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Building-Level DC-Aware Energy Management System: Experimental Realization and Outcomes

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***Abstract*— This paper proposes a novel Direct Current (DC)-aware building Energy Management System (EMS) platform. The proposed EMS is a comprehensive ecosystem that includes both the necessary hardware and software components to facilitate the transition of buildings toward compatibility with future intelligent power grids and DC Technologies. A key advantage of this platform is its hybrid topology, which enables simultaneous interfacing with and supply of both Alternating Current (AC) and DC loads. The platform integrates real-time monitoring, optimization, and solar power generation forecasting and demand forecasting units. The focus of this paper is the experimental realization of the proposed solution and an evaluation of the hardware and software performance during their synergetic operation.**

Keywords—energy management systems, DC technology, hybrid networks, renewable energy systems, power flow optimization

I. INTRODUCTION

Buildings are expected to play a pivotal role in the development of future intelligent grids. For decades, they have been passive consumers. However, with the integration of solar Photo Voltaic (PV) systems and Battery Energy Storage Systems (BESSs), their role is evolving. As energy prosumers, buildings present both challenges and opportunities for stability, resilience, and security of future renewable-dominated power networks [1]. Rooftop PV installations are key enablers in realizing near-Zero Energy Buildings (nZEB). A notable issue with nZEBs located in the same geographic region is their synchronous behavior. Buildings with nearby PV setups tend to exhibit similar generation and consumption patterns—drawing minimal power from the grid on sunny days and relying heavily on it when solar production drops. This poses challenges for grid congestion management [2].

The deployment of Energy Storage (ES) systems offers a promising solution to improve building energy flexibility. However, their adoption remains limited, primarily due to uncertain economic feasibility. Although battery costs are expected to decrease, with expectations ranging between $245/kWh and $403/kWh in 2030 and between $159/kWh, $348/kWh in 2050, significant barriers still hinder the integration of ES systems in residential and building-scale applications [3]. To accelerate ES deployment and decrease their capital costs extensive research is being conducted to propose reliable solutions for shared ES asset management and operation [4], [5]. However, currently, building specific BESSs are the dominant solution in the market.

As electricity grids evolve into smarter and more interactive systems, new market opportunities are emerging for buildings. These include participation in regional energy communities for peer-to-peer energy trading [6], as well as the provision of ancillary services such as flexibility [7], phase balancing, and demand response. Assuming the widespread proliferation of distributed PV systems and BESSs and the emergence of renewable dominated intelligent power networks, two major directions for enhancing building energy performance can be identified: 1- the development of advanced Energy Management Systems (EMSs), 2- the adoption of DC-aware technologies.

The EMSs are deployed to ensure the optimal use of local renewable energy sources [8], control ES utilization [9], schedule shiftable loads, and automate the buildings' interaction with electricity grid, neighboring buildings, or other grid-connected components, such as charging stations [10]. Simultaneously, DC-aware technologies offer the potential to reduce energy losses by eliminating redundant AC/DC conversion stages [11]. For example, DC electricity generated by PV panels can be directly routed to DC-based storage and subsequently used by DC-compatible loads. This streamlined architecture can reduce losses by up to 15% [12].

Realizing these benefits requires significant progress in both DC-compatible hardware and intelligent control technologies. To address this emerging need, we propose a DC-aware EMS platform, which is illustrated in Fig. 1, it integrates both hardware and software components.

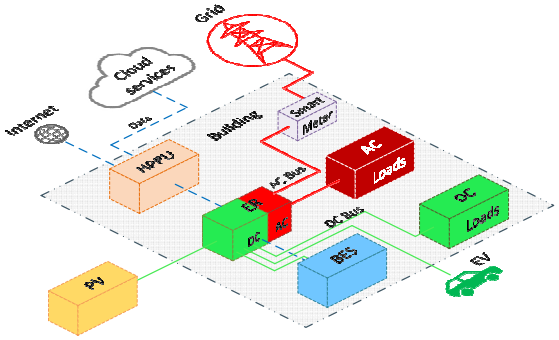


Fig. 1. Proposed DC-aware energy management platform.

This platform enables buildings equipped with PV and BESS to monitor, manage, and evaluate their internal energy flows and overall performance. Moreover, it prepares buildings for seamless integration into future intelligent, renewable energy-driven electricity networks, unlocking

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participation in energy markets and local energy communities. By incorporating DC loads, along with dedicated DC buses and outlets, the platform is adaptable to both fully DC and hybrid Alternating Current (AC)/DC configurations.

II. Methodology

A. DC Aware Energy Router Topology

The backbone of the proposed EMS platform is a device called the Energy Router (ER), first introduced in [13]. The ER is capable of simultaneously delivering power to both AC and DC buses. Fig. 2 shows the ER topology and its prototype. It is a single-cell, three-phase system, meaning that instead of using a dedicated three-phase ER, a cost-effective single-cell topology is employed. The system includes controllable relays that allow the device to connect to the phase with the highest demand. This single-phase topology interacts with all phases, but not simultaneously.

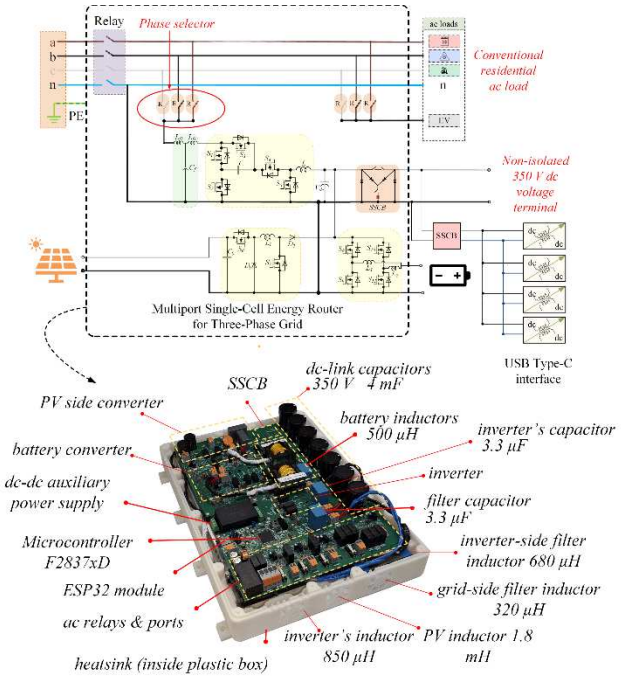


Fig. 2. Single-cell three phase ER topology and its TRL-5 prototype.

The hybrid DC-aware solution is achieved by providing one non-isolated 350 VDC and an isolated 48 VDC buses. The non-isolated solution is suitable for heavy DC loads, while the 48 V DC sockets offer a safe DC supply for light DC loads, such as phone chargers and other low-power devices. Fig. 3, shows the isolated DC sockets topology and prototype. However, the focus of this paper is not on evaluating the performance or efficiency of these sockets, they are included solely to provide a general overview of the system. The experimental tests and outcomes will be shared in the future.

In future smart buildings, power electronic devices must offer high power density, support a wide input voltage range, maintain flat efficiency across various power levels, and enable bidirectional power flow, all while supporting standard communication protocols such as Controller Area Network (CAN), Modbus, and Wi-Fi for networking [14]. The ER supports both CAN, and Wi-Fi interfacing and, as the sole power electronics device, provides low-loss power exchanges between DC sources and loads, and enables the DC system's smooth operation beside AC systems. Fig. 4 illustrates two operational modes during the ER's interaction with PV systems and the BESS. In Fig. 4(a), the ER performs Maximum Power Point Tracking (MPPT), while in Fig. 4(b), the ER interfaces with the BESS to supply power to the DC-link, as PV generation is unavailable.

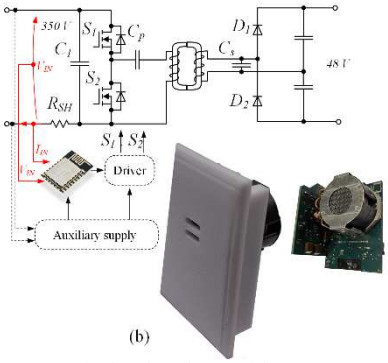


Fig. 3. Smart 48V DC isolated sockets, with USB type-C output. The topology, and the prototype for the proposed DC sockets.

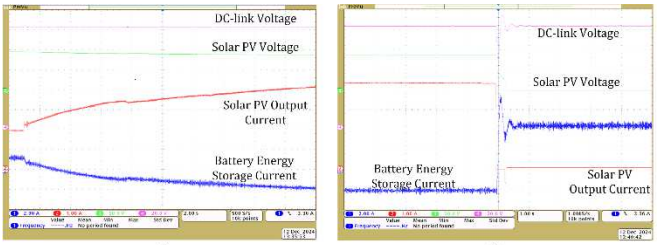


Fig. 4. ER's experimental tests performance. (a) ER's MPPT performance, and (b) DC-link current and voltage statuses when solar PV power is unavailable, and the BESS is supplying the demand.

B. Software Architecture

From a software perspective, the platform features a six-layer architecture designed to handle user interactions, application services, data management, communication tasks, local computational processes, and hardware integrations. Fig. 5 illustrates the software architecture. The software for EMS can be designed in centralized, decentralized, or distributed styles, each offering its own advantages and disadvantages, as discussed in [15].

Since typical processing units in power electronic devices lack the computational capacity for complex algorithms, these tasks must be outsourced to cloud services or executed locally on more powerful hardware. In the proposed platform, the latter approach is adopted. The ER is therefore controlled by a High-Performance Processing Unit (HPPU), which runs the EMS algorithm and sends high-level control commands. Thus, the centralized HPPU is responsible for selecting the appropriate power source to meet demand by minimizing a dedicated objective function. The cost function, objectives, and constraints are detailed in [16].

During operation, the HPPU generates control signals for the ER with a 15-minutes resolution. Additionally, cloud-based software services, a database, an online web server, and a local Graphical User Interface (GUI) have been designed and integrated into the platform. These advancements prepare buildings for seamless integration into future intelligent grids by addressing both hardware and software requirements.

C. Energy Management Systems

To enhance EMS performance, various software services are necessary to provide essential data for optimal resource allocation. These include solar power generation and AC-DC demand forecasting tools, along with third-party services such as time-of-use electricity tariffs and numerical weather

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predictions. Details on solar power generation forecasting and demand forecasting services are published in [17] and [18], respectively.

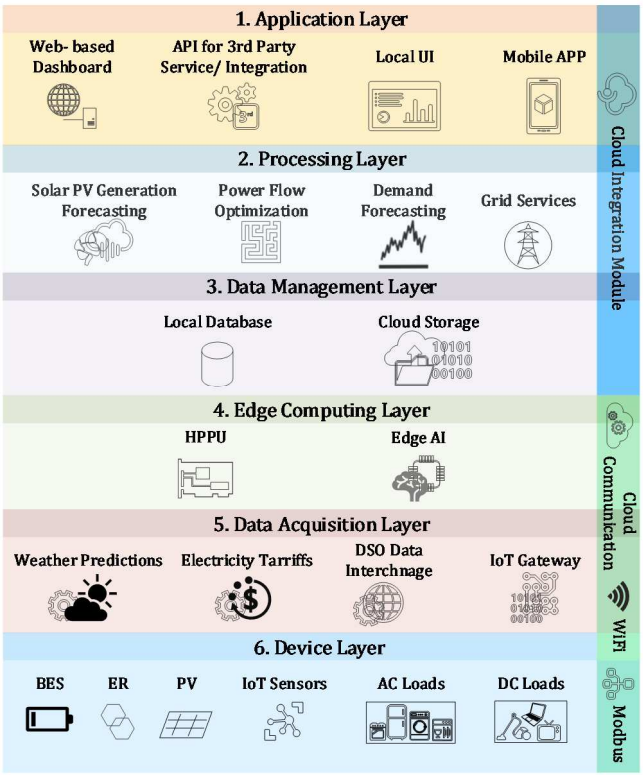


Fig. 5. Developed 6-layer software architecture for DC-aware Building EMS.

EMSs are expected to effectively tolerate uncertainties related to energy generation and demand and satisfy their main objectives ensuring economic performances [19]. For optimization and control tasks, numerous methods have been proposed. These range from model-dependent approaches, such as Model Predictive Control (MPC), and Linear Programming (LP), to model-free methods like rule-based systems, evolutionary and heuristic algorithms, and Artificial Intelligence (AI) techniques, including reinforcement learning and deep learning based controllers. Here, the EMS uses a optimization method described in [16]. The optimization problem is formulated as a Mixed-Integer Linear Programming (MILP) problem, defined in Pyomo, and solved using the Gurobi solver. At this stage, uncertainties are not considered, and the proposed EMS approach is deterministic. While neglecting uncertainties may reduce the system's performance, it helps keep the complexity of the EMS algorithm at a reasonable level.

D. Experimental Setup

The EMS platform is installed and operational at TalTech's nZEB building, a detached house equipped with a solar PV installation and a BESS. Fig. 6 illustrates the installed system's hardware and software components. The BESS is a custom-assembled energy storage system with an 11 kWh capacity and a 350 VDC output. A load simulator was used to emulate the house's demand profile based on historical data, as human presence during testing was not feasible.

In this setup, a Raspberry Pi 4 is used as the HPPU. The HPPU exchanges data with components, including ES, the GUI, ER, load simulator, cloud, and the internet. The load simulator is a board equipped with an ESP32 module, along with several mechanical relays and protection circuits to turn various loads on and off during experimental tests. During system operation, the HPPU, runs an optimization function based on the collected data, and then sends control commands to the ER to determine the appropriate energy source (PV system, BESS, or grid) for meeting the demand. Fig. 7 presents the temporal flowchart of the HPPU's operation.

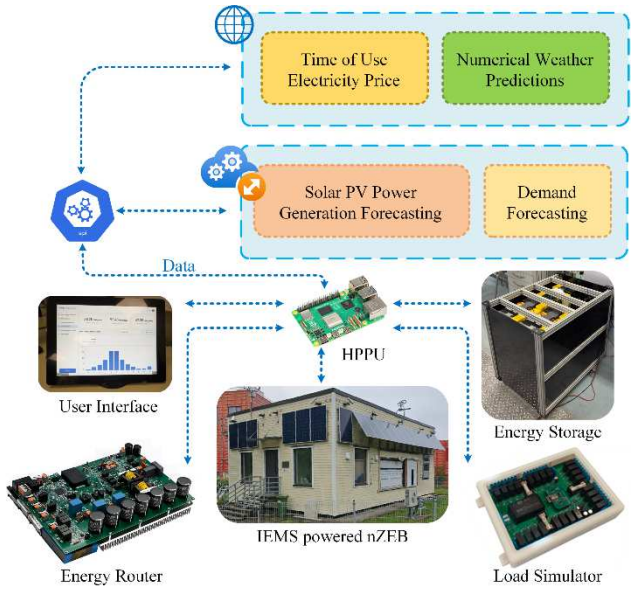


Fig. 6. nZEB test bench at TalTech's campus, powered by DC aware EMS platform including: HPPU, user interface unit, ES, ER, and load simulator.

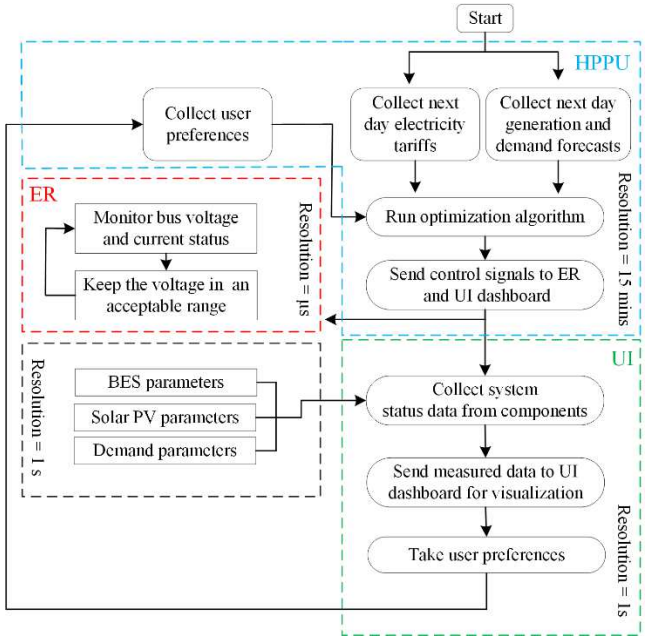


Fig. 7. Temporal flowchart for HPPU operation and various sections operational resolutions.

Fig. 8 illustrates the interior installations. In this study, several loads with various power ranges are connected to a load simulator to synthesize a demand profile. The DC power outlet supplies a voltage of 340 VDC. The GUI displays the current and past status of the building's energy performance, the amount of generated renewable solar energy, and BESS parameters such as state of charge, and cells' temperature. It

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also provides insights into house-grid interactions, including phase balancing conditions and power flow in each phase.

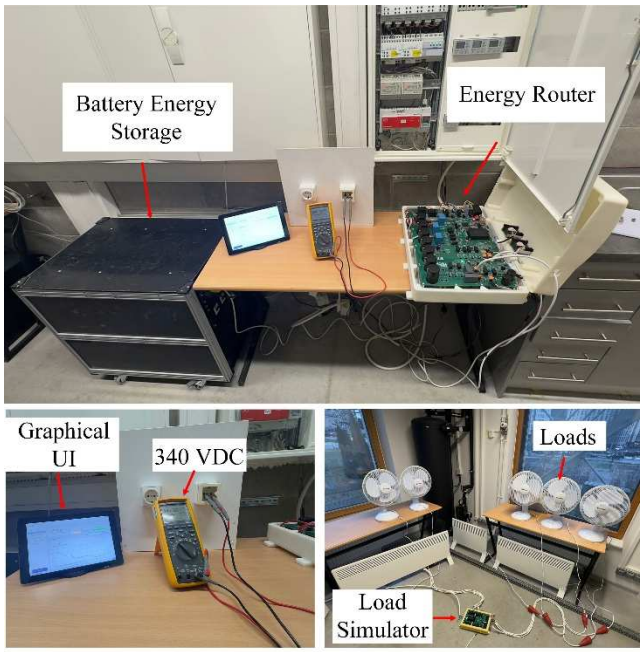


Fig. 8. Infrastructure installed in TalTech's nZEB, for running the experimental tests, and investigating the EMS performance.

III. Experimental Results

A. AC and DC Loads Shares

Over time, the share of inherently DC-powered loads has been increasing compared to pure AC loads. Most modern home appliances use switched-mode power supply (SMPS) units to convert input AC power into suitable DC power. However, AC technology still dominates the market, and DC-compatible devices remain limited. In our study, DC loads are assumed to account for 15% of the total power demand. This estimate is based on electricity consumption data collected from a family house. Table I lists the AC and DC loads along with their average daily power consumption.

TABLE I. DC and AC loads daily consumption shares

Name	*AC/DC*	*Avg. demand (kWh/day)*	*Avg. active time per day**
Lights	DC	0.9	6 hours
Personal computers	DC	1.2	4 hours
Mobile chargers	DC	0.015	3 hours
Vacuum robot	DC	0.1	1 hour
Oven	AC	0.5	10 minutes
Fridge	AC	1.2	24 hours
TV	AC	0.55	5 hours
Dish washer	AC	4.5	2.5 hours
Luandry machine	AC	0.8	0.5 hour
Cook-top stove	AC	6.4	2 hours
Microwave	AC	0.1	10 minutes
Iron	AC	0.17	5 minutes
Hair dryer	AC	0.4	30 minutes
Misselenous	AC	1	1 hour

* Numbers are daily averaged based on total weekly consumption of devices. The house is considered to have a 3-phase connection with 17.32 kW capacity.

From the EMS perspective, both DC and AC loads behave similarly; the primary difference lies in the energy losses incurred when supplying these loads from an AC or DC bus. For example, by connecting devices such as lights, personal computers, mobile chargers, and a vacuum robot to a DC bus, we achieved a daily energy saving of 110.75 Wh. This saving is primarily due to the elimination of dual DC/AC/DC conversions, which are independent of EMS performance. Theoretically, the energy saved could reach up to 891.75 Wh per day, representing approximately 5% of the total daily energy consumption.

During wintertime, when solar power is often unavailable due to snow coverage and limited daylight hours, the impact of using DC technology becomes negligible. This is because the loads are primarily supplied by electricity from the AC grid, and an AC/DC conversion stage is still required to feed DC loads. In such periods, economic savings are the main focus, achieved through energy arbitrage—storing energy during low-cost hours and supplying loads during peak pricing periods.

B. Solar PV Power Generatation Forecasting

The AI-powered solar PV power generation forecasting model, developed in our previous research and detailed in [17], has been deployed on a Microsoft Azure cloud service for real-time operation. At the start of each day, the HPPU sends a request for the next day's solar power generation forecast. Forecasts are generated using numerical weather predictions for the following day, obtained from the Open-Meteo weather service via its Application Programming Interface (API). Fig. 9 shows the real measurements versus the forecasted values. These forecasts are utilized as an input for EMS for energy optimization and resource allocation.

C. EMS Performance

The EMS utilizes hourly electricity tariffs, solar generation forecasts, and an ideal demand profile for optimal resource allocation. In each iteration, it minimizes the objective function based on current and future system states. The details of EMS operation are extensively discussed in [16]. However, it is important to note that high-level control signals lack the resolution needed to effectively regulate AC and DC bus voltages and prevent any violations related to power quality. Therefore, high-resolution underlying control algorithm is needed to operate at a microsecond scale and ensure uninterrupted power delivery to the end user. The ER is using proportional–integral–derivative (PID) controller for this purpose. For example, suppose the EMS sends a command to use solar PV-generated power to meet the demand for the next hour. However, a partially cloudy sky may frequently interrupt solar power generation, making it infeasible to supply the required power at certain moments. In such scenarios, the ER must take over and utilize stored energy or draw electricity from the grid to compensate for the power deficiency.

Fig. 10 illustrates the EMS performance over a single day of operation. As shown, the algorithm decides to charge the energy storage system when there is a surplus of solar PV power generation and later uses it to supply the demand when electricity tariffs are high. A key highlight is that the EMS chooses to charge the batteries during the early hours of the day. Based on the forecast for solar PV generation on the following day, the algorithm anticipates insufficient renewable power to meet all the demand, and it is evident in Fig. 10(b) that the BESS is discharged during the peak hours at the end of the day. Fig. 11 shows the snapshots, collected from power signals during ER's operation including power conversion stages for interfacing various energy sources to the AC and DC loads.

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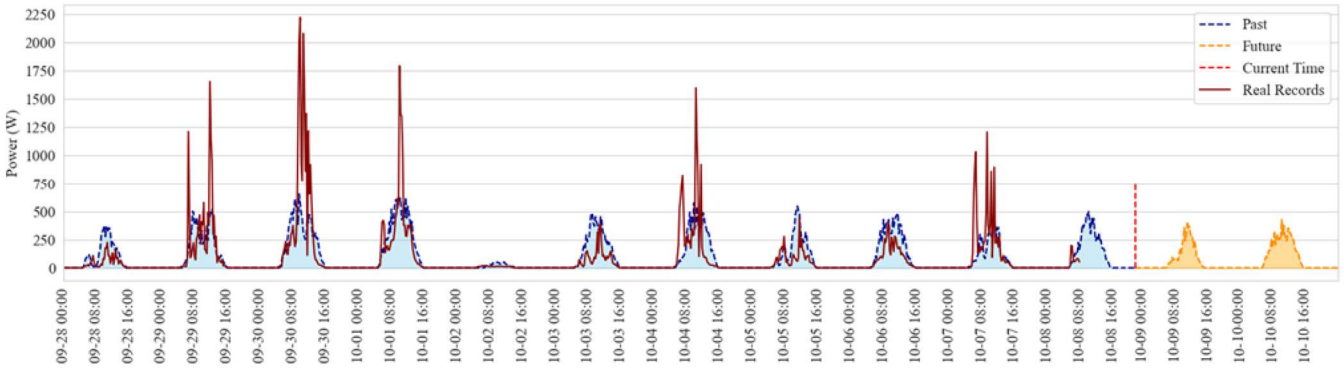


Fig. 9. Solar PV power generation forecasting tool logs during its operation. The "past" label is for previous predictions, and "Future" tags show the future forecasts.

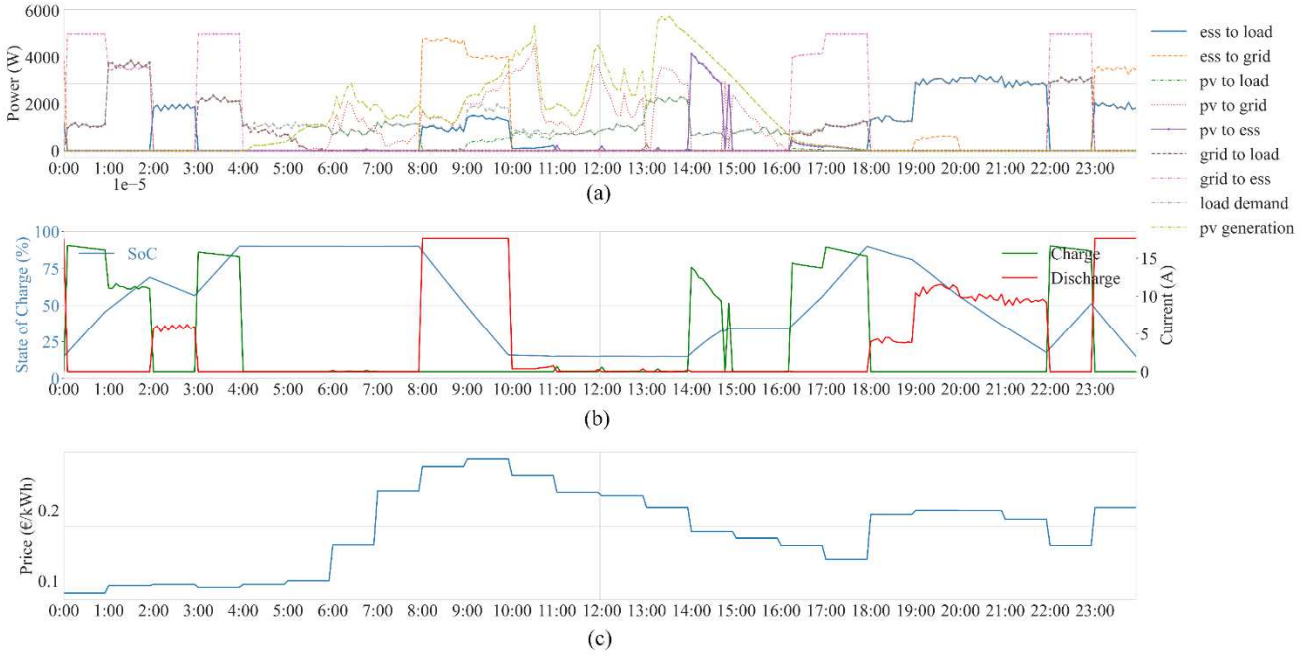


Fig. 10. EMS performance logs during its operation. (a). Energy flow inside the building electricity network and building-grid power exchanges. (b).

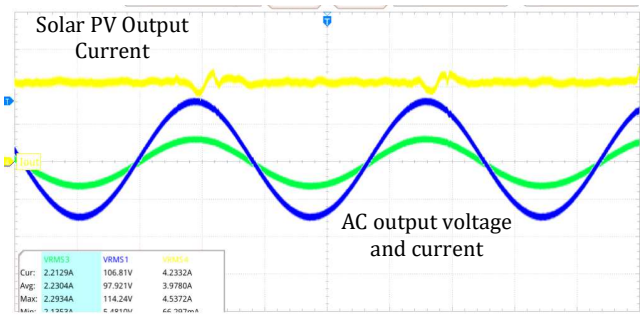


Fig. 11. ER experimental results supplying AC bus by means of solar power as the main energy source.

D. *BESS operation:*

Fig. 12 presents the BESS status logs during its charge and discharge cycles. The State of Health (SoH) ratio—representing the battery's remaining useful capacity relative to its nominal capacity—is also monitored during energy storage operation. Capacity fading or degradation is a major factor affecting the economic performance of battery storage systems. Intense BESS usage can lead to accelerated degradation; however, batteries often recover a portion of lost capacity after adequate rest periods. In our experiments, based on short-term degradation monitoring and assuming a linear degradation pattern, it is estimated that the BESS will reach 80% of its nominal capacity in approximately 10 years, which is commonly considered the end-of-life threshold [20]. After this point, battery degradation accelerates, and their round-trip efficiency drops.

E. *Time of Use Electricity Tarriff Impact*

The time-of-use (ToU) electricity tariffs have a great impact on decisions made by the EMS system. To investigate the performance difference between different scenarios, the optimization algorithm has been run for one month, assuming the electricity tariffs are constant and equal to the average ToU electricity tariff during the corresponding day. Based on comparative analysis, removing ToU electricity tariffs influences the algorithm's performance in both positive and negative ways.

As collected in Table II, the electricity bill decreases when the flat tariff is applied (negative price shows earned profit), but on the other hand, the self-consumption ratio is lower in comparison. This is mostly due to the fact that ToU tariffs are usually selected in accordance with renewable generation and demand patterns in the energy market. For instance, the electricity is cheaper during sunny hours due to high volume of solar power generation. Thus, for a local solar power system, exporting the electricity is not an attractive solution during these times. Yet, when tariffs are flat, the power

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exchange with the grid is no longer dependent on the time of the day. Also, the charging of BESS during the early hours of the day and benefiting from energy arbitrage becomes meaningless in such scenarios. This comparison is done since currently some grid operators suggest flat tariff policies for the end users. However, a comprehensive study should be conducted, and the results presented here are based only on one month data.

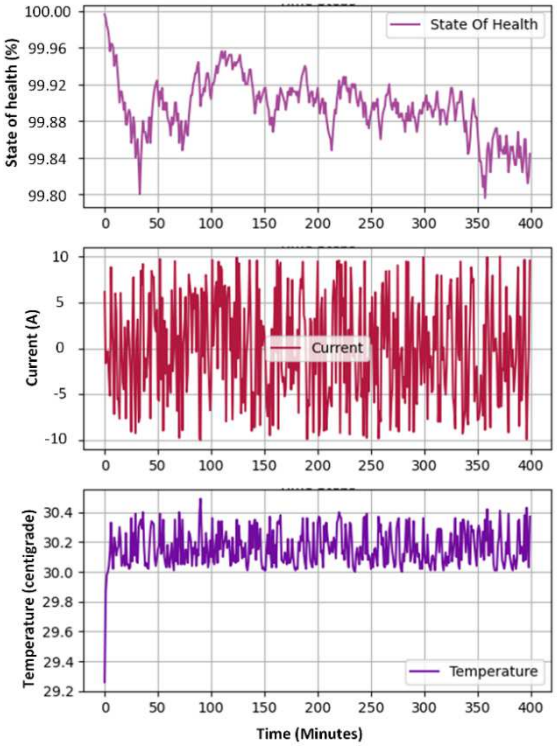


Fig. 12. BESS Operation logs during charge and discharge cycles.

TABLE II. TOU AND FLAT TARIFFS EFFECTS ON EMS PERFORMANCE

Parameter	*Flat Tariff*	*ToU Tarriff*	*Unit*
Self Conusmption Ratio	64.83	67.3	%
BESS Average Stored Energy	6.660	6.256	Wh
Electricity bill for one month	-29.21	1.68	Euro

IV. CONCLUSIONS

This paper presented a comprehensive DC-aware solution for equipping PV-BESS-integrated buildings with a DC-aware EMS. The proposed topology improves building energy efficiency by eliminating dual AC/DC power conversion stages and supports the effective integration of buildings into future intelligent, RES-dominated power grids. Experimental tests show that the hybrid DC solution can reduce total energy usage by up to 5%. Moreover, incorporating DC technology alongside AC enables a smoother transition from fully AC-powered houses to fully DC-supplied ones. The applied optimization algorithm follows a deterministic approach; however, due to various underlying uncertainties in energy generation and consumption, stochastic optimization algorithms will be explored in future work.

ACKNOWLEDGEMENT

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