TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue Special I, February, 2026

A THEMATIC REVIEW OF ONSHORE POWER SUPPLY CHALLENGES

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Abstract: *The introduction of Onshore Power Supply (OPS) to ports is crucial to decrease greenhouse gas emissions from ships and push forward the transition to sustainable maritime transport. Despite the Fuel EU Maritime Regulation requires the use of OPS after January 1, 2025, several technological and infrastructural barriers currently prevent the broad implementation. This study employs a two-step mixed-methods approach, combining systematic literature review and qualitative data analysis to identify and analyse the key challenges associated with OPS application. PRISMA methodology was used to select relevant publications, which were then analysed using thematic coding in the Computer-Assisted Qualitative Data Analysis Software (CAQDAS) ATLAS.ti, enabling a structured synthesis of insights. The results highlight a number of critical obstacles, including technical compatibility limitations, grid capacity issues, and a lack of standardization and technical regulations, which are mostly caused by unclear implementation frameworks. These findings are presented through thematic maps and critically interpreted to offer actionable insights for policymakers, port authorities, and industry stakeholders, in order tp support the strategic planning of sustainable port electrification initiatives.*

Key words: *Onshore Power Supply;* Greenhouse *gas emissions; Sustainable maritime transport.*

1. INTRODUCTION

The shipping industry has a significant impact on global trade, with over 80% of the volume of goods transported by sea [1], but contributes to greenhouse gas (GHG) emissions, particularly when ships are in ports and use auxiliary engines to fulfill their energy needs.

Decarbonization during port operations can be achieved by using Onshore Power Supply (OPS), also known as Alternative Maritime Power (AMP), Cold Ironing, or Shore Side Electricity.

To reduce the environmental impact of ship traffic in ports, the World Port Climate Initiative suggests the use of Onshore Power Supply.

This system permits ships at the berth to shut down their auxiliary engines and obtain power from the local electricity grid, contributing to reducing emissions of pollutants and noise [2].

According to existent studies [3], energy mix produces roughly 50% less carbon dioxide than diesel engines [3]. Coal-fired power plants emit less nitrogen oxides, particulate matter, and sulphur oxides compared to diesel engines, particularly those with higher sulphur content. In addition, because ports are typically located in urban areas, ships at berth frequently release emissions into city centres [3]. Moreover, the stationary power sources, like power plants, are usually located far away from residential areas. In this context, the air quality and health issues are the main reasons why ports must install OPS systems [4],[5],[6].

The European Commission has been analysing this issue for a long period of time [3] and recommended that EU Member States shall install shore-side electricity, especially in ports where air quality limits and noise pollution level are exceeding regulatory limits presenting public concern. As a result, these recommendations contributed to the adoption of the FuelEU Maritime Regulation. Consequently, ships over 5,000 gross tonnage are required to utilize OPS in EU ports from January 2025 onwards [7].

To improve the technical performance and to align with the European Commission's strategies for green ports, several port administrations are implementing infrastructure upgrade projects. For example, Romania is undertaking a project to upgrade the electricity distribution infrastructure at 10 berths in the Port of Constanta, enhancing the economic efficiency of electricity use.

Despite its potential benefits and supporting EU regulations, the implementation of OPS varies across regions. There is an advanced adoption in some ports in North America and across parts of Europe, while many other ports are experiencing delays.

Although evidence shows that OPS systems reduce the environmental impact of docked ships and improve crew working conditions by allowing them to utilize shore-based electricity instead of running auxiliary engines, several barriers still exist [8],[9],[10].

Therefore, the implementation of Onshore Power Supply remains in diverse phases of development at different ports.

This discrepancy highlights the need for more thorough investigation to understand the difficulties encountered and the solutions used by the most developed ports, providing insightful information for boosting sustainability in the industry [11],[12].

This study aims to identify and analyse the key technological, infrastructural, and organisational challenges that affect the widespread adoption of OPS systems. Specifically, it seeks to answer the research question: What are the main obstacles preventing the wide-scale adoption of Onshore Power Supply in ports?

For this research, the authors used a mixed-methods approach that involves a critical literature review of recent scientific articles addressing the use of onshore power supply and qualitative research with the aid of ATLAS.ti Computer-Assisted Qualitative Data Analysis Software. The research investigates successful case studies, best practices and challenges across international ports to answer this question.

The reminder of this paper is structured as follows: research methodology presenting the sampling strategy and qualitative data analysis method, research findings on the challenges in Onshore Power Supply system in ports, and finally, discussion and conclusions presented along with limitations and further research.

2. RESEARCH METHODOLOGY

2.1 Data collection

The first phase of the research involved a systematic review of the existing literature. The methodical selection of papers followed the process outlined below in Figure 1, to identify the technological and infrastructural barriers that continue to hinder OPS adoption.

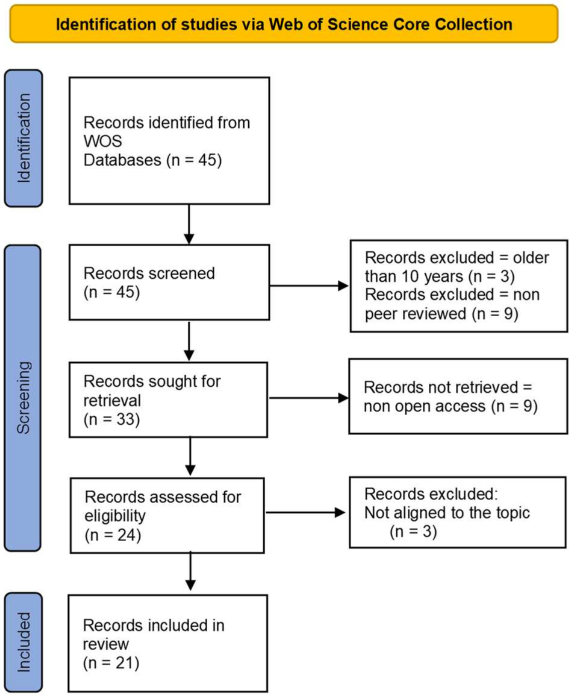

Fig. 1. PRISMA flow diagram for systematic reviews

The PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses method was used for selection of relevant studies. [13].

Table 1

Systematic selection of the publications

Parameter	Content	No
The initial search formula	("cold ironing" OR "onshore power supply") AND ("challenges")	45
Time frame selection	To focus on contemporary research, only publications from the last 10 years were retained.	42
Document type	Only articles and review articles were included in the analysis.	33
Open Access	To ensure accessibility and transparency, open access publications were prioritized.	24
Relevance Assessment	As a result of reviewing the abstracts, 21 publications resulted as relevant for qualitative analysis.	21

2.2 Data preparation

The data preparation phase involved systematically organising the selected corpus of literature for qualitative analysis. Titles, abstracts, and key sections of the 21 peer-reviewed articles, identified through the systematic review, were compiled and imported into ATLAS.ti v25, data analysis software. This process facilitated structured data management and ensured the traceability of all coding and analytical steps.

2.3 Analysis and interpretation

The qualitative analysis employed thematic analysis to identify recurring themes, patterns, and relationships within the selected publications. The coding process was guided by both inductive and deductive approaches [14]. This process allows the authors to identify emergent challenges. Using ATLAS.ti, thematic codes were applied to relevant text segments, and code co-occurrence queries were executed to explore intersections between themes, enabling the identification of both converging and diverging areas of research focus.

3. RESEARCH RESULTS

The results of the thematic coding present several critical factors and barriers to OPS adoption, as summarized in the table 2.

Table 2

Distribution of quotations

Codes	Quotations	%
Shore power	51	14.91
Cold ironing system	18	5.26
Cold ironing technology	106	30.99
Seaports microgrids	37	10.82
Energy storage system	12	3.51
Port operations	31	9.07
Energy management	35	10.23
Costs	52	15.21
Total: 8	**Total: 342**	**100**

The codes were grouped into themes discussed below sections: High installation and maintenance costs; Infrastructure compatibility and technical challenges; Energy security and grid dependency; and Standardization and technical regulations.

3.1 High installation and maintenance costs

The development of Marine Renewable Energy installations, including OPS, is still at an early stage, and ports implementing these technologies face challenges similar to those experienced in offshore wind energy development. Due to high installation and maintenance costs, offshore wind power investment has increased over the last 20 years, but it is still far lower than onshore installations [15]. Similarly, OPS adoption requires large-scale investments in electrical infrastructure, such as ship-to-shore communication, frequency converters, and grid reinforcements [16]. Several studies highlight that the cost of OPS implementation can range from 2 to 6 million $ per port, with expenses varying depending on port size and operational requirements [17]. Additionally, the costs associated with ship-side retrofitting, infrastructure development, and berthing modifications further increase financial burdens on ports [18].

When evaluating cost and system needs, the subsequent cost factors are usually considered the most significant, for both shoreside and onboard installations. The first category includes costs of supplying high-voltage electricity, transformers, switchboards, the possible need for a frequency converter, control panels, as well as the cabling and cable routing. On the other side, the onboard system requires transformers, electrical distribution equipment, switchboards, control panels, and cabling [3].

Nevertheless, there are some associated benefits. The main operational costs and savings of OPS include auxiliary-engine fuel savings, reduced maintenance costs, electricity charges and taxes, and standing charges [3].

3.2 Infrastructure compatibility and technical challenges

A major barrier to OPS adoption is the need for compatible infrastructure between ports and vessels. Ports must integrate OPS with existing shipboard electrical systems, voltage, and frequency requirements, which vary globally [19]. The involvement of multiple heavy loads, such as all-electric ships, cranes, and buildings, complicates the arrangement of shore power facilities and necessitates further research for optimization [20].

Furthermore, various ways of charging the onboard batteries (onshore, onboard and hybrid) in addition to OPS configurations require frequency converters to be installed in different locations compared to other setups, which increases both technical complexity and costs [21],[22]. This lack of standardization in OPS configurations hinders interoperability and necessitates continuous upgrades to port infrastructure [23].

Another challenge is the integration of shore power with port microgrids. Seaport microgrids enable the integration of renewable energy sources into port infrastructure, making OPS more sustainable [19]. It shall be noted that OPS installations that depend solely on grid supply may experience inefficiencies, raising concerns about energy security and power reliability.

Electrical frequency can vary based on the category and size of the ship. Larger ocean-going ships visiting European ports operate in general on 60 Hz electrical systems, while small ships mainly use 50 Hz systems [3].

The frequency requirements for different types of ships and sizes are presented in Table 3.

Table 3

Different electrical frequency requirements [3]

Type of ship	**50Hz [%]**	**60Hz [%]**
Container ship. Length < 140m	63	37
Container ship. Length >140m	6	94
Container ship	26	74
RoRo and car carrier	30	70
Tankers	20	80
Cruise. Length < 200m	36	64
Cruise. Length < 200m	-	100
Cruise	17	83

Currently, systems worldwide are not fully compatible with one another, as they differ in voltage, frequency, and design. This lack of standardization is a result of the varying system frequencies in North America, European countries and Asia [3].

The power requirements of various vessel types and sizes are presented in Table 4.

Power demands influence the expenses of an OPS system, making it essential to explore energy-saving strategies and evaluate peak power requirements beforehand [3].

Table 4

Different power requirements [3]

Type of ship	**Power need [kW]**		
	Average	Peak	Peak for 95% of ships
Container ship. Length < 140m	170	1000	800
Container ship. Length >140m	1200	8000	5000
RoRo and car carrier	1500	2000	4000
Tankers	1400	2700	2500
Cruise. Length < 200m	4100	7300	6700
Cruise. Length < 200m	7500	11000	9500

There are various companies offering frequency conversion solutions for shore power systems, which include integrated container structures, as shown in Figure 2, that can provide power for one or more berths simultaneously through multiple output circuit configurations.

Fig. 2. OPS container solution, ACTEMIUM [24]

In order to supports the transition towards green ports, some containerised units are designed to allow the output to vary depending on the power source, producing lower noise and zero carbon emissions while offering a higher power density in a more compact unit [25]. This type of OPS solution detailed in Figure 3, has been implemented in Jiangsu Province and demonstrated strong reliability and safety. Sharing from experience, the Jiangsu authorities, who leads the energy transition, issued a set of “Guidelines to improve the regulation capacity of the power system”. With this approach they demonstrate how energy storage (batteries), demand-response solutions and grid upgrades support high shares of variable renewables, while ensuring system reliability and cost-effectiveness. [26].

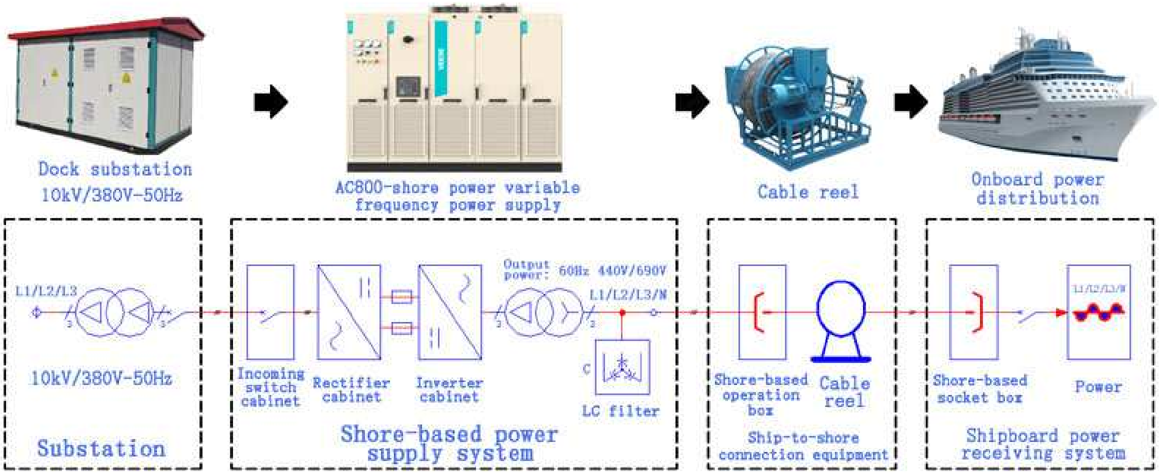

Fig. 3. Frequency conversion solution for OPS, VEICHI [25]

3.3 Energy security and grid dependency

The reliability of OPS is highly dependent on a stable and sufficient energy supply from the grid. If ports rely entirely on external electricity providers, energy efficiency and reliability may be compromised [19]. Research suggests that a combination of shore power and microgrid systems could improve resilience by allowing ports to integrate renewable energy sources [27],[28]. However, this requires additional investments in microgrid optimization and energy storage solutions [38],[19], as well as shore power energy management [29],[30].

Furthermore, ships with electric cargo systems, such as tankers using electric-driven instead of steam-driven cargo systems, exhibit reluctance towards OPS adoption, as these systems require extensive power compatibility checks [31],[32]. This further complicates the technical feasibility of OPS for diverse vessel types [33]. The efficiency of shore power is also influenced by the time ships spend at berth. Since OPS can only be used while vessels are docked, ports need to evaluate operational efficiency and power consumption based on berthing timeframes [28],[31].

3.4 Standardization and technical regulations

The lack of technical standardization presents another significant challenge for the widespread adoption of OPS. Several studies emphasize that technical guidelines, standardized protocols, and regulatory frameworks are essential for ensuring safety and efficiency in OPS operations [2],[34],[35].

The lack of harmonized electrical characteristics between ports and ships, particularly regarding voltage and frequency, is a significant source of difficulty. Because of this unpredictability, the OPS system implementations necessitate the employment of devices like frequency converters and transformers to modify shore-side energy to meet ship requirements.

The IEC/IEEE 80005 series of international standards were designed to address these challenges by providing shore-to-ship power connections for vessels, primarily for high-voltage (HVSC) systems. The standards ensure safety, interoperability, and standardized communication protocols between ships and shore-based electrical systems. The international series of standards address general requirements, data interfaces, and specific applications like cruise and container ships. While IEC/IEEE 80005-2 describes the communication protocols and data interfaces for both low and high voltage shore connection systems, with an emphasis on non-emergency functions, IEC/IEEE 80005-1 describes the basic requirements for HVSC systems, including safety, control, monitoring, and power management. Additionally, the standard has modifications and annexes that address certain types of ships, like container and cruise ships (for example, in IEC/IEEE 80005-1:2019/Amd 2:2023).

In essence, this standard provides a framework for safe, reliable, and interoperable shore-to-ship power connections, promoting the use of shore power and reducing reliance on onboard auxiliary engines, especially for larger vessels and those operating in ports with HVSC infrastructure.

Despite the wide investigation of HVSC technologies, many ports continue to face challenges in determining optimal technical requirements for high-power OPS implementation [36]. Moreover, the quality of electricity supply can significantly impact the performance of OPS, as fluctuations in energy distribution may cause inefficiencies in ship operations [17].

The absence of relevant standards and differences in electrical layouts of grids and ships have led to differences in several aspects, as Table 5.

In addition, automation has the potential to enhance the operational efficiency of OPS, but the degree of automation needs to be evaluated on a case-by-case basis [37].

Table 5

OPS systems in different ports [3]

Port	Country	Voltage		Freq
		High [kV]	**Low [V]**	**[Hz]**
Antwerp	BE	6.6	-	50/60
Goteborg	SE	6.6/10	400	50
Helsingborg	SE	-	400/440	50
Stockholm	SE	-	400/690	50
Piteå	SE	6	-	50
Kemi	FI	6.6	-	50
Oulu	FI	6.6	-	50
Kotka	FI	6.6	-	50
Lübeck	GE	6.6	-	50
Zeebrugge	BE	6.6	-	50
Los Angeles	USA	6.6/11	-	60
Long Beach	USA	6.6	480	
San Francisco	USA	6.6/11	-	60
San Diego	USA	6.6/11	-	60
Seatlle	USA	6.6/11	-	60
Juneau	USA	6.6/11	-	60
Pittsburg	USA	-	440	-
Vancouver	Canada	-	-	-
Oslo	NO	6.6	-	50
Rotterdam	NL	6.6	-	50

Figure 4 presents the thematic map generated using the ATLAS.ti software for qualitative coding, synthesising the coded evidence into themes, showing the key challenges in OPS implementation.

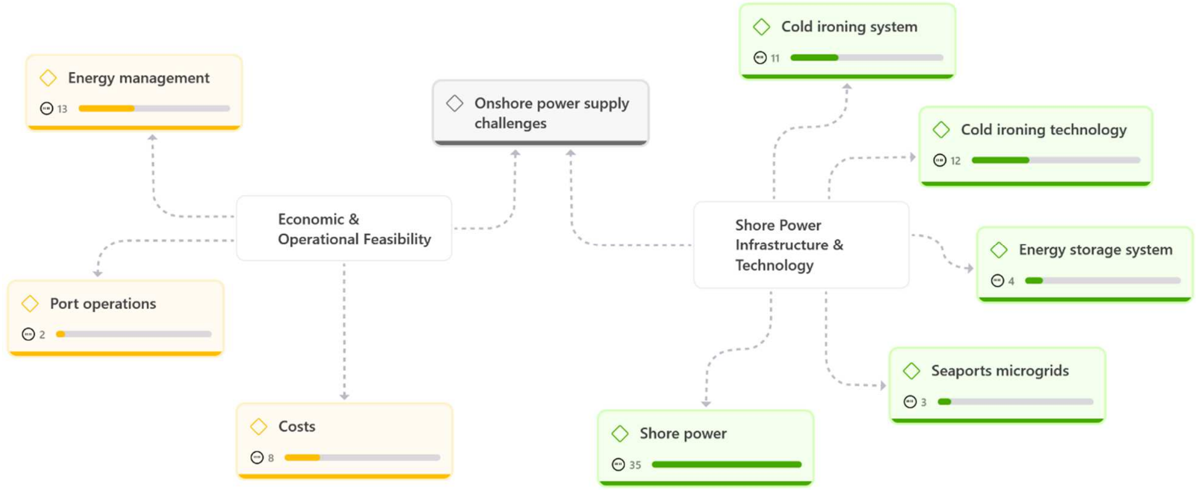

Fig. 4. Thematic map of OPS challenges, Visuals with ATLAS.ti

Two overarching thematic clusters are evident: Economic & Operational Feasibility and Shore Power Infrastructure & Technology. The numbers next to each subtheme represent the frequency of coded segments across the analysed literature, indicating the relative emphasis placed by researchers on each topic. Among these, Shore power (35 coded segments) emerged as the most discussed theme, followed by Energy management (13) and Cold ironing technology (12), highlighting their central role in OPS implementation challenges. Although some nodes such as Port operations (2) and Seaports microgrids (3) appeared less frequently, their inclusion reflects emerging issues that may warrant increased attention in future research and practice.

4. DISCUSSIONS

This study identified the key challenges that affect the widespread adoption of Onshore Power Supply (OPS) systems in ports, highlighting the technical, infrastructural and regulatory factors.

One of the primary barriers revealed by the analysis is the high costs associated with OPS infrastructure development, including grid reinforcements, frequency converters, and ship retrofitting. Moreover, the variation in electrical requirements between ports and vessels, especially in terms of voltage and frequency, underscores the need for harmonised technical solutions. While there is a standard series that offers a framework for high-voltage shore connection systems, its application is still limited, and many ports struggle with defining optimal technical configurations.

Another key finding is related to dependence of OPS on local grid capacity and energy security. Those ports that rely solely on external electricity providers face vulnerability to supply fluctuations, which affect OPS efficiency.

Despite the FuelEU Maritime Regulation mandating OPS use from 2025, the lack of consistent enforcement mechanisms generates resistance among key actors, particularly shipowners who must invest in onboard modifications.

The literature offers useful technical and economic evaluations, but it frequently lacks comprehensive cost-benefit models that take operational, social, and environmental variables into consideration. The research showed that multi-criteria guidance or frameworks that can assist ports to decide on OPS adoption methods have received little attention. Filling in these gaps would serve realistic implementation strategies. The limitations of this study include the reliance on secondary data and literature, without empirical input from port authorities, shipowners, or regulators.

In Romania, the implementation of OPS technology creates both challenges and opportunities for research and innovation institutes, as well as for companies involved in producing and installing such systems. To align with the European Commission's strategies for green ports and to increase the technical and economic efficiency of electricity use, the Ministry of Transport and Infrastructure has proposed financing the implementation of OPS solutions in TEN-T seaports. These systems are intended to support key port activities such as loading, unloading, heating, lighting, and the operation of technical installations on board ships and at berth, in line with the objectives of the European Green Deal.

5. CONCLUSIONS

This study presents a thematic review of the main challenges facing the adoption of onshore power supply (OPS) systems in ports, combining systematic literature review and qualitative data analysis. Results show four critical domains that influence the feasibility of OPS implementation: High installation and maintenance costs; Infrastructure compatibility and technical challenges; Energy security and grid dependency; and Standardization and technical regulations.

While OPS offers long-term savings in auxiliary engine fuel and maintenance, the upfront costs limit the scalability of OPS implementation across the maritime sector.

In addition, the lack of infrastructure compatibility between port electrical systems and vessels continues to hinder OPS adoption, which highlight the urgent need for harmonised technical solutions and better interoperability between ship and shore systems. OPS implementation requires stable and sufficient energy supplies, and the research emphasize that combining OPS with port microgrids and renewable energy integration can enhance resilience and sustainability.

To support the effective implementation, the study emphasizes the significance of promoting regulatory harmonization, broadening the application of international standards, and creating precise operational guidelines.

It is recommended that manufacturers develop adaptable, modular systems compatible with both low and high voltage outputs (400 V to 11 kV) and dual-frequency operation (50/60 Hz). OPS equipment should also support scalable power demands, from 1 MW to 2x5 MW to enable efficient integration with existing infrastructure. As part of their strategic investment, ports can access external funding sources, as exemplified by the Port of Constanta's initiative to modernise its power distribution infrastructure to accommodate diverse vessel types. Compact, mobile frequency conversion units with multiple output circuits and advanced automation capabilities can maximise berth coverage without the need for extensive fixed installations.

The study concludes that addressing the identified barriers can help to advance the decarbonisation goals outlined in the FuelEU Maritime Regulation, as well as to achieve a decrease in greenhouse gas emissions from berthed ships. Future studies should be directed towards developing multi-criteria decision-making frameworks that can help port authorities and shipowners in implementing specific OPS adoption strategies.

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7. ACKNOWLEDGEMENT

The study is funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor the granting authority can be held responsible for them. Project Number: 101139879.

O analiză tematică a provocărilor legate de alimentarea cu energie electrică de la țărm

Rezumat: Implementarea sistemelor de alimentare cu energie electrică de la țărm (Onshore Power Supply – OPS) în porturi este esențială pentru reducerea emisiilor de gaze cu efect de seră provenite de la navele aflate la cheu și pentru a sprijini tranziția către un transport maritim sustenabil. Deși Regulamentul FuelEU Maritime, care impune utilizarea OPS, a intrat pe deplin în vigoare la 1 ianuarie 2025, diverse bariere tehnologice și de infrastructură continuă să împiedice adoptarea sa pe scară largă. Acest studiu utilizează o abordare mixtă în două etape, combinând o revizuire sistematică a literaturii cu o analiză calitativă a datelor, pentru a identifica și examina principalele provocări asociate implementării OPS. Publicațiile relevante au fost selectate și analizate utilizând codificare tematică în software-ul de analiză calitativă asistată de calculator (CAQDAS) ATLAS.ti, facilitând o sinteză structurată a concluziilor. Rezultatele evidențiază mai multe obstacole critice, inclusiv limitări de compatibilitate tehnică, probleme de capacitate a rețelei electrice, lipsa standardizării și a reglementărilor tehnice – determinată în mare parte de cadrul ambiguu de implementare. Aceste constatări sunt prezentate prin hărți tematice și interpretate critic pentru a oferi informații concrete și utile factorilor de decizie, autorităților portuare și actorilor din industrie, sprijinind planificarea strategică a inițiativelor de electrificare durabilă a porturilor.

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