Small-Scale DC Grid Demonstration in Port of Funchal

Pedro Costa[1,2], Luis Rodriguez[1,2], Manuel Neto[1,2], Diogo Reis[1,3], Anne Niin[1,2], Lucas Pereira[2,4], Hugo Morais[1,2*]

[1]INESC-ID, Department of Electrical and Computer Engineering, Lisbon, Portugal
[2]Instituto Superior Técnico – IST, Universidade de Lisboa, Lisbon, Portugal
[3]Universidade da Madeira, Madeira, Portugal
[4]Interactive Technologies Institute, Lisbon, Portugal
**Corresponding author: hugo.morais@tecnico.ulisboa.pt*

Keywords: DC microgrids, Digital Twin, Energy Hub, Sea Ports, Shore Side Power

Abstract

Maritime ports are undergoing a profound transformation driven by global decarbonization targets and increasing electrification demands. In this context, Direct Current (DC) grids emerge as a promising solution to increase efficiency, facilitate renewable integration, and support advanced services. This paper presents the design, implementation, and validation of a DC microgrid demonstrator deployed at the Port of Funchal within the Shift2DC project. The system integrates a bidirectional AC/DC front-end, photovoltaic generation, battery energy storage, electric vehicles charging infrastructure, and controllable DC loads, coordinated through a distributed droop-control strategy aligned with the CurrentOS framework. In parallel, a modular Digital Twin (DT) platform was developed using a microservice-based architecture to enable real-time monitoring, predictive vessel energy modeling, and automated DC power flow simulations. The DT integrates live measurements from 32 electrical boards, synthetic vessel demand profiles, and an interactive geospatial interface, providing both operational awareness and scenario analysis capabilities. Experimental validation demonstrates stable DC bus operation, effective multi-converter coordination, and interoperability between physical and digital layers.

1 Introduction

Maritime ports are key infrastructures, supporting more than 80% of worldwide trade and ensuring the people transportation (cruises). However, they are also significant contributors to greenhouse gas emissions and local pollution, primarily due to the reliance on diesel-powered vessels and energy-intensive port operations. As international regulatory bodies, particularly the International Maritime Organization, reinforce decarbonization targets, including carbon neutrality by 2050, ports must accelerate the adoption of clean, electrified, and digitally optimized energy systems [1]. Solutions such as Shore-Side Power (SSP), renewable energy deployment, and electrification of cargo handling and mobility infrastructures are essential steps toward sustainable port operations [2]. Yet these innovations impose stringent requirements on the electrical infrastructure, demanding flexibility, efficiency, and robust control capabilities.

In this context, Direct Current (DC) grids have gained growing attention as an enabling technology for the next generation of green ports [3]. Their high efficiency minimizes conversion losses, and their compatibility with photovoltaics, battery storage, and electric vehicle charging makes them an attractive alternative to conventional AC-based architectures. Another important aspect in Green Ports, considering the capabilities of SSPs, is the need to supply energy to ships in DC as well as in AC at both 50 Hz and 60 Hz [4].

Despite their potential, real-world implementations in maritime contexts remain limited, highlighting the need for practical demonstrations that validate interoperability, protection schemes, and distributed control.

In this context, this work presents a proof-of-concept physical demonstrator of a DC microgrid deployed at the Port of Madeira, designed to evaluate DC-grid behavior under realistic operational conditions. The demonstrator integrates a 11 kW AC/DC front-end, 10 kW of photovoltaic generation, a 10 kW / 10 kWh battery energy storage system, a 22 kW EV charging station, and some DC loads. Its architecture is built upon the CurrentOS ecosystem, which provides decentralized decision-making, interoperability, and communication across devices. Additionally, the eco-system supposes the use of distributed voltage droop control, an efficient and effective operation of the medium and low-voltage. DC grids.

2 Proposed Approach

The DC demonstrator in Port of Funchal in Shift2DC project enabled a comprehensive experimental assessment of several key performance aspects relevant to port-integrated DC grids. Figure 1 presents the single-line diagram of the setup and its connection to the port's supervision infrastructure considering four different layers [5].

The first layer "Existing Port Grid (Adapted to DC)" represents the existing loads that are connected to 32 partial electric panels. The panels are classified as "normal" or "critical" depending on the type of circuits. Leveraging the monitoring system installed across 32 electrical boards, detailed measurements were collected to characterize system behavior under diverse operating conditions. The second layer,

"Physical Demonstration", represents the setup of the installation that is being developed in Shift2DC project allowing the validation of distributed droop control functions according to the specification proposed by Current OS [6]. This layer id described in Section 2.1. The third layer, the "Port Energy Hub," represents a virtual layer that integrates a large-scale photovoltaic (PV) system, a battery energy storage system (BESS), and a hydrogen system composed of an electrolyzer, a storage system, and a fuel cell. This layer reflects a long-term vision for the port, considering its role and operation as an energy hub. Finally, the fourth layer, "Shore-Side Energy" represents the connection with cruise ships that is planned to be developed in a near future.

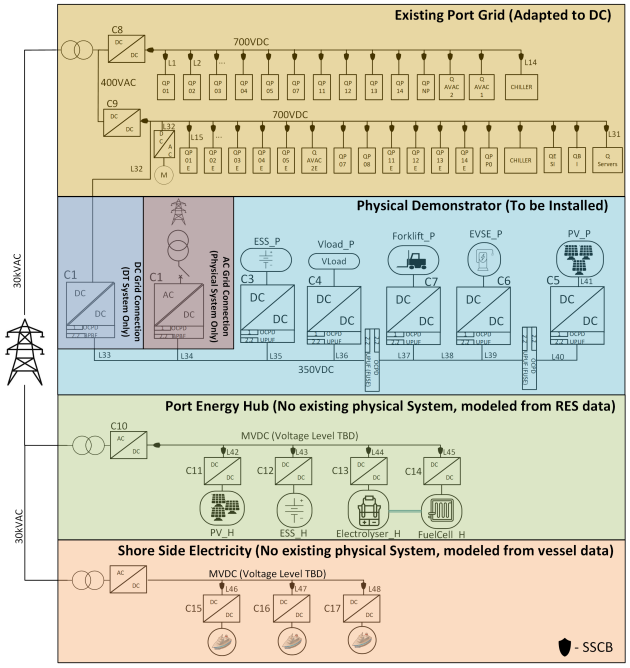


Figure 1 – DC Demonstrator in Port – Single Line Diagram

2.1 Digital Twin Implementation

Fundamentally, a Digital Twin (DT) is a dynamic, virtual representation of a physical asset or system that maintains a continuous data connection with its real-world counterpart [7]. Beyond static digital models, a true DT integrates real-time and historical data, and predictive algorithms to mirror the physical system's operational lifecycle, offering both continuous monitoring and advanced "what-if" scenario planning without disrupting actual operations [8].

To effectively monitor, manage, and optimize the interactions within the port's DC microgrid, a DT was developed. Recognizing the complexity of integrating heterogeneous systems, ranging from physical IoT sensor networks to predictive machine learning models and power systems simulations, a monolithic architecture was discarded. Instead, the DT was designed utilizing a modular, microservice architecture [9], as seen in Figure 2. This approach ensures high scalability, fault isolation, and interoperability between different technological stacks (e.g., Python analytical models and React web interfaces).

The foundation of the DT relies on a data acquisition pipeline that serves as the Single Source of Truth (SSOT). Real-time electrical measurements (voltage, current, and power) are captured by smart meters monitoring 32 distinct loads across the port's electrical boards. This data is aggregated by industrial microcomputers (StratoPi) and transmitted over the local network to a central Energy Management System (EMS), which keeps the data in a centralized database.

Operating as a containerized component, the vessel modeling microservice generates synthetic energy demand profiles for incoming vessels. To ensure the DT accurately reflects the real-world operational state of the port rather than just theoretical scenarios, an automated routine was developed to scrape the official port authority website. This process synchronizes the DT with the next day's vessel schedule, allowing the microservice to automatically generate predictive energy profiles for the specific ships scheduled to dock, linking the models with the actual port logistics.

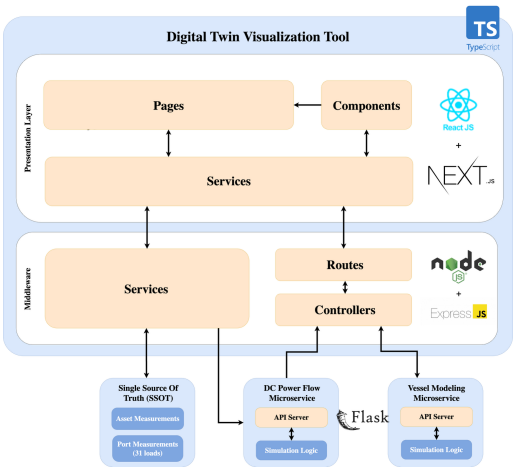


Figure 2 – DT System Simplified Architecture

Integrating the DC design tool was architecturally challenging, as it was originally developed within the Shift2DC project as an offline, static application reliant on Excel configuration files [10]. To transform this into a dynamic microservice suitable for a DT, a "hybrid data model" was implemented as presented in Figure 3. The static network topology (buses, lines, converters) remains defined in a base configuration file, while dynamic, real-time device loads are injected via structured JSON files. This separation prevents file corruption from constant read/write operations and allows the service to run continuous, automated power flow simulations using live operational data without manual intervention.

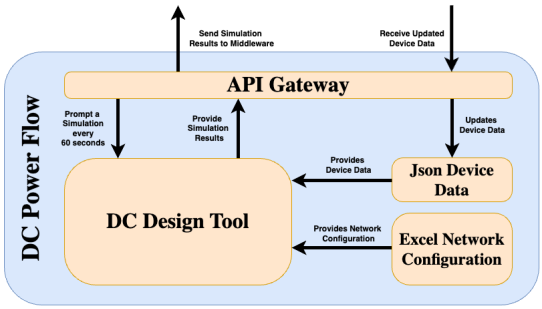


Figure 3 –DC Power Flow microservice

Operating as the central orchestrator and API Gateway, the Middleware layer (developed in Node.js) connects the microservices with the user interface. It uses a dual communication strategy: synchronous RESTful APIs are used for user triggered events (e.g., running a custom vessel energy simulation), while asynchronous WebSockets (Socket.IO) manage the continuous real-time data pipeline. To avoid overwhelming the network and database, the middleware polls the SSOT every 5 seconds and pushes updates to all connected clients, for near real-time synchronization with the physical asset.

The visual component of the DT consists of a interactive web platform built with React, Next.js, and Tailwind CSS. The presentation layer has the objective of translanting complex electrical and predictive data into insights for the users without requiring deep technical expertise in power systems.

Upon accessing the DT, the users first contact with the system is the Main Dashboard, which serves as the central hub for operational view. The dashboard consists of a simple layout providing immediate visibility into critical key metrics, aggregating live data to display the total monitored devices, active devices, current total power (kW), and average power factor across the microgrid.

The interface also features an interactive "Device Power Distribution" visualization (Presented in Figure 4). Utilizing a dynamic stacked area chart, this component provides a comprehensive breakdown of power consumption across individual devices over customizable time periods (ranging from the last 15 minutes to 6 hours). This options allows the user to track aggregate demand and also instantly pinpoint which specific infrastructure components are driving load spikes. The modular design of the interface reflects the platform's ability to grow, accommodating new integrated microservices in development, such as PV Solar generation and specific Converter monitoring, alongside the core simulation tools.

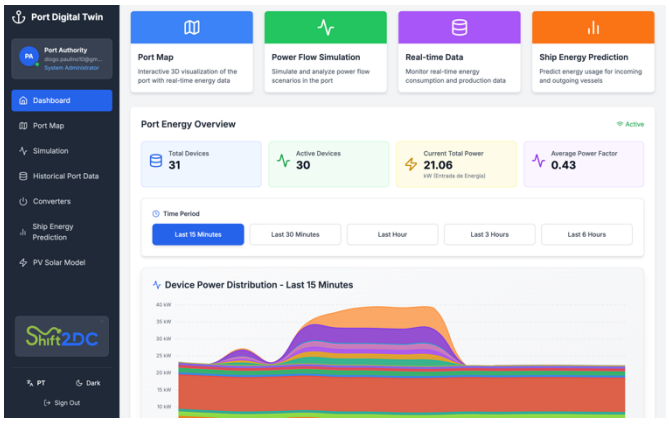


Figure 4 – Main dashboard of the Digital Twin providing real-time port energy metrics and device power distribution.

Beyond the main dashboard, the rest of the application features similar, cohesive design choices. Across all microservices pages, from historical data to the PV Solar Model, the platform uses a variety of specialized graphing libraries. These graphical interfaces are purposefully designed to facilitate the understanding of the high volumes of data generated by the microservices (such as JSON arrays of power flow) into real useful information.

The most distinct and visually complex component of the system is the interactive 2.5D geospatial map, seen in Figure 5. While traditional dashboards prove to be good at quantitative summaries, this page provides the spatial context necessary for a true DT. It projects the port's live electrical topology directly onto the geographical layout of the Port of Funchal.

Another feature of this interface is its dynamic representation of maritime traffic. The map renders 3D models of vessels that accurately reflect the current physical state of the port, synchronized with the vessel modeling microservice. These 3D models act as interactive nodes, which by selecting a specific ship on the map, users can instantly access the dedicated predictive energy demand profile generated for that exact vessel.

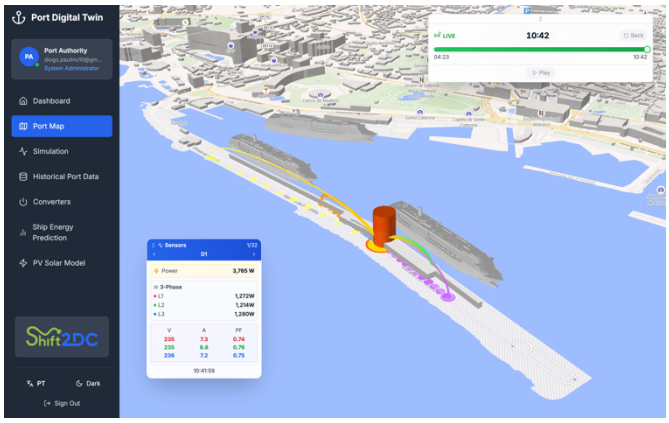


Figure 5 – 2.5D geospatial interface of the Digital Twin, featuring real-time sensor data, historical playback controls, and spatially mapped vessel models.

To provide a more complete view, the map is augmented with floating analytical panels. As shown in the interface, a dedicated "Sensors" panel allows operators to actively browse through the 32 monitored electrical boards in real-time. This panel provides the data for each specific board, detailing total power alongside breakdowns (L1, L2, L3) for voltage, current, and power factor.

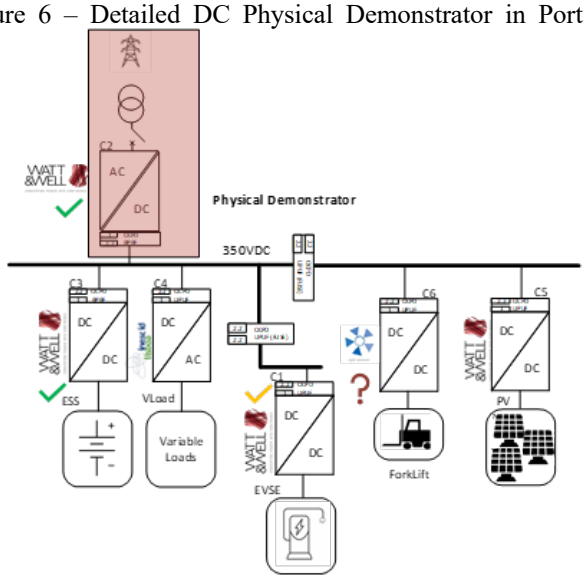
Finally, the interface is also equipped with a time slider playback tool. This feature allows users to move from the "Live" data stream and travel backward through the different states of the port in the near past. By interacting with the slider, operators can visually replay the grid's behavior, load distributions, and vessel schedules over recent hours.

2.2 Practical Implementation

This section describes the design, implementation, and commissioning of the DC microgrid demonstrator installed at the Port of Funchal, highlighting its architecture, main subsystems, and control framework. Figure 6 presents the detailed single-line diagram of the DC demonstrator installed

at the Port of Funchal. The physical demonstrator consists of a DC microgrid structured around a 350 V DC bus, generated by an 11 kW bidirectional AC–DC converter interfacing with the utility grid. All main power converters are installed in 19" industrial rack cabinets, ensuring modularity, compactness, and ease of maintenance.

Figure 6 – Detailed DC Physical Demonstrator in Port of Funchal – Single Line Diagram



System Architecture and Subsystems

The demonstrator integrates the following subsystems:

- PV power source converter (11 kW)
- Battery energy storage converter (11 kW)
- Two EV charging station converters (2 × 22 kW)
- Forklift charging station converter (11 kW)
- Interlink converter AC–DC converter (11 kW)

Photovoltaic Subsystem

The photovoltaic (PV) subsystem is interfaced through an 11 kW DC–DC converter connected to the 350 V DC bus. A Maximum Power Point Tracking (MPPT) algorithm was implemented at the control layer to ensure optimal energy harvesting under varying irradiance conditions.

Battery Energy Storage System

The BESS comprises four batteries connected in series, forming a module with a nominal voltage of 250 V and a total energy capacity of 25 kWh. The battery pack is directly connected to a bidirectional DC–DC converter, enabling controlled charging and discharging operations, voltage regulation support, and power balancing within the DC microgrid.

EV Charging Stations

The EV charging station is designed to charge electric vehicles at up to 800 V and 22 kW. The architecture consists of two DC–DC converters connected in series to achieve the required output voltage. The charger is integrated with a dedicated control board that communicates with the vehicle through the Open Charge Point Protocol (OCPP 1.6/2.01), enabling standardized charging management and interoperability. Additionally, a physical user interface is being developed to allow customers to easily connect and operate the charger. During the project bi-directional charging based on ISO15118-20 will be tested increasing the type of management that can be performed by the system

Forklift Charging Station

The forklift charging station required a different DC–DC converter model capable of operating at lower voltage levels. To achieve the nominal voltage of 50 V and a charging power of 11 kW, a solution based on three coordinated DC–DC converters was implemented. This configuration allows flexible voltage adaptation while maintaining high power capability.

Interlink Converter (Active Front End)

An 11 kW bidirectional AC–DC utility converter is connected to the DC bus as a multi-purpose asset. Beyond providing grid support and power balancing, it enables the physical emulation of different load profiles by controlling the power exchanged with the grid, thereby supporting experimental validation and stress testing scenarios.

Control and Communication Architecture

One of the main implementation challenges was the development of a distributed control interface capable of coordinating multiple converters while guaranteeing DC bus stability and operational flexibility.

Each converter is connected to a CAN bus operating under the CANopen protocol. The control layer enables:

- Configuration of different power setpoints;
- Adjustment of droop control curves;
- Real-time acquisition of voltage, current, and power measurements from each device.

The supervisory and control layer was implemented in Python and structured around modular components, including CAN communication management, message handling, and power setpoint configuration. The system communicates via TCP/IP with a central server that aggregates device states and operational measurements.

The entire control system runs on a Raspberry Pi controller connected to the converters through a Kvaser CAN interface, ensuring reliable real-time communication and scalability.

Development, Testing, and Commissioning

The system was initially developed and tested at Instituto Superior Técnico, where the demonstrator was validated using programmable power supplies to emulate the PV array and battery system. The EV charging station was also simulated in Lisbon prior to on-site deployment. These preliminary tests were essential for refining the supervisory and control layer and for assessing DC grid stability under different operational scenarios.

The commissioning phase at the Port of Funchal included the installation of all converters and battery modules in a 19" industrial rack (see Figure 7). All associated infrastructure, cabling, electrical protections, and low-voltage auxiliary power supplies, was properly dimensioned and installed. A separate industrial rack was used for the EV charging converters, ensuring safe operation and clear physical separation between subsystems.

This demonstrator represents a fully integrated DC microgrid platform, enabling the validation of advanced control strategies, multi-converter coordination, and flexible energy management solutions tailored to port environments.

Figure 7 – Funchal port demonstration commissioning

4 Conclusions

This work presented a comprehensive proof-of-concept of a port-integrated DC microgrid supported by a fully operational DT, implemented at the Port of Funchal. The demonstrator validated the technical feasibility of operating a 350 V DC bus architecture integrating photovoltaic generation, battery storage, EV fast charging (including preparation for bidirectional charging under ISO 15118-20), forklift charging systems, and a bidirectional interlink converter. The DT complemented the physical demonstrator by providing real-time situational awareness, predictive vessel demand modeling, automated DC power flow simulations, and an intuitive geospatial visualization interface. The microservice-based architecture proved effective in integrating heterogeneous systems, ensuring scalability, interoperability, and resilience. The synchronization with vessel schedules and live electrical measurements enabled near real-time alignment between the physical and digital environments. Future work will focus on extending the platform to higher power levels, integrating hydrogen-based assets, validating ship-to-port energy exchange scenarios, and assessing long-term operational and economic performance.

5 Acknowledgements

Work supported by national funds through Fundação para a Ciência e a Tecnologia, I.P. (FCT) under projects UID/50021/2025 (DOI: https://doi.org/10.54499/UID/50021/2025) , UID/PRR/50021/2025 (DOI: https://doi.org/10.54499/UID/PRR/50021/2025) and within the scope of the project nº 56 - "ATE", financed by European Funds, namely "Recovery and Resilience Plan - Component 5: Agendas Mobilizadoras para a Inovação Empresarial", included in the NextGenerationEU funding program. This work received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101136131 (Shift2DC project). Views and opinions expressed in this document are however those of the authors only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the grating authority can be held responsible for them.

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