Evaluating Microgrid Controllers Using an Advanced Hardware-in-the-Loop Testing Chain Integrated with Digital Twin Technology

Athanasios Vasilakis[1], Dimitrios Lagos[1], Ilias Katsambiris Grapsas[1], and Nikos Hatziargyriou[1]

[1] *Department of Electrical and Computer Engineering, National Technical University of Athens, Greece*
**Email: avassil@mail.ntua.gr*

Abstract

Digital twin technology, leveraging sensor data to replicate physical systems, offers a potent means to validate equipment dynamics and control strategies. This paper presents an advanced Hardware-in-the-Loop setup coupled with a Real-Time Digital Twin for evaluating the performance of the ecoMG tool—an Energy Management System tailored for microgrids and small off-grid systems. Demonstrating its effectiveness, the digital twin of Gaidouromantra MG is utilized with real-time data from the field. The results demonstrate that the proposed setup, despite its complexity, enables the thorough evaluation of the tool as part of the overall system.

1 Introduction

Microgrids (MGs) have emerged as transformative elements within active Distribution Networks, drawing increasing attention from the research community over the past two decades[1]. Positioned as essential components in power system decentralization, they offer viable solutions for rural electrification, enhancing resilience, and supporting local energy communities. However, the promise of microgrids comes with inherent complexities [2]. The successful deployment and operation of these systems hinge on sophisticated control mechanisms capable of efficiently managing the intricate interactions among various components and the main grid.

As microgrids transition from concept to reality, evaluating the performance of their controllers has become paramount. This critical process is essential to refine the controllers and helps identify potential issues before field deployment. Real-time Hardware-in-the-Loop (HIL) simulation is a state-of the art technique for achieving highly realistic laboratory testing of both power and control equipment. It provides a controlled environment that closely resembles real-world conditions, allowing researchers to thoroughly evaluate the tool's performance [3]. Recent advancements include the development of digital twins, enabling more accurate simulations and controller design. The integration of Real-Time Digital Twin (RTDT) technology with HIL testbeds has further enhanced the reliability of the method. These advanced testing chains offer numerous benefits, including cost-effectiveness, time efficiency, and the ability to validate both control and communication functions of Harware Under Test (HUT) [4].

This paper presents an advanced Hardware-in-the-Loop setup coupled with a Real-Time Digital Twin for evaluating the performance of the ecoMicrogrid (ecoMG) tool. By coupling the ecoMG with a digital twin, which is a virtual replica of the physical microgrid running on a real-time digital simulator (RTDS), a dynamic simulation of the microgrid system can be created. This simulation is fed with real-time data from the actual Microgrid, enabling an accurate replication of the behavior and interactions within the microgrid. To demonstrate its applicability, this setup has been employed to evaluate the ecoMG tool's performance and functionality within the Gaidouromandra MG in Kythno.

The remainder of this paper is organized as follows. Section 2 presents the ecoMG tool, detailing its high-level architecture and core functionalities. Section 3, provides an in-depth overview of the proposed HIL experimental setup, describing each component of the validation environment. Section 4 demonstrates the application of the proposed testing chain using the ecoMG tool integrated with the RTDT of Gaidouromandra MG in Kythnos. Section 5 concludes the paper and presents key findings.

2 The ecoMicrogrid tool

The ecoMG tool is an Energy Management System (EMS) tailored for microgrids and small off-grid systems [5]. The tool incorporates an advanced optimization algorithm based on model predictive control techniques, that enables proactive decision-making and precise energy management by predicting future load and generation patterns. Moreover, load scheduling mechanisms, and dynamic pricing capabilities contribute to the effective management of energy demand and supply within the microgrid. The tool helps reduce operational costs, improve energy efficiency, and enhance RES utilization.

The tool follows a control system architecture, based on the IEEE 2030.7 standard [6]. It comprises two main components: the Data Concentrator for real-time data collection and the High-Level Functions. ecoMG is offered as an all-in-one solution with low hardware requirements. By integrating multiple functionalities into a single hardware device.

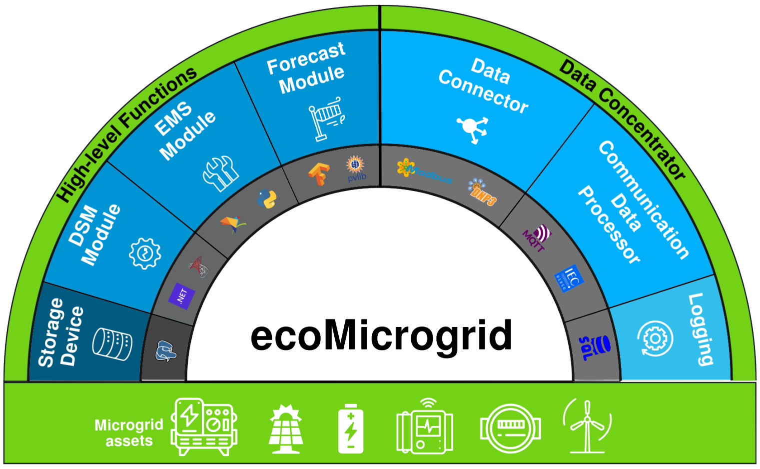


Figure 1: Key system components of the ecoMicrogrid tool.

The diagram in Fig. 1 shows the key system components of the tool.

The *Data Concentrator* gathers real-time data from microgrid assets using protocols like DNP3, IEC 61850 MMS, and Modbus. It features the *Data Connector* that establishes direct links to devices for data retrieval, and the *Communication Data Processor* that converts this data into the internal format of the ecoMG and stores it in the *Storage Device.*

The *High-Level Functions* optimize microgrid operation through several modules: the *EMS module* implements control algorithms to optimize performance, the *Forecast module* uses meteorological and historical data to provide accurate forecasts for renewable energy production and load demands, and the D*emand Side Management* (DSM) module offers functionalities for load scheduling of flexible loads and price forecasting to enable effective pricing strategies. Each module operates as an independent service, enabling flexible integration and technology-agnostic implementation for cohesive, coordinated system operation.

3 Advanced testing chain for assesing MG controllers

This paper uses the ecoMG tool as a case study, with validation tests conducted at the Real-Time Digital Testing facility of the Electrical Energy Systems Laboratory of the National Technical University of Athens (NTUA). A real-time digital simulator is used to build a grid-level digital twin of Gaidouromantra microgrid to digitally reproduce the equipment, environment and other key aspects of the physical grid.

The test bed architecture, as shown in Fig.2, consists of three major parts. The first part is the *physical system*, which includes specific power equipment, distribution lines, communication equipment, etc. The second part is the *simulation system*, utilizing the RTDS to simulate the actual microgrid. The third part is the *hardware under test*, which in this case refers to the ecoMG tool. Additionally, a *data acquisition service* acquires data from the physical microgrid and feeds it to the digital twin in real time.

3.1 Dynamic simulation model of physical system

The digital twin model of the microgrid is a high-precision, multi-coupling electromagnetic transient (EMT) system, designed to accurately emulate the real equipment installed at the Gaidouromandra site. This model incorporates refined digital representations based on actual field data, making it highly suitable for studies involving control, integration, and protection.

The microgrid system simulation is conducted using a commercially available RTDS, located at the NTUA system laboratory. RTDS hardware leverages advanced parallel processing techniques to achieve the computational speeds necessary for continuous real-time operation. In this experiment, the core components of the RTDS employed are the NovaCor processing core and the GTNETx2 network interface card, both provided by RTDS Technologies.

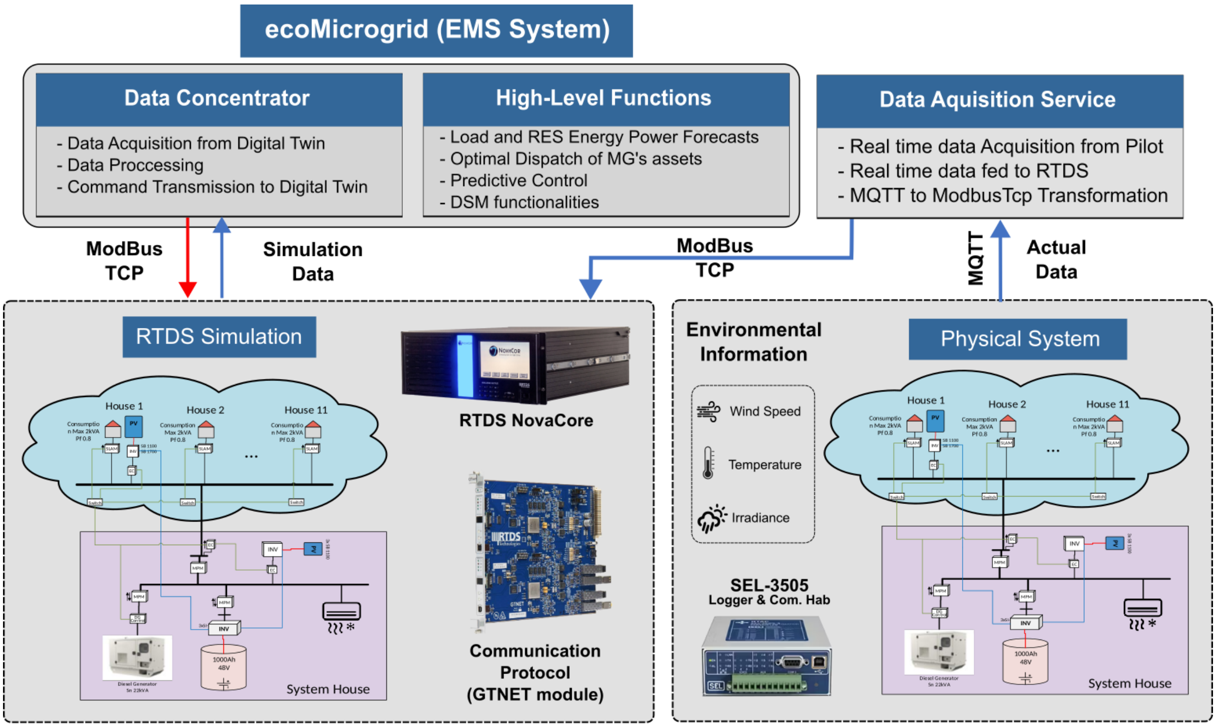


Figure 2: HIL and digital twin test architecture.

The Gaidouromandra distribution grid was modeled to accurately capture all electrical network parameters, including complex line resistances and the technical characteristics of diesel generators (DG) and Power Electronics interfaces (PELs).

Battery storage dynamics were represented using a second-order system model, while an average model was applied for the PEL interface. Photovoltaic PELs and DG were also modeled with average models, with parameters derived from live measurements or disition setpoints provided by the ecoMG tool.

Loads, encompassing household consumption and HVAC flexible load, were represented as dynamic P/Q sources with power parameters dynamically defined based on real-time measurements or decisions setpoints from the ecoMG tool.

The thermal model consists of a single thermal unit, the HVAC system, and the building envelope for estimating heat losses. It also accounts for heat gains from solar exposure, based on building orientation, and from PEL, using average heat emission values determined by the units' operation.

Additional power-related data includes the operational status of the DG and the HVAC system. During testing, the ecoMicrogrid tool delivers real-time feedback to the model, defining the intended operational states for the DG and HVAC, which subsequently directs their behavior within the simulation.

3.2 Communication and real time data

At the Gaidouromandra pilot site, a Real-Time Automation Controller functions as the central communication hub. This controller facilitates data collection from various microgrid assets and smart meters, transmitting the gathered information via the MQTT protocol. A 4G router supports this communication infrastructure, serving as a critical gateway that ensures reliable and continuous internet connectivity. To effectively interface the collected data with the digital twin model, a specialized data acquisition service has been developed. This service actively listens to communication topics and dynamically converts the received data into Modbus TCP commands. The captured data encompasses comprehensive information, including active and reactive power consumption and production for each asset, along with outer environment temperature, all recorded at a precise one-minute resolution.

The HIL simulation, requires bidirectional communication between the ecoMG and the RTDT. A second Modbus instance of the GTNETx2 card is utilized for exchanging data and control commands between the two systems. The data concentrator module of ecoMG monitors 161 real-time variables from the RTDT simulation, providing dispatch and control set points for the DG and HVAC system, respectively.

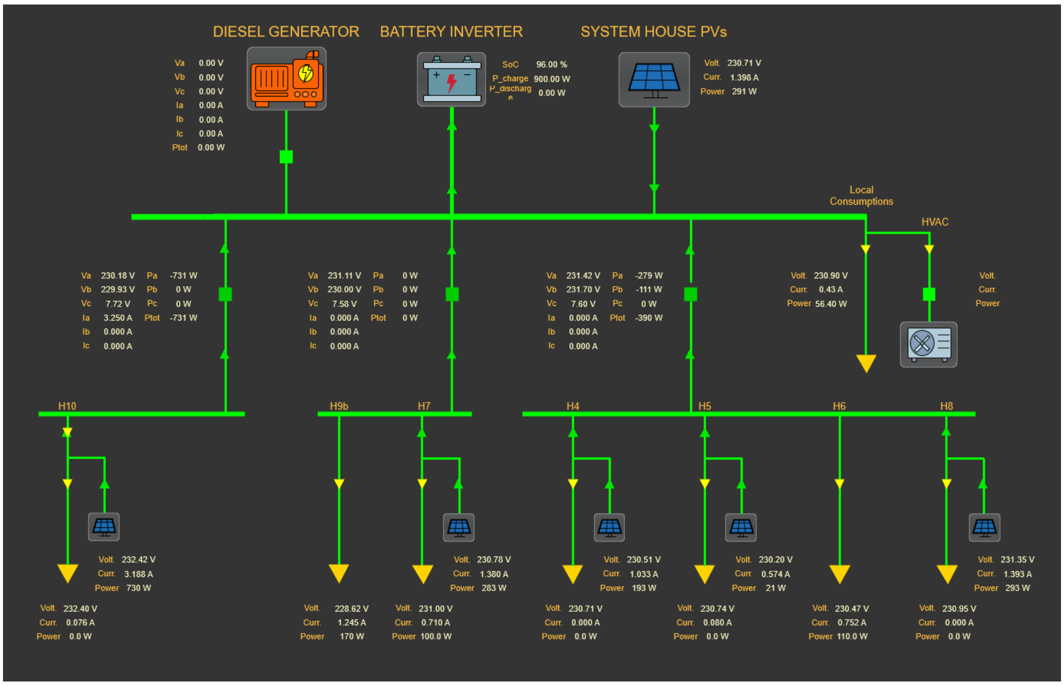


Figure 3: Single-line diagram of the Gaidouromandra's microgrid as displayed in the SCADA HMI of the ecoMG system.

4 Case study

4.1 Study System

The functionality of the ecoMG management system was validated through a case study conducted at the Gaidouromandra microgrid in Greece, which serves a community of 14 vacation houses. The central infrastructure comprises a 30 spm system house located at the settlement's center, housing essential components including battery inverters, battery banks, a diesel generator with its fuel tank, and monitoring and communication equipment [7].

The microgrid's generation system consists of six distributed PV arrays with a combined capacity of 20 kWp, supported by a 22 kVA backup diesel generator and a 96 kWh/15 kW battery energy storage system. Three single-phase battery inverters manage the power system, providing a three-phase power supply.

The distribution network includes three low-voltage feeders, protected by three industrial relays monitoring electrical lines. A fiber optic cable runs parallel to the overhead power lines, facilitating communication and control functions.

Each vacation house is equipped with smart meters that measure energy consumption and function as load controllers. These meters enable remote monitoring and load management.

A key component of the communication and data management infrastructure is the industrial RTAC, which serves as a centralized communication hub.

Table 1 presents comprehensive details of the assets available within the microgrid. Additionally, Figure 3 offers a single-line diagram of the microgrid as visualized through the SCADA Human-Machine Interface (HMI) of the ecoMG system. This diagram illustrats essential components, interconnections, and real-time data.

4.2 Experimental Setup

The experimental test facility was developed and validated through a systematic three-phase approach.

- The first phase focused on comprehensive microgrid system modeling in RSCAD, encompassing detailed representations of power electronic converters, diesel generator, loads, and battery energy storage system. The model integrated both electrical network topology and thermal system dynamics, alongside the control logic for DG and HVAC operations.
- Model validation was subsequently conducted in open-loop configuration, prior to ecoMG integration. This phase verified battery system dynamics including the State of Charge (SoC) estimation algorithms, and network model accuracy through direct comparison with physical microgrid measurements.
- The final phase implemented closed-loop HIL testing, with the ecoMG controller serving as the Hardware Under Test.

The ecoMG hardware consists of a mini PC equipped with an Intel Core™ i7-11700 Processor running at 2.5 GHz, supported by 32 GB of RAM and a 64-bit Windows Server operating system on which the ecoMG services are installed.

4.3 Performance Evaluation

The Gaidouromandra Microgrid was evaluated through specific operational scenarios designed to assess its key functionalities. These scenarios are carefully chosen to align with the specific characteristics of the Gaidouromandra MG, which include:

- SoC Reduction During the Night: In normal conditions, the MG relies solely on PV generators to charge the batteries during the day. As a result, the SoC of the batteries decreases during the night.
- Considerable RES Curtailment: During the summer months, when the MG is predominantly inhabited, the batteries reach their SoC upper limit around noon. Consequently, there is a restriction in the potential power production from renewable energy sources (RES) for the remainder of the day.
- Diesel Generator Control Strategy: The existing control mechanism initiates the diesel generator when the SoC reaches 40% and shuts it down when it reaches 60%. This strategy is implemented to account for the night discharge of the batteries, which often occurs during days with high consumption around 5-7 a.m..

Table 1: Available assets in Gaidouromandra microgrid.

Equipment Type	Available Equipment
Buildings	14 vacation houses, Syte, House
Distributed PVs	6 distributed PV arrays with 20kWp
Diesel Generator	22kVA (Perkins 404A-22G engine), DSE8610 synchronizing auto start load share control module
Batteries	96kWh (@20h), 48V
Feeder Relay	SEL-751, feeder management, lots of protection features, metering units
Smart meterers	Advanced smart meters and load controller (SLAMs),
Cooling system	Daikin, 9000 BTU, A++, 30 sqm building
Real Time Automation Controller	SEL-3505, Real-Time Control and Logic Processing
Communication network	Fiber optic, 1Gbps

The EMS validation process aimed to optimize microgrid efficiency through intelligent resource management and power consumption reduction strategies. Three key validation objectives were established.

- *Optimizing HVAC Usage:* The EMS activates the HVAC system at night only as needed, ensuring minimal runtime to maintain target room temperatures while reducing battery discharge.
- *Pre-cooling Control Room:* During daytime PV curtailment, the EMS initiates pre-cooling of the control room to lower night-time HVAC demand and minimize renewable energy curtailment.
- *Minimizing Diesel Generator Usage:* The EMS reduces diesel generator reliance by leveraging PV power forecasts, using the generator only as needed, thus lowering microgrid operational costs.

4.3.1 Operational Scenarios:

To evaluate the EMS objectives, the ecoMG system was tested under two distinct scenarios:

- Scenario 1 - This scenario is designed to demonstrate the multi-vector capabilities of the ecoMG tool by utilizing surplus photovoltaic power during the day to implement a pre-cooling strategy for the control room. By cooling the space before nightfall, the ecoMG aims to minimize the reliance on HVAC operation overnight, thus optimizing energy usage.
- Scenario 2 - This high-load scenario focuses on optimizing the utilization of the diesel generator under peak load conditions. The ecoMG aims to reduce the operational time of the diesel generator compared to traditional control methods, thereby enhancing overall system efficiency and reducing fuel costs.

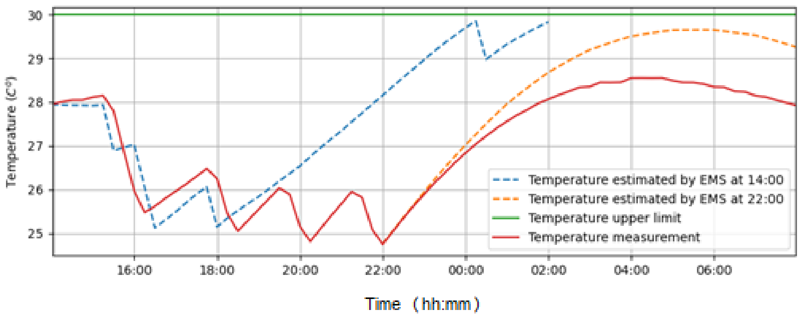
4.3.2 Results from Scenario 1:

In this scenario, the ecoMicrogrid operates under normal loading conditions, with the actual load from the Gaidouromandra microgrid.

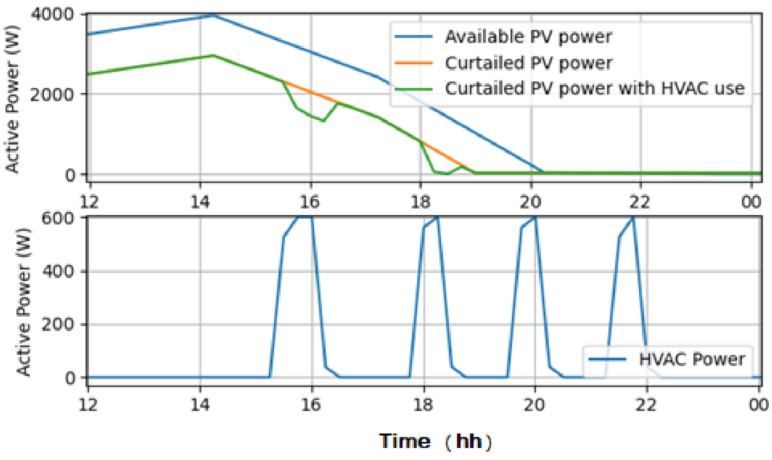
The initial SoC is set to 90%, and the temperature limits for the room are established with an upper limit of 30°C and a lower limit of 25°C to ensure effective HVAC cooling. The EMS is choosing to utilize the HVAC system during periods of curtailed RES production to maintain a comfortable room temperature, strategically minimizing excessive HVAC usage at night.

Figure 4a presents the EMS's estimated indoor temperatures at 14:00 and 22:00, alongside the measured temperature and the upper temperature limit. The HVAC system operates between 15:00 and 16:30 and again from 18:00 to 18:30, effectively reducing the room temperature near the lower limit.

During these operational periods, battery charging occurs, as indicated in Figure 4b, maintaining SoC levels above 90%. To prevent battery overcharging, PV generation is curtailed, but the utilization of the HVAC system contributes to a reduction in curtailed PV power. This proactive cooling approach effectively mitigates nighttime battery drain and alleviates daytime renewable energy curtailment.



(a)



(b)

Figure 4: (a) Temperature estimation by EMS at 14:00 and 22:00 and actual indoor temperature measurement from digital twin. (b) PV available power, curtailed and HVAC consumption.

4.3.3 Results from Scenario 2:

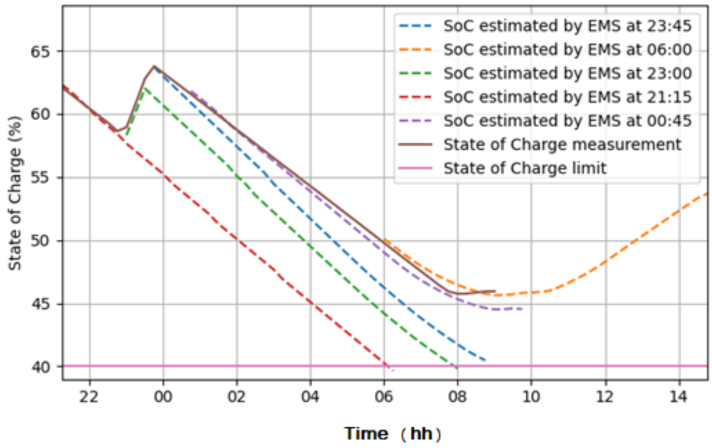
In this high-load scenario, the actual load from Gaidouromadra is doubled to simulate increased demand, starting with an initial SoC of 70%.

Figure 5a illustrates the measured SoC, operational limits, and the SoC estimated by the ecoMG EMS algorithm over various time intervals. Until 21:45, the EMS predicts a notable SoC drop due to increased nighttime demand; however, the diesel generator remains inactive as the SoC stays above the lower limit. Subsequently, the EMS recognizes the need to engage the diesel generator to prevent SoC violations, activating it at 23:00.

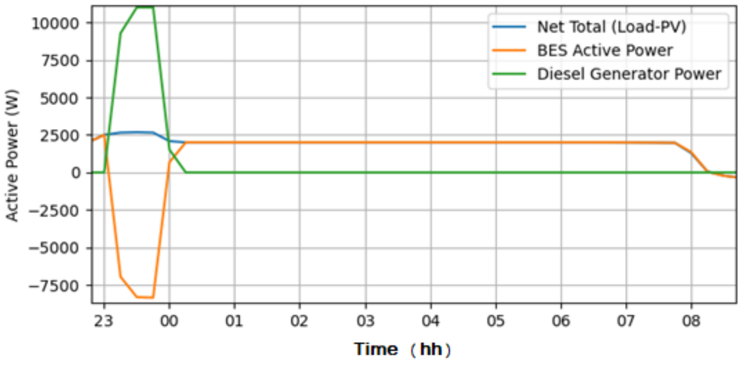
The DG runs for 45 minutes, increasing the SoC by approximately 5-6% before shutting down at 23:45, as the EMS assesses that the SoC is adequate. In subsequent executions at 00:45 and 06:00, the EMS accurately identifies that no further power from the DG is required, as PV generation resumes, allowing for battery charging. Figure 5b presents the DG production, BES power, and net load - PV power.

Without the ecoMicrogrid EMS algorithm, the batteries would have reached the 40% limit around 08:00. Based on the measured load and PV generation, the diesel generator would have operated for an additional two hours to restore the SoC to the 60% threshold before shutting down.

The results indicate a 37.5% reduction in operational costs compared to the existing control scenario while effectively regulating the SoC within operational limits



(a)



(b)

Figure 5: (a) SoC estimation by ecoMicrogrid EMS at different intervals and SoC measurement. (b) Net load (total consumption minus total PV generation), BES and diesel generator power.

5 Conclusion

This paper presents an experimental setup designed to validate the energy management system capabilities of the ecoMG tool. The facility leverages a real-time digital simulator integrated with a hardware-in-the-loop architecture, allowing for robust testing and evaluation.

The proposed testing facility offers several key advantages. First, it enables a thorough evaluation of the tool under realistic conditions, allowing for testing across various operational scenarios to ensure that the EMS can perform effectively in real-world applications. Second, the facility facilitates comprehensive validation of both control algorithms and communication protocols within the EMS, thereby enhancing system reliability and performance. Additionally, the flexible design of the setup allows for straightforward implementation in real-world applications following testing, promoting faster integration into existing systems.

The results indicate that, despite the complexity of the proposed setup, it provides an in-depth evaluation of the ecoMG tool as part of the overall microgrid system. The findings demonstrate the effectiveness and reliability of the ecoMicrogrid tool. Four use case scenarios were employed, encompassing normal operation and high-load operation, showcasing its ability to optimize energy management, minimize operational costs, and enhance the overall performance of the microgrid.

6 Acknowledgments

This work was financially supported by the European Union's Horizon 2020 Research and Innovation Program and the Department of Science and Technology (DST), India through the RE-EMPOWERED Project under Grant Agreement No 101018420 and DST/TMD/INDIA/EU/ILES/2020/50(c) respectively.

7 Notice

This paper is a postprint of a paper presented in 14th Mediterranean Conference on Power Generation Transmission, Distribution and Energy Conversion – MED POWER 2024 and is subject to Institution of Engineering and Technology Copyright. When the final version is published, the copy of record will be available at IET Digital Library.

References

[1] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power and Energy Magazine*, vol. 5, no. 4, pp. 78–94, Jul. 2007.

[2] A. Vasilakis, I. Zafeiratou, D. T. Lagos, and N. D. Hatziargyriou, "The evolution of research in microgrids control," *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 331–343, 2020, Conference Name: IEEE Open Access Journal of Power and Energy.

[3] A. Paspatis, A. Kontou, P. Kotsampopoulos, D. Lagos, A. Vassilakis, and N. Hatziargyriou, "Advanced hardware-in-the-loop testing chain for investigating interactions between smart grid components during transients," *Electric Power Systems Research*, vol. 228, p. 109 990, Mar. 1, 2024.

[4] G. M. Casolino, M. Russo, P. Varilone, and D. Pescosolido, "Hardware-in-the-loop validation of energy management systems for microgrids: A short overview and a case study," *Energies*, vol. 11, no. 11, p. 2978, Nov. 1, 2018.

[5] P. Kotsampopoulos, A. Dimeas, A. Chronis, *et al.*, "EU-india collaboration for smarter microgrids: RE-EMPOWERED project," in *2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Novi Sad, Serbia: IEEE, Oct. 10, 2022, pp. 1–6.

[6] *IEEE standard for the specification of microgrid controllers*, New York, 2017.

[7] N. Hatziargyriou, A. Dimeas, N. Vasilakis, D. Lagos, and A. Kontou, "The kythnos microgrid: A 20-year history," *IEEE Electrification Magazine*, vol. 8, no. 4, pp. 46–54, Dec. 2020, Conference Name: IEEE Electrification Magazine.