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APPLIED RESEARCH

Digital Twin Modelling for a Renewable Energy Community: A Case Study of the Culatra Island's Smart Grid

IDRIS O. OGUNSOLA[1], **JÓNI B. SANTOS**[1,2], **JÂNIO MONTEIRO**[1,3], **AND ANDRÉ PACHECO**[2]

[1]Instituto Superior de Engenharia, Universidade do Algarve, 8005-139 Faro, Portugal
[2]CIMA/Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
[3]CISCA, 8005-139 Faro, Portugal

Corresponding author: Idris O. Ogunsola (oiolalekan@ualg.pt)

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ABSTRACT This study develops and tests a Digital Twin (DT) of the Culatra Island's distribution grid to enable the evaluation of demand side management strategies, in the scope of Renewable Energy Communities. Built in MATLAB/Simulink and structured across five functional layers, the DT integrates real-world data from five photovoltaic (PV) production units, monitored and fixed electrical loads, and realistic network parameters derived from the island's infrastructure. Three steady-state test scenarios were simulated to assess voltage stability, and power flow under: 1) baseline grid operation without PV generation, 2) distributed PV integration under normal load conditions, and 3) high-demand operation near generation-load equilibrium. Results show that PV integration improves voltage regulation and reduces losses through localized energy injection and bidirectional power flow. However, under peak load conditions, the system exhibits significant undervoltage, revealing the need for advanced control strategies and infrastructure reinforcement. Overall, the DT proves to be an effective analytical and decision-support tool for optimising distributed energy systems. This work provides a replicable application-oriented framework for data-driven planning in emerging Renewable Energy Communities and supports Culatra Island's transition toward full energy self-sufficiency. Unlike prior studies that report generalized benefits of PV integration, this work explicitly identifies voltage instability thresholds under high-demand conditions in a real REC configuration, providing actionable insight into when passive operation becomes insufficient.

INDEX TERMS Digital twin, energy management, renewable energy communities, smart grid.

I. INTRODUCTION

One of the most pressing global challenges today is the urgent need to drastically reduce carbon dioxide (CO_2) emissions to mitigate the effects of climate change. According to the Intergovernmental Panel on Climate Change, the energy sector remains the largest contributor to global greenhouse gas emissions, primarily due to its dependence on fossil fuels [1]. To meet the targets of the Paris Agreement [2], countries must commit to decarbonizing their energy systems, which requires both technological innovation and systemic change.

A key component of this transition involves consuming less energy through increased efficiency while generating more energy from Renewable Energy Sources (RES) such as solar and wind. These energy sources offer low or zero emissions and reduce reliance on environmentally harmful fossil fuels [3]. Meanwhile, this shift demands not only increased RES generation but also systemic changes in

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energy consumption patterns, as traditional fossil fuel-based systems and industry are responsible for 89% of global CO2 emissions that are increasingly incompatible with climate goals [4].

To address these challenges, the European Union and its Member States have been promoting the establishment of Renewable Energy Communities (RECs), which decentralize energy production and empower local stakeholders such as residents, small businesses, and municipalities to participate in energy generation, management, and consumption.

These communities provide opportunities to reduce dependence on fossil fuels, promote local economic development, and democratize energy access. According to the European Commission, RECs are legal entities that allow citizens and local actors to produce, consume, and manage their own renewable energy in a collaborative, transparent, and cost-effective way [5].

Culatra Island, located off the southern coast of Portugal within the Ria Formosa Natural Park, represents one of the first six sites for transitioning to a sustainable energy community, as part of the “Clean Energy for EU Islands” initiative launched by the European Commission in 2018. Since then, the island’s objective is to become energy self-sufficient, relying solely on RES such as solar and wind.

Culatra’s ongoing transformation into a smart, community-based energy system illustrates how the REC model can be implemented in practice [6]. However, this transition comes with technical and operational challenges. One of the fundamental issues associated with some RES is their variability. For instance, solar power is inherently intermittent, depending on weather conditions and natural cycles. This unpredictability can lead to mismatches between energy supply and demand, especially in isolated or standalone systems such as those found in islands or off-grid regions [7]. In energy communities that operate through distributed energy systems, traditional centralized grid control strategies are insufficient. Instead, these communities require localized, real-time mechanisms to dynamically balance energy supply with consumption while maintaining grid stability [8]. As such, the island transition requires a rethinking of its power infrastructure, which traditionally relied on a mainland-connected grid via a submarine cable — a costly, environmentally unsustainable, and disruption-prone configuration.

To address these challenges, Energy Management Systems (EMS) need to apply advanced load scheduling and optimisation methods. Load scheduling allows smart buildings to adjust energy use according to residents’ preferences or grid conditions, reducing costs by shifting energy-intensive activities to periods of higher renewable generation [9]. Optimisation algorithms enhance this process by evaluating multiple variables such as user preferences, generation forecasts, and pricing signals to determine the most efficient energy distribution plan. These algorithms can be deployed within EMS, which monitor, analyse, and control energy flows in real time [10]. This approach is critical for maximizing self-consumption, minimizing energy waste, and reducing reliance on backup fossil-fuel systems.

The execution and testing of energy management strategies normally require platforms that allow the evaluation of different solutions. While simulators have been used traditionally for this purpose, a more recent and powerful development in this domain is the use of a Digital Twin (DT).

A DT is a virtual representation of a physical energy system that mirrors its real-time state through data collected from sensors and Internet-of-Things (IoT) devices. It enables simulations of different grid conditions, operational strategies, and fault scenarios, allowing stakeholders to test various solutions before implementing them physically. This tool also supports predictive maintenance, energy forecasting, and strategic planning, enhancing both the voltage stability resilience and adaptability of local energy systems [11]. In this regard, Culatra Island provides an excellent testbed for applying and validating such an initial application-oriented DT-based simulation and management strategies, due to its scale, isolation, and well-established REC framework.

This study integrates RES, load flow analysis, and application-oriented DT technology to simulate and assess the performance of the Culatra Island smart grid. It explores how RES integration can support demand-response strategies and help the island progress toward energy self-sufficiency in the near future. The research includes the development of detailed models of the island’s electrical distribution network, the implementation of load scheduling and optimisation algorithms, and the design of an application-oriented DT capable of representing real-time energy behaviour. These tools are applied to evaluate alternative energy scenarios, enhance self-sufficiency, and improve overall system reliability. In doing so, the study contributes to broader goals of decentralizing and decarbonizing energy systems and aligns with the European Union’s vision of energy democracy, where citizens and communities play an active role in shaping their energy future. Lessons learned from this work provide valuable insights for similar initiatives on other islands and remote communities, in Portugal and beyond.

Overall, the study demonstrates that an application-oriented DTs of Distribution Grids are important tools to perform real time assessment of load scheduling solutions, in the context of intelligent energy management and optimisation systems for RECs particularly in evaluating system voltage stability and operational tolerance under varying generation and demand conditions.

While DT frameworks have been explored in broader smart grid contexts, this study distinguishes itself by proposing an initial, application-oriented DT specifically tailored to the operational realities of a REC in transition, i.e., Culatra Island. Unlike generic DT architectures that prioritize scalability or theoretical completeness, the approach used is grounded in real-world infrastructure, actual PV generation profiles, monitored household loads, and community-specific network constraints. This pragmatic orientation enables immediate utility for scenario testing, and voltage stability assessment within a live REC initiative, rather than serving as a conceptual or simulation-only construct.

As such, this work bridges a critical gap between abstract DT models and actionable, data-driven energy management in decentralized, community-led systems.

The remainder of this paper is organized as follows: Section II reviews relevant literature on RECs and the role of DT applications. Section III presents the DT model of the Culatra Island distribution grid. Section IV defines the test scenarios and simulation conditions. Section V reports the main simulation results, while Section VI discusses their implications for grid stability and management. Finally, Section VII concludes the paper and outlines directions for future work.

II. BACKGROUND

Energy is of vital importance in all economies. As a matter of fact, energy is a basic input in virtually all production processes and an important final consumption item for households. Portugal aims to be climate-neutral by 2050 and to cover 80% of its electricity consumption with renewables by 2030 [12] and has also developed a hydrogen strategy to decrease natural gas imports and reduce greenhouse gas emissions by 2030 [13]. Achieving these goals requires not only renewable energy deployment but also new governance and management models based on decentralization.

In this context, RECs have emerged as citizen-driven initiatives that produce, consume, share, and manage renewable energy locally, fostering energy democracy and social cohesion. As defined within the Clean Energy for All Europeans Package [5], RECs empower citizens, local authorities, and small enterprises to jointly lead the energy transition through decentralized ownership and participation [8]. Beyond energy generation, RECs contribute to grid flexibility, energy efficiency, and local reinvestment, strengthening the social and economic fabric of communities.

Several studies have examined the technical and governance aspects of RECs and decentralized renewable systems. Ghiani et al. [17], for instance, explored RES integration in the municipality of Berchidda, Italy, employing load profile analysis, resource assessment, and optimisation modelling. Their results showed that integrating solar PV, wind, and biomass resources through local generation significantly reduced costs and emissions, particularly when organized as an energy community. Similarly, Diestelmeier and Swens [8] analysed the Dutch energy sector's legal evolution, demonstrating how reforms under the 2013 Energy Agreement stimulated community-led renewable projects—growing from 34 initiatives in 2011 to 623 in 2020. Yet, they also identified persistent challenges such as high connection costs and limited legal transposition of EU directives. Collectively, these works show that while community participation enhances sustainability and equity, technical and operational models for real-time grid management remain underdeveloped. Parallel efforts have explored community-based renewable integration in non-European contexts.

The Climate Policy Initiative [18] evaluated hybrid microgrids combining solar PV, diesel, and battery systems in remote Indonesian communities. The results confirmed a 30% cost reduction compared to diesel-only systems and demonstrated the importance of local capacity-building for long-term sustainability. In the United Kingdom, the Low Carbon Hub [19] developed a smart community energy system in Osney Island, integrating rooftop solar, peer-to-peer energy trading, and IoT-based demand response. The initiative achieved a 25% reduction in peak load and a 40% reduction in grid imports, illustrating the potential of smart digital tools for local optimisation. Similarly, research by LUT University [20] in Mussalo, Finland, used blockchain and AI-driven battery management to increase transparency and extend battery life by 15%, though scalability remained limited by high technological costs.

Within the Portuguese context, the Culatra Island initiative—today known as Culatra2030 - Sustainable Energy Community—stands as a pioneering example of local renewable transition. The effort began with the Culatra Clean Energy Transition Agenda [14], which laid the strategic foundation for 100% renewable energy integration through intelligent grid management. Subsequent studies have expanded this groundwork: Pacheco et al. [15] conducted a community participatory diagnosis to involve residents and local authorities in defining sustainable solutions, achieving a self-consumption ratio of 85.7% through PV integration and energy-efficient retrofitting; Ewart et al. [21] developed a genetic algorithm to optimise PV panel orientation, improving both self-consumption and the levelized cost of energy; and Santos et al. [6] analysed participatory economic models based on community-owned production quotas, achieving full self-consumption and highlighting the social and financial benefits of collective renewable ownership. Together, these works showcase the evolution of Culatra' transition—from strategic planning and participatory governance to optimised technical implementation—while addressing energy autonomy, economic efficiency, and replicability in insular contexts.

A comparative synthesis of the reviewed works (Table 1) identifies five core research dimensions: (1) renewable energy integration, (2) social and economic impact, (3) energy market participation, (4) predictive algorithms, and (5) simulation and energy management. While most studies ([8], [17], [18], [19], [20], [21]) extensively address renewable integration and social impacts, energy market participation and predictive simulation remain insufficiently developed. Only a few works ([17], [21]) employ optimisation or forecasting models, and very few adopt full digital simulation frameworks to support operational decisions.

This analysis reveals a persistent gap: despite growing experience with decentralized RECs, few studies provide integrated, simulation-based approaches that dynamically couple real data, predictive modelling, and energy

TABLE 1. Comparative synthesis of reviewed works on renewable energy communities and smart grid applications.

Ref	RES Integration	Social/Economic Impacts	Energy Market Participation	Predictive Algorithms	Simulation & Energy Mgt.
[6]	✓	✓	✗	✗	✗
[8]	✓	✓	✗	✗	✗
[14]	✓	✓	✗	✗	✗
[17]	✓	✓	✗	✓	✓
[18]	✓	✓	✓	✗	✓
[19]	✓	✓	✗	✗	✗
[20]	✓	✓	✗	✗	✗
[21]	✓	✗	✗	✓	✗

management. Addressing this shortcoming, the present study constitutes an initial attempt to develop a DT of Culatra Island's smart grid, bridging physical and virtual layers to demonstrate its utility in evaluating operational scenarios, informing load management strategies, and supporting the island's pathway toward energy self-sufficiency and resilience.

III. DIGITAL TWIN OF THE DISTRIBUTION IN CULATRA-ISLAND

Building on the need for adaptive, data-driven management systems in decentralized energy contexts such as RECs, this section presents the development of DT for the Culatra Island smart grid. The DT serves as a simulation framework that virtually replicates the physical energy infrastructure, enabling real-time monitoring, analysis, and optimisation of grid operations [22]. The approach adopted for Culatra integrates load metering, smart meter data analysis, and simulation using MATLAB/Simulink and Python, forming a dynamic platform that links the physical and digital domains. Through this integration, the DT supports operational decision-making, enhances predictive maintenance, and strengthens the system's voltage stability resilience and sustainability. The overall architecture combines physical assets (sensors, actuators, and electrical equipment) with a virtual environment capable of simulating multiple operating scenarios and providing feedback to the real system [23], [24]. Figure 1 illustrates the five-layer architecture developed for the Culatra Island energy distribution system, ensuring seamless interaction between data collection, simulation, and optimisation processes.

Layer 1 – Physical Layer

This layer encompasses the physical infrastructure of the island's distributed grid, including the transformer, cabling network, protection panels, five PV systems, the battery storage unit, and typical electrical loads such as washing machines, water heaters, dishwashers, and air-conditioning units.

Together, these components represent the real system that the DT replicates and interfaces with to monitor and optimise energy flows.

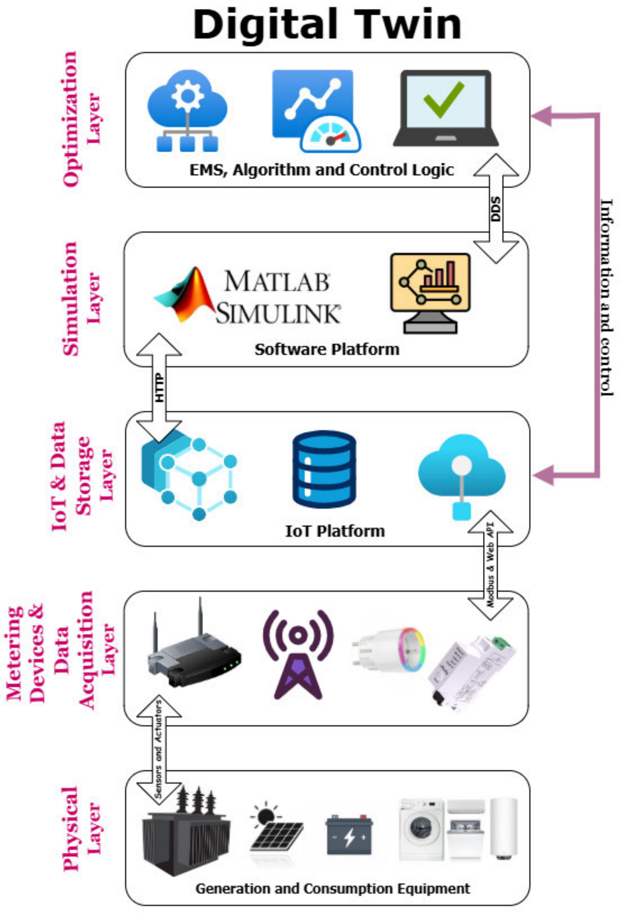


FIGURE 1. A five-layers DT architecture for Culatra-island smart grid implementation.

Layer 2 – Metering and Data Acquisition Layer

This layer acts as the interface between physical energy assets and the DT. It integrates sensors and actuators deployed on PV panels, inverters, charge controllers, batteries, and household appliances to monitor real-time values of voltage, current, and power. The continuous exchange of information between Layer 1 and Layer 2 ensures accurate data collection for system modelling and operational control.

Layer 3 – IoT and Data Storage Layer

Layer 3 functions as the communication and data management hub of the DT. It collects, preprocesses, and stores operational data from Layer 2 using an IoT platform (Emoncms) that manages heterogeneous streams such as PV generation and total household consumption. Data exchange relies on standardized protocols: Modbus for field-level communication with industrial equipment [25] and RESTful Web APIs for secure and asynchronous transmission of structured data to higher layers [26], [27]. This configuration guarantees interoperability and low-latency communication, forming a cohesive cyber-physical environment for the island's smart grid.

To enable easy identification during data extraction and analysis, the smart meters were renamed for production and consumption units as follows:

- PV means "PV Production Unit". It's used to distinguish between the production units in the system. It explicitly states that the data relates to energy production and identifies the specific production point (e.g., PV1, PV2, etc.), used when there are multiple generators in the simulation.
- House means "Non-Monitored Houses" in the installation set-up.
- M_House means "Monitored Houses" in the installation set-up.
- 1, 2, 3…stands for the "House Number" in Culatra-Island. It's the number assigned to each house to helps pinpoint the exact household e.g House 1.

Layer 4 – Simulation Layer

Layer 4 forms the analytical backbone of the DT, enabling scenario testing, parameter tuning, and predictive analysis to improve system efficiency and resilience. It leverages MATLAB/Simulink to dynamically replicate the behaviour of the physical system. It receives real-time data from Layer 3, formatted as JavaScript Object Notation (JSON) payloads via HTTP-based REST interfaces, and runs continuous simulations to evaluate voltage profiles, power flows, and energy balances under varying conditions.

In transitioning the framework from a static model to a functional DT, a continuous verification protocol is established as the DT evaluate the grid's state by calculating the Voltage drop at each node. Using the MATLAB/Simulink load flow analyzer solver, the voltage drop in per-unit (V_{pu}) is obtained as follows:

$$\Delta V_{pu} = V_{ref} - V_{LF} \tag{1}$$

where V_{LF} is the voltage magnitude derived from the Load Flow solver in MATLAB/Simulink. Given that all buses in the grid-connected microgrid are assigned a reference voltage (V_{ref}) of 1.0 pu, the expression is simplified to:

$$\Delta V_{pu} = 1 - V_{LF} \tag{2}$$

To validate these digital insights against physical field measurements from the Emoncms platform, the deviation is converted to standard volts (V) using the system's base voltage ($V_{\text{base}} = 400\text{V}$):

$$\Delta V_{(V)} = \Delta V_{pu}\, xV_{base} \tag{3}$$

Layer 5 – Optimization Layer

The final layer is designed to host the EMS and advanced control algorithms such as Model Predictive Control (MPC), heuristic scheduling rules, or AI-driven strategies that would translate simulation insights into real-time operational decisions. However, in the current implementation, this layer remains conceptual and is not actively engaged in the simulated test scenarios. The present study focuses on steady-state load-flow analysis using Layers 1 to 4 to evaluate baseline grid behaviour under varying PV and load conditions. Closed-loop optimisation and autonomous control via Layer 5 are planned for future phases, contingent on the deployment of actuation infrastructure and real-time communication capabilities on the island. Communication protocols such as Data Distribution Service (DDS) are provisioned to support future low-latency exchange between simulation and control layers, enabling reliable closed-loop operation once hardware and policy frameworks are in place [28].

It should be noted that the current implementation constitutes an initial, simulation-based DT, validated using real-world network parameters (e.g., cable types, transformer ratings), actual PV generation profiles, and monitored household load data from the Emoncms platform. While the DT architecture is designed to support real-time data ingestion and closed-loop control (Layers 2 to 5), full real-time or hardware-in-the-loop (HIL) validation is not yet feasible due to the ongoing deployment phase of the island's sensing and actuation infrastructure. The present study therefore focuses on demonstrating the DT's analytical feasibility and scenario-testing utility under steady-state conditions - a necessary first step before advancing to dynamic, real-time validation.

Together, these five layers constitute a comprehensive digital representation of Culatra Island's distribution network.

The DT architecture not only enables continuous monitoring and control of the island's smart grid but also provides a flexible platform for testing new energy management strategies, simulating fault conditions, and evaluating the long-term performance of renewable integration under real operational constraints.

IV. TEST SCENARIOS AND CONDITIONS

To evaluate the performance of Culatra Island's distribution grid under different operating conditions, three test scenarios were designed within the DT simulation environment. Each scenario progressively increases system complexity and renewable penetration to assess the impacts on voltage stability, power flow distribution, and overall network efficiency.

Scenario 1 – Baseline (No PV Generation). This configuration represents the conventional operation of the island's grid with all 112 loads as shown in Figure 3 and electrical power supplied from the main distribution transformer through the submarine cable connection. It provides a baseline for comparison by simulating voltage behaviour and line losses under grid-only conditions, without any PV injection.

Scenario 2 – Distributed PV Integration. In this scenario, five PV production units are integrated into the network to assess the effects of distributed generation on voltage regulation and power flow. The units have individual capacities of 4 kWp, 8 kWp, 13.8 kWp, 20 kWp, and 40 kWp, resulting in a total installed PV capacity of 85.8 kWp. The objective is to evaluate how localized renewable production reduces dependency on the main grid and enhances voltage stability during normal load operation.

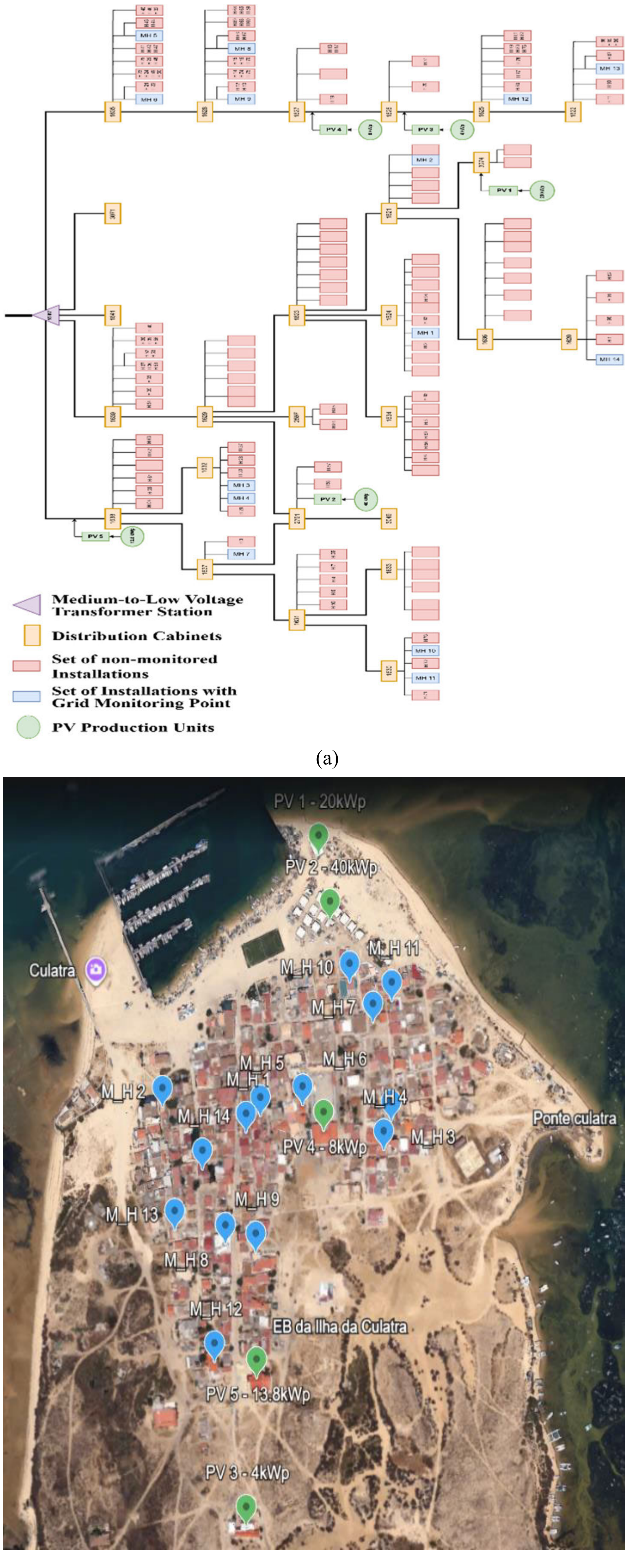
Scenario 3 – High-Demand Conditions with PV Generation. This final configuration builds upon Scenario 2 by introducing additional load demands that bring the total consumption close to the sum of local generation and grid supply. The aim is to replicate peak consumption periods, testing the resilience in terms of voltage stability of the network under stressed conditions and identifying potential bottlenecks or instability zones.

Across all scenarios, the DT model includes a detailed representation of the island's load and infrastructure profile:

- Generation: Five PV production units totalling 85.8 kWp.
- Monitored Loads: Fourteen real-time consumption units equipped with smart meters connected to the Emoncms platform. These provide real-time, time-stamped consumption data (in watts) collected at 15-minutes intervals during representative operational days. This data reflects actual residential and commercial demand patterns.
- Non-Monitored Loads: Ninety-eight additional households lacking smart metering were modeled as static Resistive, Inductive and Capacitive (RLC) loads representing constant background consumption.
- Network Topology: A three-phase PI section model with accurate cable parameters (e.g., LVAV 3 × 185 + 95 mm^2, LSVAV 4 × 95 mm^2) with impedance parameters sourced from manufacturer datasheets.
- Nominal Grid Voltage: 400 V.

All simulations were conducted in a steady-state environment using MATLAB/Simulink's Powergui Load Flow Analyzer, leveraging real operational data where available. This approach enables a controlled, reproducible assessment of grid behaviour under representative conditions. Real-time and/or HIL validation - requiring synchronized physical actuators, grid-edge controllers, and high-frequency communication is beyond the current infrastructure readiness but is explicitly planned as part of the next development phase of the Culatra2030 initiative.

The Culatra-Island Schematic Smart-Grid Simulation Diagram used for the three scenario tests is shown in Figure 2.



(a)

(b)

FIGURE 2. **(a) Culatra-island schematic smart-grid simulation diagram. (b) Culatra-island schematic diagram showing the PV production points (green) and the monitored houses points (blue).**

Steady-state load flow simulations were executed using the Powergui Load Flow Analyzer in MATLAB/Simulink to

FIGURE 3. Voltage profile, voltage drop and load profile in test Scenario 1. The green line represents the actual voltage at each load, the red line shows the corresponding voltage drop in volts while the purple line represents the load profile.

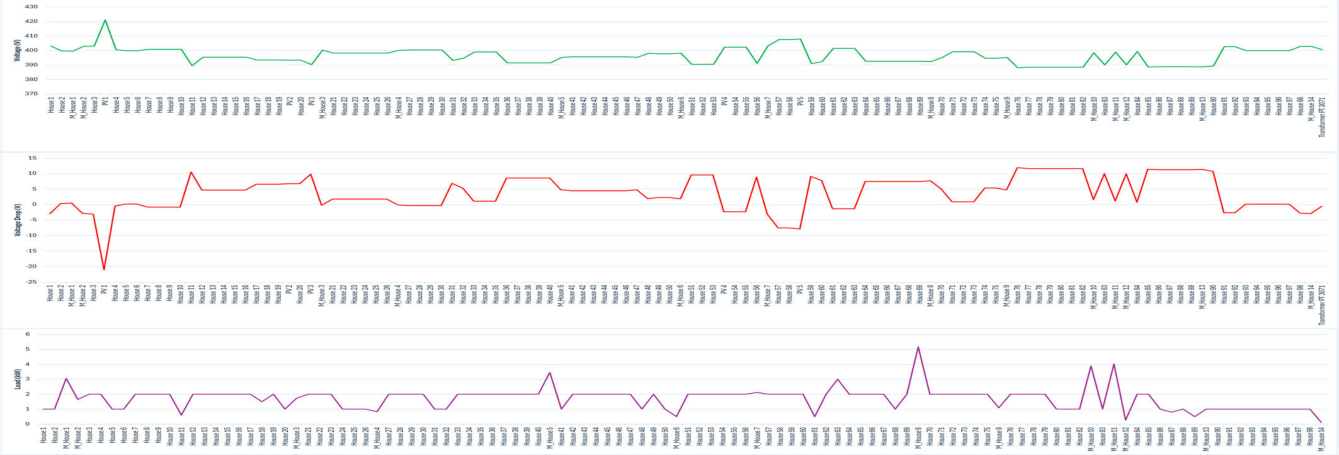


FIGURE 4. Test Scenario 2 voltage profile, voltage drop and load profile. The green line represents the actual voltage, the red line shows the corresponding voltage drop while the purple line represents the load profile.

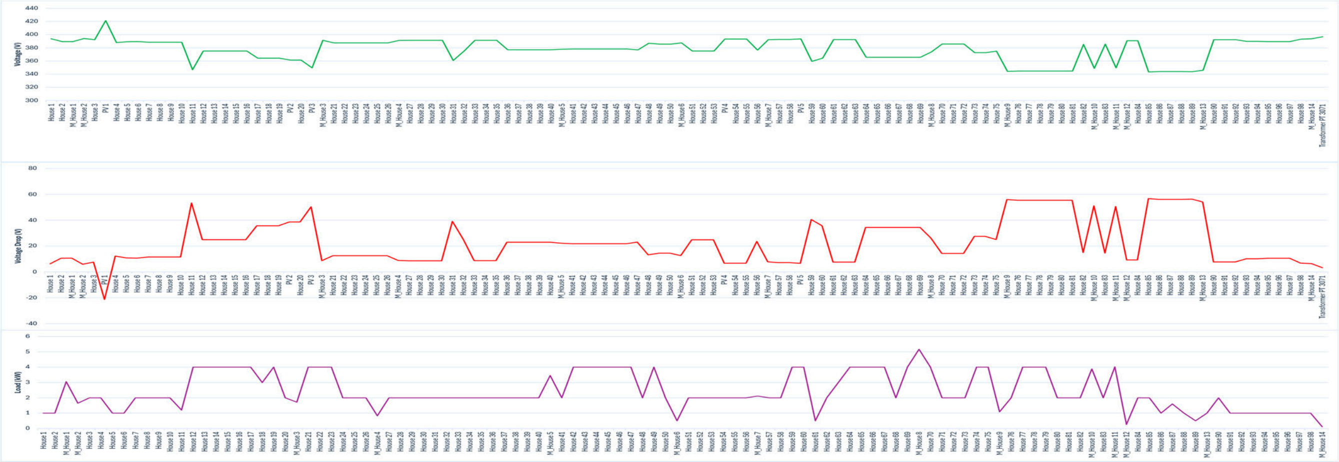


FIGURE 5. Test Scenario 3 voltage profile, voltage drop and load profile. The green line represents the actual voltage, the red line shows the corresponding voltage drop while the purple line represents the load profile.

compute bus voltages, active/reactive power distributions, and line losses for each scenario. These results formed the basis for the comparative analysis presented in the next section.

V. RESULTS

Before conducting scenario-based tests, the DT framework was validated by comparing its simulated state against real-time synchronization data from the Emoncms IoT platform (Layer 3). The verification process uses the mathematical logic established in Section III, where the digital voltage output V_{LF} is compared against the physical smart meter readings V_M at specific high-impact nodes as shown in Table 3. The results obtained from the tests simulations illustrate how distributed PV generation and varying load conditions influence system voltage levels and overall performance. These findings are based on a validated simulation model grounded in real infrastructure and consumption data, though they remain confined to steady-state analysis.

Scenario 1 – Baseline Condition. In the absence of PV production, all loads were supplied exclusively by the main grid. Figure 3 shows the voltage profile (green), the corresponding voltage drops (red) across all network nodes and load profile (purple). The simulation reveals that nodes House 21 to House 26 experience the lowest voltage drops (of 3.28 V), as they are located closer to the distribution substation and thus subject to minimal impedance. Conversely, House 76 shows the highest voltage drop at 19.08 V, followed by House 77 to House 82 all situated farther downstream on the same branch. These values show that distance from the transformer and cable characteristics are decisive factors in voltage quality. Overall, voltage drops range between 3.28 V and 19.08 V (0.82 % – 4.77 %), remaining within the IEC/EN 50160 standard's ±10 % tolerance (360 – 440 V). This confirms stable operation, though marginal regulation under grid-only supply.

Scenario 2 – Distributed PV Integration. The inclusion of the five PV production units markedly improves the grid's voltage profile and reduces losses. Figure 4 illustrates the new profile, showing higher voltages near generation points. The PV 1 unit records a voltage of 421.08 V (a +21 V increase from nominal), while PV 5 rises by 7.88 V. Nodes located near these PV systems (e.g. House 57 and House 58) also display smaller voltage drops than in the baseline scenario. The lowest drops (0.12 V) occur at House 93 to House 97 as all positioned on shorter feeders. Power flow becomes bidirectional, reflecting energy injection from PV systems back into the network. Voltage variations remain well within operational limits, confirming improved stability and efficiency under distributed generation.

Scenario 3 – High-Demand Condition. The third test simulates near-equilibrium between total demand and renewable generation, emulating peak load conditions. In this scenario, the DT's primary function is to verify the stability limits of the Culatra distribution network. As shown in Figure 5, the DT's load-flow engine identified several nodes where the operational constraints defined in Section V Scenario 1 were violated.

Specifically, the IEC/EN 50160 voltage limits threshold of -10% (black lines in Figure 6) [29] was exceeded at multiple locations, indicating stress in the network which can eventually leads to system collapse. While the DT recorded a minimum voltage drop of 5.88V at M_House 2, it flagged critical undervoltage at House 11 (53.4 V), House 59 (40.52 V), and M_House 9 (56.0 V). Using the established verification logic from Equation 2, the DT successfully mapped these deviations as system-wide instability risks. The calculation at House 85 yielded a per-unit voltage of 0.1419 pu (56.76 V), significantly below the 0.90 pu safety limit. This confirms the usability of the DT framework as it accurately predicts and verifies network collapse under sustained high loads even when distributed PV generation is active. These results provide the empirical evidence that the current infrastructure requires the advanced control mechanisms provisioned in Layer 5 to maintain steady-state stability.

TABLE 2. Test scenarios comparison analysis.

Parameter	Test 1	Test 2	Test 3
Transformer Output Voltage	399.60 V	400.56 V	396.72 V
Load Maximum Voltage	396.72 V	407.52 V	394.12 V
Load Minimum Voltage	380.92 V	388.08 V	343.24 V
Load Maximum Voltage Drop	19.08 V	11.92 V	56.76 V
Load Minimum Voltage Drop	3.28 V	-7.52 V	5.88 V
Power Flow Direction	Unidirectional	Bidirectional	Bidirectional
System Stability	Moderate	Stable	Unstable
System Resilience	Moderate	High	Low

A comparative summary of the numerical results is presented in Table 2. The comparison across scenarios confirms the potential of distributed PV generation to enhance voltage stability, operational robustness under steady-state conditions, and self-sufficiency, while also revealing the technical constraints that emerge under peak load conditions. These insights are essential to guide future optimisation and control strategies for Culatra's DT implementation.

VI. DISCUSSION

The simulation results reveal how the performance of Culatra Island's distribution grid evolves with varying levels of renewable generation and load demand.

In Scenario 1, where no PV generation is present, the network operates entirely under centralized supply.

TABLE 3. DT prediction error analysis (Steady-state verification).

Identifier	Type	Measured V_M (field)	DT Predicted V_{LF}	Absolute Error (ΔV)	Percentage Error (%)
Transformer	Reference	400.0 V	400.0 V	0.0 V	0.00 %
PV 1	Generation	421.1 V	421.4 V	0.7 V	0.17 %
M_House 2	Load (Monitored)	394.8 V	394.2 V	0.6 V	0.15 %
House 76	Load (Non-Monitored)	380.9 V	379.8 V	1.1 V	0.27%
PV 5	Generation	407.9 V	407.4 V	0.5 V	0.12 %

FIGURE 6. Comparison of three test Scenarios on voltage profile, voltage drop and load profile. The upper section represents the actual voltage, the middle section shows the corresponding voltage drop while the lower section shows the corresponding load profile. The two black lines show the threshold points that can lead to system collapse.

Voltage levels are mainly affected by feeder length and line impedance. Although all values remain within regulatory limits, the grid exhibits limited operational flexibility and a clear dependence on distance from the transformer. This underscores the vulnerability of a fully centralized configuration and the need for local generation to mitigate voltage drops in remote branches.

In Scenario 2, the introduction of distributed PV units produces a marked improvement in voltage regulation and overall power quality. Localized injections from PV sources offset feeder losses, reducing voltage drops and stabilizing the network. The emergence of bidirectional power flow indicates increased self-consumption potential and opens the possibility of peer-to-peer energy exchanges—essential features for the island's evolution toward a REC.

In Scenario 3, which simulates peak load conditions as shown in Figure 6 (With PV & Equilibrium Load), the limitations of passive operation become evident. Despite the same level of PV generation, the grid fails to maintain stable voltages under high demand, with several nodes surpassing acceptable voltage drop thresholds. These results highlight the need for advances control strategies, such as adaptive inverter regulation, localized storage management, and reactive power compensation, to ensure stability during stress conditions.

The novelty of this work does not lie in proposing a new or universal DT architecture, but rather in delivering a context-sensitive, application-first DT implementation for a real REC undergoing an active energy transition. While many DT-based smart grid studies focus on large-scale transmission networks, hypothetical microgrids, or idealized control environments, the DT presented here is grounded in verified field data from five heterogeneous PV units and 112 residential and commercial loads. It explicitly reflects the actual cable topology, impedance characteristics, and operational constraints of Culatra Island's distribution grid. This high level of physical fidelity allows the DT to function not merely as a simulation tool, but as a practical decision-support system for local operators, policymakers, and community stakeholders. Anchored in an ongoing EU-backed REC initiative, the proposed approach demonstrates a transferable pathway for other islanded or remote communities seeking to leverage digitalization for resilience and energy self-sufficiency without relying on extensive upfront standardization or idealized assumptions.

Although the test scenarios presented in this study could, in principle, be simulated offline, the DT framework provides added value by establishing a persistent and updatable digital representation of the physical system.

Unlike static simulations, the DT is designed to evolve as new data become available, infrastructure is modified, and control strategies are progressively introduced. This capability is particularly relevant for RECs undergoing phased deployment, where planning, validation, and operation occur iteratively rather than as isolated analytical exercises.

While the DT is implemented at island scale, the adopted five-layer architecture is inherently extensible to larger RECs or interconnected distribution grids through the replication of physical assets and expansion of data streams. Scalability challenges are expected primarily at the data acquisition and simulation layers, especially in terms of communication latency and computational burden. However, these challenges are well addressed by existing edge–cloud and hierarchical DT approaches. As such, the Culatra case should be interpreted as a reference configuration rather than a site-specific solution.

It is also important to clarify the scope and limitations of the current implementation. Although the DT architecture includes an Optimization Layer (Layer 5) intended to support demand-response coordination, battery management, or model predictive control, no active optimization strategy was deployed in the present simulations. The scenarios analysed are limited to open-loop, steady-state assessments aimed at understanding system behaviour under varying generation and demand conditions. The absence of quantitative benchmarking against alternative DT or EMS frameworks is likewise intentional at this stage; the primary objective is to demonstrate feasibility and analytical utility rather than to optimize or compare control algorithms.

As the Culatra2030 initiative progresses toward closed-loop operation, future work will integrate active optimization routines and standardized performance metrics to enable rigorous comparison with other DT-based energy management approaches.

Finally, while this study focuses on modelling and simulation capabilities, real-world deployment of the DT will require careful consideration of cyber-physical challenges, including cybersecurity, communication latency, and data reliability. Risks such as data tampering, denial-of-service attacks, or network delays could affect both simulation fidelity and operational safety. These aspects are recognized as critical areas for future development, particularly as the DT evolves toward real-time control and hardware-in-the-loop integration.

Overall, the results confirm that while distributed generation significantly enhances grid performance under nominal conditions, intelligent energy management becomes indispensable as the system approaches its technical limits.

The simulations confirmed that grid stability and power quality are highly sensitive to the interaction between PV generation and load patterns. Under Scenario 1 (no PV injection), the network operated within acceptable voltage limits but showed moderate stability and significant voltage drops across distant feeders. Introducing Scenario 2 (distributed PV integration) improved voltage regulation, reduced losses, and enhanced system resilience through localized energy injection and bidirectional power flow. However, Scenario 3 (high-demand conditions) exposed operational limits, with undervoltage exceeding regulatory thresholds, indicating the need for advanced control mechanisms and infrastructure reinforcement.

In this context, the DT proves to be a powerful analytical and operational tool: it enables real-time visualization of grid behaviour, supports predictive maintenance, and allows safe testing of control strategies prior to implementation. By tightly integrating physical and digital layers, the proposed DT provides both a diagnostic and decision-support platform that supports infrastructure planning, control optimization, and policymaking, reinforcing Culatra Island's pathway toward a resilient, self-sufficient, and community-driven smart grid.

VII. CONCLUSION AND FUTURE DEVELOPMENT

This work developed and tested a comprehensive DT of the Culatra Island distribution grid using MATLAB/Simulink, demonstrating the platform's effectiveness for simulating smart grid dynamics with distributed PV generation. From a DT perspective, the technical contribution lies in the structured implementation of a five-layer architecture explicitly aligned with REC operational needs. The five-layer DT architecture integrated real-world elements of the island's energy system, including five PV production units (4–40 kWp), monitored and fixed electrical loads, and realistic network parameters derived from the island's infrastructure. Unlike generic DT frameworks, the proposed model emphasizes interoperability with existing IoT platforms, realistic distribution-level constraints, and progressive activation of optimization layers. This practical DT instantiation addresses a gap between conceptual DT designs and deployable energy community applications.

Overall, the study demonstrates that DTs of Distribution Grids are important tools to perform a real time assessment of load scheduling solutions, in the context of intelligent energy management and optimisation systems. The DT proved invaluable as both an analytical and decision-support tool, allowing real-time simulation of grid conditions and providing a foundation for predictive control, demand-response coordination, and system optimisation.

A key limitation of the current study is the absence of reliability metrics. While the DT effectively captures voltage stability and power flow behaviour under three representative scenarios, it does not model transient events, and equipment failures. Future work will extend the DT to incorporate stochastic outage models, real-time fault detection, and reliability indices (e.g., SAIDI/SAIFI) through co-simulation with protection and communication layers and also should focus on enhancing the DT architecture through the inclusion of load prediction models, adaptive optimisation algorithms, forecast errors, and real-time control strategies capable of autonomously balancing generation and demand.

Also, although this study does not perform a quantitative economic assessment, the DT provides the necessary technical foundation for evaluating cost–benefit trade-offs related to PV sizing, storage deployment, and grid reinforcement. In regulatory terms, the DT aligns with EU REC frameworks by enabling analysis of self-consumption, bidirectional power flows, and local congestion - key elements influencing tariffs and market participation. Integrating techno-economic optimization is a natural extension of the proposed architecture and will be addressed in future work.

These developments will be essential for achieving Culatra's vision of a resilient, self-sufficient REC and can serve as a replicable framework for similar island and remote systems worldwide.

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IDRIS O. OGUNSOLA received the degree in electronic and electrical engineering from the Ladoke Akintola University of Technology, Ogbomoso, Nigeria, in 2014, and the M.Sc. degree in electrical and computer engineering from the University of Algarve, in 2025, with specialization in information technologies and telecommunications, where he is currently pursuing the Ph.D. degree in informatics engineering. He previously had seven years of industry experience in the telecommunications field as a Field Service Engineer, a Telecommunication Engineer, and a Professional Service Coordinator in a leading ISP in Nigeria.

JÓNI B. SANTOS received the B.Sc. and M.Sc. degrees in electrical and electronics engineering from Universidade do Algarve, Portugal, where he is currently pursuing the Ph.D. degree in electrical engineering. He is a Research Fellow with Centro de Investigação Marinha e Ambiental, Universidade do Algarve, supported by the Portuguese Foundation for Science and Technology, and an Invited Assistant Lecturer with Instituto Superior de Engenharia, Universidade do Algarve, teaching in the field of programming. His research interests include smart grids, renewable energy communities, demand-side management, sensor networks, and the Internet of Things.

JÂNIO MONTEIRO received the degree in electrical and computers engineering from the University of Porto, and the master's and Ph.D. degrees in electrical and computer engineering from Instituto Superior Técnico, University of Lisbon, Portugal. He is currently a Professor with the Institute of Engineering, Universidade do Algarve, Portugal. He is also the President of the Board of Directors of CINTAL, a Technological Research Center of the Algarve. He is also a member of the Coordination Team of the Culatra 2030 Project, a Pilot Project supported by the Clean Energy for EU Islands Secretariat, which aims to create a Sustainable Community in the Culatra Island, Portugal. His research interests include sensor networks, the Internet of Things, smart grids, communication networks, and machine learning.

ANDRÉ PACHECO received the degree in environmental engineering and the Ph.D. degree in physical oceanography from Universidade do Algarve, Portugal. He is currently a Researcher with Centro de Investigação Marinha e Ambiental (CIMA), Universidade do Algarve, where he leads the research team on marine renewable energy and sustainable islands. He is also the Coordinator of the Culatra2030–Sustainable Energy Community initiative, a pilot project supported by the Clean Energy for EU Islands Secretariat of the European Commission that aims to create a fully sustainable, decentralized energy community on Culatra Island, Portugal. His research interests include marine renewable energies (tidal and offshore wind), digital twin modelling, and the design of resilient island energy systems.

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