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Transition of Seaports into Smart Energy Hubs Using Integrated Energy Management Systems

Abstract

This paper proposes a general, comprehensive solution for port energy transformation that considers sustainable port growth in line with green shipping requirements, on the one hand, and the smart grid concept, on the other. In this context, it is shown that it is of great importance to design and develop a centralized system for monitoring and managing the energy network in the port area, which can integrate, monitor, and manage available energy sources, as well as supply demanding loads.

Keywords: energy systems, monitoring and management, maritime transport, energy transition, artificial intelligence

1. Introduction

Maritime transport significantly contributes to global energy consumption, accounting for about 3% of the world's total consumption [8]. This sector mainly relies on fossil fuels, making it a significant source of global greenhouse gas emissions. Energy consumption patterns are expected to change as the industry advances towards decarbonization, with increased adoption of low-emission and zero-emission fuels driven by international regulatory pressures and environmental sustainability goals.

Efforts to reduce dependence on traditional fossil fuels include the integration of alternative fuels such as biofuels, methanol, hydrogen, and ammonia, which are seen as promising paths for achieving the necessary reduction in greenhouse gas emissions. The transition of the maritime sector to these cleaner energy solutions is crucial for achieving global climate goals and reducing the environmental impact. The total number of seaports in the world in 2024 is about 4209 in 170 countries [11]. Of these, 1200 ports are located in Europe. The number of ports that globally maintain regular liner container services is 939 [14]. The global port infrastructure market was estimated at 151 billion dollars in 2023 and is expected to grow to 249.49 billion dollars by 2024, with a compound annual growth rate (CAGR) of 5.2% [15]. Based on available statistics from service providers, regulators, and other relevant institutions, the current demand for energy management in port communities also shows continuous growth. According to the “Shore Power Market” report, the market was estimated at 1.6 billion dollars in 2022 and is expected to grow to 2.8 billion by 2027 with a CAGR of 11.2% [18]. These projections only refer to the “cold ironing” aspect of the proposed project, i.e., the technical enabling of ships at berth to be powered by electricity from the shore, which is just one of the energy segments covered by the project proposal. Increased awareness of the need to reduce greenhouse gas emissions, along with stricter regulatory requirements, leads to an increased need for sophisticated energy management systems. Port communities, as key points of international trade, face challenges of increased energy consumption and the emissions that result from it.

2. Problem Description

The maritime industry, according to the International Maritime Organization (IMO) and EU directives for reducing ship atmospheric emissions, is focused on designing and building new “greener” ships and adapting existing ones. Promoting this concept, modern port communities, which play a key role in the transport chain, face challenges in providing services without negative impacts on the environment and society. The challenges of port communities are further highlighted by the adoption of the EU directive packages EU 2023/1804 [3] and EU 2023/1805 [4] on September 13, 2023, according to which EU member states commit to ensuring a minimum supply of shore-side electricity for container and passenger ships at sea in maritime ports within the trans-European transport network (TEN-T) in the following five-year period. Accordingly, port communities are beginning to introduce low-carbon energy technologies to transition the energy infrastructure and limit the use of carbon fuels. These transition activities include shore-side power supply for ships at berth (cold ironing), electrification of loading/unloading equipment, and integration of combined energy sources (e.g., renewable energy, natural gas, hydrogen, and methane), which will undoubtedly contribute to the interconnection between individual energy systems (ES). However, the infrastructural energy transition of port communities with a focus on electrification is long-term and financially demanding and does not guarantee optimal

and efficient energy management. To meet the IMO criteria and EU directives, port communities undoubtedly need to thoroughly upgrade their energy infrastructure, which is insufficient in the context of competitiveness and survival in the energy market, and because the existing energy systems are not designed for significant electrical load. Alongside infrastructural transition, it is necessary to implement smart energy management systems for multiple energy networks, transforming port communities into smart low-carbon energy hubs. Smart energy management systems in port communities are applicable and necessary regardless of the energy infrastructure, which will change over time and create the so-called “energy mix,” as they are focused on optimizing the operation of energy systems to reduce greenhouse gas emissions. Electrification and infrastructural integration of various advanced energy systems (ES) are key ways to reduce greenhouse gas emissions in port communities. The use of renewable energy sources such as wind and solar, as well as “clean” fuels – natural gas and hydrogen, is becoming increasingly widespread. At the same time, the use of advanced technologies such as multi-participant energy storage systems, shore-side power supply for ships and reversible electric cranes is increasing. This deepens the interconnection and mutual influence of different forms of energy, logistics and transport, i.e., different energy systems, which requires a thorough understanding of energy optimization to reduce carbon emissions. Therefore, it is necessary to research and develop a methodology for the operation and models of various energy processes with the presence of low-carbon technologies and optimization of multiple coupled energy systems.

Energy systems in port communities are equipped with systems for monitoring and controlling associated processes, consisting of various measuring and control devices connected to control units. Existing control systems for energy processes in port communities are completely autonomous and closed, use different IT protocols, and are subordinate to logistics systems and transport requirements, making them unsuitable for new infrastructural changes and optimal energy management. Port communities are adopting advanced technologies for process automation, such as terminal operation management, cargo handling, and land transport, resulting in increased efficiency and reduced human errors. Advanced technologies such as the Internet of Things (IoT) and artificial intelligence (AI) are also being implemented to improve operational activities, data processing, and ensure greater resilience of various processes. Port communities are increasingly adopting centralized digital platforms that allow stakeholders in the port ecosystem (such as port authorities, terminal operators, shipping companies, and customs) to efficiently and securely exchange information. Following the above, it is undeniable that there is a need for interconnected energy systems and the sharing of key information to achieve a satisfactory level of observability and manageability to optimize operation and reduce atmospheric gas emissions, which includes new adaptive management algorithms and identification of key data according to the specific requirements of each individual energy system. Interaction and data sharing between horizontal energy systems would enable the observability of energy networks beyond their boundaries, providing flexibility to the energy system as a whole.

One of the most significant drawbacks of the current infrastructure is the lack of capacity to implement “cold ironing” technology, i.e., the ability to supply ships at berth with electricity from the shore power grid instead of using their own generators, usually powered by fossil (diesel) fuel. This is caused by a lack of infrastructural capacity. Most ports are not equipped with the necessary electrical installations and capacities to support the high energy consumption required to power larger ships. High initial costs for setting up the necessary infrastructure are entry barriers for ports already operating with limited budgets. Besides infrastructural shortcomings, a more sophisticated challenge arises, which is the absence of systematic centralized energy management of multiple interactive energy processes. In the existing environment, energy management in port communities often boils down to ad hoc measures that do not consider overall energy flows or potential savings. There is no commercial solution for a centralized system that would enable monitoring, analysis, and optimization of energy flows, resulting not only in higher costs but also a higher ecological footprint. The lack of integrated technological solutions limits the ability of port communities to effectively respond to fluctuations in energy demand or implement advanced strategies for optimal energy management.

It is also worth highlighting the problem of the lack of standardized protocols and legislative frameworks at the international level, which complicates the electrification of port communities, primarily cold ironing as a universal practice. On the other hand, new EU directives very strictly define the timeframes within which electrification must be available in maritime port communities. Some attempts to solve these problems are highlighted in the following EU projects:

- ◇ Port Energy Systems Optimisation (PESO) project [13]
- ◇ SEANERGY [17]
- ◇ MAGPIE [9]
- ◇ The Maritime Energy Transition project (MAREN) [10]
- ◇ INTERPORT – Integrated energy systems in ports [7]

3. Integrated energy management systems in port communities

In the long-term context of financially demanding carbon neutrality, infrastructure development and the use of new forms of energy are necessary to transform port communities into low-carbon energy hubs [2]. However, by combining advanced measurement techniques and associated energy management software solutions (Energy Management System – EMS) with the use of adaptive algorithms, it is possible to initiate energy transition and ensure its long-term sustainability through energy management optimization aimed at reducing harmful emissions. The energy system of a port community, based on the concept of an energy hub, is a tripartite system that includes energy supply/sources, energy conversion, and consumption. The energy system operates in conjunction with the logistics system, which includes transport

logistics and is an integral part of energy consumption [5]. On the supply/source side, the energy system encompasses the existing land-based electrical grid, primary gas network, and renewable energy sources such as wind and solar power plants [12], energy storage, and regenerative load operation. Energy conversion and the connection of all entities are achieved through a set of different types of energy networks – electrical grid, natural gas network, and thermal network, as well as energy conversion equipment. Consumption is diverse, consisting of port electrical and thermal loads, ship consumption, and coastal cranes [19], all the way to powering vehicles/vessels. The management of various energy device outputs, along with the operational status of ship equipment, is individually achieved through separate control systems (EMS). To optimize multiple energy systems of the port community, coordination of their management will be explored and developed to achieve the efficiency of the overall complex energy system of the port community.

Traditionally, energy systems (ES) and logistics systems (LS) have been built independently, although in reality, there is an interdependence in their architectures and functioning [6]. Logistics systems are oriented towards transport efficiency, while energy systems are entirely subordinated to achieving these goals. In recent years, researchers have begun to recognize the interdependence between LS and ES brought by the electrification of port communities.

4. Solution proposal – EMS.Integrator

We propose a solution for the energy optimization of port communities to reduce carbon emissions based on the interaction of multiple energy systems, establishing their models and associated characteristics, developing control-optimization algorithms, and connecting energy systems on multiple data-time scales. A solution for coordinated optimization of energy subsystem operation is proposed, using the integration of information technology (IT) into existing and smart control systems (OT), i.e., an integrated energy management system (EMS).Integrator, as shown in Figure 1.

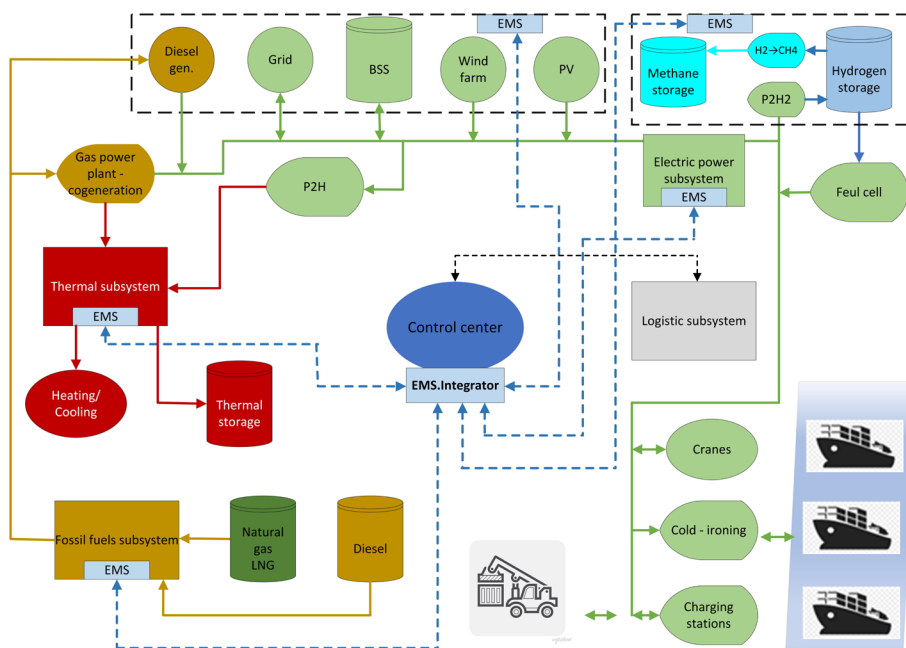


Figure 1. Scheme of integrated energy management in port communities – EMS. Integrator.

The figure depicts an integrated energy management system for port communities, emphasizing the interaction between various energy sources and subsystems. It includes components like the diesel generator, power grid, wind farm, PV, and energy storage systems, all controlled by a central control centre through the EMS.Integrator. The system integrates thermal and electric power subsystems, utilizing renewable energy sources and advanced technologies like fuel cells and P2H (power-to-hydrogen) conversion. The logistics subsystem and energy demands from cranes, cold ironing, and charging stations are also managed under this comprehensive EMS framework to optimize energy usage and reduce carbon emissions.

4.1 IT-OT convergence

Accelerated technological development of digital innovative solutions is reflected in various industrial sectors, with significant importance in the energy sector in today’s geopolitical context. IT leads the energy transition, as the transformation of the traditional energy system into advanced networks (Smart Grid) is implemented through real-time monitoring of technological processes, system observability, and providing a

high level of cybersecurity, making them more efficient, secure, reliable and resilient. In the field of energy and energy management, there is a convergence of operational technology (OT), such as SCADA/EMS systems, and information technology (IT). IT-OT convergence integrates traditionally separate networking tools with process monitoring and control, servers and data storage devices into one cohesive product with central management. The basis for establishing the EMS.Integrator proposal is the integration of information technology (IT) and its functionalities into traditionally “closed” control technologies (OT). The proposed EMS.Integrator is used for optimal management of energy systems of the port community based on IT-OT integration, with a previously developed core architecture for collecting, storing and exchanging data from various interconnected processes in real-time. EMS.Integrator is predominantly oriented towards software and data convergence with support for AI algorithms and to a lesser extent towards IT-OT process convergence.

A significant benefit of integrating IT with OT is the possibility of introducing artificial intelligence algorithms for optimal management with a high degree of adaptability according to the energy-logistics environment in real-time. The necessity of adaptability is conditioned by specific concepts and heterogeneous topologies of port communities and daily changes in demands on energy systems. This forms the basis for developing an optimal management algorithm for the energy systems of port communities.

4.2 Core of the EMS.Integrator Software Solution

The biggest problem with existing energy management systems is the insufficient exchange of information between energy processes and other significant users of port communities, making traditional monitoring, protection and management systems inefficient [5]. Relatedly, the problem of the lack of identification of key data needed for adequate operation of energy systems as a whole and congestion with a large amount of collected information from various existing or newly developed so-called Smart Grid solutions can be highlighted.

The superior comprehensive energy management system for the energy systems of port communities – EMS.Integrator, should be available as an executable software package, upon establishing and qualifying the technological system that includes the system core. Therefore, the assumption for creating the EMS.Integrator is the development of a software system core that will enable the collection, processing, storage, and sharing of key data related to management based on a developed unified pattern applicable to different energy systems of port communities; as well as the development of a hardware-software architecture of the master EMS system of energy processes of port communities. The foundation should use positive experiences in EMS systems of advanced power networks (Smart Grid). The orchestration architecture of the underlying IT system is shown in Figure 2.

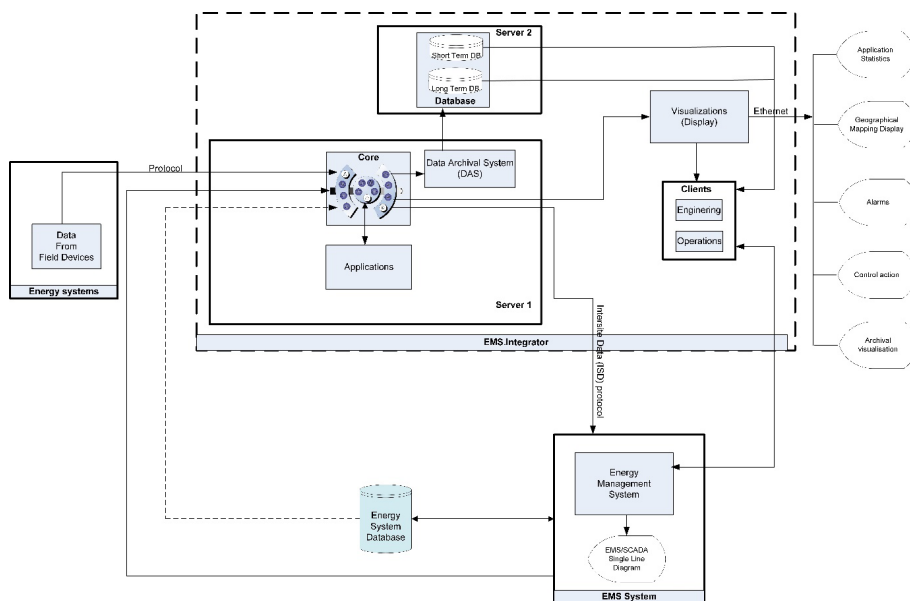


Figure 2. Core of the EMS.Integrator system for data collection and exchange.

Figure 2 illustrates the architecture of an integrated energy management system for port communities, highlighting data flow and system interactions. It shows data collected from field devices within energy systems being processed through the EMS.Integrator. The system includes components like a Data Archival System (DAS) and a database for short-term and long-term storage. The processed data is used for applications, visualizations, and client interfaces for engineering and operations. Additionally, the system supports functionalities such as application statistics, geographical mapping displays, alarms, control actions, and archival visualizations.

4.3 Technological Risks

The defined solution for optimal management of multiple correlating horizontal energy systems of the port community is a complex task with potential identified technological barriers as follows:

- ◊ The challenge of managing different energy systems of port communities given the diversity of protocols and the time domain of sampling [16]. To overcome this barrier, it is necessary to create a unified pattern of data collection, processing, storage, and sharing adapted to existing and advanced energy systems of port communities.

- ◇ Overlapping different areas of activity of individual energy systems when determining the objective function in a single optimized system. The imperative of the modern energy system of the port community is to establish communication and data exchange of all entities using IT functionalities in OT management activities.
- ◇ Ensuring the security and confidentiality of related data and information flow given the use of different communication paths and protocols, as well as different users and owners [1]. The solution to this risk should be found in a single platform for unifying and sharing data with integrated algorithms to ensure the security of information flow.

5. Discussion

The proposed solution has a direct and significant impact on end-users within port communities and represents an innovative response to the technical challenges posed by EU directives, aimed at promoting the reduction of greenhouse gas emissions and enhancing energy efficiency. Three main areas of impact on end-users include the following:

1. Energy cost reduction: Through the optimization of energy resource management, financial savings are enabled for end-users. By integrating advanced technologies and algorithms, EMS.Integrator optimizes consumption and reduces energy losses, directly lowering the financial burden on users.
2. Increased energy supply reliability: Infrastructure and operations of energy systems are improved, leading to a more stable and reliable energy supply. The implementation of EMS.Integrator allows quick adaptation to changes in demand and resource availability, minimizing the risk of supply interruptions.
3. Enabling control and management of own consumption: Through advanced systems for data collection and analysis, end-users gain detailed insights into their consumption habits. This allows for better planning and conscious decision-making regarding consumption, promoting energy awareness and responsibility.

EMS.Integrator thus not only aims for technical improvement and ecological sustainability but also promotes economic efficiency and social welfare within port communities, making it a crucial step towards achieving carbon neutrality and energy independence goals. By implementing this solution, end-users will have the opportunity to realize direct benefits from reducing harmful emissions, improving energy efficiency and reducing operational costs, which represents a fundamental contribution to transforming port communities into smart low-carbon energy hubs.

The proposed solution directly impacts port terminal operators and employees who manage ports and perform port operations, including cargo handling, warehouse

management, and infrastructure maintenance. The proposed technological intervention will provide these users access to sophisticated energy management tools, contributing to the optimization of their operations. Through automated systems and adaptive algorithms, operators will be able to adjust energy consumption in real-time according to actual needs, thereby reducing unnecessary losses and increasing overall efficiency.

Companies operating within port communities, concessionaires, from shipowners to logistics operators, will directly benefit from improved energy infrastructure and integrated management systems. By implementing the proposed solution, operational costs will be reduced through more efficient energy use and the possibility of using renewable energy sources, achieving reduced dependence on fossil fuels and increasing their market competitiveness.

Local communities and residents near port communities are often exposed to the negative impacts of traditional energy practices, including air pollution and noise. By implementing this solution, the quality of life for local residents should be significantly improved through the reduction of emissions and noise, thanks to cleaner and quieter port operations.

For regulatory agencies and state and local government bodies, the solution offers tools and metrics for monitoring and verifying emission reductions in accordance with local and international regulatory requirements. Additionally, the successful implementation of this solution can serve as a model for similar initiatives in other port communities and industries, promoting wider transfer effects and the adoption of sustainable energy practices.

6. Conclusion

The aim of this paper is to propose a comprehensive solution for a smart centralized system for monitoring and managing the energy subsystems of port communities through the pilot solution EMS.Integrator, which has the functionalities of adaptive energy optimization, connection, and sharing of key data from various energy subsystems based on the integration of IT into OT with the aim of transitioning port communities into low-carbon energy hubs.

The proposed solution catalyzes the start of the energy transition of port communities and ensures the effects of the IMO and EU directives in a short period and is applicable regardless of the transformation of the energy infrastructure of port communities, making it sustainable and applicable to a wide range of target groups extending beyond maritime traffic.

One significant limitation of the research presented in this paper is the high initial cost associated with setting up the necessary infrastructure for implementing advanced energy management systems in port communities. The transition to low-carbon energy hubs requires substantial financial investments, which can be a barrier for many ports operating on limited budgets. Furthermore, the lack of standardized protocols and

legislative frameworks at the international level complicates the implementation of technologies like cold ironing. This lack of standardization makes it challenging to achieve a universal practice across different ports, potentially limiting the widespread adoption and efficiency of proposed solutions. Additionally, the current state of existing infrastructure in many ports is insufficient to support the high energy demands of larger ships, presenting a significant hurdle to the effective implementation of new energy management systems.

The innovation of the project is manifested in several directions of multidisciplinary areas of information technology (IT) and supervisory and control systems (OT). EMS Integrator is based on current research and the consequently developed methodology of integrating advanced IT functionalities into traditionally closed supervisory and control systems (OT), primarily through access to OT system data in real-time, their sharing, and the possibility of adaptive operation through artificial intelligence algorithms based on historical operating scenarios. This opens up innovative schemes for connecting multiple energy systems of port communities with different information protocols and measurement sampling time domains, enabling previously isolated control systems to optimize operation based on key external data.

Future research can explore several avenues to address these limitations and enhance the effectiveness of energy management systems in port communities. One potential area is the development of cost-effective solutions for infrastructure upgrades, possibly through innovative financing models or public-private partnerships. Research can also focus on creating standardized protocols and legislative frameworks to facilitate the global adoption of technologies such as cold ironing. Additionally, investigating the integration of renewable energy sources and advanced storage solutions within the energy management systems can provide sustainable and resilient alternatives to traditional power sources. The role of artificial intelligence and machine learning in optimizing energy usage and reducing emissions can be another promising area, offering adaptive and real-time management capabilities for complex energy networks in port environments. By addressing these areas, future research can significantly contribute to the transition of port communities into efficient, low-carbon energy hubs.

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