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BRIEFING NOTE

Predicting Optimal Grid Stability and Welfare in Onshore Power Supply (OPS)

Source:

Ennis, S., Mammassis, C., Markellos, R., & Wood, G. (2026). Predicting optimal grid stability and welfare in onshore power supply (OPS). *Journal of the Operational Research Society*, 1–19.

<https://doi.org/10.1080/01605682.2026.2691129>

Keywords:

onshore power supply (OPS)
multi-objective optimisation
predictive modelling
grid stability
electricity markets
maritime regulation
decarbonisation
energy regulation
sustainability

Executive Summary

This paper examines the **operational and economic challenges** of implementing **Onshore Power Supply (OPS)** for berthed ships, highlighting the limitations of current market designs that rely on port authorities as intermediaries. Existing structures often lead to **monopoly pricing**, information asymmetries, and heightened risks of **grid instability** and blackouts, particularly in distribution networks with constrained capacity and small to medium-sized port towns. To resolve these coordination and financial hurdles, the authors propose a novel **Extension-to-Grid market design** where the electricity network operator assumes direct responsibility for infrastructure coordination. This regulated approach successfully balances **system welfare**, consumer protection, and technical stability by aligning price signals with actual network capacity and reserve management.

Key points

The decarbonization of maritime transport through Onshore Power Supply (OPS)—also known as Cold Ironing (CI) or Alternative Maritime Power (AMP)—represents a critical regulatory imperative and a complex market design challenge. By allowing berthed vessels to turn off auxiliary diesel engines and connect directly to the terrestrial electricity grid, OPS eliminates local air pollution, noise, and greenhouse gas emissions in port communities. However, as international mandates transition OPS from voluntary pilot programs to mandatory large-scale infrastructure, severe market and operational coordination failures are emerging. This briefing document synthesizes key insights from operational research by Ennis, Mammassis, Markellos, and Wood (2026), published in the *Journal of the Operational Research Society*. The authors demonstrate that existing market designs—predominantly controlled by port authorities—suffer from potential structural limitations:

- **Market Power and Monopoly Pricing:** Port-led "Intermediary" models expose shipowners to extreme pricing markups once onboard self-generation is legally restricted, threatening overall OPS adoption.
- **Grid Instability:** "Facilitator" models allow direct contracting between ships and electricity suppliers but fail to coordinate discrete, massive load surges with Distribution System Operators (DSOs), risking severe frequency deviations, brownouts, and blackouts.
- **Price-Based Control vs. Operational Coordination:** Mathematical modeling using swing-equation dynamics proves that relying solely on dynamic price signals to manage network stability imposes massive economic penalties on shipowners (increasing costs by up to 26 times). In contrast, institutional market design innovations that achieve high-quality operational communication ($CQ \rightarrow 1$) eliminate stability risks without distorting energy prices. To resolve these failures, the authors propose a novel **"Extension-to-Grid"** market design. Under this framework, OPS shore-side infrastructure is integrated directly into the regulated electricity grid under the oversight of the DSO. Competing energy suppliers contract directly with vessels for energy delivery, while the DSO manages connection logistics, capacity planning, and reserve coordination within its Regulated Asset Base (RAB). Real-world application of this model in Greece—specifically for the strategic ports of Igoumenitsa and Rafina—illustrates how the "Extension-to-Grid" approach unlocks diversified EU funding, protects shipowners from monopoly rents, and guarantees power network resilience.

Background and Regulatory Requirements

OPS technology allows ships at berth to replace auxiliary diesel generation with grid electricity. While the environmental benefits to coastal populations are substantial, the transition requires massive capital outlays and complex institutional alignment across shipping lines, port authorities, energy suppliers, DSOs, and regulators.

Regulatory Driving Forces

- **European Union "Fit for 55" Framework:** The EU aims for climate neutrality by 2050, enforcing strict intermediate compliance deadlines starting in 2025 and 2030.
- **FuelEU Maritime Regulation (EU 2023/1805):** Mandates that container and passenger vessels of 5,000 gross tonnage (GT) or greater connect to OPS while berthed in EU ports by 2030. Crucially, it penalizes unnecessary onboard diesel self-generation.
- **Alternative Fuels Infrastructure Regulation (AFIR, EU 2023/1804):** Requires TEN-T (Trans-European Transport Network) core and comprehensive ports exceeding specific annual port-call thresholds (>100 calls for cargo; >40 for Ro-Ro/high-speed; >25 for cruise) to supply shore-side power covering at least 90% of those calls by December 31, 2029.
- **Global Adoption Leadership:** California pioneered mandatory shore power via the California Air Resources Board (CARB) 2020 At Berth Regulation, mandating 80% fleet visit compliance. Similar imperatives face port cities across the Asia-Pacific and North America.

Financial and Demographics Scale

- **Population Impact:** Nearly 206 million EU citizens live across 378 coastal regions, with 40% of the population residing within 50 kilometers of the coast.
- **Alternative Fuels Infrastructure Expenditures:** Estimated at €9.9 billion across the EU between 2025 and 2050.

- **Port Infrastructure Upgrades:** Broader port layout and grid integration costs are projected to reach €80 billion by 2034.
- **Fleet Retrofit Capital Costs:** Shipowners face an estimated €25.8 billion in capital expenditures to retrofit existing fleets or build compliant vessels.

Structural Challenges in Conventional OPS Deployment

The transition from voluntary, small-scale shore power to mandatory, high-volume operations introduces severe technical, economic, and operational bottlenecks:

1. Grid Capacity Peripheral Weakness

Port infrastructure is historically situated at the geographic and topological periphery of electricity distribution networks. While historical port demand was modest, OPS demands massive capacity additions:

- Large ports require indicative connection capacities exceeding 100 MW.
- Medium ports require 10 to 40 MW.
- Small and island ports require 5 to 10 MW. Upstream investments in substations, distribution lines, and transmission connections lie outside the physical and contractual remit of port authorities, creating a severe disconnect between investment responsibility and network impact.

2. Power Quality and Asset Degradation

Shore-side energy transfer relies on high-capacity frequency converters (typically 1 to 20 MVA) and complex switching equipment. These systems introduce power quality risks, including harmonic distortion, switching transients, and common-mode currents. Inadequate grounding between vessel hulls and terrestrial networks accelerates galvanic corrosion, shortening the operational lifespan of both port and grid assets.

3. Peak Capacity vs. Utilisation Mismatch

OPS infrastructure must be engineered to satisfy maximum instantaneous peak demand. However, vessel usage is highly intermittent (e.g., cruise ships berthed less than 14 hours per day). This yields low load factors paired with high standing and fixed capacity charges, driving up the average cost per unit of energy delivered per kWh.

4. Information Asymmetries and Planning Gaps

DSOs currently lack granular, real-time data regarding vessel arrival schedules, power demand curves, and connection durations. Ports and shipping lines hold this operational information but lack formal mechanisms to feed it into active grid balancing and network expansion planning.

5. Discrete Demand Shocks and Blackout Vulnerabilities

Vessel connections introduce sudden, lumpy step-changes in electricity load. In large, well-meshed mainland grids, these shocks are easily absorbed. In smaller, isolated, or island networks, a single cruise ship connection can double the local baseline load. Without coordinated reserve dispatch, discrete connections trigger severe frequency drops, brownouts, or total system blackouts.

- **Economic Cost of Outages:** A simulation study by Wing et al. (2025) demonstrates that a single-day blackout in Illinois results in a \$1.8 billion (1.3%) quarterly GDP loss, rising to \$15.2 billion (10.4%) for a 14-day blackout, with 88% of damages caused by supply chain disruptions and production halts. Real-world data from the April 2025 Iberian blackout revealed direct economic damages of €0.4 billion to €1.6 billion in Spain alone.

Critical Evaluation of Existing OPS Market Archetypes

Prior market implementations—classified by Ennis et al. (2026)—fall into three primary archetypes, all of which position the port authority as the primary operational or commercial intermediary.

ARCHETYPES

1. STANDARD INTERMEDIARY

- Asset Owner/Operator: Port Authority
- Pricing Discretion: Port sets markups & energy prices
- Grid Upgrade Bearer: External (DSO)
- Flaw: High risk of monopoly pricing; no grid balancing coordination

2. ACTIVE INTERMEDIARY

- Asset Owner/Operator: Port Authority / Local Microgrid
- Pricing Discretion: Connection fees & maintenance charges
- Grid Upgrade Bearer: Port Authority or External (DSO)
- Flaw: High capital burden on port; shared but limited balancing capacity

3. FACILITATOR

- Asset Owner/Operator: Port Authority or Ship
- Pricing Discretion: Ships contract directly with competitive suppliers
- Grid Upgrade Bearer: Port Authority or Ship
- Flaw: Protects pricing efficiency but ignores real-time grid stability

Market Power and Price Exploitation Risk

Under EU Regulation 2023/1805, ships face severe penalties for non-compliance if they fail to connect to available OPS, set at 1.5 times the ship's total auxiliary power demand multiplied by hours at berth, supplemented by EU Emissions Trading System (ETS) carbon penalties (€80–€100 per tonne). With onboard self-generation effectively outlawed, vessel demand for shore power becomes highly inelastic—especially for cruise ships that cannot easily reduce passenger energy consumption or install space-consuming battery storage.

- **Monopoly Rent Extraction:** Private or revenue-maximizing port authorities acting as sole electricity intermediaries can exploit this inelasticity. Simulations indicate that as demand elasticity shifts from moderate (cargo/container vessels, -0.75 to -1.01) to highly inelastic (cruise ships, -0.07 to -0.33), port monopoly markups can push final electricity charges up to 20 times the actual marginal cost of power.
- **Empirical European Price Disparities (March 2024 Data):**
- **Bergen (Public):** €0.52 per kWh plus €881.03 per call (compared to average Norwegian industrial electricity rates of €0.0515 per kWh).
- **Marseilles (Public):** €1.02 per kWh.
- **Kiel (Public):** €0.52 per kWh plus €29.00 connection fee.
- **Cuxhaven (Private):** €0.41 per kWh.
- **Kristiansand (Private):** €0.32 per kWh plus €461.55–€1,075.51 connection/disconnection fee.
- **Stockholm (Public):** €0.17 per kWh plus daily usage fees.
- **Gothenburg (Public):** €0.13 per kWh.
- **Antwerp (Public):** €0.27 per kWh.

Multi-Objective Optimisation: Analytical Framework and Findings

The paper formalizes OPS market design as a multi-objective optimization problem linking social welfare, consumer pricing, and grid frequency dynamics.

1. Frequency Dynamics and the Swing Equation

Network frequency stability following a discrete vessel connection is modelled using a rotational swing equation modified to incorporate Communication Quality

2. Relative Demand Shock

The vulnerability of a grid depends on the relative demand shock ratio: $\phi = \frac{d_s}{d_o}$

3. Inefficiency of Price-Based Control (Proposition 1)

If a regulator attempts to maintain stability purely through price signals—forcing ships to internalize the societal frequency instability cost (γ)—the social welfare maximization function yields the optimal risk-adjusted prices for **Linear Demand, Constant Elasticity (CES) Demand, and Exponential Demand**. Pricing out frequency risk forces vessel tariffs to rise potentially far above marginal generation costs. Numerical parameterization reveals that managing stability via price penalties in constrained grids could increase ship electricity charges by up to **26.6 times** standard industrial rates. This severely suppresses legitimate demand and destroys social welfare.

4. Dominance of Information Coordination (Propositions 2 & 3)

To prevent blackouts through operational coordination rather than punitive pricing, Communication Quality must be good enough to prevent reaching the maximum allowable frequency deviation threshold before triggering automatic load-shedding or blackouts (e.g., 1.0 Hz in European synchronous zones).

- **Proposition 2 Outcome:** When relative demand is large, the quality of communications must approach its maximum of 1 (perfect, real-time data sharing and automated pre-approval between vessel, port, and DSO) to prevent blackouts without requiring excessively wasteful standby reserves.
- **Proposition 3 Outcome:** Market design innovations that achieve maximal communication quality strictly dominate price-based mechanisms. Structural coordination eliminates blackout risks at zero marginal distortion cost, delivering maximum social welfare and protecting consumer pricing.

The "Extension-to-Grid" Market Design

To solve the dual failure of monopoly pricing (Intermediary models) and grid instability (Facilitator models), Ennis et al. propose the **"Extension-to-Grid"** market framework.

Under Extension-to-Grid, the electricity distributor treats shore-side power as an extension of the regulated network. It contracts for, finances and oversees the port's OPS facilities, and competing suppliers sell the electricity directly to ships through the grid.

Distributor and regulator. The distributor brings the OPS investment into the regulated asset base, which gives it regulated, transparent cost recovery. It owns the connection point and handles coordination: real-time data, pre-approval of ship connections and reserve activation, so that communication quality approaches its ideal value. It is responsible only for regulated network access, system coordination and network charges. It does not set the price of the electricity. A distributor can fund and operate this role because it already has the authority and capital to adjust networks.

Competing suppliers. Suppliers contract directly with shipowners and can offer spot prices or longer-term contracts such as PPAs and CfDs, so the price comes from competition.

Port authority. The port returns to its core landlord and berth role. It no longer resells electricity, which removes its power to add a monopoly markup. This matters because FuelEU Maritime removes ships' self-generation option, which makes their demand more inelastic. The model also helps small and island ports, which often lack the capital to build OPS themselves.

Shipowners. Ships pay cost-reflective tariffs set by competing suppliers and connect with pre-coordinated, non-disruptive grid access. This avoids the pricing risk the paper models. It estimates port-run charges of 10–20 times energy cost or more for cruise ships, and stability-risk pricing up to 26.6 times industrial cost.

Consequences. Better coordination lowers the risk of frequency deviations, brownouts and blackouts, especially where one ship can match or exceed local load, as in island ports. HEDNO's analysis of Igoumenitsa found local demand could double from 10 MW to 20 MW when large ships connect, and it showed that out-of-port upgrades were needed. The paper finds that this design needs no extra investment or operating cost compared with the intermediary or facilitator models, only a different organisational structure. Welfare is higher than under price-based stability control because near-perfect communication avoids the demand distortions that high prices cause.

Core Features of Extension-to-Grid

1. **DSO Infrastructure Ownership and Financing:** OPS shore-side equipment (transformers, frequency converters, cable management systems) is categorized as an extension of the public distribution network. Capital expenditures are incorporated into the DSO's Regulated Asset Base (RAB), leveraging the DSO's superior credit ratings, low capital costs, and long-term utility cost-recovery mechanisms.
2. **Direct Energy Supplier Competition:** Port authorities are completely removed from the electricity reselling chain. Energy suppliers compete directly to sell power to berthed vessels via standardized network access, enabling long-term Power Purchase Agreements (PPAs) or Contracts for Difference (CfDs).
3. **Built-in Operational Coordination (CQ = 1):** Because the DSO directly controls the physical OPS terminal, vessel connection schedules are fully integrated into real-time network dispatching, reserve management, and upstream capacity planning.
4. **Resolution of Off-Port Investment Gaps:** Upstream substation construction and grid line reinforcements are executed seamlessly by the DSO under unified regulatory oversight, eliminating disputes over off-port cost allocation.

Research Impact Case Study: Implementation in Greece

Greece serves as a primary, real-world testing ground for the Extension-to-Grid model due to its high maritime intensity, extensive island network, fragile coastal grids, and heavy cruise traffic (over 7 million cruise passengers across 5,000 annual ship calls).

National Scope and Requirements

- **Regulatory Scale:** Under EU AFIR and FuelEU Maritime rules, at least 19 Greek ports must install operational OPS systems. More are expected to do so.
- **National Power Capacity Need:** Hellenic Electricity Distribution Network Operator (HEDNO)—the sole Greek DSO—estimates a required nation-wide OPS demand of

350 MVA by 2030 (installed nominal capacity of 420 MVA in baseline scenarios, with higher estimates ranging up to 622–801 MVA).

- **Capital Outlay:** Estimated at €250 million for port-side OPS equipment plus €75 million for initial grid reinforcements.

Port-Specific Live Case Projects

- **Port of Igoumenitsa:** A primary gateway to Western Europe.
- *DSO Grid Investment:* HEDNO committed €3.0 million for a new dedicated substation and €1.5 million for a 4.5 km medium-voltage distribution line.
- *OPS Terminal Deployment:* Project budget of €8.9 million (85% co-financed by the EU Connecting Europe Facility - CEF) installing two 3 MVA positions, one 0.5 MVA position, and Front-End Engineering Design (FEED) for cruise berths.
- **Port of Rafina:** A vital hub connecting mainland Attica to the Cyclades islands.
- *OPS Terminal Deployment:* Budget of €9.7 million (CEF-funded) to construct four 1.5 MVA positions starting in 2027.
- **Additional Greek Sites:** FEED studies are underway, at time of writing, for the ports of Kavala, Corfu, and Lavrio.

Regulatory and Policy Transition

Despite physical construction progress, Greece currently lacks a comprehensive legislative framework permitting the DSO to own and operate assets within semi-autonomous or privately operated port domains, or to automatically integrate port-side OPS assets into its RAB. Research by Ennis et al. is actively informing draft Greek national legislators to establish an Extension-to-Grid regulatory framework, providing a blueprint for European distribution system operators through E.DSO (representing 38 leading European DSOs).

Strategic Implications and Policy Recommendations

The synthesis of operational research modelling and real-world deployment data yields distinct policy recommendations for key sector stakeholders:

For Regulators and Policy Makers

- **Move Beyond Subsidies:** Mandates and capital subsidies alone cannot guarantee successful port electrification. Market design is the primary determinant of long-term affordability and grid stability.
- **Enact Legal Grid Extensions:** Update national energy frameworks to grant DSOs the legal right to construct, own, and operate OPS infrastructure inside port boundaries as regulated grid extensions.
- **Cap Monopoly Markups:** Eliminate port authority electricity reselling rights, enforcing Article 6.6 of Regulation (EU) 2017/352 to ensure unbundled, competitive energy supply to vessels.

For Distribution System Operators (DSOs)

- **Treat OPS as Complex Discrete Demand:** Recognize that OPS loads cannot be treated as ordinary industrial connections, particularly in peripheral or island networks where relative demand shocks are high.
- **Standardize Operational Data Protocol (CQ → 1):** Establish hardwired, real-time data connections and automated pre-approval procedures with shipping lines and port schedules prior to vessel plug-in.

For Port Authorities

- **Divest Energy Reselling:** Relinquish roles as electricity intermediaries to avoid severe reputational risks, pricing litigation with shipping lines, and capital investment burdens.
- **Focus on Core Landlord Functions:** Retain focus on berth management, physical land access, and maritime traffic coordination while leaving energy balancing and grid investment to regulated utility actors.

For Shipping Companies

- **Demand Transparent Tariffs:** Insist on direct contracting options with competitive electricity suppliers backed by regulated grid access rates, avoiding opaque, port-imposed energy markups.
- **Engage in Long-Term Energy Contracting:** Leverage competitive supplier access under the Extension-to-Grid model to enter into long-term PPAs or fixed-rate energy contracts, mitigating shore-side price volatility.

Briefing note prepared with help of NotebookLM