24th International Conference on Renewable Energies and Power Quality (ICREPQ'26)
Santander (Spain), 10th to 12th June 2026
E&Q Journal - ISSN:2659-8779. Volume 4. July 2026

Renewable Generation and OPS Demand Optimisation in Ports: A Decision-Support Tool

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Abstract. The electrification of port activities through Onshore Power Supply (OPS) and the integration of on-site renewables are key levers to reduce emissions, yet they also increase peak power requirements and operational exposure to price variability. Robust planning therefore requires consistent forecasting of future renewable generation and future demand (including OPS uptake), coupled with an optimisation layer to allocate renewable electricity and schedule hydrogen production via electrolysis. This work proposes a forecasting-and-optimisation methodology for port energy planning and presents its implementation as a decision-support tool. Renewable generation is estimated from meteorological projections and technology performance models, while future port demand is projected from historical load patterns, and OPS demand is computed from call schedules and vessel technical characteristics. An optimisation model is run daily (day-ahead) to schedule renewable usage, grid imports and hydrogen production subject to operational constraints and cost/emission objectives. A case study of the application of the proposed methodology to the Port of Valencia is shown, producing comparable scenarios (baseline, OPS, renewables, and combined strategies) and KPIs including annual energy cost, peak demand, renewable share and CO_2 emissions. The resulting tool enables transparent, repeatable assessments to support investment screening and operational decision-making, contributing to the port's transition towards a sustainable energy hub.

Key words. Onshore power supply, renewable energies, energy hub, forecasting, optimisation.

1. Introduction

Seaports are evolving into highly electrified, energy-intensive infrastructures where operational performance and decarbonisation targets must be reconciled with grid constraints and cost exposure. This transition is driven by the increasing electrification of port operations and by European decarbonisation policy, including the Fit for 55 framework and the related AFIR and FuelEU Maritime regulations, which set requirements for the deployment and use of shore-side electricity (OPS) in key EU ports from 2030 onwards [1,2]. As a result, ports face rising electricity demand and higher peak power requirements, making robust planning and operational coordination increasingly critical.

A major driver of future port demand is the deployment of Onshore Power Supply (OPS), which enables ships at berth to switch off auxiliary engines and connect to shore electricity, reducing local air pollution, noise and greenhouse gas emissions. OPS demand, however, is intrinsically linked to maritime traffic: it depends on the number and type of vessels calling at the port and on ship-specific technical characteristics (e.g., power requirements at berth, voltage/frequency needs). Accordingly, in our methodology the OPS demand is estimated using a bottom-up approach based on vessel call data and ship technical characteristics, complemented by published auxiliary-to-main engine ratios and activity-dependent load factors for different ship categories and operational phases [3]. This coupling between logistics and electrical loads increases the complexity of planning and makes reliable estimation of future power and energy requirements critical not only for port authorities but also for grid operators and energy suppliers, who must anticipate reinforcements and operational measures to ensure adequate service quality.

At the local level, the OPS Valenciaport initiative targets shore power supply for ferries, cruise ships and containerships across three terminals (APM Terminals, CSP and Trasmed), together with network reinforcements and energy management components - illustrating the urgency of coordinated planning for port energy infrastructures [4]. Even under staged OPS deployment (limited-scale implementation through a small number of supply points), ports may experience step changes in both annual electricity demand and peak power, intensifying challenges related to network capacity, tariff exposure and operational scheduling and reinforcing the need for reliable demand and renewable generation projections coupled with day-ahead optimisation.

In parallel, ports are accelerating the integration of on-site renewable generation and storage to mitigate grid constraints and support decarbonisation. Valencia currently considers and/or develops multiple renewable projects, including photovoltaic plants, floating PV and marine renewable demonstrators, with additional wind and PV capacities envisioned towards 2030 [5,6]. The literature and recent initiatives highlight that smart-grid and microgrid-based energy management in ports is a key enabler to integrate renewables under operational uncertainty while maintaining supply reliability and economic performance [7–9].

Motivated by this context, this work addresses the lack of port-specific, reproducible methods that integrate demand forecasting, renewable generation estimation, and operational optimisation within a unified framework. The objective of this work is to develop a decision-support methodology capable of projecting near-term renewable generation and port electricity demand, including OPS-driven loads, and optimally managing energy resources through a day-ahead optimisation framework.

The proposed approach combines: (i) projection of near-term renewable generation profiles based on meteorological data, (ii) estimation of port electricity demand including an explicit OPS module derived from vessel calls and ship characteristics, and (iii) a daily day-ahead optimisation to coordinate renewable utilisation, grid imports and hydrogen production.

Beyond the methodological framework, the main contributions of this work are fourfold. First, a structured workflow is developed to integrate heterogeneous port data and define comparable energy scenarios. Second, a traffic-driven OPS demand model is implemented to capture the impact of maritime activity on electricity demand. Third, a renewable generation and techno-economic assessment module is introduced to evaluate alternative energy configurations in terms of cost and emissions. Finally, a day-ahead optimisation framework is proposed to enable intelligent energy management, complemented by decision-oriented KPIs that support operational planning and investment decisions.

The methodology is applied to the Port of Valencia through a decision-support tool that enables consistent scenario assessment (baseline, OPS, renewables and combined strategies) and supports the transition towards a more efficient, resilient and low-carbon port energy system.

The paper is organized as follows. Section 2 presents the developed methodology. Section 3 shows the study case in Valencia port. Finally, in Section 4, some conclusions of the presented work are drawn.

2. Methodology

This section presents the proposed methodology to project port electricity demand (including OPS), estimate renewable generation, and optimise the day-ahead operation of the energy system. The approach integrates heterogeneous data sources and combines physical modelling with techno-economic optimisation to support decision-making in port energy planning.

A. Data Integration and Pre-processing

The methodology is based on the integration of multiple data sources into a unified and consistent framework. The main inputs include:

1. Measured port electricity demand, obtained as hourly time series for a representative period.
2. Meteorological data, including solar irradiance (W/m²), ambient temperature (°C), wind speed at 10 m (m/s), and oceanographic variables such as significant wave height (m) and wave period (s).
3. Electricity price data, corresponding to hourly day-ahead market prices.
4. Maritime traffic data, including vessel calls (arrival and departure times) and ship technical characteristics (e.g., gross tonnage, main engine power).

All data are temporally aligned to a common hourly resolution and processed to ensure consistency in units, completeness, and continuity. When required, missing values are complemented with representative assumptions to maintain model operability.

B. OPS Demand Modelling

The additional electricity demand associated with Onshore Power Supply (OPS) is estimated using a bottom-up approach based on vessel calls and ship characteristics.

For each vessel call i, the OPS power demand is calculated as:

$$P_{OPS,i} = P_{AE,i} \cdot LF_i \quad (1)$$

where:

- $P_{AE,i}$ is the auxiliary engine power of the vessel,
- LF_i is the load factor during the hotelling phase, dependent on vessel type.

Since auxiliary engine power is not always directly available, it is estimated from the main engine power:

$$P_{AE,i} = \left(\frac{AE}{ME}\right)_{type} \cdot P_{ME,i} \quad (2)$$

where $(AE/ME)_{type}$ is a literature-based ratio depending on the vessel category.

Typical load factors are assumed as:

- 40% for non-tanker vessels (e.g., container ships, ferries, cruise ships),
- 60% for tanker and liquid bulk vessels.

To reflect real deployment constraints, a limitation on the number of simultaneous OPS connections is introduced. The number of vessels connected at each terminal and time step is restricted by the available infrastructure capacity, ensuring realistic demand estimation.

The total OPS demand is obtained by aggregating the contributions of all vessels present at berth for each hourly time step.

C. Renewable Generation Modelling

Renewable generation is estimated for photovoltaic (PV), wind, and wave energy technologies using meteorological data and simplified performance models.

1) Photovoltaic Generation:

PV power output is calculated as a function of solar irradiance, installed capacity, and system efficiency, including temperature effects:

$$P_{PV}(t) = G(t) \cdot P_{inst} \cdot \eta \cdot f(T) \quad (3)$$

where:

- $G(t)$ is the solar irradiance,
- P_{inst} is the installed capacity,
- η is the system efficiency,
- $f(T)$ accounts for temperature-related performance losses.

2) Wind Generation:

Wind power is estimated using a simplified power curve defined by cut-in, nominal, and cut-out wind speeds. The output is expressed as:

- Zero below cut-in speed,
- Increasing up to nominal power within the operational range,
- Constant at nominal power until cut-out speed.

3) Wave Energy Generation:

Wave energy production is derived from oceanographic conditions using a simplified relation based on significant wave height $H_s$and wave period T:

$$P_{wave}(t) \propto \frac{H_s^2}{T} \quad (4)$$

This formulation is scaled by the effective capture area and technology efficiency to obtain the hourly power output.
The total renewable generation at each time step is computed as the sum of all technologies:

$$P_{RES}(t) = P_{PV}(t) + P_{wind}(t) + P_{wave}(t) \quad (5)$$

D. Economic Modelling

A techno-economic layer is incorporated to evaluate the cost of energy supply and support scenario comparison.
For each renewable technology, the Levelized Cost of Energy (LCOE) is estimated as:

$$LCOE = \frac{CAPEX + \sum OPEX}{E_{annual}} \quad (6)$$

where:

- $CAPEX$ is the initial investment cost,
- $OPEX$ represents annual operational costs,
- E_{annual} is the annual energy production.

Hourly renewable generation costs are computed using the corresponding LCOE values and combined with electricity market prices to estimate the total system cost.

E. Day-Ahead Optimisation

A day-ahead optimisation problem is formulated to determine the optimal allocation of energy resources for the following day. The optimisation minimises the total operational cost:

$$\min \sum_t \left(C_{grid}(t) \cdot P_{grid}(t) + C_{RES}(t) \cdot P_{RES}(t) \right) \quad (7)$$

subject to:

- Energy balance constraint:

$$Demand(t) = P_{grid}(t) + P_{RES}(t) + P_{H2,dis}(t) - P_{H2,prod}(t) \quad (8)$$

- Storage dynamics (hydrogen tank):

$$SOC(t) = SOC(t-1) + P_{H2,prod}(t) - P_{H2,dis}(t) \quad (9)$$

- Operational limits:
  - Capacity limits of renewable generation,
  - Electrolyser and fuel cell constraints,
  - Storage bounds.

The model enables the coordination of renewable usage, grid imports, and hydrogen production/consumption, ensuring cost-efficient operation under technical constraints.

3. Results

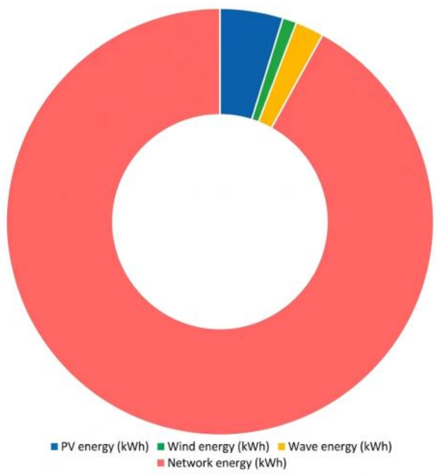
This section presents the main results obtained from the application of the proposed methodology to a representative case study of a port environment. The analysis focuses on comparing different energy scenarios and evaluating their impact on demand, cost, renewable integration, and emissions.

A. Scenario Definition

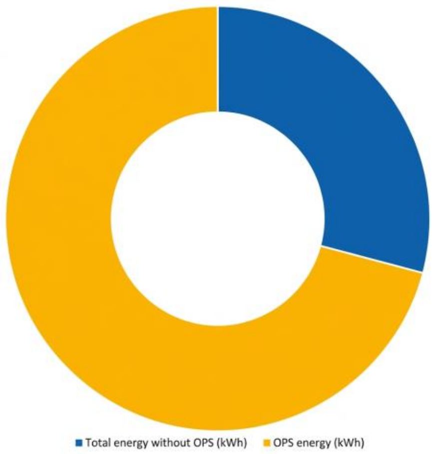
Four scenarios were defined to assess the impact of electrification and renewable integration:

- Baseline scenario: current electricity demand without OPS or additional renewable generation.
- OPS scenario: inclusion of additional demand from Onshore Power Supply.
- Renewables scenario: integration of on-site renewable generation without OPS.
- Combined scenario: simultaneous deployment of OPS and renewable generation, including optimisation of resource allocation.

These scenarios allow for a consistent comparison of different energy transition pathways within the port.
The overall energy balance of the system is illustrated in Figure *1*, where the contribution of different energy sources and the distribution of consumption (with and without OPS) can be observed. The results highlight the dominant role of grid electricity, as well as the relative contribution of renewable generation and the impact of OPS on total demand.



(a)



(b)

Figure 1: Energy balance showing: (a) supply sources and (b) demand distribution.

B. Impact of OPS Deployment on Demand

The incorporation of OPS leads to a significant increase in total electricity demand, as vessels at berth shift from onboard auxiliary engines to shore-based electricity supply. Results show that:

- Total energy consumption increases substantially due to the electrification of maritime operations.
- Peak demand experiences a pronounced rise, driven by the simultaneity of vessel connections.
- The temporal demand profile becomes more variable and strongly dependent on maritime traffic patterns, rather than remaining relatively stable over time.

In particular, the magnitude of the demand increase is directly influenced by the number of available OPS connection points, which determines how many vessels can be simultaneously electrified.

As illustrated in Figure *2*, the demand profile under OPS conditions exhibits higher variability and sharper fluctuations compared to the baseline case.

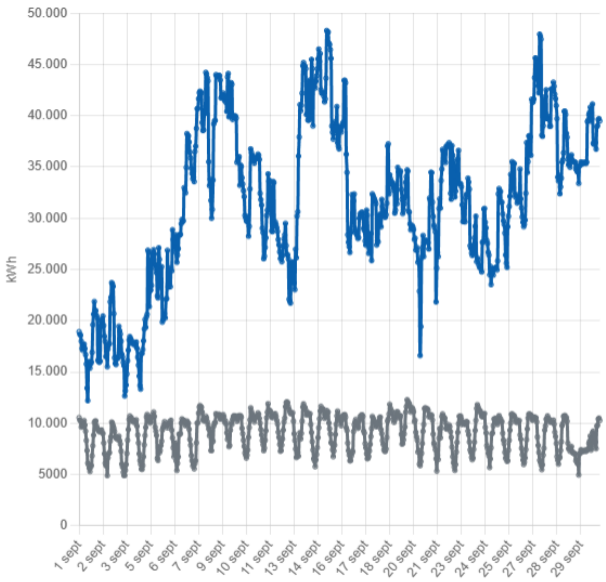


Figure 2: Comparison of baseline electricity demand (grey) and OPS-driven demand (blue).

These fluctuations are closely linked to vessel arrival and departure dynamics, indicating that port electricity demand becomes traffic-driven rather than following a smooth or predictable pattern.

This behaviour reinforces the importance of incorporating operational constraints - such as the limited number of OPS supply points - into demand modelling, as well as the need for flexible energy management strategies to accommodate demand variability.

C. Renewable Generation Contribution

The integration of renewable generation enables partial coverage of the increased demand, reducing reliance on grid electricity.

The results indicate that:

- Photovoltaic generation provides a stable contribution during daylight hours, aligning partially with demand.
- Wind generation introduces additional variability but contributes significantly during specific periods.
- Wave energy offers complementary generation patterns, enhancing overall system diversity.

The combination of different renewable technologies improves the overall renewable share and reduces energy imports from the grid.

D. Economic and Environmental Performance

The techno-economic evaluation shows that:

- The integration of renewables reduces total energy costs, particularly under high electricity price periods.
- The optimisation model enables cost-efficient scheduling by prioritising renewable usage and shifting energy consumption.
- Significant reductions in CO_2 emissions are achieved in scenarios including renewable generation and OPS.

The combined scenario demonstrates the best overall performance, balancing cost savings, emission reductions, and energy efficiency.

E. Optimisation Results

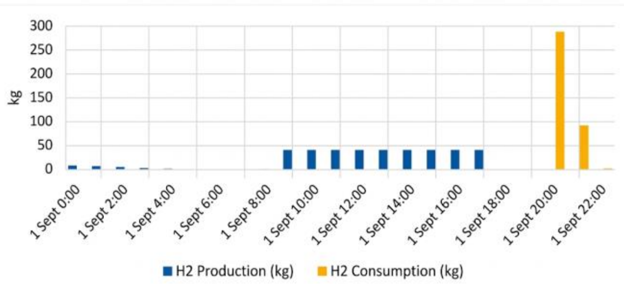
The day-ahead optimisation model enables dynamic coordination between renewable generation, grid imports, and hydrogen production.

Key observations include:

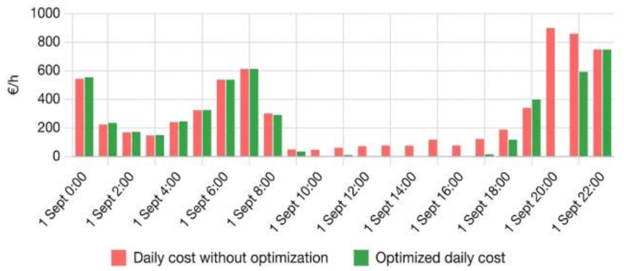
- Surplus renewable energy is effectively utilised for hydrogen production, reducing curtailment.
- Hydrogen storage allows temporal shifting of energy, improving system flexibility.
- Grid dependency is reduced during periods of high renewable availability.

The optimisation framework enhances system performance by integrating flexibility mechanisms and enabling more efficient energy management.

As shown in Figure *3*, the optimisation framework leads to a significant reduction in daily operational costs, demonstrating the economic potential of coordinated energy management in port environments. The optimised schedule prioritises energy usage during low-price periods and leverages hydrogen production and consumption to balance the system.



(a)



(b)

Figure 3: Optimisation results: (a) Hydrogen operation and (b) Daily cost comparison.

4. Conclusions

This work presents a methodology for forecasting and managing port electricity demand, including OPS deployment, together with renewable generation estimation and a day-ahead optimisation framework for intelligent energy management.

The results demonstrate that the electrification of port operations through OPS significantly increases total demand and introduces higher variability, making electricity consumption strongly dependent on maritime traffic patterns. This highlights the importance of combining demand forecasting with operational planning capabilities.

The integration of renewable generation contributes to reducing grid dependency and emissions, while introducing additional variability that requires coordinated management. In this context, the proposed optimisation approach enables a more efficient allocation of energy resources, reducing operational costs and improving the utilisation of renewable energy.

The case study shows that combining forecasting, optimisation, and hydrogen-based flexibility allows for a more adaptive and resilient energy system, capable of responding to both demand fluctuations and market conditions.

Finally, the implementation of the methodology as a decision-support tool enables more intelligent, efficient, and sustainable operation of port energy systems, supporting the transition towards integrated low-carbon energy hubs.

Acknowledgement

This work is part of the GENEPORT project, Idea I-4.43, with public funding received from the "Puertos 4.0" Fund of Puertos del Estado (Spain). Research support has been received from the research support plan of the Instituto de Automática e Informática Industrial ai2, Universitat Politècnica de València.

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