Integration of Electric Vehicles in Buildings: Optimization Model and Economic Assessment by a Digital Twin Representation

Integration of Electric Vehicles in Buildings: Optimization Model and Economic Assessment by a Digital Twin Representation

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***Abstract*—The accelerating adoption of electric vehicles and their integration into smart grids through Vehicle-to-Everything technologies present novel opportunities for enhancing energy efficiency and grid stability. This study explores the potential of leveraging electric vehicles within building energy systems, employing a digital twin model for comprehensive analysis and optimization. By simulating various scenarios, including standard and cloud-impacted photovoltaic production and different energy pricing strategies, the research assesses the operational and economic impacts of utilizing a V2G-enabled car park. The proposed formulation is cast as mixed-integer linear programming, tested through a digital twin approach, demonstrates improvements in energy management and cost efficiency. The findings suggest that, under certain conditions, the bidirectional energy flow capabilities of electric vehicles can effectively substitute for traditional stationary storage systems, offering a dual benefit of vehicle charging and grid support.**

***Index Terms*—V2G, G2V, Digital Twin, Electric Vehicle Chargers, EV,Optimization**

I. Introduction

According to [1] the sales of Electric Vehicle (EV) doubled in 2021 from the previous year and this trend seems to be continuing. The storage capabilities of EVs led to the development of smart charging technologies that allow to use their batteries in the most cost-efficient way. In this scenario, Vehicle To Grid (V2G) applications are becoming interesting, as they enable a bidirectional flow between vehicles and the network itself, providing benefits to both the vehicle owners and grid operators [2]. According to the IEA [3], by 2030 EVs will represent more than 60% of vehicles sold, so the location of charging points will continue to expand to all types of buildings which could exploit this diffused storages to enhance the overall energy management strategy. In this context, the introduction of diffused storages into the building's infrastructure needs to be correctly evaluated in each specific case, especially if this technology has not been implemented since the project state, making the impact unpredictable. This aspect prompted us to the use of the Digital Twin (DT). Indeed, by simulating these scenarios, DTs enable a detailed examination of V2G system performance. Through this framework and the optimization of the available resources, this study aims to evaluate the economic implications of V2G systems focusing on the test infrastructure and on the problem formalization rather than on comparing the results of different optimization methods. Indeed, due to the relatively low number of variables, other stochastic approaches have not been considered. This involves analyzing the costs and benefits associated with integrating electric vehicles into the grid and using them as a form of energy storage. The study seeks to compare the performance and cost-effectiveness of V2G systems with traditional stationary storage solutions. This comparison will help determining the feasibility and advantages of replacing stationary storage with EVs. The study uses a DT model in order to create a test bed involving real hardware through Power Hardware In the Loop (PHIL) simulation, in order to test novel approaches for the V2G analysis and optimization. This will enable the validation of real-world settings and the necessary adjustments to research models and algorithms. These objectives are aimed at exploring new perspectives for the integration of renewable energy and EVs, highlighting the potential for significant cost savings and network optimization. The study also underscores the value of DTs as tools for exploring complex energy scenarios and optimizing energy management strategies.

II. Literature Review

The DT in this paper involves the optimization and economic assessment of EVs integrated in the building. Regarding the optimization, the model described in the document [4] aims to maximize on-site PV production consumption. This approach, which seeks to minimize power exchange with the grid, incorporates both electric storage decisions and the dynamic balancing of renewable energy supply against

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residential demand, highlighting the technical feasibility and economic benefits of such systems.

Some references in this field, provide a solid foundation for understanding the complexities of managing energy flows within microgrids (as the set composed of the buildings and vehicles can be conceptually associated to). The work in [5] explores optimal power management strategies, taking into account also the voltage profile. Moreover, in [6], the comfort of EVs participating in the grid ancillary services is also examined; additionally [7] emphasizes also technical considerations of incorporating storage solutions in a building infrastructure. According to the document [8], the integration of EVs as flexible storage solutions alongside stationary storage systems, represents an innovative approach to optimize energy utilization within grid-connected residential buildings. This strategy not only supports the maximization of renewable energy consumption but also offers a way to enhance grid stability and reduce dependency on external energy supplies. By leveraging high-resolution load modeling and real-time data analytics, as highlighted in the model presented in [6], such an approach can achieve a more efficient and sustainable energy ecosystem, capable of responding dynamically to the fluctuations in both supply and demand. DTs have emerged in the energy sector, offering unparalleled insights into system performance, enabling real-time monitoring, and significantly enhancing operational efficiency. This review synthesizes findings from several key studies to illustrate the breadth of DT applications for optimization purposes. Chen et al. (2022) [9] outline DT techniques for energy conversion systems, stressing the potential of DTsto revolutionize energy system management through sophisticated simulation and analysis tools. Sifat et al. (2022) [10] and Semeraro et al. (2021) [11] discuss the integration of DTs within electric grids and their broader paradigm, highlighting the role of DTs in achieving operational excellence and enhancing grid resilience. DT applications are useful for building energy efficiency, showcasing the potential for DTs to significantly reduce energy consumption and optimize building management systems. The application of real-time monitoring and control through simulation and modeling techniques, including the OPAL simulator, highlights DTs' role in enhancing system resilience and operational efficiency. Furthemore, digital twins are categorized in two main types, as in the survey presented in [12]: Digital Twin Instance (DTI) and Digital Twin Prototype (DTP). While the former one can be used to evaluate or predict the performances of the real object based on the current state, the DTP enables to simulate the behaviour of the component even before its production. However, often, the studies are focused only on a specific domain, so, according to the approach of [13], DTs can be broken into fundamental blocks that can be connected to others to form the complete representation of the system, enabling only the functional block needed for the specific evaluation to be used. These references collectively underscore the versatility and impact of DTs in the energy sector. From optimizing grid operations and manufacturing processes to enhancing the energy efficiency of buildings and predictive maintenance, DTs serve as a cornerstone for innovation, enabling energy systems to meet contemporary challenges and future demands.

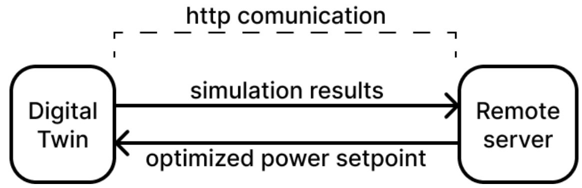

Fig. 1. EMS integration structure.

III. Methodology

A. Digital Twin Framework

The DT developed in this work exploits the Real Time Simulation (RTS) technology. In fact, due to the programmed developments, there is the need to couple real devices to the developed electrical DT. The main advantage with respect to a one bus system is that in this model the losses on the internal distribution network can be assessed and used to feed the Energy Management System (EMS). The hereby used model represents the internal electric low voltage distribution of the building, based on the project of the building, thus creating an electrical twin of the network of the building. Finally, the model has been created in simulink in order to be compatible with the OPAL-RT real time simulation platform. Through this framework it is possible to study both the fast and the slow dynamics of the system. In the presented case, no real hardware were connected to the system due to the needs of simulating an entire day to understand the behavior of the parking EMS. Moreover, because of the desire to export the algorithm to a proprietary device, the DT has to be connected to a separate entity that hosts the optimization algorithm and, more in general, handles the signals used to control the chargers present in the DT. The cited software is running on a separate server reachable from the simulator through a simple *Hypertext Transfer Protocol (HTTP) Application Programming Interface (API)* requests in order to ensure an high modular structure, represented in Figure 1, not hard coding the management system directly inside the model.

B. Optimization Algorithm

The optimization algorithm takes in account different parameters in input, scheduling the charging program for the entire day starting from midnight. The main objective of the operation strategy is the minimization of the costs due to the purchasing of the electricity considering at the same time the possibility of selling energy if it is convenient, as shown in Eq. (1), where $p_h^{grid\_in}$ and $p_h^{grid\_out}$ are the power drawn from and fed into the grid at time h respectively, while $c_h^{grid\_in}$ and $c_h^{grid\_out}$ are the costs of drawing from and feeding into the grid per kWh at time h. The used approach considers a rolling time horizon for the optimization, by basically repeating the optimization for each considered time-step. In this work, the update of the chargers power set-points has been done every 15 minutes, by consequently adjusting the trajectory of the optimization process throughout the day. The model considers as input the load profile of the building, the Photovoltaic (PV) production of the selected day, the energy prices of the ongoing day, the time step (i.e., quarter-hour) considered and the State Of Charges (SOCs) of the vehicles because in this work one of the objective was the assessment of V2G-ready chargers. This enables to considered available the information about the SOC, because this datum is exchanged by the DC Electric Vehicle Supply Equipments (EVSEs) communication protocol detailed in the Standard ISO 15118-9 [14]. In Figure 2 a simplified representation of the algorithm has been shown; the operations can be summarized in:

1) **Forecast**: the process begins with a the forecast of the needed input variables. In this work the forecast of the input variables has been done "offline", by estimating the profile for a typical day; in future versions of the algorithm, the forecast algorithm will be implemented "online", by updating also the forecast in real time with the measured values at the computation time.
2) **Constraint settings**: the optimization strategy takes into account dynamic constraints, which are updated every quarter-hour. These constraints may include limitations on energy consumption, powers, car SOCs and other relevant factors shown from Eq. (3) to Eq. (21)
3) **Connected Vehicles**: the presence of connected vehicles is also factored into the algorithm to make it more robust. The vehicles may contribute to energy demand or provide energy back to the grid. The vehicles during the tests are considered available from 9 a.m. to 18 p.m. due to the use case, which models a buildings with offices occupied during the working hours. At the departure time, the considered vehicles have been charged 10% with respect to the arrival SOC.
4) **Day-End**: the strategy checks whether the day has ended. If not, it loops back to update dynamic constraints and continues the optimization procedure. If the day has ended, the process concludes.

$$\min \sum_{h=0}^{24} (p_h^{grid\_in} \cdot c_h^{grid\_in} - p_h^{grid\_out} \cdot c_h^{grid\_out}) \tag{1}$$

In Eq. (2) it is shown the equality constraint, represented by the power balance of the system, taking into account the load as p_h^{load}, the grid exchange as p_h^{grid}, photovoltaic, stationary storage as p_h^{batt} exchange and the vehicles contributes.

$$\begin{aligned} &\sum_{h=0}^{nTs} (p_h^{load} - p_h^{grid\_in} + p_h^{grid\_out} - p_h^{pv} - p_h^{batt\_dch} \\ &+ p_h^{batt\_ch} + \sum_{i=0}^{n_{car}} (p_{i,h}^{g2v} - p_{i,h}^{v2g}) = 0 \end{aligned} \tag{2}$$

To track the SOC level of both the vehicles and the stationary storage it has been computed each time step following the Eq. (3,14), considering the charging and discharging efficiencies. Some constraints are then set to assure that the SOCs and the power sent or withdrawn from the cars stay in the right intervals respectively in the Eq. (4,5,15,16) and in Eq. (8,11,18,19,20,21)

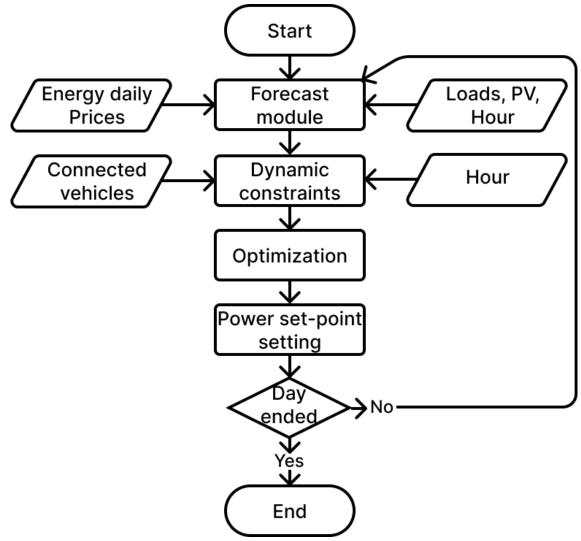

Fig. 2. Daily optimization logic

$$SOC_{i,h}^{cars} = SOC_{i,h-1}^{cars} + \Delta t_{cars} \left(p_{i,h}^{g2v} \cdot \eta_{g2v} - \frac{p_{i,h}^{v2g}}{\eta_{v2g}} \right) \tag{3}$$

$$SOC_{i,h}^{cars} \geq SOC_{\min i,h}^{cars} \tag{4}$$

$$SOC_{i,h}^{cars} \leq SOC_{\max i,h}^{cars} \tag{5}$$

Through Eq. (6) it is assured an higher SOC to the cars at the time of leaving the parking as an incentive to use the service.

$$SOC_{i,18}^{cars} \geq SOC_{i,9} * 1.1 \tag{6}$$

In Eq. (7,17) are then represented the flag variables used to linearize the problem.

$$flag_{i,h}^{g2v} + flag_{i,h}^{v2g} \leq 1 \tag{7}$$

$$p_{i,h}^{g2v} \leq flag_{i,h}^{g2v} \cdot p_{i,h}^{g2v,\max} \tag{8}$$

In Eq. (9,10,12,13) are then stated the constraint used to virtually disconnect the cars outside the considered hours.

$$p_{i,18-24}^{g2v} = 0 \tag{9}$$

$$p_{i,1-9}^{g2v} = 0 \tag{10}$$

$$p_{i,h}^{v2g} \leq flag_{i,h}^{v2g} \cdot p_{i,h}^{v2g,\max} \tag{11}$$

$$p_{i,18-24}^{v2g} = 0 \tag{12}$$

$$p_{i,1-9}^{v2g} = 0 \tag{13}$$

$$SOC_h^{batt} = SOC_{h-1}^{batt} + \Delta t \left(p_h^{ch} \cdot \eta_{ch} - \frac{p_h^{dch}}{\eta_{dch}} \right) \tag{14}$$

$$SOC_h^{batt} \geq SOC_{\min}^{batt} \tag{15}$$

$$SOC_h^{batt} \leq SOC_{\max}^{batt} \tag{16}$$

$$flag_h^{batt\_ch} + flag_h^{batt\_dch} \leq 1 \tag{17}$$

$$p_h^{batt\_ch} \leq flag_h^{batt\_ch} \cdot p^{batt\_ch,\max} \tag{18}$$

$$p_h^{batt\_dch} \leq flag_h^{batt\_dch} \cdot p^{batt\_dch,\max} \tag{19}$$

$$p_h^{grid\_in} \leq flag_h^{grid\_in} \cdot p^{grid\_in,\max} \tag{20}$$

$$p_h^{grid\_out} \leq flag_h^{grid\_out} \cdot p^{grid\_out,\max} \tag{21}$$

C. Case Study Design

This study investigates some scenarios to evaluate the performance and economic impact of integrating EVs into building energy systems using a DT model. The cases include real-time price variation, standard PV production, PV production with unexpected cloud cover, and a comparison with stationary storage. The prices for electricity sold back to the grid are based on the real contract specific to the DT under test, which includes surcharges for losses as per Italian regulations. Additionally, the EV chargers are modeled accounting for the time required to receive charging commands. These factors are crucial for accurately simulating the charging process taking into account the energy not transferred to the vehicles due to the dead time. Real-time pricing reflects the fluctuations in energy costs throughout the day, influencing the optimization of energy flows between the building, the grid, and the EVs. The standard PV production, considers a typical day with consistent PV energy production. The goal is to optimize energy usage and storage under predictable solar energy generation conditions. Then some variability has been introduced in PV output due to unforeseen cloud cover, while the load is considered fixed among all the cases as shown in Figure 3. This scenario tests the system's resilience and ability to adapt to sudden changes in solar energy availability. In the end, a comparison with stationary storage has been evaluated, assessing the performance of the system using EV batteries for energy storage. Based on the Italian regulations, for the building we simulated, the selling prices for the injected energy must follow the zonal price established by the electricity market, so we used a price profile for a typical day. Furthermore, a second price profile has been considered, which is a typical profile of the Northern Europe countries, shifting the peak price at 10 a.m to show the responsiveness of the algorithm with a very volatile prices. Both profiles are shown in Figure 4.

From the point of view of the buying prices, they were based on the same profile of the Figure 4 applying a spread to the prices to consider taxes and the distributor revenue. The spreads have been set as follows:

- +0.1 €/kW h for the first Italian based scenario.
- +0.2 €/kW h for the second Italian based scenario.
- +0.06 €/kW h for the first volatile price scenario.
- +0.1 €/kW h for the second volatile price scenario.

The analyzed scenarios are summarized by Table I. For each case, the combination among V2G and Battery Energy Storage System (BESS) was tested.

TABLE I
ANALYZED SCENARIOS

Case	Price	Spread [€/kW h]	Cloud
Case 1	Ita	0.1	✓
Case 2	Ita	0.2	✓
Case 3	Volatile	0.06	✓
Case 4	Volatile	0.1	✓
Case 5	Ita	0.1	-
Case 6	Ita	0.2	-

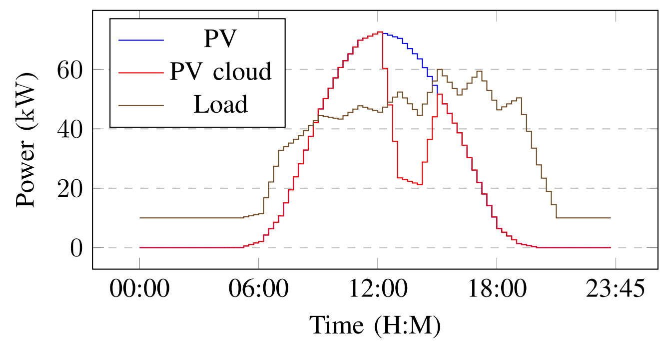

Fig. 3. Daily PV production and total load

IV. RESULTS

In the study, the power profiles of both generation and load units under six different scenarios combining V2G operations and BESS are analyzed. As depicted in Figure 5. A notable difference in these profiles was the operational hours of BESS, constrained by the limited availability of vehicles during the working day. Importantly, the algorithm demonstrated robust performance in handling non standard situation, such as cloud cover, effectively managing the associated challenges in real-time. The power profiles at the Point Of Common Coupling (PCC) also revealed discrepancies, primarily due to the building's load predictions based on typical loads, which were aggregated to compute the total load. Our framework incorporates a DT, which enables the PCC profile to account for losses in the low-voltage distribution line differently than the grid-exchanged power, computed in the optimization algorithm. This model iteratively feeds power measurements back into the algorithm, ensuring that losses are considered in the optimization process. From the scheduling perspective, the power set-points for chargers and BESS were dynamically

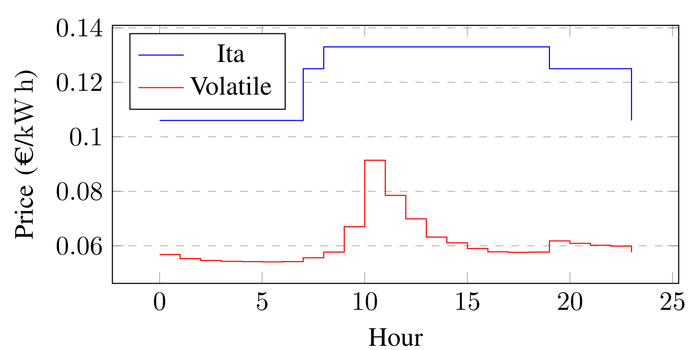

Fig. 4. Daily price profile used for the tests

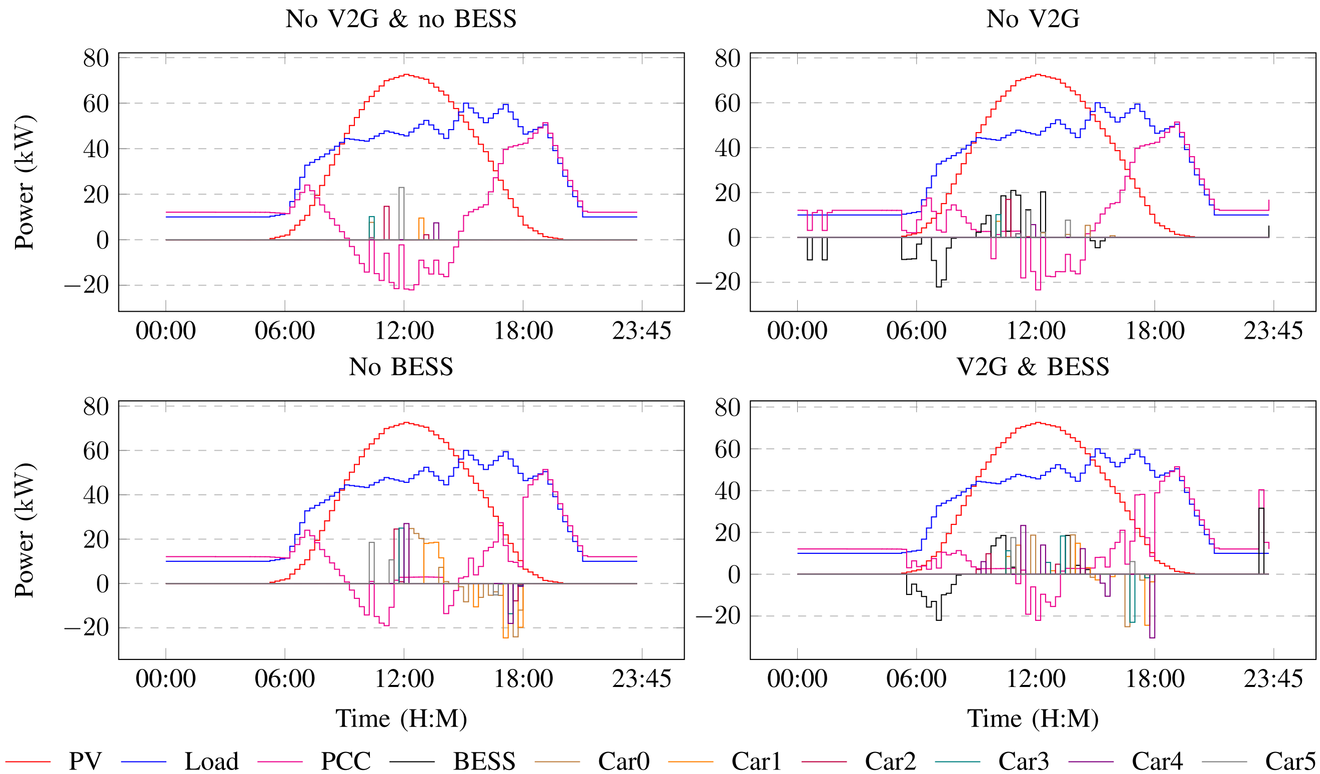

Fig. 5. Generation and consumption profiles for case 6

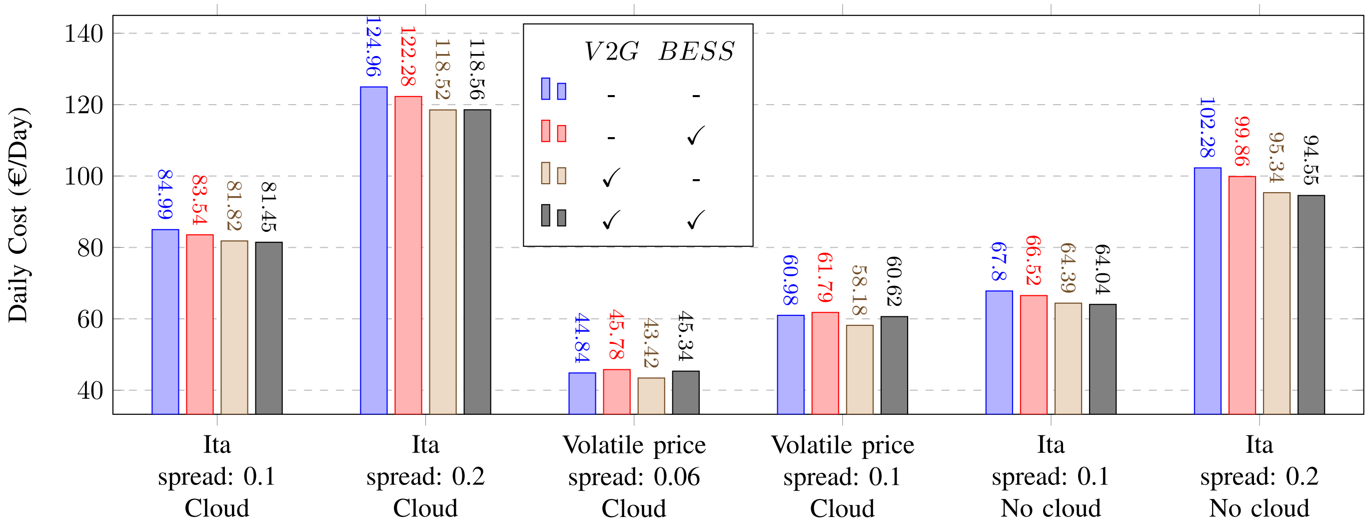

Fig. 6. Test Groups

adjusted in response to changes in other parameters. The initial daily schedule and subsequent real-time adjustments played a critical role. Notably, despite the optimization is based on price references, a peak shaving contributions is visible. This effect were primarily driven by PV generation, especially during midday high-price periods. The BESS and vehicles in V2G mode were activated predominantly when PV generation was insufficient to meet peak demand. Additionally, BESS was strategically charged during periods of high PV output and at night, aiming to maintain an 85% of SOC. Following the Peak Shaving Factor (PSF) defined in the Eq. (22), where X_i is the sample at the quarter i and X_i^{ref} is the sample at the quarter i for the reference scenario without BESS and V2G, it is possible to understand how the control strategy has a beneficial effect reducing the demand with respect to the reference case without both BESS and V2G. Indeed, in all the cases with BESS or V2G this indicator results lower than the reference, showing an effective peak shaving. For example, in Case 6, $PSF = 0.922$ with BESS only, $PSF = 0.819$ with V2G only and $PSF = 0.796$ with both V2G and BESS.

$$PSF = \sum_i \frac{\frac{abs(X_i)}{abs(X_i^{ref})}}{N} \quad (22)$$

The efficiency of our algorithm in reducing electricity costs was evident, with cost analysis for each case study presented in Figure 6. A general trend was observed where costs decreased with the activation of more storage systems, particularly under the Italian price profile. Interestingly, regardless of the price profile considered, the daily costs associated with V2G operations alone were nearly identical to scenarios where both V2G and BESS were active, indicating that V2G operations were the principal factor in cost reduction. A more synthetic view is showed in Table II, which compares the savings in euro per day of each combination in each case with respect to the scenario without both BESS and V2G. This outcome suggests that the additional contribution of the BESS, deliberately undersized at 40kWh to cover non-vehicle hours without incurring high costs of larger batteries, was negligible. This sizing decision was based on the assumption that the BESS would primarily cover gaps when vehicles were not available, rather than making substantial contributions to load management. Furthermore, while the results presented are specific to the scenarios tested in this study, the architecture of our system is designed to generalize well to other conditions of price and load, suggesting broader applicability of our findings. This adaptability underscores the potential for our approach to be implemented in diverse settings, enhancing its practical value.

TABLE II
SAVINGS

Case	€/Day		
	BESS	**V2G**	**V2G&BESS**
Case 1	-1.45	-3.17	-3.54
Case 2	-2.68	-6.44	-6.4
Case 3	+0.94	-1.42	+0.5
Case 4	+0.81	-2.8	-0.36
Case 5	-1.28	-3.41	-3.76
Case 6	-2.42	-6.94	-7.73

V. Conclusion

In conclusion, our study has demonstrated the potential of leveraging EV within building energy systems to enhance energy efficiency and grid stability. Despite the reference for the optimization problem being the price, the load profile is still relieved during peak hours, especially when looking at the tails of the PV, ensuring a less burdensome network situation. To guarantee an economical revenue, the size of the BESS, must be large. Indeed, our findings suggest that, under certain conditions, the bidirectional energy flow capabilities of EVs can effectively substitute for traditional stationary storage systems, offering a dual benefit of vehicle charging and building support. This opens up new perspectives for the integration of renewable energy and electric vehicles, highlighting the potential cost savings and network optimization. These results underscore the value of our digital twin model as a tool for exploring complex energy scenarios and optimizing energy management strategies. We look forward to continuing this work and further exploring the potential of EVs as a key component of smart grids for enhancing energy efficiency and grid stability. In fact, there are still many aspects that need further investigation:

- **Hardware Testing**: our study has relied on a DT model for analysis and optimization. It would be beneficial to validate these findings with real hardware testing through PHIL configurations. This would allow us to validate the performance of our optimization in the real-world.
- **Improved Forecasting**: the optimization algorithm currently uses an "offline" forecast of input variables. Implementing an "online" forecasting algorithm that updates in real time with measured values could improve the efficiency of the EMS.
- **Harmonics Study**: another interesting area is the study of harmonics in the electrical system. By replacing the loads in our model with real hardware or a model derived from it, we could gain a better understanding of the impact of EV integration on the building's distribution network.

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