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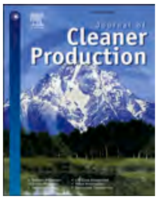

Future pathways for decarbonization and energy efficiency of ports: Modelling and optimization as sustainable energy hubs

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ABSTRACT

The increasing energy demand in harbour areas, coupled with the need to reduce pollutant emissions, has led to the development of renewable energy-based polygeneration systems to face the carbon footprint of ports and ships at berth. In this way, in the coming years, ports can be converted into modern energy hubs.

From this point of view, this paper presents a new dynamic simulation model for assessing and optimizing the energy and economic impact of ports. Here, energy systems and renewable sources can be designed to be connected to national electricity and natural gas grids and can include also alternative fuels (hydrogen, biomethane, etc.) and thermal energy networks, as well as different biomass fluxes (to be exploited for energy aims). Energy availability/demands of near towns and port buildings/infrastructures, as well as on-shore power supply are also included in the dynamic assessments. Hourly weather data and different prices for all the considered energy carriers are taken into account hour by hour. A multi-objective optimization approach is also implemented in the model considering energy and economic indexes to be optimized. The whole model is implemented in a computer tool written in MATLAB.

For showing the capability of the developed model, a novel case study referred to the port of Naples (South-Italy) is presented. Here, several renewable energy sources are considered, including an anaerobic biodigester for producing biogas from the organic waste of docked cruise ships. A combined heat and power system (fed by biogas) is implemented in the port energy hub also for supplying absorption chillers. PV panels, and marine power generators are also included. In the conducted analysis, optimization targets are the maximization of system self-consumption and self-sufficiency as well as the minimum simple payback period. The proposed system can effectively contribute to the decarbonization of the port energy demand and reduce harmful pollutant emissions. Results showed that very high rate of renewable energy produced on-site can be exploited (up to 84%) by the considered port facilities, ensuring increasing independency from utility power grid (self-sufficiency index up to 40%). By the obtained results and through the developed simulation/optimization tool, novel design and operating criteria can be achieved for future port energy hubs featured by renewables and bi-directional energy exchange between ships and port.

1. Introduction

Ports are today important hubs for passengers, maritime transport, logistics and global trade, and have important functions in connecting different regions of the world. According to the United Nations Conference on Trade and Development (UNCTAD) report (Unctad, 2021), over 80% of the volume of international trade in goods is carried by sea, and the share is even higher for many developing nations. Therefore, ports may ideally play a key role in the energy transition towards a more sustainable future (Oloruntobi et al., 2023). They serve as primary nodes in the complex network of fuel supply for maritime transports and are pivotal in facilitating the shipping industry decarbonization, a *hard-to-abate* sector in terms of greenhouse gas (GHG) emissions (Alamoush et al., 2022). In addition, ports consume a significant amount of energy and they are sources of different contaminant emissions (Song et al., 2022), as well as harmful noise pollution and loss of biodiversity

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(Sordello et al., 2020). The GHG emissions attributed to the port industry amount to approximately 3% of the total emissions (Misra et al., 2017a).

To address this challenge, ports should take the role of innovative energy communities (Maturo et al., 2021) by switching to modern *Energy Hubs* and providing to users a cleaner, more sustainable, and more efficient energy supply (Geidl et al., 2007; Eladl et al., 2023). However, it is recognized that additional policy measures to enhance ship efficiency and port energy management are required to achieve shipping decarbonization goals (Chen et al., 2023a; Chuah et al., 2023).

A port *Energy Hub (EHub)* is a system that integrates various energy sources/storage systems and delivers energy to ships, cargo handling equipment, port vehicles and other port-related activities, also including different energy carriers for import/export (Damman and Steen, 2021). The diversification of energy vectors, the integration of renewable energies (Barone et al., 2019, 2021a) and systems electrification are the most promising alternatives to foster the decarbonization of port areas by promoting their environmental, social and economic sustainability (Lim et al., 2019).

1.1. Literature review

Ports often have different energy needs that can include electricity, natural gas, thermal/cooling energy, and traditional or new alternative fuels such as hydrogen, ammonia, biofuels, etc. The specific energy requirements can depend on the types of activities that take place in the port, such as loading and unloading cargo, providing power to docked ships, and running various port facilities and infrastructures as service for commercial operators and passengers.

The increasing demand for energy in port areas, coupled with the need to reduce pollutant emissions, has led to the development of renewable energy-based polygeneration systems that can provide multiple forms of energy using sustainable sources (Elnajjar et al., 2021).

There is a growing body of literature on energy efficiency and renewable energy-based systems in port areas, including their design, optimization, and operation. State-of-the-art technologies and management strategies to save anergy and reduce environmental impact are comprehensively reviewed in a recent study by Iris and Lam (2019). This work identifies advanced economic analyses and operational optimization as key areas of focus for the industry, highlighting the future pathways to be pursued. Suitable models and simulation-based tools are presented as future research directions, necessary to plan innovative and diversified energy supply systems for ports and to optimize their operation. Data-driven models are promising solutions too (Petrucci, 2022).

The relationship between ships and ports plays a crucial role in decarbonizing the maritime industry. The study conducted by Hoang et al. (2022) examines energy-saving solutions applicable to both ships and ports. However, its primary focus is on reporting successful implementations of port-ship interaction, which effectively reduces energy consumption and mitigates pollutants. Ports can provide important infrastructures and services that support the use of cleaner fuels and technologies on board ships. For example, ports can offer shore power (cold ironing) or fuelling stations and other facilities for alternative fuels (bunkering), such as liquefied natural gas (LNG) and, in the future, hydrogen, ammonia, methanol. However, the authors advocate for additional incentives and appropriate policies to ensure the short- and long-term effectiveness of these measures. The industry is also focusing on biofuels such as bio-methane, HVO (Hydrogen Vegetable Oil), or biodiesel. The main disadvantage is that the processes to produce biofuels may be more expensive than traditional ones (Chuah et al., 2022).

The future ship-port binomial will help to reduce the GHG emissions and other pollutants from the maritime activities. This objective will be achieved by developing sustainable and efficient port *EHubs* and establishing the necessary infrastructures for international green fuels trading. However, the latter is still in its early stages as concern the import/export of hydrogen and its derivatives. Only 20 ports in the world are identified as possible forerunners (Chen et al., 2023b).

On the other hand, the design and management of efficient and effective *EHubs* are also challenging due to the difficulty in accurately assessing the related energy consumptions and ecological footprint (Erdas et al., 2015). Conducting a bottom-up analysis of energy consumption can prove to be a valuable technique for stakeholders (Barone et al., 2022; Vassiliades, 2022). As promoted by Alzahrani et al. (2021), a total life cycle approach leads to increasing awareness on environmental impact and economic benefits of energy management strategies and helps to identify port areas for the implementation of innovative energy technologies. In their critical analysis of seaport decarbonization pathways, the authors also identify model-based optimization as an interesting approach to improving energy management and dealing with complex energy systems in real-time operations.

Achieving the goal of a nearly zero energy port (nZEP) requires a comprehensive analysis of available technologies and tools to achieve the optimal outcome. Sifakis and Tsoutsos (2021) classified the current state of technologies and techniques adopted in ports based on their economic attractiveness and technology maturity. These technologies and techniques are capable of advancing the journey towards the net-zero energy scenario. While energy storage systems (ESS), clean fuels, and wind energy systems are mature technologies, their economic viability may still be limited. Conversely, automation and smart energy management systems (SEMS) have the potential to generate positive business implications but are not yet commercially ready. In this regard, more research is needed on less mature technologies and management systems. The use of wind turbines (WT), photovoltaic (PV) and ESS systems was investigated for a port hybrid renewable energy system (HRES) by Sifakis et al. (2021) through simulative approach. The study examined a total of 17 solutions, including two dispatch strategies and various ESS technologies, to evaluate their suitability. The simulations were conducted using HOMER and incorporated actual measured data from the primary port in Crete. Various indices were examined to assess the penetration of renewable energy and economic viability. However, the optimal solutions are not assessed by a multi-objective approach.

Strengthen the relationship and cooperation between ports and the nearby urbanized areas is particularly beneficial for city ports, as it promotes the creation of an integrated energy system enabling the exchange of energy resources between different actors. Additionally, it can foster the innovation and development of new business models, thereby enhancing the resilience and competitiveness of the port industry. It also presents a significant opportunity for the development of port cities. The partnership between public bodies and private stakeholders has been shown to be a valuable strategy in this context (Campisi et al., 2022; Barone et al., 2021b).

EHubs with high electrification rates require the implementation of grid-connected or islanded micro-grids (Barone et al., 2021a, 2021d) which serve as essential infrastructures for supplying power to ships that may demand a high electricity rate (Barone et al., 2020a). They also provide energy to cargo-handling equipment, which is another operation with high energy requests in ports (Prousalidis et al., 2019).

Zhang et al. (2022) found that optimal berthing vessel scheduling can be achieved by a two-step approach based on forecasting the day head timetable. Specifically, the authors proved through their simulation tool based on data from Yangshan Port in Shanghai, China that an overall energy performance enhancement of the port is achieved by the proposed approach so that CO_2 emissions are reduced by up to 85% when port berths are fully powered by OPS. The optimization problem is formulated to reduce operational costs related to waiting time and delayed departure time of vessels, however, the study does not encompass investment costs related to the OPS implementations.

A similar approach is considered by Iris and Lam (2021). They developed a mathematical model to investigate ports energy management system based on load shifting, renewable energies and energy storage systems. The simulation model was adopted for analysing different pricing schemes and demand flexibility strategies for a case study inspired to the Port of Singapore and Jurong Port. As demonstrated by the authors, the use of peak/off-peak pricing is less convenient than dynamic energy price varying over time considered in the study. The implementation of the strategies and technologies investigated in this study may be unfeasible in small ports. Indeed, these technologies require significant capital costs, and the potential for operational cost reduction heavily relies on the flexibility capabilities of port facilities. Other studies (Geerlings et al., 2018) prove that optimal port equipment scheduling leads to reduced power during peak demand up to 50%. In terms of costs, results by Song et al. (2020) showed that total planning cost dropped by nearly 26% for a Chinese port comprised of three energy hubs. Each energy hub includes a combined cooling, heating and power system, a power-to-gas unit, an electric air conditioning device, a gas-fired boiler, and a gas storage. It supplies energy for all the port activities, including cargo loading and unloading and onshore power supply to terminals. Additionally, the system is also connected to a wind power unit and is able to provide demand response services.

The combination of different renewable energy sources may lead to great benefit to ports also in terms of environmental footprint of berthing ships. Ygit and Acarkan (Yigit and Acarkan, 2018) studied several scenarios to exploit solar and wind energy by the shore-side power supply and energy storage systems. They developed a MATLAB model to assess the environmental and economic performance of the proposed energy management method for ports located in Brazil, United Kingdom, Turkey, and Japan. Main results showed that in Brazil CO_2 emissions can be reduced up to 90% while for Turkey ports costs are reduced by 58%. This particular study focuses on the on-shore power supply (OPS) for bulk carrier ships, which typically have lower power demands compared to other types of ships. In contrast, large vessels like cruise ships have high power demands for hoteling services (Barone et al., 2021c). Storage systems can enhance cold ironing capacity for cruise ships and facilitate the utilization of renewable energy sources, considering the high power demand of cruise ships, which can reach up to 11 MW per ship, as for the case of the Port of Civitavecchia. (Caprara et al., 2021). Therefore, fully covering such high electricity demand for OPS with renewable energy poses a significant challenge that should further investigated (Abu Bakar et al., 2023).

The green production and use of hydrogen in harbour areas are of interest for ports for fostering their energy sustainability and independence. Presently, for obtaining green hydrogen the use of renewable energy is required. From this point of view, some studies are focused on specific technologies such as Oscillating Water Column (OWC) combined to hydrogen-based energy storage (Huertas-Fernández et al., 2021; Vichos et al., 2022) or fuel cells (Kinnon et al., 2021). Roy et al. (2021) proposed a two-level optimization procedure for energy management and system sizing, applied to a multi-energy system with electricity and hydrogen as energy vectors for the port of Saint Nazaire (France). The implemented technologies included photovoltaic panels, an electrolyser, a fuel cell, and suitable storage systems, which together achieved an energy utilization range of 82–85%. However, it is worth noting that the port's power load does not consider highly demanding OPS systems, as the maximum power load is limited to 3 MW. Similarly, the Odoi-Yorke et al. (2022) optimized a combinations of RES technologies to identify the optimal one for the port land services of Takoradi in Ghana (with peak load of 1.65 MW). The simulation and optimization processes were performed with HOMER software. Here, a suitable decision matrix for the multi-criteria analysis was obtained by also exploiting available data regarding environmental and social criteria to be followed. One interesting result is that high renewable energy source (RES) penetration rates are achieved with high investment costs. However, the authors estimate that the net present costs, analysed throughout the lifecycle, are similar for all solutions, including those with low capital costs.

While hydrogen production can be expensive, the utilization of biomass to produce biogas through circular management is a promising approach. Onshore biogas production from biomass is considered a mature technology compared with systems to be implemented on ships because of space limitation and safety issues (Schumüller et al., 2022). Fishing harbour waste can be exploited to produce biogas through landside biodigesters. The biogas produced can be utilized as a fuel in stationary engines, with approximately 30%–40% of its energy harnessed for electricity generation. The remaining energy is effectively converted into heat. The projected annual electricity generation is estimated to reach 3.5 GWh through the implementation of this system at the Port of Chennai (Misra et al., 2017b).

Biomass, such as organic waste or sewage from ships, can be transformed into biogas using anaerobic digestion. By implementing circular management, which emphasizes the reduction, reuse, and recycling of waste, biogas production from biomass can be integrated with other waste management and energy systems onshore to create a more sustainable and efficient energy ecosystem at harbours (HaminaKotka, 2021; Attanasio et al., 2023; Acciaro et al., 2014). In this context, biogas production from organic waste generated by the port and docking ships can provide a renewable source of energy (Vaneeckhaute and Fazli, 2020). By utilizing this biogas as a fuel source, the port can reduce its dependence on fossil fuels and lower its carbon footprint. Additionally, other anaerobic digestion processes, such as digestate, can be utilized as organic fertilizer or soil amendment, creating a closed-loop system that benefits both the environment and the local community, and enhance the resilience and efficiency of port operations while minimizing their environmental impact (Kasinath et al., 2021). Despite the potential positive impact of in-port biogas production, it should be underlined that this strategy is poorly investigated by other authors, and to the best of the authors' knowledge, there are no studies that investigate the valorisation of ship organic waste for energy purposes.

As highlighted in the literature review, the main drivers behind the development of renewable energy-based polygeneration systems in port areas are multi-faceted and align with global efforts to transition to a more sustainable and environmentally friendly energy landscape in the maritime sector. The development of *Energy Hubs* systems in port areas is driven by a combination of environmental, economic, regulatory, and technological factors. By embracing these systems, ports can contribute to global sustainability goals and benefits of cleaner, more reliable, and cost-effective energy supply.

1.2. Research question, contribution, and objectives of the study

The concept of energy hubs (*EHubs*) has gained attention in recent years, and several studies, which are discussed in the literature review, developed simulation models to optimize energy flows and dispatching strategies within ports (Zhang et al., 2022; Iris and Lam, 2021; Geerlings et al., 2018; Song et al., 2020). While some studies have integrated multiple renewable energy technologies into their models (Yigit and Acarkan, 2018; Huertas-Fernández et al., 2021; Vichos et al., 2022; Kinnon et al., 2021; Misra et al., 2017b), few have conducted comprehensive analyses of port *EHubs* that consider both economic and energy aspects from a multi-objective perspective (Roy et al., 2021; Odoi-Yorke et al., 2022). Existing research primarily focuses on energy dispatching for port microgrids, with only a limited number of studies considering the holistic integration and optimal design of renewable technologies across the entire port system, including infrastructure and services for both passengers and ships in transit (Roy et al., 2021).

In addition, supply electricity to ships docked at ports with intensive power demands, particularly in the case of berthing cruise ships, requires further investigation, as high power demand from on-shore power supply (OPS) poses a significant challenge in implementing green systems capable of meeting high shares of load. The literature also lacks research on bidirectional energy flux exchange between ships and port systems, with existing studies predominantly focusing on the assessment of electricity exchange from the port *to* the ship (Hoang et al., 2022), overlooking the deployment in ports of energy sources *from* ships.

This study fills this gap by providing a comprehensive model that includes several renewable energy sources, including biomass and electricity, to optimize the energy management of ports, the *port-to-ship* (P2S) and *ship-to-port* (S2P) energy interaction.

By considering the exchange of biomass and electricity between the ships and the port facilities, the developed model provides important insights into the optimization of the energy management system in a holistic manner. It can assist engineers, port authorities and port stakeholders to answer the question: *"Which is the best pathway to reach port decarbonization goals?"*.

In summary, this study represents a significant advancement in the field of port energy management by.

- developing a comprehensive simulation model that enables the study of various port scenarios and the optimization of renewable energy-based *Energy Hubs* within harbour areas. This approach adopts a multi-objective optimization, considering both economic and energy aspects.
- providing valuable references for the development of new and more advanced port energy systems. The inclusion of bi-directional interaction between ports and ships in the model contributes to the existing knowledge on energy management in ports. The analysed case study offers the opportunity for the port's stakeholders to gather useful design criteria.

In this paper, a dynamic simulation model for the energy analysis and optimization of renewable energy hubs is developed and implemented in a MATLAB tool, taking into account various renewable energy technologies and their integration into the existing energy infrastructure at the port. The following technologies have been integrated in the *EHub* simulation model: biogas production system (BPS) with methane upgrading, photovoltaic (PV), ocean energy conversion system (OECS), combined cooling, heat, and power (CCHP), battery energy storage system (BESS). The simulation model includes an energy management system (EMS) for the supply of different port loads such as onshore power supply (OPS), and both thermal and electricity demand of the port facilities. In the next future perspective, the production and use of green hydrogen as well as other alternative fuels (green ammonia and methanol, etc.) will be also included.

To test the capabilities of the developed tool, a simulation experiment was carried out for the case study of the Port of Naples (South-Italy) which was used as background for the multi-objective optimization of the above-mentioned RES-based polygeneration system. By considering the variability in ship arrivals/departures to/from the port, the available biomass from ships and the electricity requirement of OPS were assessed. Detailed site solar radiation and historical data of sea wave profiles were used in the energy and economic simulations and to calculate the avoided pollutant emissions.

The analysed system contributes to the decarbonization goals of ports as.

- By harnessing solar and wave energy, the system incorporates clean and sustainable alternatives to fossil fuels, reducing carbon-intensive power generation.
- On-shore power supply allows docked ships to use electricity from the *Energy Hub,* powered by a more sustainable energy mix, replacing onboard generators and reducing harmful pollutant emissions.
- The system use biomass from ships, converting food waste and treated sewage into energy, promoting a circular economy and reducing environmental impact. Fossil fuel are replaced by biogas or biomethane.

2. Method

In this section, the methodology used to develop the simulation model and analyse the performance of the proposed energy hub (*EHub*) is described. For this purpose, a dynamic simulation model was developed for energy and economic analysis and optimization of the polygeneration system. The modelling and optimization of system parameters were performed using a calculation algorithm developed in the MATLAB environment, where each technology is modelled to calculate system performance and establish control logic for its management. The simulation model is designed to capture the transient behaviour of the *EHub*, allowing for analysis of system response to changing conditions and energy demands. Dedicated subroutines are integrated in a comprehensive tool capable of evaluating the performance of the *EHub* and optimize the design parameters of the system. Fig. 1 illustrates the algorithm architecture, which also represents the workflow of the study. The simulation model consists of the *EHub* model interacting with the ship models (P2S and S2P), considering the variability in ship arrivals and departures, the available biomass from ships, and the electricity demand of OPS and port facilities. Using detailed site-specific data, historical sea wave profiles, and solar radiation information, the simulation model calculates the energy produced by the *EHub* and the economic outcomes of different port scenarios.

Both the *EHub* and ship models are used to calculate key performance indicators (KPIs), defined in sections 2.4 and 2.5. These KPIs serve as objective functions that guide the optimization (section 2.6) of the design parameters for the port's *EHub*.

By utilizing these models and their associated KPIs, the study aims to achieve an optimal and efficient *EHub*.

2.1. *Dynamic simulation model*

The dynamic simulation model performs energy balance calculations for each energy carrier within the *Energy Hub* (*EHub*) at an hourly time resolution.

Fig. 2 illustrates the plant as modelled, including all the technologies, system interactions and energy vectors involved.

The system is designed to produce clean fuels, electricity, and thermal energy (both for heating and cooling) from renewable sources, in order to meet the port electricity and thermal loads and supply electricity to the moored ships. Biomass (food waste and sewage) generated on board the ships or within the port facilities and stored in the port is used to feed a biodigester at land. The resulting biogas is then used to power the combined heat and power (CHP) system which is connected to the port micro-grid. Thermal energy is used for the biodigester feed and port facility thermal loads, as well as to the absorption chiller that supplies cooling energy to the port's facilities. A battery energy storage system (BESS) provides grid balance service and stores surplus energy at low-demand periods. The system is grid-connected and interacts with the power utility, drawing energy when on-site energy production does not meet the demand and feeding it back when the battery cannot store the surplus. It is assumed that remaining ships' electricity loads is

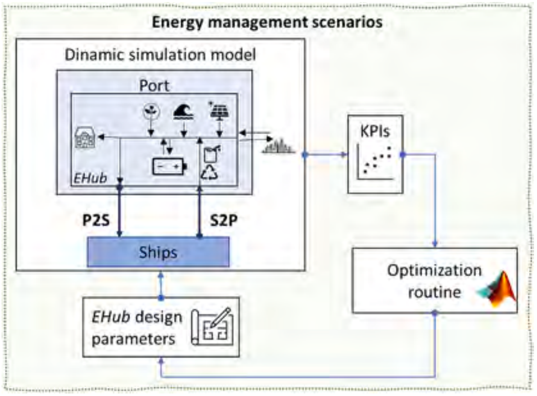

Fig. 1. Methodology description and hierarchical relationship among simulation and optimization routines.

covered by grid power.

The model takes into account the various energy conversion processes and energy storage systems present in the port's *EHub*. The energy carriers considered in the model can include electricity, natural gas, biogas and thermal energy, as well as biomass and alternative fuels. The energy balance calculations account for energy production, consumption, storage, and distribution among the various components considered for the *EHub* in the harbour area. In equations (1)–(3), all carriers are generically indicated as electricity *(el)*, thermal energy (*th*), fuels (*fuel*) and biofuels (*biofuel*).

Each terms of the following equations are calculated according to producibility (*P*) of all the *EHub* technologies (*prod,k*) and energy demand (*d*) of the port (*port*) and ships (*ships*) at berth, as well as the power from and to the grid (*grid*).

$$P_{ships,d,el} + P_{port,d,el} + P_{EHub\rightarrow grid,el} + P_{EHub\rightarrow BESS,el} = P_{grid\rightarrow EHub,el} + P_{BESS\rightarrow EHub,el} + \sum_{k}^{N} P_{prod,k,el} \tag{1}$$

$$P_{port,d,th} = \sum_{i}^{N} P_{prod,i,th} \tag{2}$$

$$P_{port,d,fuel} = \sum_{b}^{N} P_{prod,b,biofuel} + \sum_{f}^{N} P_{purchased,f,fuel} + \sum_{p}^{N} P_{purchased,p,biofuel} \tag{3}$$

2.2. Modelling of the energy hub technologies

2.2.1. Combined cooling, heat, and power (CCHP)

CCHP systems combine waste heat recovery system of power electricity engines which is a combined heat and power system (CHP) with absorption chillers (ACH). The system is modelled by product performance curves. Specifically, engine efficiency coefficients ($\eta_{CHP,el}$ and $\eta_{CHP,th}$) and the cooling capacity factor (CCF) are mapped by manufacturers and used to calculate electricity (*el*), heating (*heat*) and cooling (*cool*) power according to the following equations (4)–(6):

$$P_{CCHP,el} = \eta_{CHP,el} \cdot P_{CHP,rated} \tag{4}$$

$$P_{CCHP,heat} = \eta_{CHP,th} \cdot P_{CHP,rated} \tag{5}$$

$$P_{CCHP,cool} = CCF \cdot P_{ACH,rated} \tag{6}$$

2.2.2. Biogas production system (BPS)

To model the biodigester and determine biogas production and digestate amount, three equations are used (equations (7), (8) and (9)) which calculate biogas production ($\dot{m}_{biogas}$) based on incoming organic waste flow rate ($\dot{m}_{waste}$), percentage of total and volatile solids (*DM* and *VS*), the biogas yield (μ), and consider the energy balance of the BPS. The digestate flow rate ($\dot{m}_{dig}$) is calculated through a mass balance that takes into account the biogas flow rate and density.

Ship and city waste are stored in a buffer tank regulating waste flow into the biodigester. Equation (10) includes variables such as the state of charge (SOC), maximum tank capacity (C_{max}), waste input, and waste output. The equation considers a constant tank volume of the tank and provides inlet and outlet organic waste flows.

$$\dot{m}_{waste} = \dot{m}_{biogas} + \dot{m}_{dig} \tag{7}$$

$$\dot{m}_{waste} \cdot h_{waste} + P_{th,BPS} + P_{e,BPS} = \dot{m}_{biogas} \cdot LHV_{biogas} + \dot{m}_{dig} \cdot h_{dig} \tag{8}$$

$$\dot{m}_{biogas} = \dot{m}_{waste} \cdot DM \cdot VS \cdot \mu \tag{9}$$

$$SOC_p \cdot C_{\max} + \dot{m}_{waste,in} = SOC \cdot C_{\max} + \dot{m}_{waste,out} \tag{10}$$

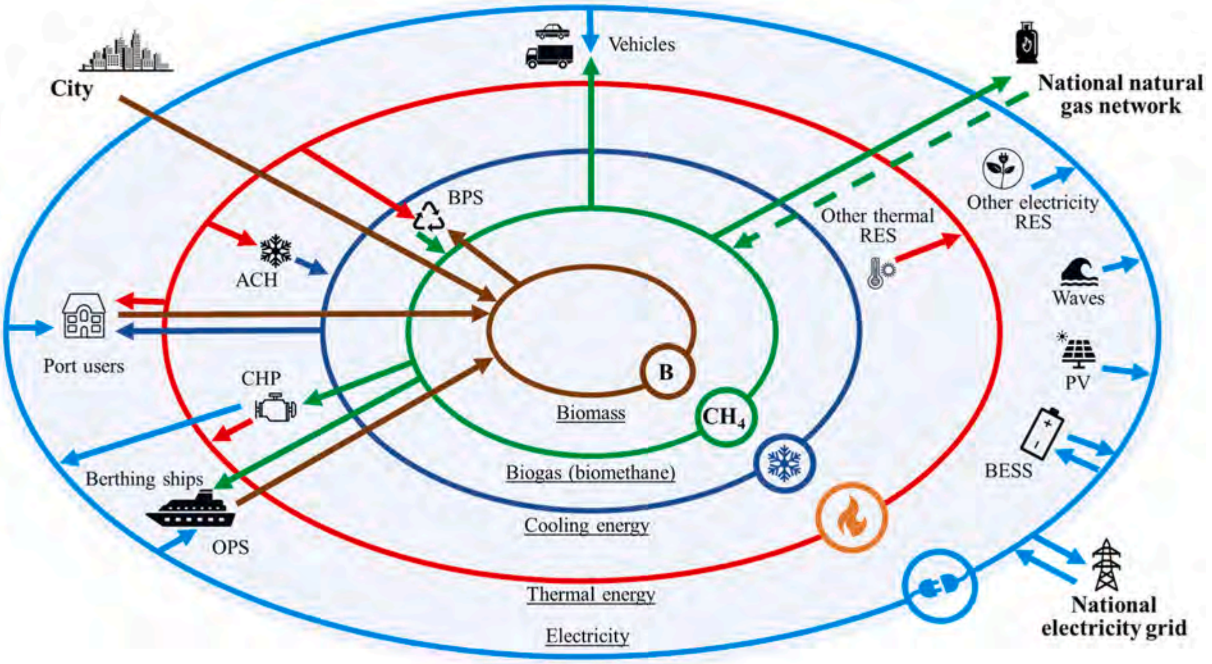

Fig. 2. Energy fluxes of the port energy hub.

2.2.3. Photovoltaic (PV)

Photovoltaic energy production simulation requires suitable weather data files (Bellia et al., 1998). To calculate energy production from photovoltaic panels, the actual incident solar radiation on the surface is determined by adjusting the horizontal solar radiation (from *epw*. Weather file (EnergyPlus. Weather Data)) according to surface slope angle, azimuth, and location coordinates. Next, a photovoltaic module is selected to evaluate actual production based on technical datasheet. The power produced is calculated using equation (11), where G_{inc} is the incident radiation calculated on the sloped surface through geometric optic model, A_{tot} is the panel area, and c_{lost} is an energy loss coefficient that accounts for deviations from standard conditions and actual operation conditions.

$$P_{PV} = G_{inc} A_{tot} c_{lost} \tag{11}$$

2.2.4. Ocean energy conversion system (OECS)

The wave motion's energy potential was modelled by assuming an average efficiency (η_{OECS}) and limiting production based on installed power ($P_{OECS,\max}$), see equation (15). Actual harvested power P_{OECS}, is calculated as function of the wave group speed (c_g), which is related to the wave propagation speed. Equation (14) links power produced, expressed in W/m, to wave characteristics such as wave period (T), height of the waves (H), the density of the sea (ρ) with acceleration due to gravity (g).

$$P_w = \frac{1}{8} \rho g H^2 c_g \tag{12}$$

$$c_g = \frac{gT}{4\pi} \tag{13}$$

$$P_w = \frac{1}{32\pi} \rho g^2 T H^2 \tag{14}$$

$$P_{OECS} = \min\left(\eta_{OECS} \cdot P_w, P_{OECS,\max}\right) \tag{15}$$

2.2.5. Battery energy storage system (BESS)

To model the battery, the function takes into account the state of charge, the required input and output flows, and maximum power of the battery ($P_{BESS,in}$, $P_{BESS,out}$, and $P_{BESS,max}$). The battery has limited power on both charging and discharging, which depends on the current and voltage values supported by the cells, and has a maximum capacity ($C_{\max}$). Thus, the function returns the actual input and output flows along with the charge level and state of charge. SOC_p refers to the state of charge at the previous timestep. It is assumed that the battery cannot discharge more than 10% and can reach 100% charge capacity. The state of charge is calculated as according to equation (16):

$$SOC = SOC_p + \left(P_{BESS,in,r} + P_{BESS,out,r}\right) \cdot \Delta t \,/\, C_{\max} \tag{16}$$

$$\begin{cases} P_{BESS,in,r} = \min\left(P_{BESS,in}, P_{BESS,\max}\right) \\ P_{BESS,out,r} = \min\left(P_{BESS,out}, P_{BESS,\max}\right) \end{cases} \tag{17}$$

2.3. Energy management system

The rule-based control logic implemented for the port's energy management system (EMS) regulates the energy and mass flows within the *EHub*. The established control logics are described by equations (18) and (19).

The biomass from ships is processed by the BPS to achieve a biogas constant rate which is sold to the city gas distribution network or used to fuel the CCHP, alternatively.

The energy management system prioritizes onshore power supply (OPS) over port facility electricity demand. Therefore, all electricity generated by the *EHub* ($P_{EHub,el}$) is used to cover the ships' load ($P_{ships,d}$) as much as possible; the energy supplied to the OPS system is evaluated according to equation (18).

The electrical load of port facilities ($P_{port,d}$) is covered by surplus rate if any ($P_{EHub,el}$ - $P_{EHub \to OPS}$), which is determined by means of equation (19).

$$P_{EHub \to OPS} = \begin{cases} P_{ships,d} & \text{if } P_{ships,d} \leq P_{EHub,el} \\ P_{EHub,el} & \text{if } P_{ships,d} > P_{EHub,el} \end{cases} \tag{18}$$

$$P_{EHub \to port} = \begin{cases} P_{port,d} & \text{if } P_{port,d} \leq \left(P_{EHub,el} - P_{EHub \to OPS}\right) \\ \left(P_{EHub,el} - P_{EHub \to OPS}\right) & \text{if } P_{port,d} > \left(P_{EHub,el} - P_{EHub \to OPS}\right) \end{cases} \tag{19}$$

An electrical energy storage system is used to store excess energy produced, which can then be used at a different time. This system allows for further loading rates to be covered. The control system ensures that the required output power is within the battery limit power, as stated by equation (16).

Finally, the rates of integration and surplus are calculated, which are representative of the interaction with the grid. Excess energy is sold on the grid, while any integration is purchased from the grid. The model is implemented with the possibility to set supply priority to non-programmable energy sources or CCHP, alternatively.

The port microgrid, which includes OPS, is modelled as an ideal power supply. This means that the electricity provided to the various loads within the port, including docked ships, is calculated by neglecting any energy losses due to distribution or electronic and electric equipment (inverters, transformers, etc.).

To cover the thermal and cooling loads and demands, a similar logic is used. The heat produced and recovered by the CHP system is used to balance the thermal requirements of ACH system, users, and industrial processes (e.g. the drying of digestate, etc.) of the port under exam. The remaining heating and cooling loads are balanced by gas-fired heaters and electric chillers, respectively.

2.4. Indices for economic evaluation

The economic aspect is a key consideration in optimization, with the objective being to obtain an energy solution that balances energy benefits with the lowest possible cost. In the case under examination, economic indices including the Simple Payback (*SPB*), Net Present Value (*NPV*), and Profit Index (*PI*) were employed.

The SPB represents the time required for the investment to pay for itself, calculated according to equation (20) by considering investment (*I*) and operating costs, cost savings and incoming cashflows due to export of exceeding power (*profit-costs*).

NPV provides an estimate of the investment's value over its lifespan, accounting for cash flow and discount rate (a), with the latter set at 5% and n representing the *Ehub*'s useful life (equation (21)).

The *PI* is a measure of the value of the investment relative to the cash flow generated over the plant's useful life (equation (22)).

$$SPB = \frac{I}{profit - \text{costs}} \tag{20}$$

$$NPV = \sum_{t=1}^{t=n} \left(\frac{profit_t - \text{costs}_t}{(1+a)^n} \right) - I \tag{21}$$

$$PI = \frac{SPB}{I} \tag{22}$$

2.5. Indices for energy assessment

The main aim of this study was to identify the best trade-off between costs and energy performance, for which two indices were chosen: *self-consumption* (*SC*) and *self-sufficiency* (*SS*), see equations (23) and (24). These indices were considered suitable for providing the required information. Self-consumption measures the share of energy produced and directly consumed by the system, ranging from 0 to 1.

The self-sufficiency index, on the other hand, indicates the percentage of the load covered by energy produced by the *EHub*.

Self-sufficiency index used alone in an optimization problem would provide uncomplete information. Indeed, this approach may lead to an excessive installed power and, as a result, large amounts of energy surplus production on the load profile. Although this excess power can be injected into the grid or redirected internally through load management techniques or storage system integration, the problem formulation would be incomplete. Alternatively, if the self-consumption index is used alone in an optimization problem, the evaluation might not yield the most economically viable or the most suitable possible configuration.

$$SC = \frac{\sum_{k=1}^{k=T} \min\left(P_{prod,k}, P_{load,k}\right) \cdot \Delta t}{\sum_{k=1}^{k=T} P_{prod,k} \cdot \Delta t} \tag{23}$$

$$SS = \frac{\sum_{k=1}^{k=T} \min\left(P_{prod,k}, P_{load,k}\right) \cdot \Delta t}{\sum_{k=1}^{k=T} P_{load,k} \cdot \Delta t} \tag{24}$$

2.6. Optimization procedure

The goal of a minimization study is to find the optimal set *x** such that *f(x*)* is the minimum value of *f(x)*, with *x* varying within constrained optimization domain.

$$\min_{x \in X} f(\mathrm{x}) = f(x*) \tag{25}$$

where *x* is the design variable vector $\mathrm{x} = (\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_N)$ in the design space $\mathrm{X} \subset \mathrm{R}^N$: the objective function, *f(x)*, maps the set of design variables to an objective vector $\mathrm{y} = (\mathrm{y}_1, \mathrm{y}_2, \ldots, \mathrm{y}_M)$ where $y \subset \mathrm{R}^M$.

As shown in Fig. 3, the optimization algorithm implemented in MATLAB is defined by three separated steps: pre-processing, searching and optimization. The pre-processing step requires external information to be provided to the model, such as weather conditions, energy demands, and renewable energy sources availability at the port. At this stage, the optimization setting, and design constraints are also defined.

The searching phase involves the mathematical model to assess objective functions. The search domain for the optimal solution and objective functions are defined in this phase, and the computer processes the data. Lastly, in the optimization phase, the objective function is minimized. When dealing with a multi-criteria decision-making problem, the solution is not unique and depends primarily on budget and technical constraints. Therefore, the final step involves selecting a criterion to determine the optimal solution of the system among the set of non-dominated solution (Barone et al., 2021a).

3. Simulation experiment: input and assumptions

In this section, the input data and assumptions used for the proof of the concept are presented. With the aim to demonstrate the feasibility of the proposed model and evaluate its performance under specific conditions, it is defined a set of inputs and assumptions that represent a realistic scenario to illustrate the potential of the used approach.

The input data includes the technical specifications of the equipment and components involved in the energy system, such as PV, BESS, BPS, CCHP. The local climate and renewable energy sources conditions and energy demand patterns are also considered, which have a significant impact on the system's performance. Furthermore, the costs and financial parameters that are relevant for the economic analysis of the system are taken into account. The location selected to perform energy and economic assessment, as well as multi-objective optimization is the Mediterranean Sea port of Naples, Italy.

The site view of the port of Naples, which is located in the city, is shown in Fig. 4. The port is divided into three main areas, each with different types of activities. The western area, located closer to the city centre, is dedicated to passenger traffic, including both short- and long-distance ferries or cruise ships. The eastern area is designated for commercial vessels and provides various spaces for handling and storing cargo and containers. In the middle, the port hosts industrial and administrative activities.

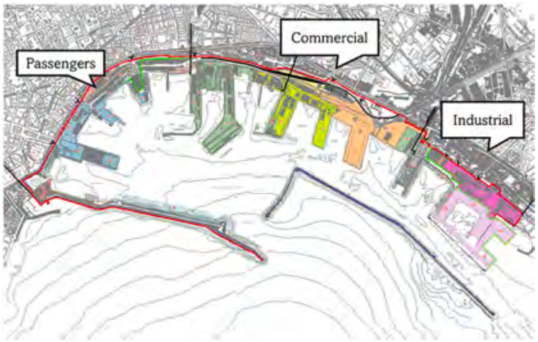

Fig. 4. Site view of the port of Naples, Italy.

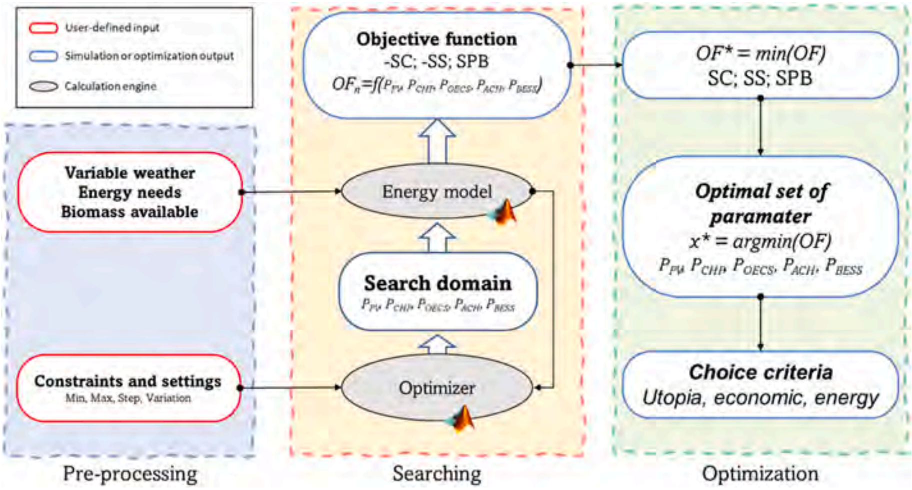

Fig. 3. Optimization procedure.

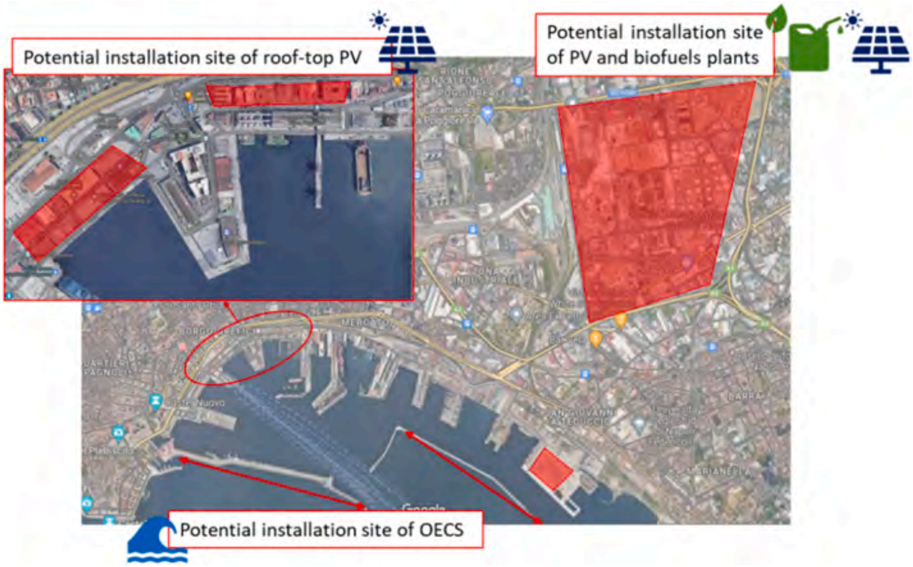

Fig. 5. Surface availability for implementation of renewable energy systems in the port of Naples or immediate surroundings.

The successful implementation of the *EHub* in the Port of Naples necessitates a significant amount of available space. Through careful assessment, disused areas were identified as potential locations for the project, which, with proper redevelopment, could provide ample room for the *EHub* facility. The surface availability for implementation of renewable energy systems is depicted in Fig. 5. Particularly, a large area of approximately 3.2 km^2, situated in the northern-eastern region near the port, can be the main site for the realization of the *EHub*. Additionally, several other areas suitable for potential photovoltaic fields or rooftop plants are identified in the port. Approximately 3.5 km along the port barriers and breakwaters could potentially host wave energy conversion systems, as depicted in the figure.

3.1. Site energy sources and demand

To perform the feasibility analysis and optimization, an assessment of the renewable energy resources was conducted at the harbour. The potential biomass sources, including food waste and sewage from ships, were evaluated, and the available solar radiation and waves height over a typical year at the site were obtained by specific online repositories (Meteonorm. (2023) for climatic data, and Tide Forecast (Tide Forecast, 2023) or Sea Temperature (Barone et al., 2022) for waves timeseries profiles). The available solar and wave energy sources are reported in Fig. 6.

To determine the electricity production capacity of the photovoltaic system at the chosen location (Latitude, 40.842; Longitude, 14.259), the solar characteristics of the site and the specifications of the photovoltaic modules are considered. The chosen site is found to have a maximum global horizontal radiation (*GHR*) of approximately 1000 W h/m^2, indicating the amount of solar energy received at the Earth's surface. Moreover, the site experiences an annual radiation of about 1600 kW h/m^2, reflecting the total solar energy available over the course of a year. South-facing solar panels with an azimuth angle of 0° and a slope angle of 30° are taken into account. These parameters are chosen to optimize solar energy capture throughout the year, maximizing energy production efficiency. Commercial photovoltaic modules with a nominal power rating of 315 W per module (1.5 m^2 each) are assumed for the calculations.

Analysing the data extracted from the Sea Temperature website (Barone et al., 2022), the wave height has shown a maximum value of 2.5 m, while on average, it is 0.55 m. Another critical parameter for production evaluation is the wave period, which, according to data from the Tide Forecast website (Tide Forecast, 2023), varies between 6 and 7 s in the Gulf of Naples. The data collected on a monthly basis have been processed to obtain realistic hourly time series, including random variability over the year. The chosen technology to harness wave energy is assumed to be an oscillating water column (OWC) system, as to the one adopted for the feasibility study of the Civitavecchia port (Peviani et al., 2012).

The assessment of power demand for on-shore power supply (OPS)

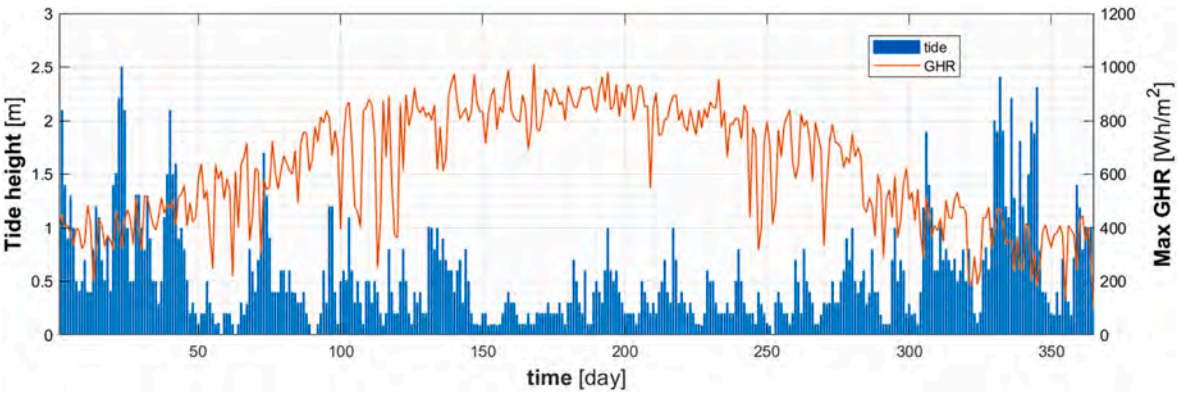

Fig. 6. Waves height and global horizontal radiation estimated for the port of Naples.

and port activities, as well as the availability of biomass from ships, was carried out using realistic assumptions and references from the literature.

To estimate the biomass discharge and the magnitude of electrical loads, the scheduling of ship arrivals and departures in the port played a vital role. The first step involved identifying the types of ships frequenting the port and making assumptions about their duration of stay. Three types of vessels were considered, representing those with the highest power demand: cruise ships, passenger ships (Ro-Ro and ferries), and container ships. For passenger ships, the maximum time at berth considered was 3 h, while for container ships and cruise ships, it was 8 h and 8–10 h, respectively. The simulation model incorporated various daily scheduling scenarios for each ship type, which were then replicated over the course of a year. A maximum number of berths for cruise ships was considered, as they represent the most significant power-demanding users and the main source of biomass from ships. Daily occupancy schedules were constructed based on these assumptions, assigned randomly but considering the variation in maritime traffic based on the different seasons. To determine the annual number of ships arriving at the Port of Naples, official information from the Port Authority was used (Barone et al., 2020b), which reported an average of 500 cruise ships transiting through the port annually.

Regarding the assessment of power demand and biomass availability for cruise ships, data are taken from a cluster of eleven vessels, taking into account their size and typical power demand for hoteling in port, which ranges from 4 to 13 MW. For example, a large cruise ship with extensive hotel operations may have a power demand of up to 12 MW and accommodate up to 7000 people, including passengers and crew staff. As a result, the power demand profile for the on-shore power supply, and passenger volume are generated based on arrivals-departures scheduling, which follows a trend similar to the profile shown in Fig. 7 for available biomass. It reaches a maximum value of 55 MW during the summer season, encompassing power demand from containers (800 kW) and passenger ships (1200 kW). The average power demand over the year is approximately 12 MW.

As concern biomass production, Vaneeckhaute et al. (Vaneeckhaute and Fazli, 2020) retrieved estimations of food waste production from other studies for different ship typologies. The main categories identified are reported in Table 1 and are used for the estimation of the case study of the Port of Naples.

A sewage production of 25 m^3/h was considered according to the information obtained from technician crew of cruise ships. To determine characteristic biomass parameters, such as dry matter, volatile matter, biogas yield, etc., reference was made to the article by Schumüller et al. (2021), which specifically addresses biogas production from waste on board ships. According to Schumüller et al. whose data are reported in Table 2, both sewage and food waste can be mixed and treated as a unique biomass substrate to supply biodigesters.

Table 1
Estimations of food waste production per ship typologies from Vaneeckhaute et al. (Vaneeckhaute and Fazli, 2020).

Estimation of food waste production **[kg/(person day)]**	Ship type
1.3–3.5	Cruise
1.04	Ro-Ro and ferries
0.67	Cargo ships
0.48	Chimneys

Table 2
Biomass features and biogas yield.

Substrate	Dry matter **[*wt.*%]**		Volatile solids **[*wt.*% of d. m.]**		Biogas yield **[m^3/t of d. m.]**		CH_4 in biogas **[*wt.* %]**	
	from	to	from	to	from	to	from	to
Food waste	9	37	80	95	650	800	50	60
Sewage	1,32	85,1	314	76,2				

Fig. 7 reports the daily dynamic profile extrapolated for food waste and sewage quantities according to the estimation of ships traffic described above. The profile is estimated considering the average accumulated biomass over 7 days of sailing for each ship at berth. So, a maximum biomass quantity of about 450 t/day is recorded during summer when port traffic is high. On an annual basis, 59 kt/y of food waste and 8.7 kt/y of treated sewage (dry matter) are provided to the port facilities. It is estimated that by exploiting the waste from ships, it is possible to obtain up to $20{\cdot}10^6$ m^3/y.

The energy demand associated with port activities was based on typical load profiles for electricity, heating, and cooling. However, it can be challenging to accurately estimate these loads due to variations in conditions from one port to another. To address this, the load profiles were modelled based on the daily load assumed by Song et al. (Yang et al., 2020), taking into account daily and seasonal variability and that ports generally have similar activities such as conveyor systems, high-temperature water or vapor for industrial processes, and refrigeration for food preservation. The generated yearly load timeseries are considered representative of all the loads (electricity and thermal) associated with the port's land activities, including buildings and port infrastructure power demand. The maximum and average power, heating and cooling needs of port users are summarized in Table 3.

Table 3
Power, heating, and cooling energy demand of port users' activities.

Port users **[MW]**			
	Electricity	Heating	Cooling
Max	4.7	3.5	1.9
Average	1.3	0.8	0.3

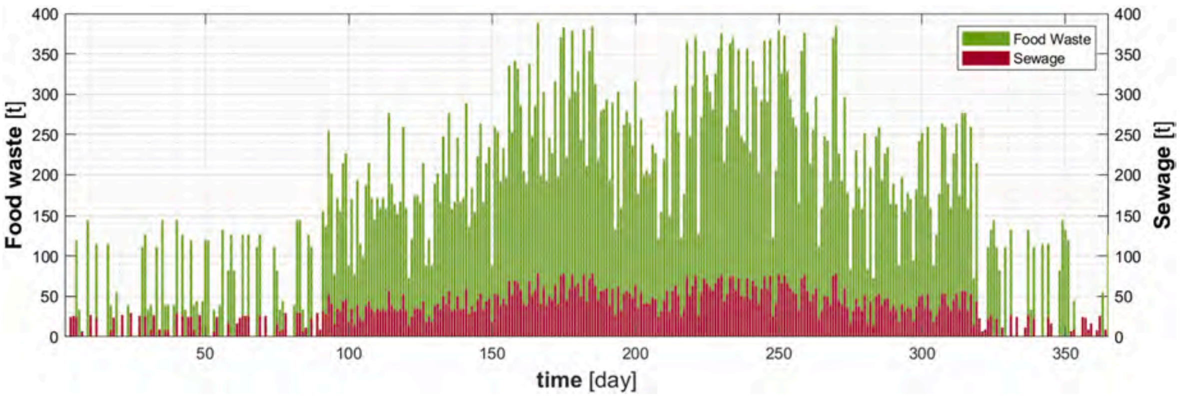

Fig. 7. Available biomass from berthing ships.

The energy sharing of excess power production between the port *EHub* and the nearby town is facilitated through the utilization of the national power grid which supplies power to the *EHub* when needed and efficiently dispatch any available power surplus to meet the energy demands of the city.

3.2. Multi-objective optimization

The optimal sizing of renewable energy systems in the context of port electrification is a complex problem that involves multiple objectives, such as minimizing the total cost of the system, maximizing its energy efficiency, and reducing its environmental impact. To tackle this problem, a multi-objective optimization approach is used, which allows us to explore the trade-offs between different objectives and identify the Pareto-optimal solutions. In this section, the technology size range and cost functions involved in the optimization procedure are described, as well as the objective functions and constraints used to define the problem.

The multi-objective optimization procedure aimed at identifying the optimal solution by investigating the entire search domain of all possible combinations of technology sizes. The cost functions for each technology were defined, taking into account capital and operational expenses, while the developed system simulation model was utilized to estimate the annual energy consumption. Operational expenses account for revenues from the sale of energy (electricity, biogas, cold-ironing service, etc.), any integrations (electricity from the grid utility, thermal energy from boilers, cooling energy from chillers), and operational costs of the system (maintenance, system operation, etc.).

Specifically, in this study, two separate optimizations were performed: one that optimizes self-consumption with respect to the SPB, and one that optimizes self-sufficiency (equation (20), (23), and (24)). Optimization formulation is reported by equation (26).

$$\begin{cases} \min[-SC, SPB] = f(x*) \\ \min[-SS, SPB] = f(x*) \end{cases} \tag{26}$$

Afterward, decisions on optimal solutions are made by utopia criterion with no preference between energy and economic criteria, according to equation (27).

$$\min\left\|f(x*) - z^{utopia}\right\| \tag{27}$$

z^{utopia} (utopia point) represents objective function of the ideal solution with minimum SPB and maximum SC or SS.

The optimization procedure combines the SC and SS indices with economic metrics (SPB) to achieve more comprehensive results. This approach provides valuable insights for designing *EHubs* in ports to achieve various objectives, such as minimizing reliance on external energy sources or maximizing the utilization of renewable energy while reducing overall system costs.

3.2.1. Decision variables

The nominal powers of the installed technologies, including CHP, PV, ACH, OECS, and BESS were chosen as the set of decision variables. To find optimal solutions, the optimization algorithm search among variables in the ranges reported in Table 4, determined based on specific constraints due to available resources and preliminary assessment of available installation areas (as shown in Fig. 5).

Table 4
Decision variables and search domain of the optimization algorithm.

Decision variables	Rated power	
	min	*max*
P_{CHP} [MW]	2	4
P_{PV} [MW]	1	5
P_{ACH} [MW]	0.3	1.2
P_{OECS} [MW]	2	6
P_{BESS} [MWh]	1	5

Table 5
Biodigester investment costs.

Capital costs	
	[€/t]
Civils and infrastructure	16.03
Reception and pre-treatment	13.64
Digesters and auxiliaries	20.13
Decanter	6.71
Biogas cleaning system	6.49
SCADA and control panels	16.47
Other subsystems	6.9

3.2.2. Cost functions

The biodigester represents a cost that is not included in the optimization process as it is sized on the available biomass at port. Assuming no technical constraints, such as limited available surface area, the size of the biodigester, tank, and all necessary components were evaluated based on the processed biomass, using unit costs from the article by Karellas et al. (2010), Table 5.

The *EHub* cost was evaluated based on the installed power of each technology, with reference to (Roy et al., 2021) and (Rourke et al., 2010). The costs considered are summarized in Table 6. In addition, operation costs of PV and ACH are assessed as percentage of their capital costs (i.e. 4%, 2%), while the ones related to BESS and OECS are estimated equal to 0.02 €/kWh and 620 €/kW.

Energy costs and revenues are calculated considering Italian prices for purchase and feed-in electricity tariffs based on National Unique Price (NUP, 125 €/MWh), natural gas (124 €/MWh).

3.2.3. Analysed scenarios

The system optimization was carried out considering two multi-objective problems: maximization of self-consumption and minimization of payback period (*Opt 1*), and maximization of self-sufficiency and minimization of payback period (*Opt 2*).

3.2.4. Four configurations are investigated

- Layout 1: priority to non-programmable energy sources, CHP supplies power at nominal capacity.
- Layout 2: priority to non-programmable energy sources, CHP supplies power on demand.
- Layout 3: priority to CHP which supplies power at nominal capacity.
- Layout 4: priority to CHP which supplies power on demand.

Within the set of possible solutions, both those chosen using the utopia point criterion and those using energy and economic criteria will be highlighted.

4. Results and discussion

The results obtained from the optimization are presented in Fig. 8, Fig. 9, Fig. 10, and Fig. 11. Each *Layout* has been optimized using both optimization problems, *Opt1* and *Opt2*, as defined in section 3.2.3. The

Table 6
Cost functions used to optimize components sizes.

Capital costs	
$C_{u,PV}+C_{u,inv}$ [€/kW]	1000 + 200[a]
$C_{u,ACH}$ [€/kW$_f$]	224
$C_{u,BESS}$ [€/kWh]	350
$C_{u,CHP}$ [€/kW]	1040
$C_{u,OECS}$ [€/kW]	1250

[a] Referred to the PV power.

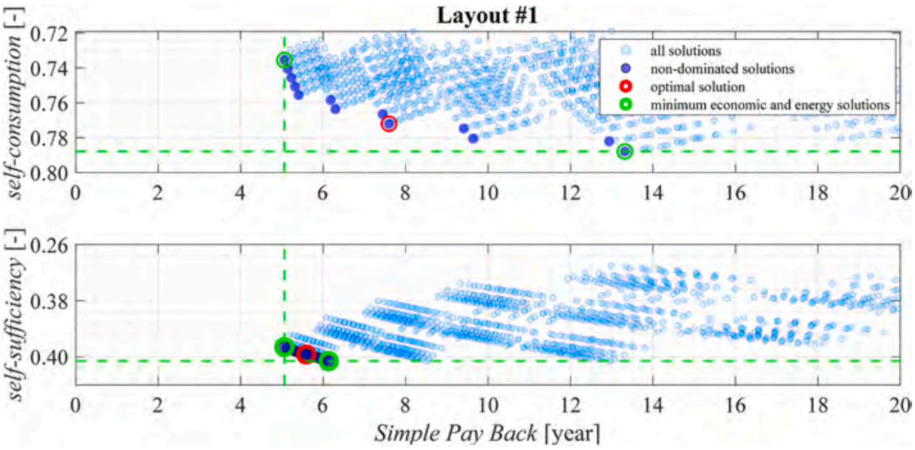

Fig. 8. All solutions (light blue) and non-dominated solutions (blue) for Layout 1.

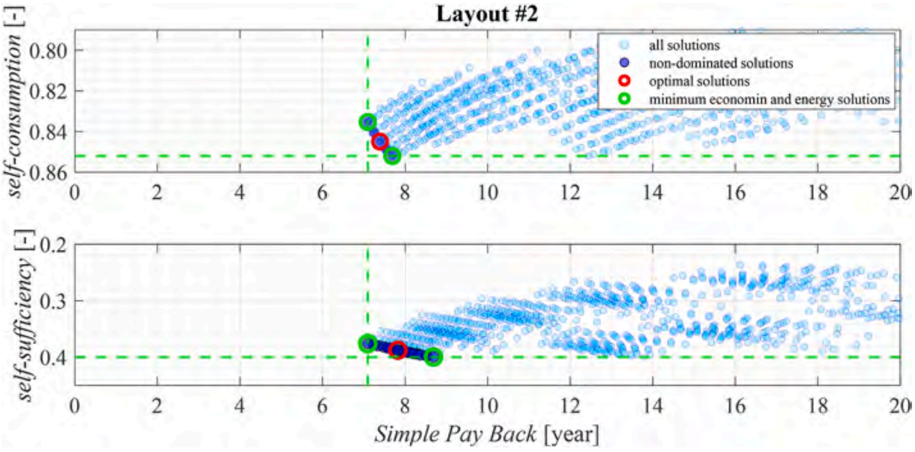

Fig. 9. All solutions (light blue) and non-dominated solutions (blue) for Layout 2.

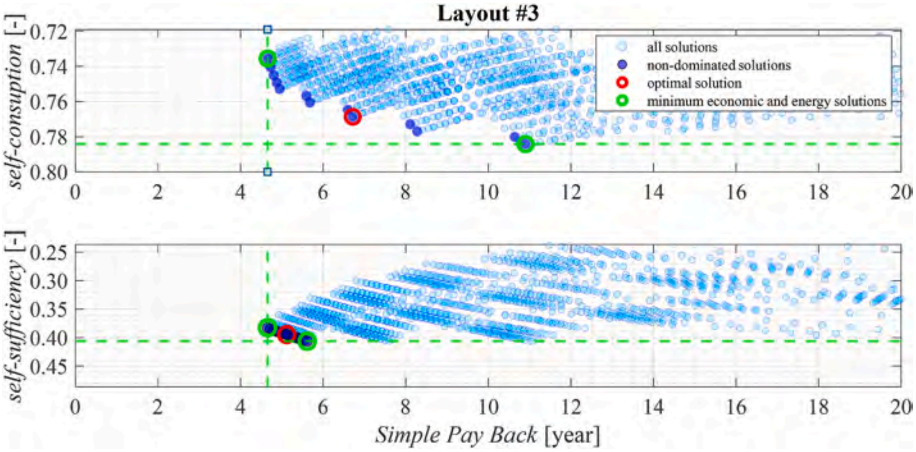

Fig. 10. All solutions (light blue) and non-dominated solutions (blue) for Layout 3.

optimization algorithm employs the dynamic model of the polygeneration system and evaluates the objective functions through an exhaustive search, considering all possible combinations for each analysed scenario.

In the figures, the objective functions (*SC-SS* and *SPB*) for all the explored solutions are represented by light blue markers, while the non-dominated solutions, which collectively form the Pareto front, are shown as blue markers. The optimal solutions based on utopia and economic/energy criteria are denoted by red and green circles, respectively.

Table 7 presents the optimal solutions that were obtained based on the utopia criterion for each layout of the optimization problem, whether it is *Opt 1* or *Opt 2*. It is worth of noticing that the optimal solutions, so the set of equipment sizes, vary significantly based on the

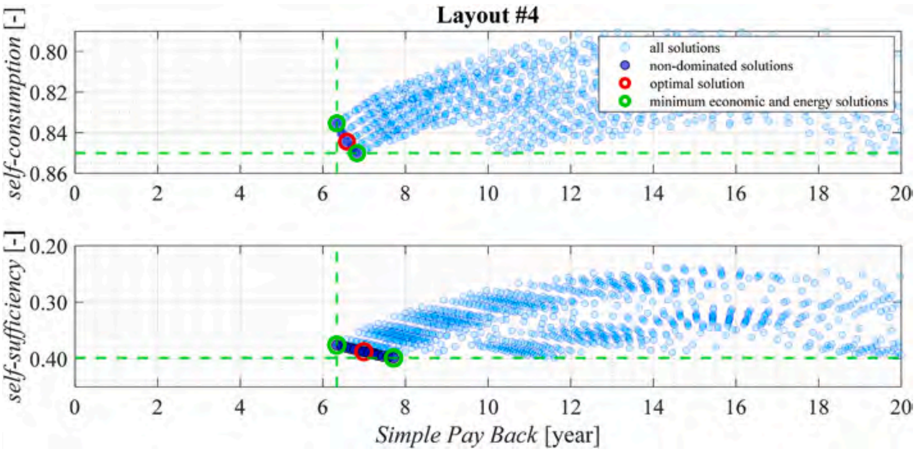

Fig. 11. All solutions (light blue) and non-dominated solutions (blue) for Layout 4.

Table 7
Optimal solutions (utopia criterion) according to optimization problem.

Decision variable	Layout 1		Layout 2		Layout 3		Layout 4		Unit
	Opt 1 (SC)	*Opt 2 (SS)*	*Opt 1 (SC)*	*Opt 2 (SS)*	*Opt 1 (SC)*	*Opt 2 (SS)*	*Opt 1 (SC)*	*Opt 2 (SS)*	-
P_{CHP}	2	3	2.5	3	2.5	3.5	3	3	*MW*
P_{PV}	5	4	4	1	1	1	1	3	*MW*
P_{ACH}	1	1	1	1	0.7	0.3	0.7	1	*MW*
P_{OECS}	4	4	6	4	4	2	2	4	*MW*
P_{BESS}	5	4	1	5	1	2	4	4	*MWh*

specific optimization problem and system layout being considered. It can be observed that in optimization problems that are based on the self-sufficiency index, battery energy storage systems (BESS) with high-capacity are preferred. For both self-consumption- and self-sufficiency-driven optimizations, Layouts 1 and 2 exhibit optimal solutions that involve larger PV and OECS power plants. When these systems are prioritized as the first dispatched energy flows, they result in higher shares of self-consumed wind and solar energy, as the Port of Naples requires high power demand for OPS. In this way, non-programmable, weather-driven renewable energy source are easily exploited.

One important observation is that the self-consumption index varies significantly based on the energy management system, thus, the energy exploitation priorities (layouts). See Table 8. When the CHP supply power at nominal capacity, the self-consumption decreases due to the excess electricity being fed into the utility power grid. On the other hand, the energy sold to the grid increases and the thermal energy recovered by cogeneration (CHP) is higher, resulting in remarkably lower return of investment (lower SPB). Among the different layouts considered, Layout 3 is the one that minimizes the SPB, while Layouts 2 and 4 maximize self-consumption. Furthermore, it is noted that self-sufficiency index is less sensitive than the self-consumption index.

Table 8
Optimal solutions according to optimization criterion.

Choice criteria	Layout 1				Layout 2			
	SPB (y)	*SC (%)*	*SPB (y)*	*SS (%)*	*SPB (y)*	*SC (%)*	*SPB (y)*	*SS (%)*
Energy	13.3	79	8.7	40	7.7	85	8.7	40
Utopia	**7.6**	**77**	**7.8**	**39**	**7.4**	**84**	**7.8**	**39**
Economic	5.0	73	7.0	37	7.0	83	7.0	37
Choice criteria	**Layout 3**				**Layout 4**			
	SPB (y)	*SC (%)*	*SPB (y)*	*SS (%)*	*SPB (y)*	*SC (%)*	*SPB (y)*	*SS (%)*
Energy	*10.9*	*78*	*5.6*	*40*	*6.8*	*85*	*7.7*	*40*
Utopia	***6.7***	***77***	***5.1***	***39***	***6.6***	***84***	***7.0***	***39***
Economic	*4.6*	*73*	*4.6*	*38*	*6.3*	*83*	*6.3*	*37*

Table 9
Optimal solutions according to optimization criterion.

NUP [€/MWh]	SPB (y)
87	8.7
125	7.4
196	5.7
250	4.9
330	4.0

As guidance for decision making in extremely changing energy market, it is shown how different electricity prices affect SPB. A discrete range of increasing NUP values was evaluated, the results referring to Layout 2 are shown in Table 9.

Very high energy prices (up to 330 €/MWh) entail very low payback (almost half), proving that investing in RES-based polygeneration systems in ports give back important advantages from both energy and economic point of view. Compared to other port energy systems studied in previous research, such as (Roy et al., 2021), the optimal design of the hybrid energy systems proposed for the Port of Naples demonstrates a similar degree of self-consumption, ranging from 73% to 85%. However, the key difference lies in the direct utilization of electricity generated from renewable sources, resulting in less energy losses due to energy conversion processes and more favourable system economics. In fact, the payback periods for the proposed system range from 4 to 14 years, which is lower than the case of the port of Nazaire investigated in (Roy et al., 2021), where the hydrogen-based renewable energy system proposed led to payback times of up to 20 years, due to higher investments required and the low costs of electricity.

As demonstrated by the data obtained from the optimization procedure, the port is a unique environment where implementing a complete off-grid system is a challenging task. The OPS load (the load of the docked ships) is by far the most significant load, and it can require very

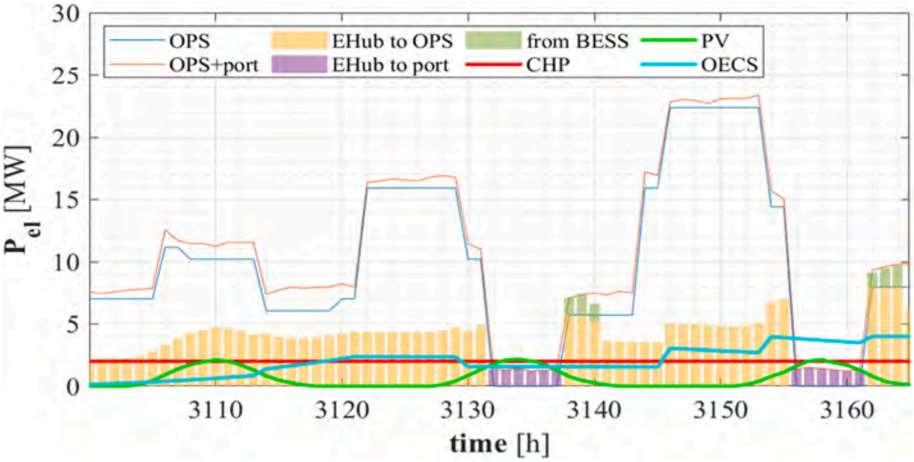

Fig. 12. Dynamic profile of Energy Hub power supply and energy demand of OPS and port facilities.

high-power demand. As depicted in Fig. 12, reporting the simulation results of the Layout 1 optimal solution, OPS requires the use of electricity from grid utility. The results are reported to show the *Energy Hub* behaviour during early summer period. However, these sudden and very high-power demands can be very costly since they require a high-power commitment from the distributor. This highlights the need for a flexible and efficient energy management system that can balance the demands of the port, especially during peak demand periods. The study conducted for the Port of Civitavecchia (Caprara et al., 2021), which is a large cruise terminal and has similar needs of the port under analysis (Naples), poses the same challenges related to OPS implementations for cruise ships, such as better management of power flows and increase of RES infiltration and usage.

On annual basis, the *EHub* supply OPS with about 30% of renewable energy (including electricity produced by treating ships waste biomass) and 70% with external electricity. It worth of noticing that during periods when there is no or minimal demand for OPS due to the absence or limited number of ships docked at the port, occurring mostly during summer, the *EHub* is capable of supplying 100% renewable energy to support port activities. This finding is consistent with what has been shown in other studies (Yigit and Acarkan, 2018; Odoi-Yorke et al., 2022).

The simulation experiment carried out in this paper demonstrated that dynamic modelling that considers multiple energy systems, different energy carriers and energy management strategies is fundamental in port's decarbonization as help in answering non-trivial optimization problems.

The installation of renewable energy systems within the port has resulted in significant reductions in greenhouse gas (GHG) emissions and local pollutants associated with the consumption of fossil fuels by ships at berth. Fig. 13 shows the simulation results in terms of avoided CO_2 emissions referred to the electricity produced by the Italian generation system supplying the: i) city network of Naples (City); onshore port facilities and activities (Port); iii) switched off ships engines due to the onshore power supply obtained by port RESs (OPS – Ehub); iv) switched off ships engines due to the onshore power supply fed by the national electricity grid (OPS – from Grid, here the computed benefit is due to the different emissions between ships' engines and the Italian generation system). For OPS conditions it is assumed that the engines of ships are fed by MGO (Marine Gas Oil, 270 g/kWh of equivalent CO_2).

An analysis was also conducted regarding the additional pollutants produced by the engines of ships docked at the port, specifically: nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM). Specifically, the avoided emissions obtained in case of OPS are reported in Table 10.

The carried out investigation demonstrates that the power supplied by the *EHub* to OPS plays a major role in reducing CO_2 emissions compared to other port energy activities. Additionally, the export of surplus electricity to the national grid contributes to mitigating the environmental impact linked to energy requirements of cities nearby to ports. The important contribution that OPS brings to GHG and pollutant reduction, even when OPS is supplied from the national power grid with a hybrid power mix that includes fossil fuels, highlights the significance of promoting and adopting technological advancements in ships.

Table 10
Avoided local pollutant emission due to ship at berth.

Avoided local pollutant emissions [t/y]	
NO_x	667
SO_x	172
PM2.5	25

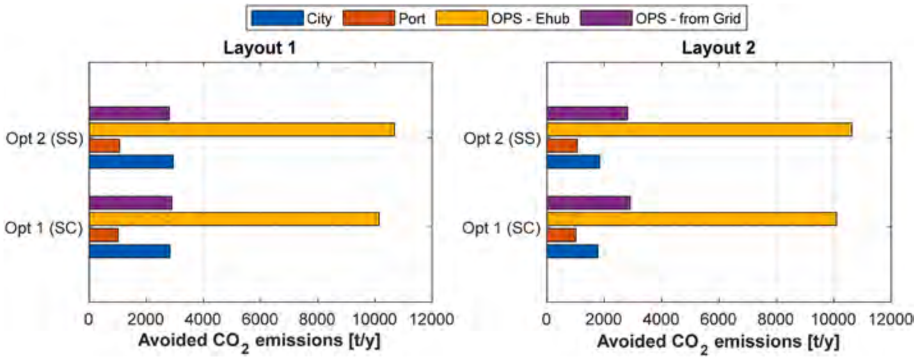

Fig. 13. Environmental impact analysis for the considered optimal solutions.

Incorporating hybrid propulsion systems, fuel-efficient engines, and improved energy management strategies can lead to reduced fuel consumption and emissions during port waiting periods, thus complementing the efforts made within the port's energy management system.

The significant carbon emission reduction and cost savings, highlighted by the optimization analysis, are attributed to the successful combination of multiple solutions. Notably, the waste-to-energy technologies implemented in the *EHub* system have proven to be highly promising. By efficiently converting waste materials into valuable energy sources like biogas and biomethane, the system not only contributes to the reduction of carbon emissions but also enhances cost-effectiveness, making it a crucial component of the overall success of the *EHub*. The estimated biofuel production proved to be sufficient to supply a 4 MW-rated CHP, which also meet the electricity demand of ships in the port. However, in scenarios where lower CHP rated power is chosen or the demand for power from the CHP system is reduced, the excess biofuel can be further utilized in two ways. Firstly, it can be sold to the national gas grid, contributing to the overall energy supply and potentially generating revenue. Secondly, the surplus biofuel can also be used as bunker fuel for the ships. So, the bi-directional energy exchange between ships and the port through the *EHub* system offers significant benefits in energy efficiency and sustainability. By valorizing food waste and sewage from the ships to produce biogas and biomethane, the system promotes circular economy principles and reduces carbon emissions from waste treatment and use of fossil fuels.

Regarding the assumptions of this study, several simplifications were made to reduce the complexity of the problem and focus on key aspects of this research. However, the simplicity of the model makes it adequate for the purpose of feasibility analysis and take decisions to optimize the design port's microgrids. In this study, the primary focus is on the optimization of energy- and cost-related objectives within the port. Costs are calculated considering electricity and fuel purchasing costs, as well as investment expenses. However, the logistics supply chain such as transportation and waste treatment, maintenance costs, etc., could play a role in the overall cost-benefit analysis of implementing renewable energy systems and energy management strategies in ports. Future research and analyses may consider the integration of these aspects to provide a more comprehensive assessment of the economic implications and benefits of energy optimization in port operations.

The results obtained for the case study of the port of Naples can be generalized, with due considerations, to other ports. Nonetheless, enlarge validity of the study on different port's microgrid layouts, weather conditions, and traffic loads is required as future perspective along with the analysis of the impact of specific policy and regulatory frameworks.

5. Conclusion

The stringent targets set by national and international bodies to limit carbon emissions in the maritime sector have encouraged the development of cleaner production systems in port areas, resulting in the emergence of modern *Energy Hubs* that supply the port facilities and ships by multiple energy carriers. However, optimizing the design and operational strategies of these energy hubs and identifying the most effective pathways for decarbonization in specific cases can be challenging.

This study presents a new dynamic simulation model suitably developed for modern ports' polygeneration systems that resulted to be a valuable tool in this context. By including different renewable energy sources and by implementing a multi-objective optimization approach, the model can help to design and operate more efficient and sustainable port *Energy Hubs*. The model was incorporated in a computer tool written in MATLAB.

A novel case study referred to the port of Naples is developed to show the capability of the model to assess various energy scenarios including renewables and to optimize the system for self-consumption and self-sufficiency while minimizing the payback period. Specifically, technologies such as biogas production system with methane upgrading, photovoltaic, sea wave energy conversion system, combined cooling, heat, and power, as well as battery energy storage system have been integrated in the *Energy Hub* simulation model. It includes an energy management system for fulfilling different port users demands, such as onshore power for ships, and heating/cooling and electricity requirements of port facilities.

The main findings can be summarized as follows.

- Optimal equipment sizes strongly depend on the selected optimization problem as well as on the considered energy system layout.
- High-capacity electricity storage systems are preferred for maximizing the port self-sufficiency.
- Optimal solutions for Layouts 1 and 2 require larger PV and sea wave energy systems compared to plant configurations with priorities to programmable power supply.
- The self-consumption varies significantly on the base of the considered energy management system and thus of the energy exploitation priorities.
- The obtained low paybacks prove that investing in RES-based polygeneration systems in ports gives back important advantages also from the economic profitability point of view, mostly in high energy cost scenarios.
- The challenges posed by high power demands for onshore power supply require the use of flexible and efficient energy management system to ensure reliable and cost-effective power supply.
- Remarkable benefits in terms of environmental impact are achieved: the avoided CO_2 due to the electricity generation (referred to the Italian power production) is about 17 kt/y; the avoided local pollutant emissions, such as SO_x, NO_x, and PM2.5, due to the docked ships (fed by the port renewables and with on-board MGO engines switched-off) are 172, 667, and 25 t/y, respectively.

Ports authorities and companies as well as other stakeholders interested in engaging decarbonization of energy demand and reducing harmful pollutant emissions may benefit from this study where some new enhanced design and operating criteria can be deduced and taken into consideration. Finally, the analysed layouts provide a reference for the optimal ship-port and port-ship energy interactions that are considered promising for achieving green port areas. It is worth noting that today such a goal can only be achieved by paying attention to the sustainability of the ship-port combination as a whole.

The impact of policy and regulatory frameworks on the implementation of sustainable energy solutions in ports should be explored in future research to better understand the role of regulations, incentives, and collaborations among stakeholders. Enhanced modelling and predictive capabilities of this aspect will help create specific regulation frameworks and contribute to the widespread adoption of green energy technologies in ports.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Nomenclature

Acronyms

ACH	Absorption Chiller
BESS	Battery Energy Storage System
BPS	Biogas Production System
CCF	Cooling Capacity Factor
CCHP	Combined Cooling, Heat, And Power
CHP	Combined, Heat, And Power
EHub	Energy Hub
EMS	Energy Management System
GHG	Greenhouse Gas Emission
LNG	Liquefied Natural Gas
nZEP	nearly Zero Energy Port
OECS	Ocean Energy Conversion System
OPS	On-shore Power Suppy
OWC	Oscillating Water Column
P2S	Port-to-ship
PV	Photovoltaic
RES	Renewable Energy Sources
S2P	Ship-to-port
UNCTAD	United Nations Conference on Trade and Development

Symbols

μ	biogas yeld
η	efficiency
$\dot{m}$	mass flow rate
A	area
C	Capacity
c	energy coefficient
DM	Dry Matter
g	gravity
G	Solar radiation
H	wave height
I	Investment
NPV	Net Present Value
P	Power
PI	Profit Index
SC	self-consumption
SOC	State Of Charge
SPB	Simple Pay Back
SS	self-sufficiency
T	Time period
VS	Volatile Solide
ρ	density

Subscripts and superscripts

biofuel	biofuels
cool	cooling
d	demand
dig	digestate
el	electricity
fuel	fuels
heat	heating
in	input
inc	incident

lost	lost
max	maximum
out	output
port	port
prod	on-site energy production
ships	ships
th	thermal energy
tot	total
w	wave
waste	waste

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