

Enhancing energy resilience and efficiency in port energy systems: An integrated framework for resilience assessment

Frans Libertson

`frans.libertson@chalmers.se`

Chalmers University of Technology <https://orcid.org/0000-0003-3872-8374>

Research Article

Keywords: Energy resilience, Energy Efficiency, Indicators, Metrics, Port energy systems, Energy hubs

Posted Date: September 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11137962/v1>

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Additional Declarations: The authors declare no competing interests.

Abstract

Maritime ports are increasingly conceptualized as energy hubs, i.e., interfaces between diverse energy infrastructures capable of producing, converting, storing, and consuming energy. However, this transformation merges two critical infrastructures, maritime transportation and energy systems, thereby amplifying exposure to systemic shocks and cross-system disruptions. Strengthening the energy resilience and efficiency of port energy systems is therefore essential. This study defines and validates a comprehensive set of resilience indicators for assessing energy systems in general and port energy systems in particular, making two primary contributions: First, it conceptualizes an Energy Resilience Matrix that organizes 77 resilience indicators across four system layers — Infrastructure, Information, Governance, and Community — and four resilience functions: Plan/Prepare, Absorb, Recover, and Adapt. Second, it incorporates port authority perspectives to evaluate the practical relevance of these indicators for port energy systems. Empirical findings support the strategic utility of both the indicators and the Energy Resilience Matrix as tools for building energy resilience capacity and efficiency. Nevertheless, the research also offers a critical reflection on indicator-based approaches to resilience measurement. Respondents identified challenges in operationalizing certain indicators due to financial and technological constraints. Moreover, an overreliance on quantitative metrics risks producing a technocentric perspective that marginalizes the governance structures and stakeholder communities integral to systemic resilience. These limitations point to the need for future research exploring alternative frameworks better suited to capturing the multidimensional character of energy resilience, alongside the development of financial incentives and robust business cases to ensure the long-term economic viability of resilience interventions.

1. Introduction

This study focuses on the increasing importance of building energy resilience capacity in the energy transition (International Energy Agency, 2022). It explores this topic by examining the role of port energy systems amid the energy transition to conceptualize an energy resilience framework that details indicators for measuring and monitoring energy resilience.

The economic and social roles of maritime ports have undergone significant evolution over the past century in response to changes in their economic and political environments (Kaliszewski, 2018). This evolution is referred to as generational shifts, in which ports have evolved from being solely points of transport to complex, community-centered commercial hubs that integrate the needs of their stakeholders into their operations (Lee & Lam, 2016). Recent literature emphasizes the potential of converting maritime ports into energy hubs (Buonomano et al., 2024; Damman & Steen, 2021; Dirzka et al., 2024; Lind et al., 2023; Prousalidis & D'Agostino, 2023), a concept that reimagines ports as interfaces between various energy infrastructures and as units of energy production, conversion, storage, and consumption (Geidl et al., 2007). Adding this new role to maritime ports constitutes a strategy to both address the substantial contributions of ports to GHG emissions (Damman & Steen, 2021; Hoang et al., 2022; Psaraftis & Zis, 2022) and support the energy transition to a low-carbon society.

However, transforming ports into energy hubs would imply a merger of two major critical infrastructures: *maritime transportation systems* and *energy systems*, each in its own right a cornerstone of modern societies that provide services essential to sustaining productivity, trade, and economic growth (Gasser et al., 2021). Critical infrastructures are commonly characterized by the interconnectedness and interdependence of their facilities, stakeholders, services, and networks (Yeh et al., 2024). This interconnectedness means that disruptions can cascade through supply chains and economies, causing major ramifications across sectors (Nguyen et al., 2022).

Maritime transportation systems constitute complex, organic structures that operate within both national and global socio-economic and political systems (Lee & Lam, 2016). Approximately 80% of global trade by volume and 70% by value travels through ports via maritime transport, which highlights the critical role of harbors in the global economy (UNCTAD, 2021, 2024). As major infrastructural nodes, maritime ports are vulnerable to numerous threats and challenges that may disrupt their operations, such as climate change and extreme weather events (A. H. Becker et al., 2013; Kim et al., 2021; Ng et al., 2018), geopolitical and economic uncertainty (Drobetz et al., 2021; Palaaios et al., 2025), infrastructure and capacity expansion (Nebot et al., 2017; Wan et al., 2025), digitalization and security risks (Brunila et al., 2021; Progoulakis et al., 2023), and decarbonization and alternative fuels (Buonomano et al., 2023; Fadiga et al., 2024).

Concurrently, energy systems are among the most complex and essential forms of critical infrastructures (Gasser et al., 2021). The infrastructure of energy systems is facing new challenges due to rapid changes in the energy sector landscape (Hojčková et al., 2018; Libertson, 2021). These challenges include system shocks resulting from climate change and extreme weather events, the growing share of renewables, the electrification of various sectors, aging infrastructure and underinvestment, and economic buoyancy (IEA, 2024).

Transforming maritime ports into energy hubs thus holds both promises and challenges. On the one hand, reimagining ports as integral parts of the energy system infrastructure may facilitate port decarbonization efforts (Buonomano et al., 2023), increase energy efficiency and reduce emissions in transportation and industrial networks (Damman & Steen, 2021), and support a broader energy transition in society (Dirzka et al., 2024). On the other hand, this strategy would increase exposure to system shocks, introducing the disruptive risks of energy systems to maritime transport systems and vice versa (Ismael, 2024). This will require greater emphasis on resilience and efficiency approaches that strengthen the systems' capacity to withstand sudden shocks and facilitate both immediate recovery and long-term adaptation strategies (Borozan, 2025; Esfahani et al., 2021; Jesse et al., 2019, 2024; Sovacool & Mukherjee, 2011).

This research addresses this gap by identifying, defining, and validating resilience indicators for assessing integrated energy systems in maritime ports. It does so by conceptualizing an Energy Resilience Matrix detailing the indicators and by incorporating port authority perspectives to assess their practical relevance. In so doing, the research provides energy experts, in general, and port authorities, in

particular, with a practical tool for building energy resilience capacity. This is the first research objective of the study (RO1). The second research objective is to explore the utility of indicators as a tool for measuring energy resilience (RO2). Through the indicator conceptualization, the research explores whether all aspects of resilience can be represented in numbers and challenges the prevailing positivist view that everything is quantifiable and measurable (Colvin, 2026). In so doing, the research outlines areas of applicability of resilience indicators and suggests ways forward. The paper is structured as follows: Section 2 outlines the methodological approach, whereas Section 3 presents previous research on energy resilience, port resilience, port electrification, and the integration of the three. Section 4 recounts the results of the port authority interviews, while Section 5 provides a discussion that integrates the results with the Energy Resilience Matrix and the utility of resilience indicators. Section 6 concludes the study by proposing avenues for future research.

2. Methodology

2.1 Research design

This study is developed as a conceptual review, i.e., a review that extends beyond a conventional literature review by not only synthesizing existing research but also creating additional value through the integration of findings into a coherent framework (Gilson & Goldberg, 2015; Jaakkola, 2020). As outlined above, the present study seeks to reconceptualize energy resilience (the domain theory) by incorporating elements from complementary indicators derived from port resilience and electrification research (the method theory). This study's research design comprises two components: resilience indicator development and interviews with port authorities to validate the framework. The indicator development was done in three steps: 1) defining the conceptual framework, 2) data collection through a targeted literature review, and 3) screening and selection of indicators. The interview process consisted of four steps: 1) sample selection, 2) interview design, 3) data collection, and 4) thematic analysis.

2.2 Resilience indicator development

Indicators are commonly organized in a framework that clearly and constructively structures them around the organization's operations (Parmenter, 2020). The framework by Linkov et al. (Linkov et al., 2013) and Roege et al. (Roege et al., 2014) was chosen as a matrix for structuring the indicators for this study. As the goal was to develop semi-quantitative indicators to increase generalizability while also maintaining specificity (Hosseini et al., 2016), this framework was deemed the most suitable. Once the framework was chosen, a literature review was conducted to identify indicators to populate it with. The literature was identified using several search strings and snowball sampling (see Table 1). The initial number of publications was 400, and the final number was 44. See Table 2 for a full outline of the screening stages. The selection criteria constituted scientific articles, conference papers, and review papers in English, with full online availability, and applicability to the energy resilience capabilities outlined in the framework by Linkov et al. (Linkov et al., 2013) and Roege et al. (Roege et al., 2014). The

literature review was conducted in the spring of 2025, and the publications were subsequently screened in the fall of 2025.

Table 1
– List of search strings

Data base	Search string	Filter	Hits
Scopus	electrification AND transport AND (port OR harbor)	ENERGY; SOCIAL SCIENCES	46
Scopus	"energy resilience" AND (assess* OR evaluation OR indicator OR metric)	ENERGY; SOCIAL SCIENCES	160
Scopus	"energy system resilience" AND (indicator OR metric)	-	26
Scopus	kpi AND resilience	ENGINEERING; ENERGY; SOCIAL SCIENCES	65
Scopus	port AND metric AND resilience AND energy	ENERGY; SOCIAL SCIENCES	4
Scopus	"port resilience" AND (strateg* OR measur* OR planning OR assess*)	-	99

Table 2
– Literature review screening stages

Stage	Number	Total
Search	+ 400	400
Duplicates	-45	355
Abstract screening	-245	110
Availability	-2	108
Full screening	-71	37
Snowball	+ 7	44

The indicators were developed by systematically translating each cell of the resilience framework into measurable variables to ensure that each resilience function (plan/prepare, absorb, recover, adapt) and system layer (physical, information, cognitive, social) was operationalized. Each indicator was developed

through one of two approaches: either by adopting and adapting existing metrics identified in the literature, or, where only qualitative resilience variables were available, by formulating new metrics through the specification of explicit formulas, units (e.g., MW, %, time), and data requirements. More specifically, formulating new indicators meant decomposing qualitative resilience concepts (e.g., flexibility, coordination, awareness) into observable system properties, selecting appropriate proxies where direct measurement was not possible, and aligning indicators with existing engineering, operational, and policy metrics.

The current literature on energy resilience metrics struggles to strike the right balance between the general and the specific. On the one hand, it is argued that adequate metrics should be quantifiable, repeatable, and comparable across energy systems (Ahmadi et al., 2021; Jufri et al., 2019). On the other hand, due to varying geographical, technological, social, and economic conditions, as well as the temporal perspective on resilience capacity, the metrics must also be adapted to the context in which they will be used (Roegel et al., 2014). Thus, resilience investments require indicators that are both precise and generalizable (Linkov et al., 2013). In order to strike this balance, this study adopted semi-qualitative metrics to enhance measurability (Hosseini et al., 2016) while maintaining broad applicability across systems, sectors, and disciplines.

2.3 Port authority interviews

The interview sample for this study consisted of relevant port authorities in Scandinavia, primarily in Sweden. The ports were purposefully selected using maximum variation sampling (Patton, 1990) to account for all port governance types, i.e., public service ports, tool ports, landlord ports, and private ports (Notteboom et al., 2026; World Bank, 2025). Within this sample, ports with either planned or ongoing projects aiming to electrify port operations were identified and subsequently contacted. In total, 16 port authorities were contacted, of which eight accepted the invitation (Table 3).

Table 3
List of respondents

Port	Port type	Respondent(s)
Port of Gothenburg	Landlord Port	R1
Copenhagen Malmö Port	Landlord Port	R2
Port of Aalborg	Landlord Port	R3
Port of Trelleborg	Tool Port / Public Service Port	R4
Port of Helsingborg	Landlord Port	R5
Port of Skellefteå	Tool Port / Public Service Port	R6
Port of Stockholm	Public Service Port / Landlord Port	R7
Port of Piteå	Landlord Port	R8, R9

Respondent recruitment, in turn, employed a dual sampling strategy that combined purposive and snowball sampling (Patton, 1990). The selection criteria were designed to ensure that respondents had sufficient domain expertise to meaningfully address energy resilience within the port's overarching strategic objectives. Accordingly, individuals were recruited based on their organizational roles, including positions such as Head of Innovation, Projects Officer, and Business Analyst. The respondents were approached via email/LinkedIn, and the interviews were held between February and March 2026.

Semi-structured interviews were conducted to probe respondents' perceptions of energy resilience capacity-building and elicit comprehensive responses (Kvale & Brinkmann, 2015). The interviews were structured around themes from the framework by Linkov et al. (Linkov et al., 2013) and Roege et al. (Roege et al., 2014). Each cell of the Energy Resilience Matrix was discussed, focusing on the most significant aspects of port energy infrastructure, port information systems, port governance, and the port community before, during, and after disruptive events. The respondents were also asked to reflect on the implications of these aspects for their port operations. Additionally, at the end of the interviews, the respondents were asked to provide feedback on the relevance and definitions of the resilience indicators, as well as the exhaustiveness of the Energy Resilience Matrix. The analytical process was initiated through a comprehensive review of the interview transcripts, during which recurring themes and discursive patterns were identified to illuminate how participants conceptualized energy resilience and how they understood the port's role in fostering resilience capacity. The material was subsequently manually coded in Excel, with thematic sub-labels related to 'Infrastructure', 'Information', 'Governance', and 'Community' applied to structure the analysis.

3. Energy resilience and indicator identification

This section is divided into four subsections, three of which summarize previous research: 3.1 Energy resilience, 3.2 Port resilience, and 3.3 Port electrification, outlining the areas the Energy Resilience Matrix must cover. 3.1 presents the energy resilience concept and the framework of the study. 3.2 outlines previous research on port resilience assessment, whereas 3.3 summarizes research on focus areas in port electrification for building energy resilience capacity. The final subsection, 3.4 Energy Resilience Matrix conceptualization, explains the identification and mapping of indicators onto the energy resilience framework.

3.1 Energy resilience

Despite the popularization of the resilience concept and its application across various fields, beginning in ecology with the pioneering work of Holling (Holling, 1973), no general approach exists (Jesse et al., 2019, 2024). However, energy resilience is commonly conceptualized as a process in which the energy system moves through a set of stages that describe the event, its effects on the system, and the system's ability to respond from pre-crisis to post-crisis levels (Arning & Venghaus, 2024; Gasser et al., 2021; Sharmin & Dhakal, 2022). The International Energy Agency (IEA, 2015) defines energy resilience as "the capacity of the energy system or its components to cope with a hazardous event or trend,

responding in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation.” The definition also encompasses the features of robustness (the ability to withstand shocks), resourcefulness (the ability to remain operational during shocks), and recovery (the ability to restore operation following shocks) (IEA, 2015). In their definition, Gatto and Drago (Gatto & Drago, 2020) broaden the disruption to also include shocks caused by economic, social, environmental, or institutional events.

To date, various frameworks for describing and assessing energy resilience exist. The review by Gasser et al. (Gasser et al., 2021) outlines their commonalities and differences. Commonly, the frameworks are designed around changing system dynamics over time and describe the system behavior throughout the resilience curve, i.e., the ‘draw-down’ and ‘draw-up’ phases. Most frameworks also divide the resilience curve into sets of enabling functions along the timeline (Brauer et al., 2025; Charani Shandiz et al., 2020; Gatto & Drago, 2020; Vugrin et al., 2010), as seen in Fig. 1. Although the labeling of the functions varies, they commonly describe a pre-event phase for proactive and preventive actions, the disruptive event and system functions for absorbing and withstanding the impact, the recovery phase for reestablishing previous system functionality, and a post-event phase for integrating the experience from the event and potentially adapting to new conditions. Since the labels are inconsistently applied and sometimes used interchangeably across resilience frameworks (Gasser et al., 2021), for the sake of clarity, this study will refer to the functions as Plan/prepare, Absorb, Recover, and Adapt. Worthy of note is that many resilience frameworks focus solely on infrastructure operations during disruptions, while neglecting other system functions, in particular, the planning and adaptation phases (Charani Shandiz et al., 2020), hence the significance of a holistic framework.

In response to the fragmented resilience literature that treats management and system performance as separate disciplines, Linkov et al. (Linkov et al., 2013) developed a matrix for resilience metrics that combines the four core functions of a resilient system with four different layers of energy systems: physical, information, cognitive, and social (this study has adapted the framework to a port setting, relabeling the layers infrastructure, information, governance, and community, as seen in Fig. 2). The infrastructure layer refers to physical infrastructure of the system, whereas information refers to data generation, analysis, and storage that informs the system. The governance layer denotes the system's governance structure and decision-making, whereas the community layer concerns the human collaborations and local knowledge that operate the system. Linkov et al. (Linkov et al., 2013) argue that, rather than treating the layers as separate system domains, they must be integrated as complex systems require a holistic approach. For example, if information about the system performance is unavailable, decision-making will be limited. Also, if social capital is lacking, the response coordination will likely be ineffective. The governance and community layers are domains of meaning-making and learning, i.e., where people make sense of system information in order to continue improving the system infrastructure.

The energy resilience matrix by Linkov et al. (Linkov et al., 2013) (and subsequently further developed by Roege et al. (Roege et al., 2014)) was chosen as the study's theoretical framework, as it was deemed the

most all-encompassing resilience framework, and thereby also the most suitable for integrating resilience metrics across disciplines, i.e., port resilience, port electrification, and energy resilience. The framework's equal focus on system performance, management, decision-making, and situational awareness renders it an appropriate tool for developing indicators that promote a holistic approach to building energy resilience capacity.

3.2 Port resilience

The concept of port resilience has evolved from focusing primarily on port infrastructure to also encompass organizational, technological, and environmental aspects, reflecting the growing complexity of modern port ecosystems and the dual roles of ports as both economic hubs and infrastructural nodes in the global economy (Tsoulfas, 2025). Ports are increasingly exposed to potential external shocks, such as climate change, rising sea levels, extreme weather events, fluctuating fuel prices, intermittent electricity production, cybersecurity threats, and economic crises, necessitating the development of resilience capacity (Barbieri & Capoani, 2025; Tang et al., 2025). Port resilience refers to a port's ability to sustain operations and service delivery to ships, cargo, and clients amid disruptions. However, port resilience also extends beyond operational performance; since ports underpin national and regional economies, their ability to recover from disruptions has broad economic and social impacts (Tsoulfas, 2025).

In the wake of the COVID-19 pandemic, Kim et al. (Kim et al., 2021) developed a framework for port resilience grounded in the literature on supply chains and risk management. The authors organize the framework around "three system resilience properties": absorptive capacity, adaptive capacity, and restorative capacity, as outlined by Vugrin et al. (Vugrin et al., 2010). These properties, in turn, are divided into nine resilience factors: robustness, redundancy, visibility, flexibility, collaboration, agility, information sharing, response, and recovery. Thus, the framework places emphasis on building: (i) a stable organizational configuration, (ii) backup of suppliers and resources, (iii) a system for efficiently monitoring port operations sharing the data among port stakeholders, (iv) the agility and speed to react to changes in the port environment, market, and customer demands, as well as fostering (v) cultures of trust among port stakeholders to facilitate (vi) joint decision-making. Kim et al. (Kim et al., 2021) applied the framework to assess the resilience performance of Korean ports, which revealed that the ports scored higher in adaptive and absorptive capabilities, but lower in restorative readiness, highlighting the need to focus on building restorative capability.

Tang et al. (Tang et al., 2025) outlined eight resilience metrics along the preparedness, response, and recovery phases of port resilience, namely reliability, survivability, vulnerability, robustness, redundancy, rapidity, adaptability, and resourcefulness. The results indicate that improvements in technology, advanced diagnostic systems, and redundant equipment are the most promising areas for enhancing port resilience. Similarly, Wang et al. (Wang et al., 2023) reached a comparable conclusion when using six resilience metrics (robustness, redundancy, visibility, flexibility, agility, and recovery) to assess resilience strategies in terms of ports' readiness and response capacities. They found that real-time data

management systems are the most significant for enhancing readiness, whereas strategies for improving technology and facility restoration are the most important for enhancing response.

Regarding information flows, Shaw et al. (Shaw et al., 2017) examined the intricate web of social interdependencies and information needs that underpin contemporary port ecosystems, aiming to understand how information sharing can be best facilitated to enhance resilience planning. The results indicate that information sharing can be orchestrated through a centralized approach applied in a decentralized manner and by engaging stakeholders based on their perceived need for information. Providing stakeholders with timely and relevant information enhances both their individual performance and their cooperation with others, thereby improving port resilience functions such as early warning signs, labor planning, and resource optimization. Conversely, silo thinking and information withholding, whether intentionally due to the commercial or political nature of the information, or unintentionally due to a lack of knowledge or data overload, create obstacles to collaboration in building port resilience capacity. Comparably, the study by González-Solano (González-Solano et al., 2025) concluded that having established Port Community Systems, digital platforms that facilitate and coordinate information flows and port activities across stakeholders, business contingency plans, and crisis management teams are essential to building port resilience capacity. Other important factors include backup data storage capacity, remote access to information, and safeguards against cyberattacks.

With regard to governance and port stakeholders, León-Mateos et al. (León-Mateos et al., 2021) developed a port resilience index that considers stakeholder interests to evaluate operational resilience. The index was developed around five dimensions – governance, society, infrastructure, operational environment, and risk management – each indicating the main impact factors for resilience. Similarly, Zhu et al. (Zhu et al., 2025) applied the ESG framework to assess the effects of ESG policies on port resilience, finding that the social dimension enhances short-term resilience, while the governance dimension is fundamental to improving long-term resilience. Becker and Caldwell (A. Becker & Caldwell, 2015) examined the roles and responsibilities of port stakeholders in implementing resilience strategies and building capacity, as perceived by the stakeholders. The findings indicated that current policies place a majority of the burden for implementation on internal port stakeholders and on state governments, thus suggesting a more holistic approach to spread the burden and costs for building resilience capacity across all stakeholders. Wu et al. (Wu et al., 2025), in turn, found that paramount to enhancing port resilience are improving emergency response mechanisms and providing emergency response training for personnel.

3.3 Port electrification

Electrifying port infrastructure is deemed the most promising strategy for decarbonizing port operations (Klaviņš et al., 2024), as electric energy is regarded as one of the most accessible and promising alternative fuels for the maritime sector (Prousalidis & D'Agostino, 2023). Port electrification may range from a narrow focus on linking electrified maritime transport to the power grid to a broader approach that combines multiple energy carriers, such as electricity, heat, and hydrogen, and accounts for interactions among different end-user groups (Brækken et al., 2025). Port electrification strategies for

building energy resilience capacity can be divided into five focus areas: 1) Renewable Energy Systems (RES) (Kļaviņš et al., 2024; Prousalidis & D'Agostino, 2023), 2) Energy Storage Systems (ESS) (Apostolou, 2025; Cholidis, Sifakis, Chachalis, et al., 2025), 3) Microgrids (Issa et al., 2025; Remoundos et al., 2025), 4) Sectoral couplings (Gabrielii et al., 2025; Remoundos et al., 2025), and 5) Digitalization and Energy Management Systems (EMS) (Apostolou, 2025; Qazi et al., 2023).

3.2.1 Renewable Energy Systems (RES)

At the core of decarbonizing ports is the sourcing of electricity from RES. Exploiting renewable energy sources, such as solar photovoltaics, wind turbines, and hydropower, would allow ports to replace conventional fuels and reduce their GHG emission (Prousalidis & D'Agostino, 2023). This could be achieved either by building, managing, and owning RES placed on the port premises or by sourcing from external production facilities in the vicinity (Cholidis, Sifakis, Chachalis, et al., 2025). Preferably, the energy mix of RESs should include a variety of renewable sources to reduce reliance on a single type of generation and increase resilience (Apostolou, 2025). However, due to the intermittent nature of renewable energy sources, these technologies should be combined with ESS to ensure a stable and resilient electricity supply for port operations (Kļaviņš et al., 2024).

3.2.2 Energy Storage Systems (ESS)

ESS refers to the capacity to store energy locally through battery storage, hydrogen, and Power-to-X (Prousalidis & D'Agostino, 2023). ESSs support the stable integration of renewable energy, enabling storage or reinjection into the main grid and mitigating issues associated with the intermittent nature of RESs (Issa et al., 2025). By integrating RES with ESS, ports will become more self-reliant and thereby also more resilient (Cholidis, Sifakis, Savvakis, et al., 2025). Furthermore, the ability to locally store energy will render the port more flexible in its energy use, as the integration of energy storage systems will facilitate load shifting and balancing, demand-side management, and reduce the need for fossil-fuel-powered backup generators (Apostolou, 2025).

3.2.3 Microgrids

A port microgrid is a localized energy system within a port that manages power generation, distribution, and consumption on a smaller scale than the main grid. Microgrids can operate independently in island mode or be connected to the central grid. Their main aims are to strengthen energy resilience, cut emissions, improve power quality, and reduce operational costs (Issa et al., 2025). Integrating RES and ESS with microgrids would render ports as energy hubs (Cholidis, Sifakis, Chachalis, et al., 2025; Kļaviņš et al., 2024), implying that ports would function as small-scale energy providers or intermediaries between energy providers and end-users, with the capacity to produce, convert, store, and consume electricity locally, as well as to facilitate bidirectional energy flow.

3.2.4 Sectoral couplings

Sector coupling refers to technologies that integrate various sectors and energy systems, enabling surplus renewable electricity to be converted and used in other sectors (Brækken et al., 2025). The level of integration with external energy systems and other sectors is determined by the port's geographical location and local conditions. For example, rural ports may benefit from proximity to renewable energy production, whereas urban and industrial ports may profit from cogeneration and industrial symbioses with adjacent industrial activities. Furthermore, port characteristics, such as position along trade routes and ship segment type, may also serve as enablers or barriers to port electrification. Thus, port location and characteristics should be considered in port strategies for building energy resilience capacity (Gabrielii et al., 2025).

3.2.5 Digitalization and Energy Management Systems (EMS)

Producing, converting, storing, and distributing energy will require real-time communication and information sharing among port units, as well as dynamic management of energy throughput (Qazi et al., 2023), underscoring the need for real-time energy monitoring (Apostolou, 2025). Integrating EMSs would enable ports to monitor and collect data, thereby improving efficiency across all energy-related operations (Issa et al., 2025). However, although digitalization and EMSs facilitate efficient energy control and management in ports, as well as scenario modeling, they also expose ports to cyberattacks, underscoring the significance of cybersecurity, well-trained personnel, and state-of-the-art software protection to enhance energy resilience (Clemente et al., 2023; Tsoulfas, 2025).

3.4 Energy Resilience Matrix conceptualization

Together, sections 3.2 and 3.3 outline important features of port resilience and electrification for a resilient port energy system. The identified features correspond to the system layers of the resilience framework by Linkov et al. (Linkov et al., 2013) and Roege et al. (Roege et al., 2014), thereby outlining a set of subthemes that were subsequently used to identify recommended resilience measures and metrics to develop the indicators and populate the matrix (see Appendix 1 – Energy Resilience Matrix). Each cell in the matrix contains a set of related indicators, totaling 77 indicators for monitoring and measuring energy resilience. The infrastructure layer covers indicators of the physical infrastructure's performance across the resilience curve, whereas the information layer contains indicators for measuring information flow during the same phases. The governance layer comprises indicators to assess systems' governance structures and decision-making throughout the resilience phases, whereas the community layer includes indicators to measure collaboration and local knowledge and skills.

4. Port authority perspectives

This section presents the results from the port authority interviews, which will subsequently be juxtaposed with the energy resilience matrix to validate the indicators in Section 5. The section is structured according to the system components of the Energy Resilience Matrix, i.e., Infrastructure,

Information, Governance, and Port Community. It also includes two subsections on indicator feedback from the port authorities and other energy resilience-related themes that surfaced during the interviews.

4.1 Infrastructure

The Infrastructure component of energy resilience refers to the state and capabilities of equipment and network structures. The port authorities emphasized the significance of installing on-site backup generators to build redundancy and ensure the power supply for vital port functions, such as IT systems, terminal operations, and cranes, in the event of blackouts (R1, R3-9). In the future, the charging infrastructure for port vehicles will likely also be a vital function that has priority (R1-2). Additional energy infrastructure solutions mentioned for building resilience were local microgrids (R3) and ESS (R4). Two port authorities also pointed out the importance of a flexible infrastructure. Not only must the infrastructure be adapted for rapid demand-reduction (R5), but it should also include a variety of flexibility options, such as load-shifting, distributed generation, and grid switching, as electrification entails greater reliance on electricity and thereby increased vulnerability to blackouts (R2).

During disruptive events, the port authorities again stressed the importance of having a functioning backup power supply and generators, as well as a flexible infrastructure that allows for load-shifting and demand reduction (R1-7). However, upgrading from backup generators to on-site RES production may prove difficult for some ports. One port authority reported that, due to the design of its power grid, it has very limited capacity to build on-site RES and is thus completely at the mercy of its distribution system operators for electricity supply:

"You could say that, at least as the power grid is currently set up in our port, it isn't exactly designed with resilience in mind. I think we have at least 30 or 40 different connection points to the public power grid, which means that a backup power supply for our operations is quite extensive" (R2).

This limits the port's ability to become self-reliant and ultimately affects its energy resilience capacity. Large-scale batteries were also mentioned as valuable ESS assets during disruptions (R1, R3), although this would require an operational microgrid, which is currently not possible within the existing infrastructure and regulations for some ports (R3).

Regarding the Recovery phase, several port authorities stated that fully restoring power is beyond their control and the responsibility of their respective energy utility and DSO (R2, R5-6, R8-9). To fully restore their operations, these ports rely on electricity from the main grid. Instead, during this phase, the ports may focus on inspecting and repairing the infrastructure (R5, R7). Thus, having readily available spare parts is important for strengthening energy resilience. This also relates to the Adaptation phase, where three port authorities highlighted the importance of compatible infrastructure that allows old equipment to be replaced with new (R2, R5-6). Although outside current practice, one port authority suggested it would be wise to also maintain a contingency budget for unexpected expenses arising from system shocks that damage port infrastructure and equipment (R2).

4.2 Information

The Information component of energy resilience relates to data preparation, presentation, analysis, sharing, and storage, i.e., EMSs. Equally important to power supply is a stable, safe internet connection—a recurring notion among the port authorities. Investing in such information and communication technology is thus vital (R2). The port authorities deemed securing both external and internal information flows as significant for contingency planning. For example, ensuring a secure flow of information and granular data between the port, its energy utility, and its grid operator is essential for EMSs (R1, R3). Another aspect of external information flows is the integration of systems across different actors. Finding ways to maintain integration even during shocks is thus important (R4), underscoring the importance of a holistic understanding when investing in new information systems (R7-9).

"I suppose it's always difficult, when things are moving so fast, to see the bigger picture. It's easy to jump on board with new systems, but they also tend to become isolated entities in a way. So having that broader perspective is important, too" (R7).

Internal information flows relate to the local administration, logistics, and security systems of ports, which will cause major problems if disrupted (R4-5). Preventative measures may include investing in alternative communication channels should the main channels be disrupted (R6), local backups of business and administrative data (R8-9), keeping physical copies of important protocols, and routines for analog recording of data should the administrative systems be disrupted (R7-9).

During system shocks, receiving regular updates and forecasts from the energy utility about the estimated duration of the disruption is important (R1, R5). Also important is maintaining alternative communication channels with port stakeholders and involved actors (R2, R5, R7). One port authority suggested having a "one point of contact" to ensure a reliable communication channel for port operations (R6). The main information recovery activity involves updating digital administrative systems with information accumulated from manual backlogs (R4, R8-9).

During the Adaptation phase, focus should be on integrating lessons learned from the disruption (R1, R3, R7) and analyzing whether the communication worked and whether all actors received the necessary information (R6). Two port authorities also suggested that there should be an exchange of best practices between ports at both national and global levels (R1, R7).

4.3 Governance

With regard to governance structure and decision-making for energy resilience capacity building, several port authorities stressed the significance of well-established routines and well-defined roles (R4-5, R7-9). Ideally, this should be outlined in readily available physical protocols, and each port stakeholder must be well aware of their role in the organization and the responsibilities that come with it. Regarding the coordination of activities, particularly electricity consumption, one port authority noted that such

coordination is complicated under the current system structures, as each port stakeholder has its own contract with the energy utility. This means that energy utilities retain all consumption data, which puts them in a much better position to coordinate energy consumption demand-response interventions than the port authority (R1). Another port authority pointed out how system structures and current energy regulations hinder them from taking preventative actions, e.g., building a microgrid to increase energy resilience. The port authority requested more flexible regulations that would allow private actors to contribute to the energy transition to a larger extent:

"I think it's quite important to give places with financial capital the possibility to invest in infrastructure. Even though we have many companies with a lot of capital and so on, we are not allowed to make a microgrid or make an energy community. And that regulation would need to be changed if we were to have a role in the improvement" (R3).

During the Absorptive and Recovery phases, several port authorities highlighted different aspects of a flexible organizational structure as important (R2-7). For example, during disruptions, the port authority should be able to act as a crisis response team, coordinating all affected port stakeholders (R5, R7) and serving as the link between authorities, energy utilities, and port stakeholders (R3) through regular meetings and short lines of communication (R6). The organizational structure should enable quick decision-making (R6), e.g., through decentralized governance structures with autonomous units (R2). Other important aspects raised were maintaining routines (R4, R7) and keeping physical copies of protocols readily available should information systems be disrupted (R4, R8-9).

One port authority stressed the importance of maintaining a contingency budget and its significance throughout the resilience phases: a monetary reserve should be established in the Planning phase, which may be used for recovery and adaptive measures in the event of system shocks. The significance of maintaining capital reserves earmarked for security incidents will only grow, as increasing global uncertainties and security risks will render borrowing money more difficult in the future (R2).

4.4 Port Community

The Community component of energy resilience refers to social networks, social capital, institutional norms, and staff training in ports. In this regard, the port authorities emphasized the importance of building strong relationships with both internal and external port stakeholders (R1, R3). Several port authorities reported the need for an established stakeholder forum (R2-3, R5, R7-9), with regular meetings also when there is no ongoing crisis (R7-9).

Another community aspect raised was the value of knowledge and training, such as investing in training to increase the overall knowledge and competencies of staff (R6-7). Interestingly, the term 'building redundancy' was used not only in relation to energy infrastructure but also to knowledge of critical functions. More specifically, to avoid reliance on a single expert, ports should strive for a multifunctional workforce (R2, R5). Making use of local knowledge was raised by one port authority (R5). Another port authority mentioned the value of having in-house staff, instead of temporary employees or consultants,

as this may improve both the staff availability and the in-house local knowledge of the facilities, both useful resources during hazardous events:

"Then there's the issue of in-house staff. Opinions on that can vary, but I still think it's often an advantage to have your own staff rather than relying on contractors or outsourced services for everything" (R7).

In addition to educational training, emergency drills should be conducted on a regular basis (R4-6).

During disruptions, it is important to share information and knowledge with other stakeholders, as it improves the collaboration (R3, R5). The availability of personnel was also mentioned, as manual labor will likely increase during blackouts (R7-9). Lastly, in the Adaptive phase, all port authorities emphasized the need to evaluate the port's collaborative performance. This activity should bring together all relevant stakeholders, both internal and external (R1-9). Ideally, this should focus on what is best for the port as a whole and include constructing a joint vision for it (R3).

4.5 Indicator feedback

The port authorities were also given the opportunity to provide feedback on the Energy Resilience Matrix. All port authorities deemed the indicators relevant to energy resilience capacity building and the matrix exhaustive (R1-9), albeit with a few additional suggestions. The suggestions concerned the inclusion of metrics for measuring a) cooperation with authorities and external port stakeholders (R2), b) prioritizations (R1, R3), and c) spare part availability (R5).

Interestingly enough, none of the port authorities currently use specific resilience metrics. Instead, existing indicators were focused on port operations, such as the number of ships on time and the amount of units handled (R4), and in general, the port authorities seemed to have adopted a metric mining approach rather than a goal-driven indicator design approach, as one interview suggested:

"I'd say we've been pretty bad at developing indicators based on operational needs or resilience, in this case. Instead, we've turned it around a bit: 'Okay, what key metrics do we have, and what can we get out of them?' Whereas we should instead focus on creating really good indicators and then collect the data needed to measure them afterward" (R2).

Another recurring theme was the feasibility of using the Energy Resilience Matrix. Although all port authorities agreed on the usefulness of the indicators, implementing them in their organizations was deemed challenging. For example, currently the ports lack the required data (R7), and data collection and monitoring will require investments in EMS technology (R1) and the development of entirely new strategies (R2), and as long as financial incentives for these investments are lacking, it will likely not happen (R2-3). Furthermore, the life cycle of port infrastructure is commonly long, meaning the current infrastructure may be too old to be compatible with the required EMS technology (R5, R7).

4.6 Challenges to implementation

A number of interesting miscellaneous themes emerged during the interviews, which were subsequently categorized according to three challenges to implementation: a) Paradoxes, b) Economics, and c) Internationalization.

Several paradoxes pertaining to electrification, digitalization, and resilience were highlighted in the interviews. For example, electrification was deemed a necessary step in decarbonizing port operations. At the same time, making port operations more reliant on electricity may increase dependency on a single or volatile energy source, rendering port energy systems less resilient and vulnerable to power outages (R2, R6, R8-9). Similarly, there is a paradox in how digitalization simultaneously contributes to resilience while increasing exposure to risks (R1, R4, R7-9). Digitalization not only increases the risk of cyber threats but also makes information and communication systems more integrated, thereby more interdependent and fragile (R4, R7-9). Digitalization has also contributed to greater efficiency and specialization, resulting in leaner organizations with fewer employees, and staff shortage during disruptions was identified as a risk by several port authorities (R2, R4, R8-9). A third paradox was how increasing the number of stakeholder collaborations may render the organization more resilient, yet less flexible, as it can increase complexity. The more stakeholders involved, the slower the organization becomes. Involving more stakeholders also risks obscuring roles and responsibilities (R4).

The second barrier concerned the economics of building energy resilience capacity. Several port authorities highlighted the importance of financial incentives and compelling business cases, as without them, it will be difficult to justify investments in resilient system structures (R1-3, 6). This may have to do with the lack of clear, immediate economic gains of building energy resilience capacity, as one port authority pointed out:

"Despite the state of the world, it's still difficult to secure funding for building resilience. Many people are talking about it, and it's at the top of the agenda; we must somehow prepare ourselves for an uncertain future. But when it comes to actually opening the purse strings, I think there are still problems" (R2).

Another economic barrier concerned an aging port infrastructure, and two port authorities reported old equipment and changing investment objectives as one of their main challenges (R5-6). Investments are constantly postponed, and some equipment is becoming so old that spare parts are no longer available.

A third barrier to implementation was increasing internationalization. For example, different countries have different standards and systems, and integrating these systems while maintaining resilience capacity will be challenging (R4). Another challenge is to align the interests of multinational companies. As one port authority reported, many port companies operate globally, and making them understand the local conditions of ports and aligning their priorities has proven difficult:

"Sometimes you have to communicate with somebody who doesn't know the local circumstances (...), and that also means that if they can't see how serious the problem is, it can be hard to get them to prioritize the problem" (R3).

5. Discussion

This section triangulates the interview results with previous research and the Energy Resilience Matrix to validate the relevance of resilience indicators. The section also provides a reflection on indicator development and the utility of using indicators in building energy resilience capacity.

5.1 Convergence and divergence

Regarding infrastructure, the port authorities reported on-site backup generators and redundancy, RES, ESS, microgrids, power flexibility options, and compatible infrastructure design as important energy resilience measures, which directly correspond to the Infrastructure indicators seen in Table 4. These findings are also supported by previous research, such as the importance of a local and diversified energy mix for self-sufficiency (Sharifi & Yamagata, 2016; Sharmin & Dhakal, 2022; Sovacool & Mukherjee, 2011), redundancy in energy sources (González-Solano et al., 2025; Kim et al., 2021; Tang et al., 2025), energy conservation and storage solutions (Apostolou, 2025; Cholidis, Sifakis, Chachalis, et al., 2025), microgrids for increased energy efficiency and management (Issa et al., 2025; Remoundos et al., 2025), system flexibility, and flexible network architecture (Roegel et al., 2014). One measure mentioned by the port authorities but not covered by the matrix was the role of spare parts in recovery.

Table 4
List of Infrastructure indicators and corresponding energy resilience measures reported by the port authorities.

No.	Indicator name	Energy resilience measure
1.1.2	Energy Source Ratio (Self-sufficiency)	On-site backup generators
1.1.4	Redundant Capacity Ratio	Redundancy
1.1.5	Energy Storage Capacity Ratio	ESS
1.1.7	Microgrid Distribution Redundancy Margin	Microgrid
1.2.5 1.3.5	Power Flexibility Options	Flexibility
1.2.6 1.3.6	Load Flexibility Ratio	Flexibility
1.2.7 1.3.7	Microgrid Load-to-Capacity Ratio	Microgrid
1.4.3	Flexible Network Architecture Index	Compatible infrastructure design

Concerning information, the port authorities described monitoring and forecasting systems/EMS, the ability to access and share data, data backups, cybersecurity, alternative communication channels,

physical copies of protocols, data recovery, and performance evaluation as crucial port energy resilience measures. These findings cover all indicators in the Information layer, as seen in Table 5. Although not explicitly stated, indicators 2.4.1, 2.4.2, 2.4.3, 2.4.4, and 2.4.5 all address different aspects of performance evaluation and the improvement of information and data. The port authorities' responses are also consistent with previous research. For example, several sources stress the importance of monitoring and forecasting (González-Solano et al., 2025; Kim et al., 2021; Sharmin & Dhakal, 2022), data sharing (Shaw et al., 2017), data backups (González-Solano et al., 2025; León-Mateos et al., 2021), remote access to information (Charani Shandiz et al., 2020; León-Mateos et al., 2021; Shaw et al., 2017), multiple communication channels (Tsoulfas, 2025), and safeguards against cyberattacks (González-Solano et al., 2025; Wu et al., 2025) for energy resilience. Measures proposed by the port authorities but not covered by the matrix were multiple system integration and routines for analog data recording and transfer.

Table 5

List of Information indicators and corresponding energy resilience measures reported by the port authorities.

No.	Indicator name	Energy resilience measure
2.1.1 2.2.1 2.3.1	Monitoring & Forecast Coverage	Monitoring and forecasting/EMS
2.1.2 2.2.2 2.2.3	Access to Real-Time Operational Dashboards	Data access and sharing
2.1.3 2.2.3 2.3.3	Remote Access Reliability	Data access and sharing
2.1.4	Data Backup Frequency	Data backups
2.1.5	Cybersecurity Maturity Level	Cybersecurity
2.2.4 2.3.4	Multi-Channel Communication Coverage	Alternative communication channels
2.2.5	Protocol Availability Rate	Physical protocols
2.3.5	Data Restoration Time	Data recovery
2.4.1	Forecast Accuracy Improvement	Performance evaluation
2.4.2	System–Documentation Alignment Rate	Performance evaluation
2.4.3	Impact Alignment Index	Performance evaluation
2.4.4	Priority Alignment Index	Performance evaluation
2.4.5	Interdependency Mapping	Performance evaluation

With respect to governance, the port authorities stated that routine and role awareness, a flexible organizational structure, and a contingency budget are important for enhancing energy resilience, which aligns directly with the Governance indicators in Table 6. The results are in line with previous research, such as enhancing energy resilience capacity through identifying stakeholders and their roles (León-Mateos et al., 2021; Roege et al., 2014), organizational structuring and inclusive governance models (Hein & Schubert, 2021; León-Mateos et al., 2021; Tsoulfas, 2025), and reserve funds and financial support for post-disaster recovery (Sharmin & Dhakal, 2022; Wu et al., 2025).

Table 6

List of Governance indicators and corresponding energy resilience measures reported by the port authorities.

No.	Indicator name	Energy resilience measure
3.1.3	Stakeholder Role Awareness Rate	Role awareness
3.1.4	Resilience Preparation Budget Ratio	Contingency budget
3.2.2 3.3.2	Adaptive Decision Cycle Time	Flexible organizational structure
3.2.3 3.3.3	Joint Decision Session Frequency	Flexible organizational structure
3.2.4	Activation Time of Alternative Command Structure	Flexible organizational structure
3.3.4	Recovery Budget Sufficiency Ratio	Contingency budget
3.4.2	Continuity of Command Score	Flexible organizational structure
3.4.4	Adaptation Budget Ratio	Contingency budget

Relating to community, the port authorities reported emergency drills, willingness to share information with other port stakeholders, a multifunctional labor force, personnel availability, and performance evaluation as significant for building energy resilience capacity. These findings directly relate to the Community indicators in Table 7 and are also echoed by previous research. For example, previous studies have identified emergency response systems and training of personnel (González-Solano et al., 2025; León-Mateos et al., 2021; Wu et al., 2025), trust and willingness among stakeholders to share information (Kim et al., 2021; Shaw et al., 2017), multifunctional personnel and alternative operation modes (González-Solano et al., 2025; Wang et al., 2023), availability of trained staff (Charani Shandiz et al., 2020; Sharmin & Dhakal, 2022), and inclusive post-disaster evaluations (Kim et al., 2021; León-Mateos et al., 2021; Roege et al., 2014) as important energy resilience measures. The matrix does not address the potential benefits of keeping in-house staff, as was raised by one port authority.

Table 7
List of Community indicators and corresponding energy resilience measures reported by the port authorities.

No.	Indicator name	Energy resilience measure
4.1.2	Drill Performance Score	Emergency drills
4.1.3	Information Sharing Willingness Score	Willingness to share information
4.1.4	Multi-Skill Coverage Index	Multifunctional labor force
4.2.3	Emergency Personnel Availability Rate	Personnel availability
4.2.4	Average Staffing Gap	Personnel availability
4.3.4		
4.4.1	Stakeholder Engagement Index	Performance evaluation
4.4.3	Stakeholder Awareness Index	Performance evaluation

Overall, the results from the interviews, strengthened by similar findings from previous research, confirm the relevance of the identified indicators and render the Energy Resilience Matrix exhaustive.

5.2 A critical reflection on indicators for measuring energy resilience

Indicators and metrics are often presented as strategic tools for businesses, industries, organizations, and governments to monitor their progress toward specific goals or objectives. In theory, indicators represent critical success factors and help concretize complex goals into measurable and manageable numbers for decision-making. As such, indicators may serve as a navigation tool that facilitates learning from past outcomes to improve future results, output reporting, and compliance demonstration, as well as informing decision-making to focus efforts and allocate resources where they are needed. (Parmenter, 2020).

However, using indicators as a tool is not without its limitations, and the notion of using metrics to quantify resilience performance has been challenged (Hallegatte & Engle, 2019; Linkov et al., 2013; Tan, 2021). For example, resilience is a complex concept with a plethora of definitions, many of which demonstrate that resilience extends beyond what is quantifiable (Hallegatte & Engle, 2019; Leštáková et al., 2024). Since resilience in many respects is a holistic framework (Björner Brauer, 2026), using indicators to assess system resilience may be misleading, as most indicators tend to focus on a single function, property, or event (Leštáková et al., 2024). Indicators reduce complex problems into simple metrics, which may lead to important aspects or dynamics being overlooked or ignored (Tan, 2021). Furthermore, poorly designed indicators will miss their marks, measuring proxies rather than the concept itself, which ultimately may distort the results or skew foci and priorities (Hallegatte & Engle, 2019; Liu et al., 2025). Although portrayed as objective metrics, indicators are still chosen by someone, meaning they, to some extent, reflect the underlying values and assumptions of decision-makers (Tan, 2021). These

aspects should serve as warnings against over-reliance on indicators for measuring and monitoring energy resilience capacity, as it may ultimately lead to goal displacements.

These limitations resonated with me as I conceptualized the indicators for this study. I was struck by what I perceive as two main challenges of measuring energy resilience: the social dynamics of resilience and the disruption phase. As established in this study, equally important to a resilient and redundant infrastructure are the information and communication systems, governance models, and communities that support the energy system (Linkov et al., 2013; Roege et al., 2014). Measuring and monitoring infrastructure performance is fairly simple (e.g., Energy Source Ratio (Self-sufficiency), Redundant Capacity Ratio, and Energy Storage Capacity Ratio). Information and communication system performance is also rather uncomplicated to quantify (e.g., Remote Access Reliability and Data Backup Frequency). However, quantifying the effectiveness of governance, let alone community performance, is more difficult, and there is a risk that any metric becomes shallow or misleading (Colvin, 2026; Hallegatte & Engle, 2019). For example, a Stakeholder Engagement Index only shows the number of stakeholders involved in the planning process, not how well they collaborate (c.f. the response by R3 on the challenge of aligning stakeholder priorities). As previous research shows, the difficulty in measuring governance and community performance results in a tendency to “only measure what can be measured”, i.e., a focus on technological performance while neglecting other system layers (Charani Shandiz et al., 2020).

The second challenge concerns the fact that actual resilience performance is only observable during an ongoing disruption (Hallegatte & Engle, 2019). Yet, this is likely the time least suitable for monitoring resilience performance, as resources will be constrained and focus will be on absorbing the shock and recovering previous system functionality. For example, sudden shocks commonly lead to tunnel vision, limiting affected individuals’ perspective and focus. Furthermore, contemporary performance monitoring systems require both electricity and a stable internet connection, i.e., the monitoring systems may not be functioning during power outages. This logic creates a paradox: despite being only truly observable during disruptive events, resilience performance can be assessed only *ex ante* and *ex post*. Together, these two challenges question the adequacy of indicators for measuring energy resilience performance, particularly the governance and community layers of energy systems, and during the disruptive phases, as shown in Fig. 3.

6. Conclusion

As the economic and social roles of maritime ports continue to evolve, and as they are being reimagined as energy hubs—a transformation that would see two major critical infrastructures merge—their exposure to system shocks will increase. This evolution will require greater emphasis on resilience approaches that enhance ports’ energy resilience.

This research has filled this gap by translating a qualitative energy resilience framework (Linkov et al., 2013; Roege et al., 2014) into 77 quantifiable and comparable indicators across both energy system

layers (Infrastructure, Information, Governance, Community) and energy resilience functions (Plan/prepare, Absorb Recover, Adapt), synthesizing them into an Energy Resilience Matrix, and validating it through input from port authorities. By quantifying qualitative resilience indicators, the research sought to strike the right balance between the general and the specific, thereby increasing the matrix's applicability to other sectors (Ahmadi et al., 2021; Jufri et al., 2019). However, as highlighted by the respondents, the indicators, although relevant, may prove difficult to operationalize, as collecting and monitoring the necessary data will be both costly and time-consuming. Yet, the support from both the literature and interviews demonstrates the relevance of the indicators, suggesting that the Energy Resilience Matrix can still serve as a guiding tool in resilience planning.

The study has also provided a critical reflection on the use of indicators to measure and monitor energy resilience performance. As resilience capacity extends beyond the quantifiable (Hallegatte & Engle, 2019; Leštáková et al., 2024), there is a risk that an overreliance on quantitative indicators for measuring resilience performance will result in a technocentric focus that overlooks the governance models and stakeholder communities that also support the system (Charani Shandiz et al., 2020).

Drawing on the findings of this study, several avenues call for attention in future research. First, the identified limitations of indicator-based approaches to governing energy resilience warrant the investigation of alternative frameworks and methodologies better suited to capturing the multidimensional nature of resilience. Second, the applicability of the Energy Resilience Matrix beyond the maritime port context remains an open empirical question. Extending its application to other sectors would contribute to establishing its validity and generalizability as an analytical tool.

The implementation challenges raised by port authorities in the course of this study equally merit further scholarly inquiry. These include the inherent paradoxes associated with electrification, digitalization, and stakeholder collaboration, given that these processes simultaneously enhance energy resilience while also introducing new vulnerabilities and systemic complexity. A further area deserving attention concerns the development of financial incentives and compelling business cases that ensure the economic viability and long-term sustainability of resilience interventions. Finally, the growing internationalization of port operations raises important questions about the potential divergence between global strategic priorities and local resilience needs, a tension that future research would do well to address.

Declarations

All participants in this study were informed of the purpose, procedures, and any potential risks and benefits associated with their participation prior to enrollment. Written or verbal informed consent was obtained from all participants before data collection began. Participants were advised of their right to withdraw from the study at any time without penalty, and confidentiality of their responses was assured in accordance with the Swedish General Data Protection Regulation ('Dataskyddsförordningen') och GDPR.

Funding

Open Access funding provided by Chalmers University of Technology. The research received funding from the Swedish Energy Agency (project no. P2024-02750) and the Clean Energy Transition Partnership (CETPartnership) under the 2023 joint call for research proposals, co-funded by the European Commission (GA N°101069750). The funding organizations are detailed on: <https://cetpartnership.eu/funding-agencies-and-call-modules>.

Clinical trial number

Not applicable.

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Figures

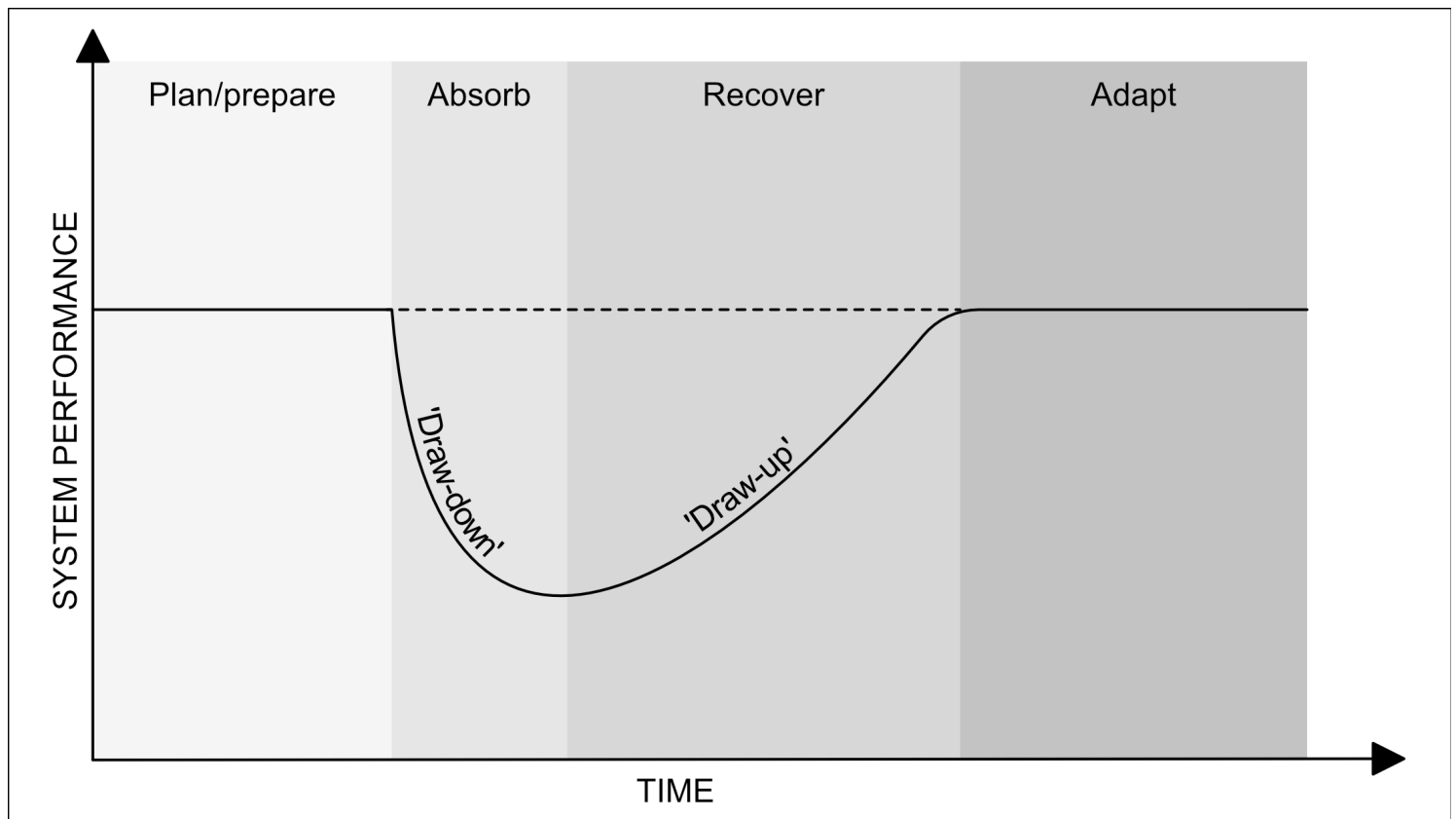


Figure 1

Fig. 1 - The resilience curve. Core system functions, plotted along a timeline and a system performance axis, indicate the 'draw-down' and 'draw-up' of the resilience curve.

Time →				
(Previous cycle) →	Plan/Prepare →	Absorb →	Recover →	Adapt →
Infrastructure	State and capability of equipment and network structure	System performance to maintain function	System changes to recover previous functionality	Changes to improve system resilience
Information	Data preparation, presentation, analysis, sharing, and storage	Real-time assessment of functionality, anticipation of cascading losses and event closure	Data use to track recovery progress and anticipate recovery scenarios	Creation and improvement of data storage and use protocols
Governance	Governance structure and decisions, with anticipation of adverse events	Contingency protocols and proactive event management	Recovery decision-making	Design of new objectives and decision criteria
Community	Social network, social capital, institutional norms, and training	Resourceful and accessible personnel and stakeholders for event response	Teamwork and knowledge sharing to enhance system recovery	Additions of or changes to institutions, training programs, and culture

Figure 2

Fig. 2. The Resilience Matrix for developing resilience metrics. Each cell provides guidelines for system dimensions that should be addressed in resilience capacity building (adapted from (Linkov et al., 2013) and (Roeger et al., 2014)).

Time →				
(Previous cycle) →	Plan/Prepare →	Absorb →	Recover →	Adapt →
Infrastructure	State and capability of equipment and network structure	System performance to maintain function	System changes to recover previous functionality	Changes to improve system resilience
Information	Data preparation, presentation, analysis, sharing, and storage	Real-time assessment of functionality, anticipation of cascading losses and event closure	Data use to track recovery progress and anticipate recovery scenarios	Creation and improvement of data storage and use protocols
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Figure 3

Fig. 3. Indicator limitation. The shading represents a generalized depiction of the areas that pose challenges for measuring energy resilience using quantitative indicators.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Appendix1EnergyResilienceMatrix.docx](#)