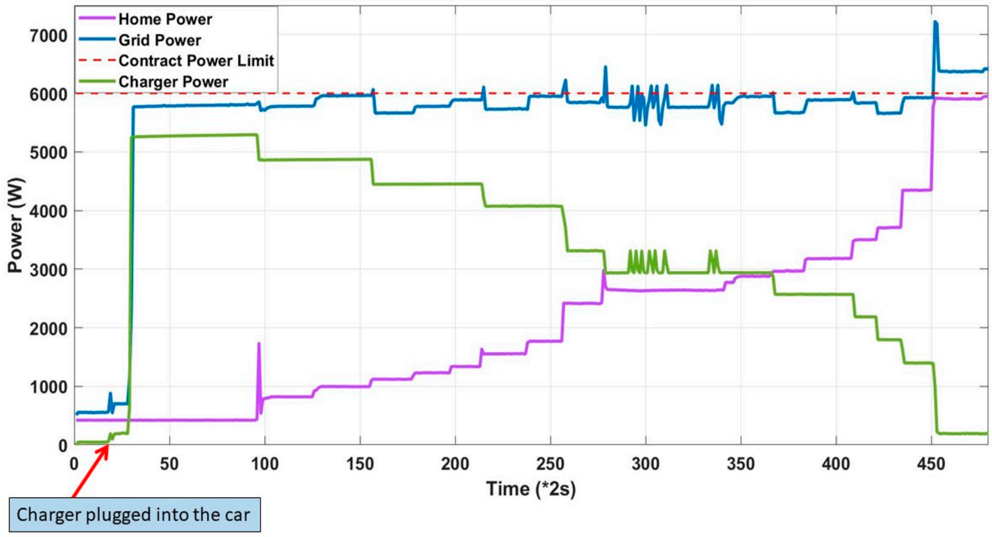


Figure 9. Power regulation of the charger based on the house consumption.

The next test examines the performance of the charger in the presence of RESs, in this case PV panels. This test has been carried out by considering the contract limit equal to 6 kW, flat tariff, and vehicle SoC higher than MBP. It is also set in the configuration file that PV panels are present in the house. Figure 10 shows the results of the test. The plot depicts how the charger causes instabilities and fails to follow the house power consumption and solar production. In both charging and discharging modes, this unsteadiness has been seen. As a result of inconsistency, it was decided not to include PV generation in the remaining tests.

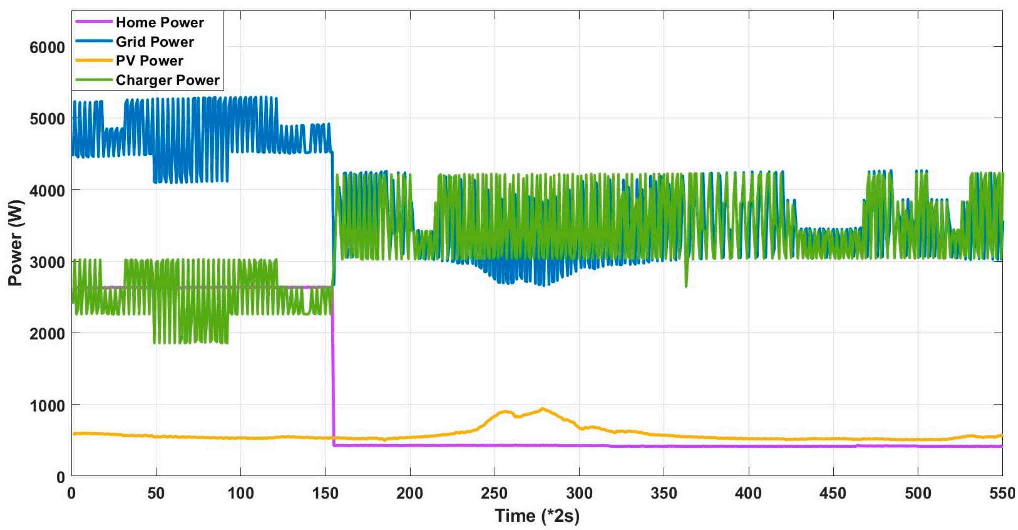


Figure 10. Charger's behavior in presence of PV generation with old firmware.

Once the manufacturer of the charger was notified of the issue, the manufacturer provided an updated firmware and configuration file to stabilize the bidirectional functioning. The previous test was then repeated to examine into how well the charger performs when there is PV production. Contrary to prior test results, the findings shown in Figure 11 show that the charger correctly adjusts its power based on the home consumption and makes an effort to keep overall power within the contract limit. As can be seen, when there is extra PV generation in the home, the charger begins charging at high levels.

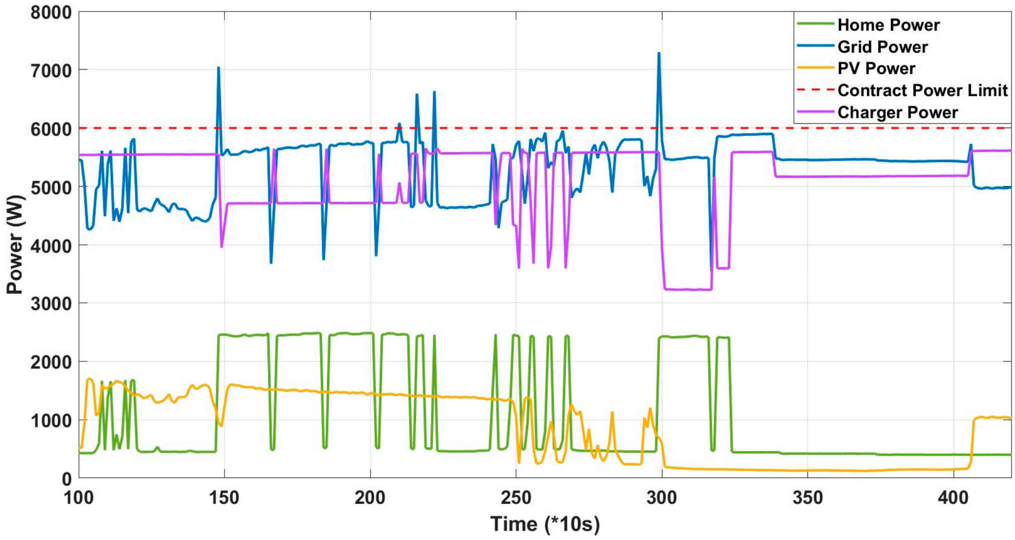


Figure 11. Charger's behavior in presence of PV generation with new firmware.

5. Discussion

5.1. Challenges of the Bidirectional Charger

During testing with the bidirectional charging station, instances of difficulty adjusting charging power and instabilities were observed. These issues are listed and briefly explained in the following subsections.

- Lacking smart charging in specific circumstances:

The following test is conducted to make sure the EV charger performs well when connected to the vehicle starting from various home consumptions. Tests with various levels of initial home consumption were conducted, and one of them, which is described below, attracted our attention. In this test, the EV is connected when the household loads match the contract limit, setting a contract limit of 3kW and a flat tariff. The results of this test are depicted in Figure 12. It is expected to have the charging process with the lowest allowed power, 190 W, but it is seen that by the time the charger is plugged to the EV, the charging power increases to 650 W. The charging continues constantly at 650 W while varying the power consumption stepwise (lowering it 200 W more in every step and returning to the starting value). When the domestic power receives around 1750 W, the next charging threshold is triggered. Here, the EV charger eventually returns to normal behaviour and the charging power reduces to 190 W when returning to the starting domestic consumption. This indicates that there are some initialization problems in the smart charging process.

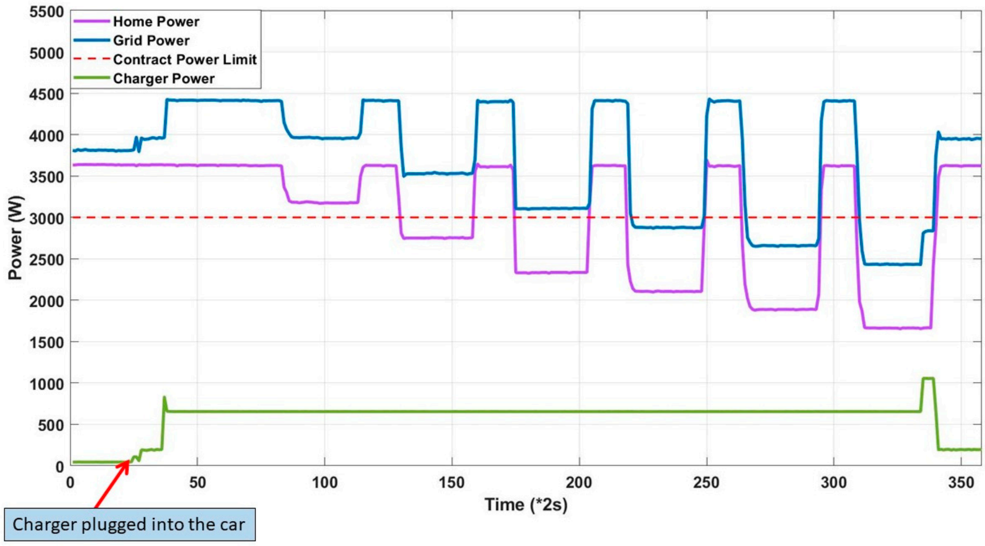


Figure 12. Power regulation of the charger starting from house consumption equal to the contract power limit.

- Unstable performance in case of variable electricity tariff:

In all previous tests, electricity tariff is considered to be constant. In the flat tariff case, there are no financial incentives for EV customers to engage in V2H. So, further tests are carried out to see how variable tariffs affect the activation of V2H. In the configuration file, it is possible to choose either dynamic or manual tariffs, but the results are expected to be identical. This test is run by a manual tariff configuration rather than by a dynamic one since we have no control and knowledge on when the grid tariff is changed. By selection of manual tariff, it is possible to a define different tariff for each hour. The contract limit is set to 3 kW in this test, the tariff is manually set (the test is conducted during more expensive hours of the day), and the vehicle SoC exceeds the defined MBP. Figure 13 shows how the charger operates in a bidirectional manner, compensating for the power consumption of household devices. This process is not always steady, and instabilities occur. Another feature that results from the data and the plot is that the charger's power compensation is larger than the domestic demand when the domestic demand is lower than the contract limit, resulting in a power injection to the grid which can be interpreted as a V2G service.

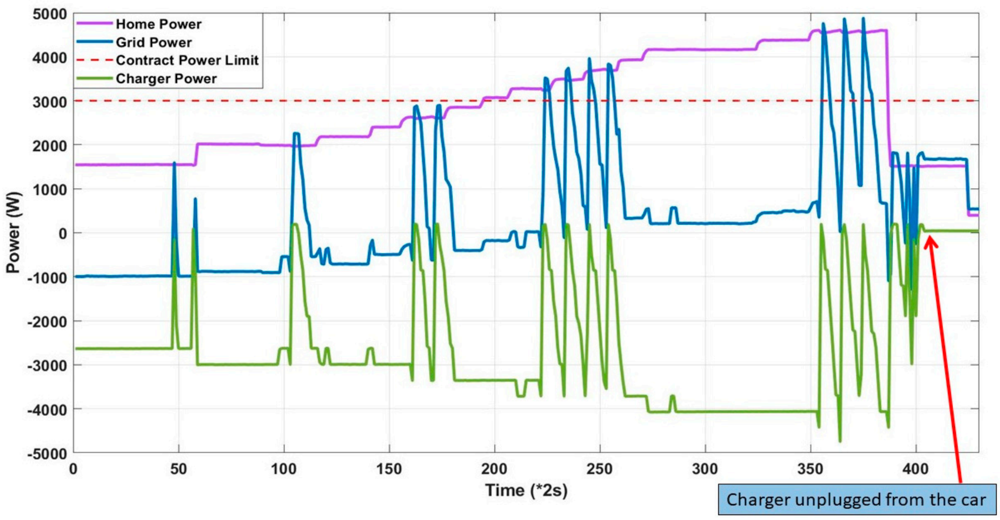


Figure 13. Charger's behavior in case of varying tariff and SOC higher than MBP.

As it can be seen in Figure 13, the charger's instabilities follow a pattern in which it raises its power by 400 W, reaches the next threshold, and then drops to zero. This is viewed as an iterative process in which the charger decreases or raises its power in order to find the optimal compensating solution. As the regulation process encounters the discrepancy, it follows an iterative approach to go back to the stable value for the same power consumption. Even with the identical configuration and operating circumstances, the instabilities displayed unpredictable behaviour.

- Unstable charging in case of low SoC:

It is also worth noting that the charger operates only in charging mode for the vehicle SoCs lower than the MBP, see Figure 14. However, the charging power is extremely unstable, indicating that the charger is having problems finding a sufficient power threshold. The charger's power consumption ranges from a minimum of 400 W to a maximum of 2 kW around a specific power value. However, the power absorbed from the grid is considerably greater than the contractual restriction of 3 kW specified in the configuration file.

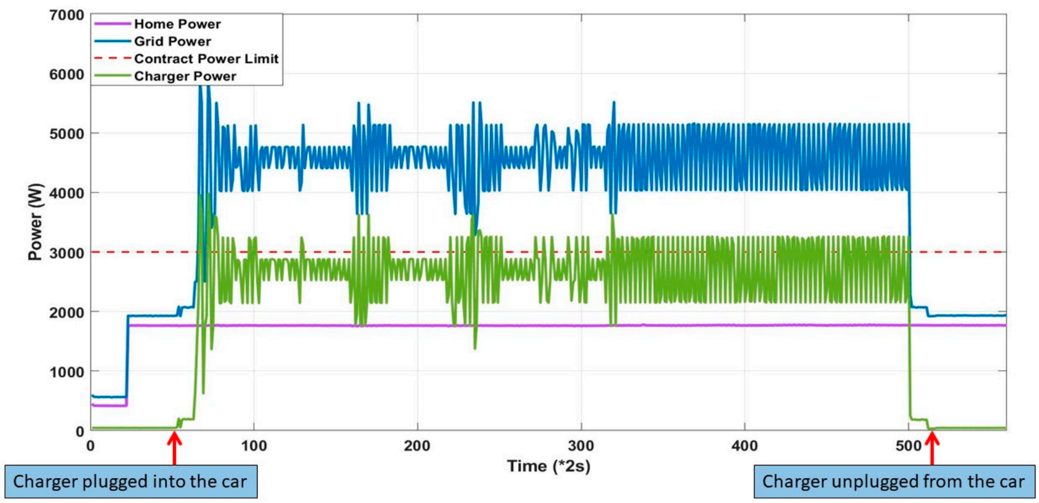


Figure 14. Charger's behavior in case of varying tariff and SOC lower than MBP.

- Unstable V2H service providing:

After reporting the problems to the charger's manufacturer, the manufacturer sent a new firmware and configuration file to stabilize the bidirectional functionality. The following test is carried out with new firmware while the vehicle SoC is higher than the defined MBP and the variable tariff is chosen in the configuration file. Figure 15 depicts the results of this test. As is clear, it begins with a short and instable charging phase and ends with a standby state, 190 W. The increase in home demand triggered a short V2H process; however, the compensation obtained was substantially larger than required (injecting 1.5 kW into the grid). After some minutes, the process came to a halt and the charger went into standby mode. By raising the domestic load gradually up to a power of 6 kW, the bidirectional operation restarts and the V2H function becomes stable and regulates the charger's power in accordance with the domestic consumption. The instability begins again at the house load of about 4.5 kW. Hence, the new firmware only partially solved the issues reported but added other problems such as missing power compensation for low values of domestic consumption.

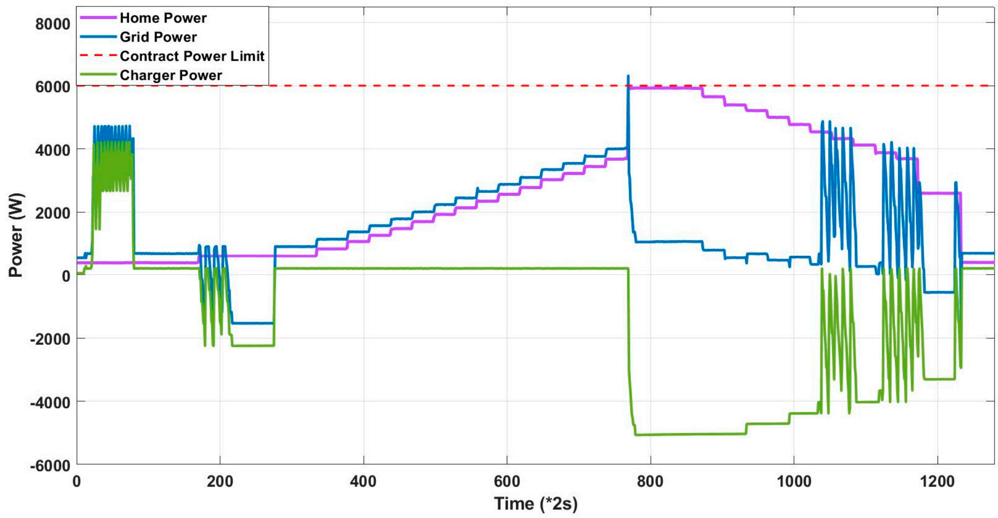
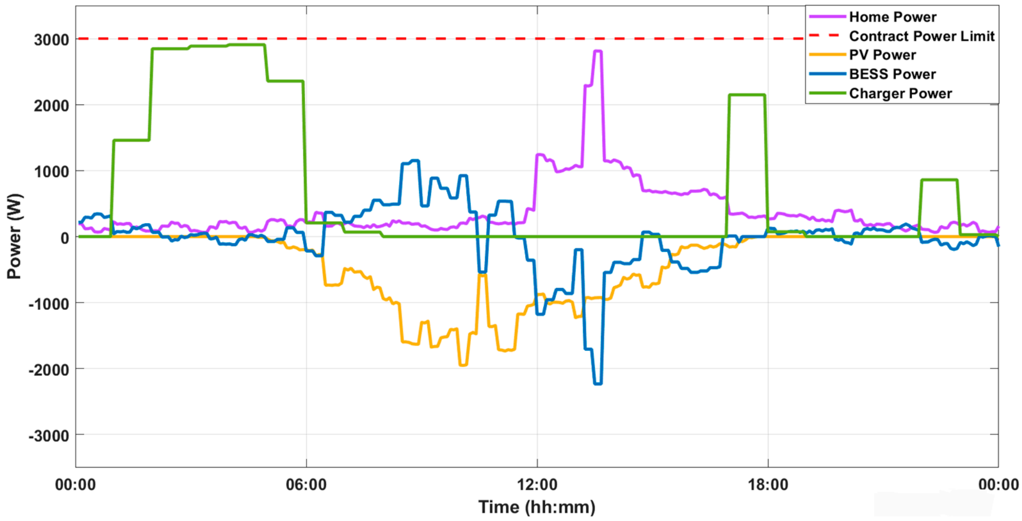


Figure 15. Charger's behavior in case of varying tariff and SoC higher than MBP (new firmware).

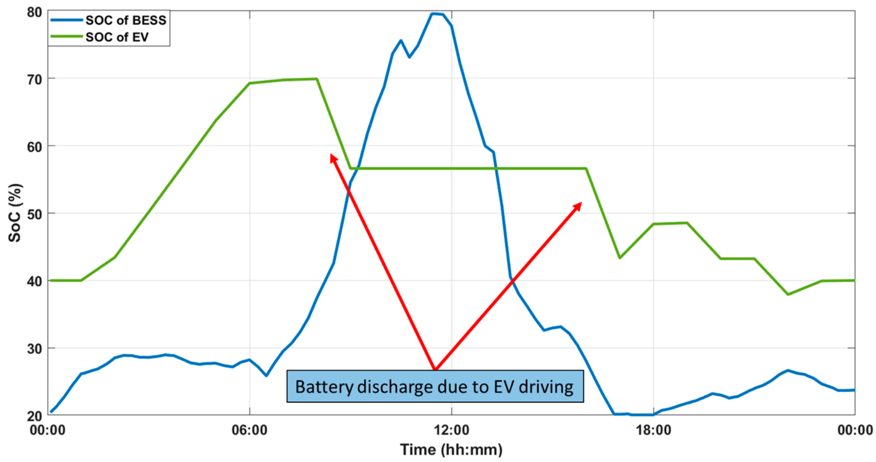
5.2. External EMS and Simulation Environment

By seeing improvements after upgrading the firmware (Figures 10 and 11) it became clear that a better EMS may alleviate most of the problems. As a result, the authors of this paper developed an EMS to test the charger using this external EMS rather than its internal one. Parallel to this EMS definition, a Simulink model of the smart house is created to explore the performance of the described EMS in the semi-real setting and compare its results with real-world test outcomes. Thanks to this simulation environment, diverse case studies can be investigated more quickly, and the roots of the difficulties noticed in results could be better identified.

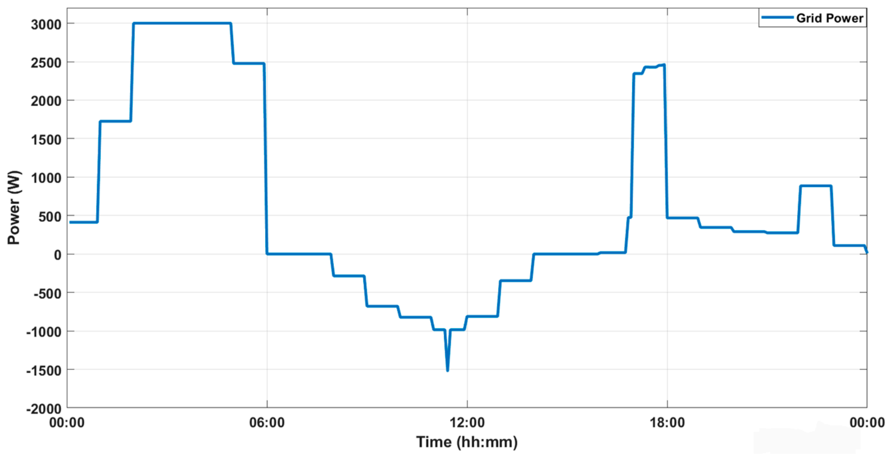
Real house consumption and PV production measurement data from a typical Italian house, as well as an employee's EV usage, are utilized as input for conducting simulations. Figure 16 shows the outcomes of a one-day simulation. As illustrated in Figure 16a, the BESS and the EV charging/discharging are appropriately managed in accordance with the amount of available PV production and consumption at home. The established EMS balances the energy in the house based on the price of selling/buying of electricity, battery ageing, and other defined constraints. For instance, limits of 20–80% are considered for the SoC of the EV and the BESS SoCs to avoid rapid battery aging (see Figure 16b). The grid exchange power for the same day is shown in Figure 16c, and it is clear that energy is mostly purchased early in the morning and late in the afternoon when the electricity buying price is lower, while extra PV is sold to the grid at noon when the electricity selling price is higher.



(**a**)



(**b**)



(**c**)

Figure 16. Results of a one-day simulation with external EMS: (**a**) power regulation of the BESS and the EV according to PV production and house loads; (**b**) SoC of the BESS and the EV; (**c**) grid exchange power.

6. Conclusions

In this article, the first outcomes of the Lab4V2H project performed by Edison's R&D staff are presented and analyzed. The final goal of this project is to define an effective

HEMS which, by monitoring and controlling the available RESs and V2H in the house, helps the household to reach energy sufficiency. According to the results of the tests on the charger installed in the house, it is obvious that the charger under investigation is not mature enough to appropriately perform the V2H services. The key issues seen include unstable performance in the presence of PV production, inability to select the correct power level when initializing the charging if the house consumption is equal to the contract limit, and poor performance in case of varying electricity tariffs. The unstable power of the EV charger in charging/discharging modes can have detrimental effects on the age of the EV battery as well as the quality of the grid power. Although the results presented in the discussion section are not satisfactory and consistent with the project's goal, they are released in order to aid future studies in better understanding the true challenges of commercial bidirectional chargers.

According to the authors of this research, the likely reasons for the instabilities identified in the test results might stem from the charger's internal EMS, which is not well-defined, or the delayed response of the converter inside the charging system. To examine how an EMS can affect the performance of bidirectional charging systems, the authors of this research developed an external EMS and a Simulink model of the smart house. The final part of the discussion section presents the results of a one-day simulation employing the defined EMS, and as can be noted, no stability issues emerged. Additionally, it is clear that the EV charging load is moved to off-peak times when the cost for electricity is lower. Additionally, the batteries' aging is taken into account, and they are not overcharged or drained. Since the charger under investigation cannot be controlled with the external EMS, other chargers have been installed in the same lab and further tests are ongoing which are utilizing the external EMS. The primary test results show that the new chargers perform much better when employing the external EMS than the charger under review in this study.

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