



A marine-based hybrid renewable energy optimization framework for cost and emission reduction in nearly zero-energy ports

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Abstract

This study investigates a marine-based hybrid renewable energy system (HRES) for port electrification, integrating wave and tidal energy with battery storage to support sustainable coastal infrastructure. A multi-objective optimization framework, utilizing a Genetic Algorithm (GA), is employed to simultaneously minimize the levelized cost of energy (LCOE) and the lifecycle carbon footprint (CF). The model is applied to a realistic port load profile and localized marine resource dataset, evaluating six system configurations under technical, economic, and environmental constraints. Results show that the optimal configuration achieves a 50.25% reduction in LCOE and an 88% reduction in CF compared to a conventional grid-based scenario, with a payback period of 7.64 years. Sensitivity analysis highlights system robustness against financial uncertainty, while emphasizing high sensitivity to marine resource variability and load dynamics. In contrast to previous studies centered on solar and wind energy, this research focuses exclusively on marine energy sources and integrates full lifecycle emissions, including embodied carbon, within the optimization process. A modular port archetype is introduced to facilitate replication across coastal sites with spatial limitations. The findings support marine-based HRES as a viable pathway for decarbonizing port operations within site-specific environmental boundaries.

Keywords Hybrid renewable energy system · Marine energy · Nearly zero-energy ports · Multi-objective optimization · Lifecycle carbon footprint assessment

Abbreviations

AI	Artificial intelligence
CF	Carbon footprint
EMS	Energy management system
ESS	Energy storage system
GA	Genetic Algorithm
GHG	Greenhouse gas emissions
GWP	Global warming potential
HRES	Hybrid renewable energy system
HVAC	Heating, ventilation, and air conditioning
IOT	Internet of things
IPCC	Intergovernmental panel on climate change
LCOE	Levelized cost of energy
NZE	Nearly zero energy
nZEP	Nearly zero-energy port
O&M	Operational and maintenance

OWC	Oscillating water column
PV	Photovoltaic
RES	Renewable energy system
SoC	State of charge
SOLCS	Smart outdoor lighting control system
TT	Tidal turbine
WEC	Wave energy converter
WT	Wind turbine

1 Introduction

The global climate crisis, driven by persistent reliance on fossil fuels, continues to intensify (Klinenberg et al. 2020), causing GHG emissions (Chalkiadakis et al. 2018; Inumaru et al. 2021) that accelerate global warming and ecological disruption (Ramachandra et al. 2015; Weisser 2007). Price volatility and energy insecurity further underscore the urgency of transitioning to clean alternatives (Hoel and Kverndokk 1996), now a central objective in global policy agendas (Banister 2019; Savvakis and Tsoutsos 2016) (Busch et al. 2022).

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Renewable energy sources (RES) have emerged as essential decarbonization pathways (Katsaprakakis et al. 2025; Ray 2019), supporting long-term energy security (Owusu and Asumadu-Sarkodie 2016). Sustainability encompasses energy efficiency and resource stewardship across all sectors (Katsaprakakis et al. 2021; Nassar et al. 2019), lowering emissions and supporting economic resilience (Algarni et al. 2023; Sifakis 2026), particularly in high-consumption sectors such as maritime operations (Mathiesen et al. 2008; Savvakis et al. 2021). High-level policies like the EU Green Deal, employing tools such as Maritime Spatial Planning (MSP), drive offshore renewable energy deployment (Kougiass et al. 2021; Marino et al. 2025; Savvakis et al. 2021).

The need to diversify the renewable energy portfolio becomes particularly acute in geographically constrained environments such as islands and densely populated coastal zones. In these locations, land scarcity and stringent legislative frameworks protecting historical landscapes and biodiversity limit conventional solar or wind deployment, making marine energy an essential and distinctive pathway to decarbonization. Coastal zones, as hubs of economic activity and tourism, face intense competition for land, while their direct interface with the sea presents a strategic advantage: marine energy offers clean generation without competing for scarce terrestrial space (Papadaki et al. 2025).

Maritime ports are key nodes in the energy transition (Dwarakish and Salim 2015): they consume vast energy for cargo, vessel services, and lighting (Puig and Darbra 2019), making them major emissions contributors (Barberi et al. 2021). There is a growing push to transform ports into low-emission (Chalkiadakis et al. 2018; Damman and Steen 2021) and highly energy-efficient infrastructures (Liu et al. 2019). The nearly zero-energy port (nZEP) concept has emerged as the key model, targeting energy self-sufficiency via on-site RES, efficiency measures, and intelligent energy management (Shi et al. 2024), reducing carbon footprint (CF) and operational costs (Sifakis et al. 2026a, b). This dual function positions ports as both consumers and producers of renewable energy. Their coastal location makes them uniquely suited to harness marine renewables (Barone et al. 2024; Katsaprakakis et al. 2022; Seddiek 2020), offering tidal, wave, and current energy (Khojasteh et al. 2018; Zabihian and Fung 2011), enabling localized, resilient generation aligned with operational and sustainability targets (Katsaprakakis 2024; Lazaroio and Roscia 2017).

Among the available marine energy technologies, tidal and wave energy stand out due to their high predictability (Land 2007), energy density, and low environmental impact (Uihlein and Magagna 2016). Tidal energy harnesses the consistent flows created by gravitational forces, offering a highly reliable source of power, while wave energy captures the kinetic force of surface waves generated by wind activity over the ocean (Barber and Ursell 1948). Both suit

port settings, leveraging existing infrastructure for effective deployment (Frid et al. 2012; Kuan et al. 2024). Diversification beyond solar and wind is essential (Golubev et al. 2021), to avoid overlooking site-specific marine solutions (Rodríguez-Monroy et al. 2018). Technologies such as oscillating water columns (OWCs) illustrate the potential for multifunctional systems serving simultaneously as wave energy converters (WECs) and protective breakwater structures, offering significant cost and space efficiency in constrained port zones (Zheng et al. 2019), offering cost and space efficiency in constrained zones (Bauwens 2016). A diversified marine energy portfolio is thus critical for sustainable port development (Gonzalez et al. 2023).

This study presents a techno-economic and environmental assessment of a marine hybrid renewable energy system (HRES) integrating wave energy, tidal energy, and an energy storage system (ESS) for an island port. Using high-resolution demand data from the Port of Souda and validated tidal data from the Strait of Messina, the system is evaluated first via single-objective leveled cost of energy (LCOE) minimization, then via a multi-objective framework jointly minimizing LCOE and carbon footprint (CF), aligned with blue economy principles. By jointly minimizing LCOE and CF, the framework supports EU decarbonization targets and advances the transition of island ports toward nZEP status through a replicable, data-driven architecture that is amenable to deployment within collaborative frameworks such as energy communities and localized energy networks.

The rest of the paper is structured as follows: Sect. 1.1 reviews the state of the art and identifies research gaps; Sect. 2 details the system design and methodology; Sect. 3 presents the results, including sensitivity analysis and comparative discussion.

2 Related work/state of the art

2.1 Port energy systems and techno-economic modeling

Research on grid-connected HRES for seaports has focused on optimal design and dispatch (Wang et al. 2019), evaluating solar, wind, and ESS configurations to minimize LCOE and CF in support of the nZEP concept (Sifakis et al. 2021). The integration of hydrogen-based energy storage has been investigated for upgrading smaller ports (Usman 2022), coupled with cold ironing to cut berthed-vessel emissions (Jayabal 2025). While full autonomy and zero emissions are targeted (Sisternes et al. 2016), economic and market feasibility remains a key barrier (Vichos et al. 2022).

More detailed techno-economic analyses delve into the implementation of cold-ironing services (Glavinović et al. 2023) and hydrogen HRES in island ports for full

autonomy (Zis 2019), though economic infeasibility at current market costs limits uptake (Sifakis et al. 2022). Comprehensive frameworks driven by Genetic Algorithms (GA) optimize the design and management of HRES and ESS (Liu et al. 2017), minimizing LCOE through smart dispatch strategies and nighttime grid charging to exploit lower electricity tariffs (Cholidis et al. 2025a, b). Building energy demand also benefits from GA-based optimization (Ying et al. 2020), balancing HVAC operational costs against occupant thermal comfort (Kampelis et al. 2019).

Beyond shoreside infrastructure, the energy systems of multi-hybrid vessels engaged in short-sea shipping have also been analyzed (Yuan et al. 2020), using stored energy to cut diesel reliance and quantify emission reductions (Barone et al. 2024). Different HRES configurations are evaluated using simulation software like HOMER Pro alongside multi-criteria decision-making methods such as TOPSIS (Roy et al. 2024), assessing hybrid scenarios via economic and environmental indicators (Xuejun et al. 2024). Existing port energy studies often neglect market variability, social acceptance, and scalability, with limited real-time EMS integration.

Initial practical attempts to transition Mediterranean ports toward the nZEP model often commence with fundamental and highly feasible interventions (Nikologiannis et al. 2024), focusing on PV installation and LED lighting upgrades (Sun 2019), providing immediate savings and a foundation for broader initiatives (Sifakis and Tsoutsos 2020). To address high energy consumption from port lighting, smart control systems have been developed (Kyba et al. 2014) employing dynamic occupancy-based dimming and daylight harvesting to achieve substantial energy savings and improve overall port efficiency. Yet systemic integration and long-term performance validation of such technologies remain underexplored.

A structured approach is essential for the transition of maritime ports toward zero-emission operations (Kyba et al. 2014), categorizing port typologies and evaluating technology maturity (Diftenbaugh et al. 2015), guiding stakeholders toward the nZEP goal (Sifakis and Tsoutsos 2021). Systematic scoping reviews analyze smart energy infrastructure for CF reduction in ports, categorizing key components such as intelligent energy networks, virtual power plants, and enabling technologies including IoT and AI (Sifakis et al. 2023), providing structured guidance for maritime policymakers and experts (Zadeh et al. 2023). Comprehensive reviews of the transition to greener seaports provide an overview of challenges, new infrastructures, and energy efficiency measures, addressing operational tactics such as energy-aware scheduling, peak-shaving, and the implementation of port (Lam and Notteboom 2014), addressing peak-shaving and port micro-grids and smart grids (Sadiq et al. 2021). Yet integrative,

port-specific frameworks and real-time performance assessment remain limited.

The development of holistic frameworks provides a structured roadmap for the complete energy transition of a port (Vanegas Cantarero 2020), progressing from baseline assessment through to system optimization (Sadiqa et al. 2018), integrating digital technologies and policy compliance (Cholidis et al. 2025a, b). Complementing technical models, quantitative stakeholder surveys gauge maritime industry readiness for the green transition, capturing collective viewpoints on financial, technological, and legal requirements and highlighting the need for public and private investment (Mohite and Mathew 2025). Existing frameworks, however, rarely integrate real-time stakeholder feedback into adaptive policy and investment decisions.

2.2 Marine renewable energy technologies

Early WEC cost analyses comparing devices such as Pelamis and Wavestar found standalone wave energy not yet economically viable. The Pelamis LCOE was \$3,464/MWh versus \$5,834/MWh for Wavestar, underscoring the need for technological maturation. Techno-economic assessments of hybrid offshore wind–wave farms, such as a 160 MW wind + 40 MW wave configuration in the Norwegian North Sea yielding a LCOE of €107/MWh, demonstrate that hybridization improves output stability but high wave energy capital costs currently limit economic competitiveness (Rönkkö et al. 2023).

Reviews of WEC technology consistently identify poor reliability in harsh marine conditions and high capital costs as primary commercialization barriers (Guo and Ringwood 2021). Extensive reviews of tidal energy note the industry remains in a pre-commercial phase. A critical finding is that the manufacturing stage—owing to energy-intensive material production—accounts for the largest share of a device's lifetime environmental impact, making sustainable design essential for long-term viability (Li and Zhu 2023).

Case studies (e.g., a 1 MW Italian tidal plant, LCOE €49.4–€89.8/MWh) show profitability is highly sensitive to energy price and capacity factor (Catalano et al. 2024). Research on the techno-economic optimal sizing of hybrid tidal turbine and battery storage systems develops models to minimize LCOE while smoothing power output and enhancing grid stability, making tidal energy a more reliable and attractive component of the energy mix (Toumi et al. 2023).

Reviews of hybrid wave-tidal energy conversion identify insufficient coupling between wave and tidal capture modules as a critical gap limiting efficiency (Chen and Wu 2024). Overall, the marine renewables literature lacks primary techno-economic analyses of real-world hybrid deployments and multi-objective optimization frameworks jointly addressing cost and emissions.

3 Research gaps and novel contribution of this work

Despite growing academic attention on port decarbonization and marine renewables, studies that integrate wave and tidal energy within fully functional, optimization-based port energy models—especially those validated by high-resolution, real-world data—remain scarce. Most existing contributions are limited to theoretical simulations or narrowly focused solar PV and wind assessments, failing to capture the operational complexity of island ports or align with blue economy and blue growth principles. This research addresses these gaps through three contributions: (i) operationalizing a marine-based HRES incorporating both wave and tidal technologies, two under-represented resources in current literature; (ii) leveraging actual hourly demand data from Souda port paired with validated tidal data from the Messina Strait, enabling a high-fidelity, empirically grounded assessment; and (iii) advancing optimization methodology via a dual-objective (LCOE + CF) formulation that reflects real-world cost–climate trade-offs under EU Green Deal and IMO targets, offering a replicable decision-support framework for coastal and island planners pursuing nZEP status. Key prior works are summarized in Table 1.

4 Proposed system design and operational conditions

This research develops a methodological framework for the design of a HRES that relies exclusively on marine-based renewable energy systems (RES), specifically wave and tidal energy, particularly relevant for space-constrained coastal areas where land for conventional renewables is limited or unavailable. To find the optimal configuration of this sea-based HRES with an integrated ESS, the methodology diverges from common simulation software like HOMER Pro. Instead, it utilizes custom-developed GA to actively handle multi-objective optimization, aiming to simultaneously minimize both GHG emissions and LCOE. The overall objective is to enable the transition of a conventional port into a nZEP, a transition motivated by the increasing GHG emissions associated with maritime operations and the need for sustainable energy solutions within the port sector. The primary goal of this study is not to conduct a site-specific feasibility analysis for the Port of Souda, but rather to develop and validate a robust multi-objective optimization framework. This archetype combines a realistic, empirically validated energy demand profile (from Souda) with a high-potential marine resource

profile (tidal data from Messina). This approach allows us to 'stress test' the model's ability to handle and balance two powerful, yet variable, renewable inputs, thereby demonstrating the full capabilities and sensitivities of the hybrid system. To this end, we constructed a conceptual archetype of a Mediterranean port. To test the system's capabilities under favorable marine energy conditions, tidal resource data from a high-potential site (Strait of Messina) were adopted (Fig. 1).

It must be clearly emphasized that while this study is centered on Chania, the use of Messina data means the resulting scenarios are indicative and not directly applicable for a real-world implementation in the Port of Souda. The main goal is not to replicate the exact local conditions, but to develop a replicable methodological framework. The value and replicability of this research are justified by the port archetype and typology developed, which employs dynamic optimization to identify optimal scenarios for marine energy integration. This conceptual approach aligns with the broader objectives of the blue economy and blue growth, focusing on creating a model rather than assessing a site-specific deployment. In this context, the Port of Souda serves as an ideal candidate for developing this archetype. Despite its small-to-medium scale, it plays a critical role in supporting both commercial and passenger traffic in western Crete and serves as a primary maritime gateway connecting the island to mainland Greece. This operational significance, coupled with its manageable scale, makes it a suitable foundation for piloting and evaluating the feasibility framework for port electrification using marine energy technologies (Gonzalez-Aregall and Bergqvist 2020; Keinänen-Toivola et al. 2025).

Besides, the methodological framework is designed to be both scalable and adaptable meaning that the model can be readily applied to other contexts, including larger industrial ports, different coastal industries, or entire island grids, by simply substituting the specific energy load profiles and local renewable resource data. Therefore, while this case study is localized, the insights into system design, energy storage requirements, and operational strategies provide a transferable blueprint for decarbonization across a wide range of maritime settings.

To facilitate this transition, the study explores six distinct scenarios, divided into two main categories based on the actual goal of objective optimization, ranging from basic integration strategies to more advanced, performance-optimized solutions. The RES selected for this study are wave and tidal energy. These two marine energy technologies are currently underutilized and have received limited attention in the context of HRES design, particularly in applications related to conventional port operations and decarbonization strategies (Awogbemi and Kallon 2023). Their potential, however, is considerable, especially for coastal infrastructure such as ports that are both proximate to and affected by

Table 1 State of the art analysis

Category	References	Location	Area type	Optimal scenario model	Objective approach	Methodology/software
Techno-economic system modeling	Sifakis et al. (2021)	Heraklion, Crete	Large-sized Mediterranean Port	PV/WT/ESS	Cold ironing	Multi-criteria analysis
	Vichos et al. (2022)	Adamas, Milos	Port (Small Mediterranean Island)	PV/hydrogen ESS/cold ironing	Single-objective	HOMER Pro, MATLAB
	Sifakis et al. (2022)	Milos	Port (Small Mediterranean Island)	PV/hydrogen ESS/cold Ironing	Single-objective	HOMER Pro, MATLAB
	Cholidis et al. (2025a, b)	Souda, Crete	Port (Small to medium-sized)	PV/WT/ESS with EMS	Single-objective	Custom Genetic Algorithm
	Kampelis et al. (2019)	Marche, Italy	Nearly Zero Energy (NZE) Industrial Building	HVAC control	Multi-objective	Genetic Algorithm, MATLAB
Systematic reviews & scoping studies	Barone et al. (2024)	Not a specific port	Short-sea shipping in Green ports	On-board ESS	Multi-criteria analysis	Dynamic simulation tool
	Xuejun et al. (2024)	Yangtze river	Typical port	PV/WT	Multi-criteria analysis	HOMER Pro, TOPSIS method
	Zadeh et al. (2023)	General/global	General smart ports	Review of smart energy infrastructure	Scoping review	Systematic scoping review
	Sadiq et al. (2021)	General/global	Modern/Greener Seaports	Review of technologies	Review of demand response	Systematic literature review
Strategic frameworks & qualitative	Cholidis et al. (2025a, b)	Souda port	General port framework	PV/WT/ESS	Framework/roadmap	Methodological framework
	Mohite and Mathew (2025)	General/global	Modern/greener seaports	Review of necessary upgrades	Analysis of Stakeholder Perceptions	Quantitative survey
Marine renewables	Rönkkö et al. (2023)	Norway	Offshore site	Hybrid wind-wave	Techno-economic assessment of hybrid farm	Case study/techno-economic assessment
	Guo and Ringwood (2021)	General/global	Not specific	Wave energy (review)	Review of WEC (wave energy converters) technology	Review
	Li and Zhu (2023)	General/global	Not Specific	Wave energy (review)	Wave energy	Review and life cycle assessment
	Catalano et al. (2024)	Italy (Port of Livorno)	Coastal port	Tidal energy	Profitability analysis with policy scenarios	Profitability analysis/economic modeling
	Toumi et al. (2023)	France (Raz de Sein)	Marine strait	Tidal energy	Optimal sizing design for hybrid system	Techno-economic optimization/sizing design
	Chen and Wu (2024)	General/global	Not specific	Hybrid wave-tidal (review)	Review of HWTec technology state	Review

Fig. 1 HYPERLINK "sps: id::fig1\\locator::gr1\\MediaObj ect::0" Souda Port aerial view



marine energy dynamics (Burrows et al. 2009; Mørk et al. 2010).

Given the unique characteristics of wave and tidal resources and the localized nature of port energy demands, this research emphasizes the site-specific integration of marine energy systems to support the electrification of coastal operations and contribute to the port's energy autonomy (Bocci et al. 2019). The Port of Souda was selected as a representative case study due to its scale and replicability (Sigrist et al. 2016). Its classification as a small-to-medium-sized port allows the methodology and findings to be generalized and applied to other similar-sized ports across the Mediterranean region. Moreover, the port is experiencing increased energy demand driven by growing cargo throughput and seasonal peaks in passenger traffic, especially during the summer months due to tourism (Nogué-Algueró, 2019). This demand profile necessitates a resilient and dynamic energy solution capable of managing significant load variability and ensuring supply reliability, particularly during peak tourist seasons (Hanson and Nicholls 2020).

In addition, the study aims to contribute to the broader exploration of underexploited coastal energy potentials in Crete and the Mediterranean at large. By doing so, it addresses a key gap in the existing literature and offers new insights into the feasibility and benefits of leveraging marine renewable energy as a core component in the transition of conventional ports towards low-carbon, energy-resilient futures.

4.1 Load profiles of the case study

The energy demand data utilized in this research, specifically for the Port of Souda, are derived from actual historical records which have undergone a rigorous process of analysis, cleaning, and formatting to ensure their accuracy and suitability for the modeling. The data preparation involved identifying and correcting any inconsistencies, filling in missing values where appropriate, and structuring the data

into a standardized format. The result is a robust and reliable dataset (enhanced from the original acquired one) that accurately reflects the real-world energy consumption patterns of the Port of Souda, forming a solid foundation for the research and analysis with a total annual energy demand of 874,623.64 kWh (Fig. 2).

Figure 2 provides a detailed breakdown of the port's actual energy consumption, which serves as the foundational load profile for the subsequent scenario modeling and sizing of the ESS. The first panel features a 3D surface plot that captures the hourly and seasonal variations in demand, visibly demonstrating how extended daylight hours in summer reduce energy needs, while shorter winter days increase overall consumption due to lighting requirements. The second panel presents a frequency histogram of these demand values, revealing a bimodal distribution that highlights the operational extremes the proposed hybrid system must be capable of accommodating.

Due to the nature of its operations and equipment, overall energy consumption remains low (Mi and Liu 2022); most of the energy demand is attributed to lighting (Duin et al. 2017). This is evident in the daily and seasonal consumption patterns. During the summer months, the extended daylight hours result in a slight decrease in energy demand, whereas during the winter months, the reduced daylight hours contribute to an increase in overall energy consumption. To reflect realistic ocean conditions, the model incorporates marine energy variability and hydrodynamic uncertainties through scenario-based simulation. This enables evaluation of HRES performance under seasonal wave-tide fluctuations, which is critical for engineering design and economic feasibility.

4.2 Wave and tidal energy potential

Wave energy reports for the Port of Souda, as well as the broader region of Crete, indicate moderate wave energy potential (Liberti et al. 2013). This potential tends to be

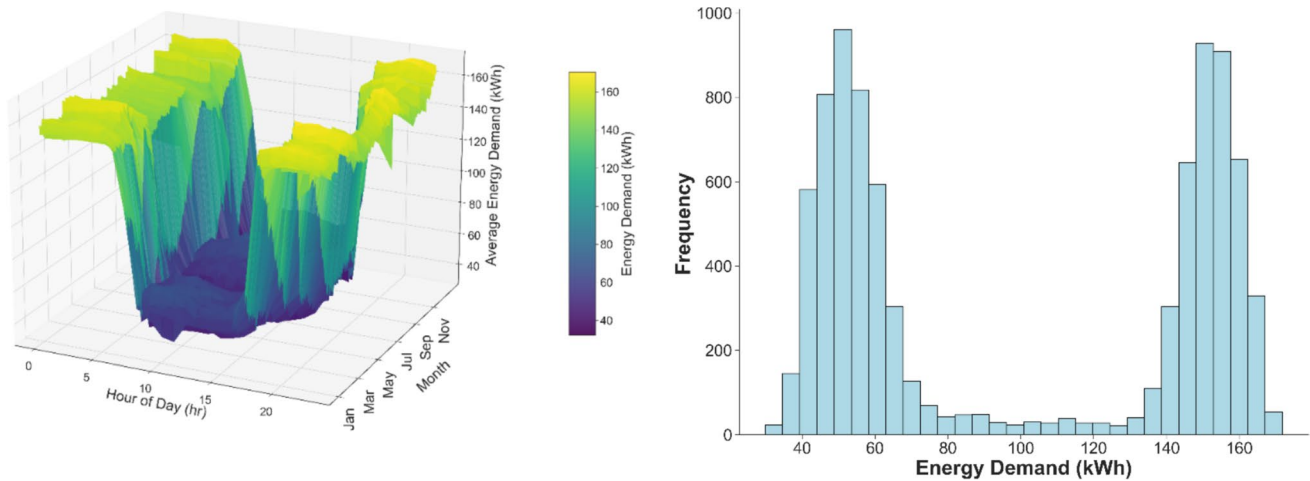


Fig. 2 Souda's Port energy demand (kWh)

higher during the winter months, and in some cases, it also increases during the summer due to specific climatic patterns in the Mediterranean and Aegean Seas. The seasonal and annual variability of this potential is reflected in the fluctuations of wave height and wave period throughout the year, as illustrated in Fig. 3a–d. In contrast, tidal energy potential across the Mediterranean is generally low, with significant potential found only in narrow straits where the Bernoulli principle increases water velocity due to the constriction of flow (Ferrarin et al. 2018; Nachtane et al. 2018). While high-potential sites like the Strait of Evripos in Chalkida, Greece (Ktena et al. 2016), exist, the Strait of Messina in Italy (El-Geziry et al. 2009) was selected for this analysis because it shares similar open Mediterranean conditions with the Port of Souda (Fратиanni and Acquaforta 2017; Markonis et al. 2016). Therefore, tidal data from the Strait of Messina were adopted to model the HRES under optimal conditions and to understand the synergistic potential of combining wave and tidal technologies. The tidal energy potential is illustrated in Fig. 3e, f, which presents water current speeds at a depth of 10 m in the region of Messina. The wave energy assessment for the Port of Souda utilizes Copernicus (CMEMS) data to ensure robustness (Schuckmann et al. 2016). Wave and tidal energy profiles were derived using resource data from the Strait of Messina which were sourced directly from the reliable and widely accepted CMEMS dataset, considering local bathymetry, tidal constituents, and directional wave spectra. Hydrodynamic parameters such as significant wave height, peak period, and current velocity profiles were input into resource estimation models to calculate annual energy production potential.

It must be explicitly clarified that the marine area surrounding Chania Island and the Port of Souda possesses negligible exploitable tidal energy potential. This limitation is not due to a lack of available measurement data but rather

stems from the fundamental hydrodynamic characteristics of open sea environments. In open Mediterranean waters, water movement speeds at a depth of 10 m are inherently minimal. Significant tidal potential is strictly concentrated in narrow geographical constrictions, such as straits, where the Bernoulli principle physically accelerates water flow to exploitable velocities. Because the integration of tidal energy represents a primary methodological novelty of this research, evaluating the hybrid system's performance requires robust, realistic resource inputs. Consequently, validated high-resolution tidal data from the Strait of Messina, a renowned high-potential site sharing broader open Mediterranean climatic conditions, was selected to rigorously stress-test the proposed multi-objective optimization framework.

4.3 Physical system components

The integration of a marine-based HRES combined with an ESS offers a sustainable pathway for the decarbonization of port operations and the improvement of energy autonomy (Abu Bakar et al. 2023; Njikatoufon 2025). Within this research, the proposed system is applied to the Port of Souda with the objective of significantly reducing GHG emissions and ensuring uninterrupted energy supply under variable operational conditions (Sadek and Elgohary 2020). For the HRES configuration, two marine RES were selected to represent the wave and tidal energy subsystems. The tidal energy component is based on the GEMSTAR tidal stream device, a tidal turbine that remains in the experimental and demonstration phase (Technology Readiness Level (TRL) 5–6) (Coiro et al. 2020). The device was selected primarily due to its ongoing testing and partial deployment in the Strait of Messina, which also serves as the origin of the tidal resource data used in this study. This alignment between data and technology enhances the validity of the simulations,

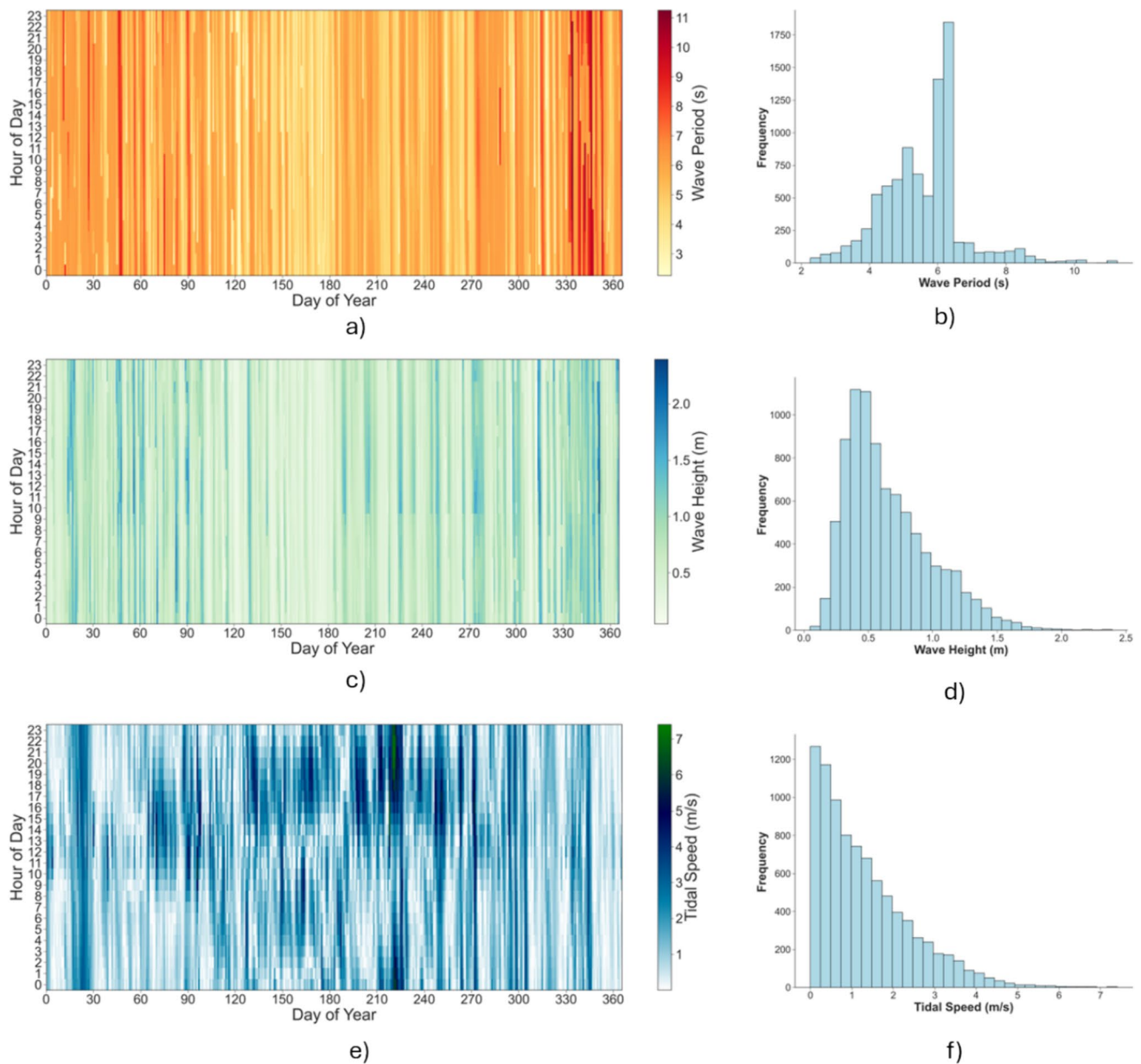


Fig. 3 Case study potential: **a** wave height heatmap, **b** wave height histogram, **c** wave period heatmap, **d** wave period histogram, **e** tidal speed heatmap, and **f** tidal speed histogram

as the modeled environmental conditions closely resemble those under which the device is already operating (Coiro et al. 2018).

The wave energy subsystem is based on the REWEC3, a type of oscillating water column (OWC) system currently implemented in Civitavecchia, Italy (Arena et al. 2017). This location was selected due to its comparable coastal and marine conditions to those of Souda. Although both GEMSTAR and REWEC3 are still in the testing and pre-commercialization phases (estimated at TRL 4–6), they were deemed suitable for inclusion in this study due to the limited availability of mature marine renewable technologies in the

Mediterranean region, and their relevance to coastal applications similar to the case study site (Arena et al. 2018). The design of the ESS is based on the Galaxy 3420 model, a 3.4 MWh lithium-ion battery storage unit. A constant minimum of 50% of the total storage capacity is always maintained in reserve. This reserve ensures that the port can maintain autonomous operations for a minimum of 8 h in the event of combined HRES and grid power failures. To define the required storage capacity, a rolling sum analysis was conducted on the port's hourly energy consumption data. The maximum cumulative energy demand over an 8-h period was identified and used as the benchmark to ensure that the

system can sustain operations even during peak demand or outage scenarios. For a comprehensive overview, an analytical table detailing the specific technical specifications of all selected technologies is provided in the Appendix.

4.4 Case study scenario conceptualization

The analysis begins with a baseline scenario where the port's energy needs are met solely by the local grid, establishing a benchmark for comparison (Fig. 4). Following this, the study investigates six distinct configurations, each integrating an ESS to provide 8 h of autonomy. These scenarios are divided into two categories based on their optimization goals. The first three are assessed using a single-objective function to minimize the LCOE for systems deploying only wave, only tidal, and a hybrid of both technologies. The subsequent three scenarios are evaluated with a multi-objective approach to find an optimal balance between minimizing both LCOE and the CF for the same wave, tidal, and hybrid RES (Table 2).

To synthesize the physical components and the conceptualized scenarios described above, Fig. 5 presents the complete architectural schematic of the proposed marine-based HRES. This diagram illustrates the physical and logical integration of the breakwater-mounted WECs, the seabed-tethered tidal turbines, and the onshore containerized ESS. By routing these marine generation inputs through an optimization controller to serve the port's variable load alongside the utility grid, this schematic serves as a modular blueprint.

Table 2 Scenario scenario conceptualization summary

Scenario	Grid	WV	TT	Single objective	Multi-objective
0	✓	x	x	x	x
1	✓	✓	x	✓	x
2	✓	x	✓	✓	x
3	✓	✓	✓	✓	x
4	✓	✓	x	x	✓
5	✓	x	✓	x	✓
6	✓	✓	✓	x	✓

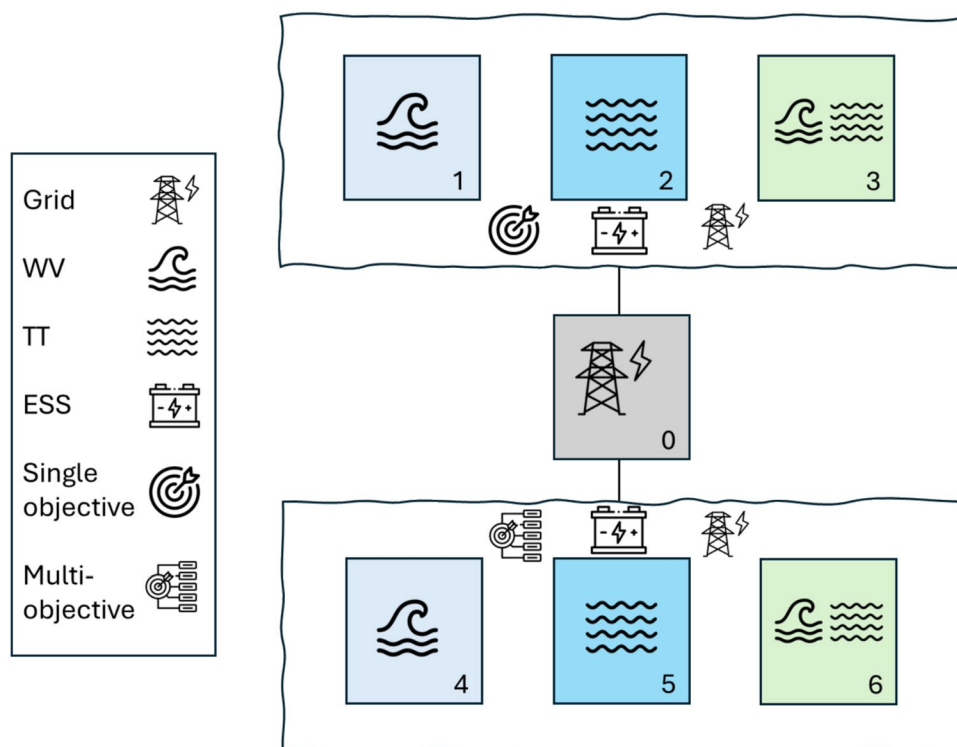
Crucially, this configuration is designed to be highly transferable; it provides a visual roadmap of how this specific hybrid architecture can be replicated at other spatially constrained coastal or island sites pursuing nZEP status.

5 Optimization methodology

5.1 Genetic Algorithm and optimization framework

The simulation and optimization of the integrated HRES and ESS were carried out using a custom-developed Python-based model. A GA was implemented to search for optimal system configurations, following principles similar to those of HOMER Pro while offering enhanced flexibility through

Fig. 4 Scenario visual conceptualization



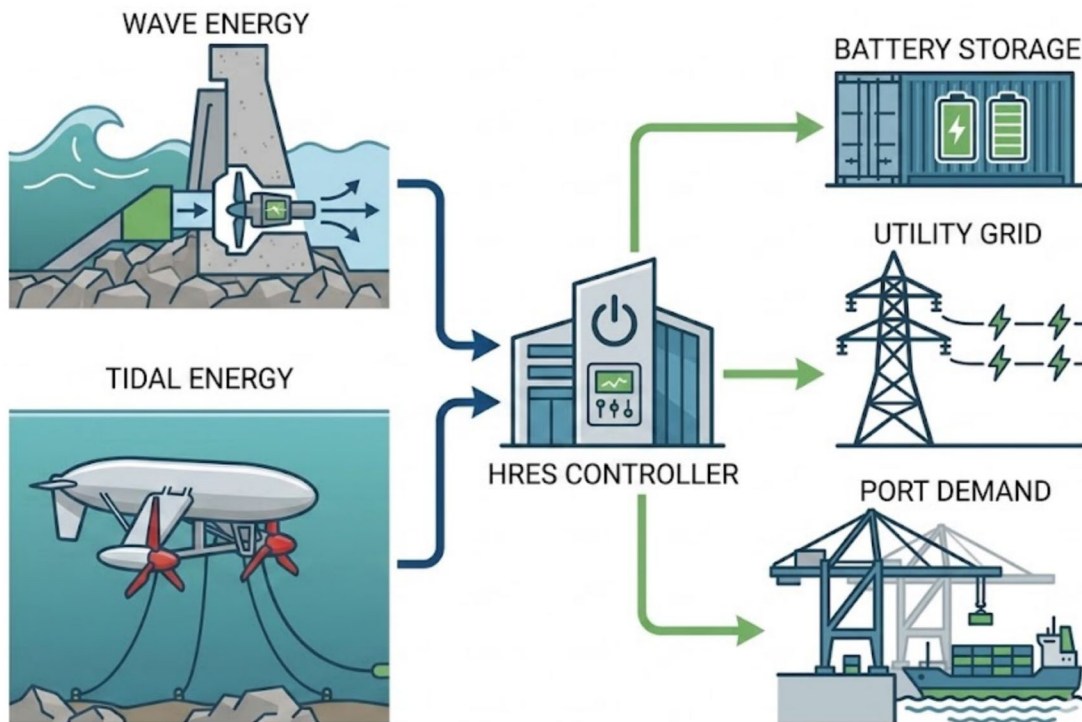


Fig. 5 Schematic representation of the proposed marine HRES

custom-defined parameters such as mutation rates, selection mechanisms, and crossover strategies (Córdoba and Gonzalez-Monroy 1999; Khalil et al. 2021). This approach allowed the model to effectively identify viable and efficient system designs within a large solution space. The Genetic Algorithm (GA) was selected for this study due to its robustness in navigating such large and complex solution spaces, which is characteristic of energy system design. Unlike traditional optimization methods that can get trapped in local optima, GA is a heuristic approach adept at identifying globally optimal solutions.

The simulation process was structured into two main phases, each corresponding to a different optimization objective. The first phase involved single-objective optimization focused solely on minimizing the LCOE, thereby identifying the most economically favorable system configuration (Lu et al. 2015). The second phase employed a multi-objective optimization framework that simultaneously considered both LCOE and the CF of the designed nZEP (Wang et al. 2017). By dynamically incorporating emissions into the optimization objectives, this approach enabled the model to minimize both economic and environmental impacts, thereby promoting a more sustainable and integrated design outcome (Saxena et al. 2023; Tran and Smith 2018). The rationale for this multi-objective framework is that the primary goals, minimizing economic cost and environmental impact, are inherently conflicting. A system configuration that is cheapest is

rarely the most environmentally friendly, and vice versa. A multi-objective approach is, therefore, essential for exploring the trade-offs between these competing objectives, ultimately yielding a set of optimal solutions that represent different balances between cost and sustainability, rather than a single, one-dimensional answer (Fig. 6).

To ensure that neither the economic nor the environmental objective would dominate the optimization process due to their inherently different scales, the LCOE and CF values were normalized. This normalization scales both metrics to a common, dimensionless range, typically between 0 and 1. By dynamically incorporating these scaled emissions into the optimization objectives, this approach enabled the model to minimize both economic and environmental impacts in a balanced manner, thereby promoting a more sustainable and integrated design outcome.

5.2 Mathematical modeling and components specification

HOMER Pro currently lacks built-in functionality for simulating tidal energy systems. However, the same fundamental physical laws that govern wind energy can also be applied to tidal energy, as both technologies rely on fluid flow to drive a turbine and produce electricity (Thapar et al. 2011). The key difference between them is the type of fluid involved: air for wind turbines and water for tidal

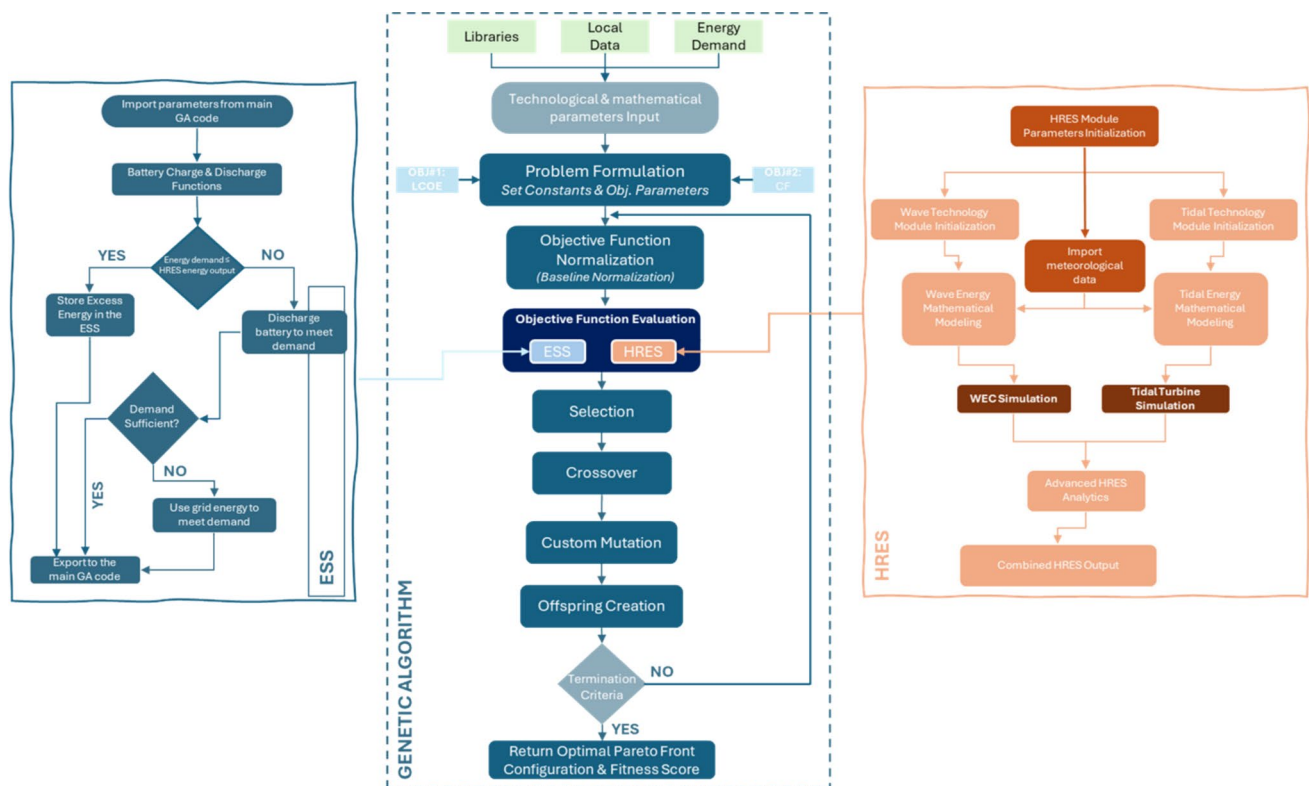


Fig. 6 GA flowchart representation

turbines. Tidal turbine (TT) rotors are developed using principles tailored to the behavior of water flow, aiming to maximize efficiency in capturing kinetic energy from tidal currents (Thomas 2021). The power output from these systems can be estimated using general fluid dynamics equations, modified to reflect conditions specific to aquatic environments. Important parameters in these calculations include the actual water density at a given depth D (represented as d) and the standard water density $d_0 = 1000 \text{ kg/m}^3$. Another critical factor is the power law exponent a , which reflects how flow velocity changes with depth and is influenced by conditions such as seabed texture and water column structure (Jung and Schindler 2021; Rodríguez-Iturbe et al. 1992). The values of a , as well as the depths D and D_i , vary by location and are determined by the characteristics of the local tidal current, which are shaped by depth, bottom friction, and geographical influences.

$$P_{\text{TT}} = \begin{cases} 0V < V_{\text{cut-in}} \text{ and } V \geq V_{\text{cut-out}} \\ P_r \times (V - V_{\text{cut-in}}) & V_{\text{cut-in}} \leq V \leq V_r \\ P_r V_r & V < V_{\text{cut-out}} \end{cases} \quad (1)$$

where,

- P_r is the TT (tidal turbine) rated power.

- $V_{\text{cut-in}}$ is the minimum water speed required for the TT to start producing power.
- $V_{\text{cut-out}}$ is the maximum water speed at which the TT shuts down to prevent damage.

V_r is the rated water speed at which the TT generates its maximum power.

The mathematical expression for wave power per unit length of wavefront is derived from Eq. 2. This equation indicates that the energy available in ocean waves is directly related to the square of the significant wave height, the wave period, and the device's width. The denominator's constant acts as a scaling factor based on the core physics of wave behavior, incorporating both gravitational energy and fluid motion principles (Kurniawan et al. 2022).

$$P = \frac{dg^2}{64\pi} H^2 T \quad (2)$$

Equation 3 is used to estimate the power output of the REWEC3 oscillating water column (OWC) wave energy converter. This system functions by capturing pressure variations caused by incoming waves, which in turn create oscillatory movements of water and air that enable energy generation. The power output and overall performance of the converter are

determined by how effectively these wave characteristics, such as height and frequency, interact with internal oscillations.

$$P_{\text{owc}} = \frac{dg^2}{64\pi} H^2 T w \eta_{\text{owc}} \quad (3)$$

where

- d is the seawater density.
- g is the earth's gravitational force.
- H is the wave's height.
- T is the wave's wave period.
- w is the OWC chamber width.

The system's total efficiency can be determined using Eq. 4.

$$\eta_{\text{owc}} = \eta_p \cdot \eta_t \cdot \eta_g \quad (4)$$

where

- η_p is the OWC chamber's efficiency
- η_t is the turbine efficiency
- η_g is the generator efficiency

5.2.1 Energy storage system

The energy stored in the ESS can be determined using Eq. 5.

$$Q_{\text{ESS}} = Q_{\text{ESS},0} + \int_a^t V_{\text{ESS}} I_{\text{ESS}} dt \quad (5)$$

where

- $Q_{\text{ESS},0}$ is the initial ESS's charge.
- V_{ESS} is the ESS's voltage.
- I_{ESS} is the ESS's current.

To calculate the percentage of the battery's usable energy at any given moment, Eq. 6 is applied. In this context, $Q_{\text{ESS},\text{max}}$ denotes the maximum energy capacity of the ESS in kilowatt-hours, which is derived using Eqs. 7, 8, and 9.

$$B_{\text{SOC}} = \frac{Q_{\text{ESS}}}{Q_{\text{ESS},\text{max}}} \% \quad (6)$$

$$Q_{\text{ess},\text{max}} = \frac{\min(P_{\text{ess},\text{max}}, \text{kbm}P_{\text{ess},\text{max}}, \text{mcr}P_{\text{ess},\text{max}}, \text{mcc})}{\eta_{\text{ess},c}} \quad (7)$$

$$P_{\text{ess},\text{max},\text{kbm}} = \frac{kQ1e^{-\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (8)$$

$$P_{\text{ess},\text{max},\text{mcr}} = \frac{1 - e^{-ac\Delta t}(Q_{\text{ess},\text{max}} - Q_{\text{ess}})}{\Delta t} \quad (9)$$

where

- $\eta_{\text{ESS},c}$ is charging storage efficiency.
- k is the constant for storage.
- Q_1 is the ESS's available energy in the initial time step.
- Δt is the time step's duration.
- Q is the initial available energy.
- c is the ESS's capacity ratio.
- a_c is the ESS's maximum charge rate.
- $Q_{\text{ESS},\text{max}}$ is the total ESS's capacity.
- N_{ESS} is the number of ESS.
- I_{max} is the ESS's maximum charge current.
- V_{nom} is the ESS's nominal voltage.

One method to estimate the charge level involves bringing the battery cells from a fully depleted state up to the desired state of charge (SoC), with the required charge amount (Q_{charge}) calculated using Eq. 10.

Conversely, the discharge process from full capacity down to the intended SoC is represented by Eq. 11, where C_{actual} refers to the actual capacity of the battery cell (Table 3).

$$Q_{\text{charge}} = B_{\text{soc}} \cdot C_{\text{actual}} \quad (10)$$

$$Q_{\text{discharge}} = -(1 - B_{\text{soc}}) \cdot C_{\text{actual}} \quad (11)$$

The GA's fitness function is designed initially with the single objective of minimizing the total LCOE across all ports, as outlined in Eq. 12:

$$[\min F(x)] = \text{LCOE}_{\text{system}} \quad (12)$$

The system's LCOE is determined by the formula in Eq. 13.

$$\text{LCOE}_{\text{system}} = \frac{C_{\text{ann}}}{E_{\text{SERVED}}} \quad (13)$$

In this formula, C_{ann} represents the total annual cost of the system, and E_{SERVED} is the total electrical load served.

Table 3 Technologies capital cost per kW

Technology	Acquisition cost (€/kW)
Wave	3000*
Tidal	5750*
ESS	212
Grid	0.36

*Cost estimates for the experimental REWEC3 and GEM-STAR technologies are sourced from literature, as economic data from their limited Mediterranean deployment are not yet available

The total annual cost (C_{ann}) is calculated with Eq. 14.

$$C_{\text{ann}} = \text{NPC} \cdot \text{CRF}(i, N) \quad (14)$$

This calculation uses the net present cost (NPC) and capital recovery factor (CRF), which is a financial ratio that converts a one-time initial investment into a series of equal annual payments over a specific period. The formulas to find the NPC and CRF are:

$$\text{NPC} = \frac{C_{\text{tot,ann}}}{\text{CRF}_{(i,n)}} \quad (15)$$

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (16)$$

For these calculations:

- i represents the interest rate, set at 5.88%.
- N is the lifespan of the project, which is 25 years.

It is important to note that this research exclusively evaluates the initial acquisition cost of the equipment, which includes the anticipated operation and maintenance (O&M) expenses over the system's expected lifespan. This methodology intentionally focuses on upfront expenditures while incorporating projected O&M costs within the initial purchase price to provide a more streamlined comparison across technologies (Bianchi et al. 2024; Lavidas et al. 2023; Sakib et al. 2025). Regarding the cost analysis for the selected ESS, a key consideration is the difference between the battery's expected 20-year lifespan and the overall 25-year project duration. To account for this 5-year gap, the financial model assumes that the total battery cost will be 2.5 times its initial price per kWh. This multiplier accounts for the necessity of a battery replacement during the project's lifetime to maintain system performance. This cost adjustment is directly integrated into the project's calculation code to ensure a more realistic projection of the total expenses.

The overall cost of the proposed system is calculated by summing up the costs of each of its individual components.

$$C_{\text{total}} = C_{\text{tt}} + C_{\text{wv}} + C_{\text{ess}} \quad (17)$$

where

- C_{TD} is the cost of the GEMSTAR.
- C_{WV} is the cost of the REWEC3.
- C_{ESS} is the cost of the installed ESS

The environmental performance of the HRES and ESS is evaluated by quantifying its GHG emissions in terms of carbon dioxide equivalent ($\text{CO}_2\text{-eq}$). This evaluation utilizes the most current 100-year global warming potential (GWP)

figures provided by the Intergovernmental Panel on Climate Change (IPCC). Comprehensive CF analysis is conducted for every system component, including WECs, TTs, and ESS, as well as for the electricity sourced from the conventional grid. This analysis encompasses all direct and indirect emissions that occur throughout the entire lifespan of each technology. To determine the overall climate impact, the emissions of various pollutants are weighted based on their individual GWP factors. The resulting CF is expressed in grams of CO_2 equivalent per kilowatt-hour ($\text{gCO}_2\text{-eq/kWh}$) of electricity generated. Furthermore, the assessment considers the carbon intensity of the electrical grid. This involves analyzing factors such as the efficiency of converting primary energy sources, consumption of diesel fuel, and the proportional mix of renewable and fossil fuel-based power generation.

$$\text{Emissions} \left(\frac{\text{tn}}{\text{y}} \right) = \frac{E_{\text{grid}} \left(\frac{\text{kWh}}{\text{y}} \right) \times \text{PollutantIndex} \left(\text{g} \frac{\text{CO}_{2\text{eq}}}{\text{kWh}} \right)}{10^6} \quad (18)$$

$$\text{CF}_S = \frac{\sum_{y \in \text{GHG}} \times \text{GWP}_y \times \text{EM}_y}{E_p} \quad (19)$$

$$\text{CF}_{\text{DS}} = F_{\text{PE}} \times F_{\text{D}} \times F_{\text{FF}} = 0.989 \times 0.785 = 0.776 \text{kg} \frac{\text{CO}_{2\text{eq}}}{\text{kWh}} \quad (20)$$

$$\text{NetEnergy} = E_{\text{grid}} - E_{\text{wv}} - E_{\text{TT}} \quad (21)$$

The new multi-objective optimization approach, as described in Eq. 22, constitutes a novel strategy that represents a departure from conventional methodologies. Its primary goal is to concurrently reduce both the LCOE and the CF of the analyzed system. A key novel aspect of this methodology lies in its comprehensive analytical framework. This framework critically addresses the existing argument that the environmental impacts of RES are often overstated. It achieves this by explicitly integrating the LCA-based life-cycle carbon emissions attributable to the manufacturing, transportation, and end-of-life phases of system components, in addition to direct operational GHGs. Consequently, this approach yields a more accurate and holistic evaluation of the system's veritable environmental impact.

$$[\min F(x)] = \text{LCOE}_{\text{system}}, \text{CF}_{\text{system}} \quad (22)$$

In this formulation, $\text{CF}_{\text{system}}$ signifies the overall annual carbon footprint of the entire system. This value is determined by aggregating the carbon emission factors linked to each technology used. To manage the trade-offs between these two competing goals, the multi-objective approach employs a weighted sum method. This technique assigns a specific weighting factor to both the LCOE and the CF

objectives. By adjusting these weights, the optimization can be guided to prioritize one objective over the other, reflecting different strategic preferences. For instance, a higher weight on the CF will steer the solution towards a more environmentally friendly but potentially more expensive configuration, while a higher weight on the LCOE will favor a more cost-effective solution that may have a larger CF. This process generates a set of optimal solutions, from which a balanced configuration that best aligns with the project's overall goals can be selected (Li et al. 2024; Llamas-Orozco et al. 2023; Singhapurage et al. 2025). The CF of the ESS is measured in kgCO₂eq per kWp, reflecting the embodied emissions of its rated capacity. Since the ESS has a 20-year lifespan and the project spans 25 years, a second unit is needed, effectively doubling the CF to around 120 kgCO₂eq (Fig. 7).

5.3 Limitations and assumptions

To simulate HRES within a computational framework, the study adopts specific assumptions to address the gap between digital models and their real-world counterparts. These baseline assumptions enable the exploration of feasible sustainable energy system configurations, as outlined below:

- The wave and tidal energy converters selected are in an experimental stage of development (TRL 4–6). The performance models used are based on theoretical characteristics from existing literature, and their actual operational output may differ significantly in real-world deployments.
- The financial model integrates both component replacement and operational and maintenance (O&M) costs to ensure a comprehensive economic evaluation. Given the experimental and pre-commercial state of the selected marine energy converters (such as the GEMSTAR tidal turbine and REWEC3 OWC), long-term empirical O&M data remains scarce. Therefore, a conservative, “worst-case scenario” approach was adopted to mitigate financial uncertainty. The total battery cost is multiplied by a factor of 2.5. This factor accounts for the mandatory capital replacement of the lithium-ion battery, whose 20-year lifespan falls short of the 25-year project duration, alongside its lifetime O&M expenses. Similarly, the capital costs of the wave and tidal components are multiplied by a factor of 1.5. This 50% buffer acts as a necessary heuristic to accommodate the elevated maintenance requirements, potential component degradation, and unforeseen operational challenges inherent to deploying early-stage technologies in harsh marine environments.

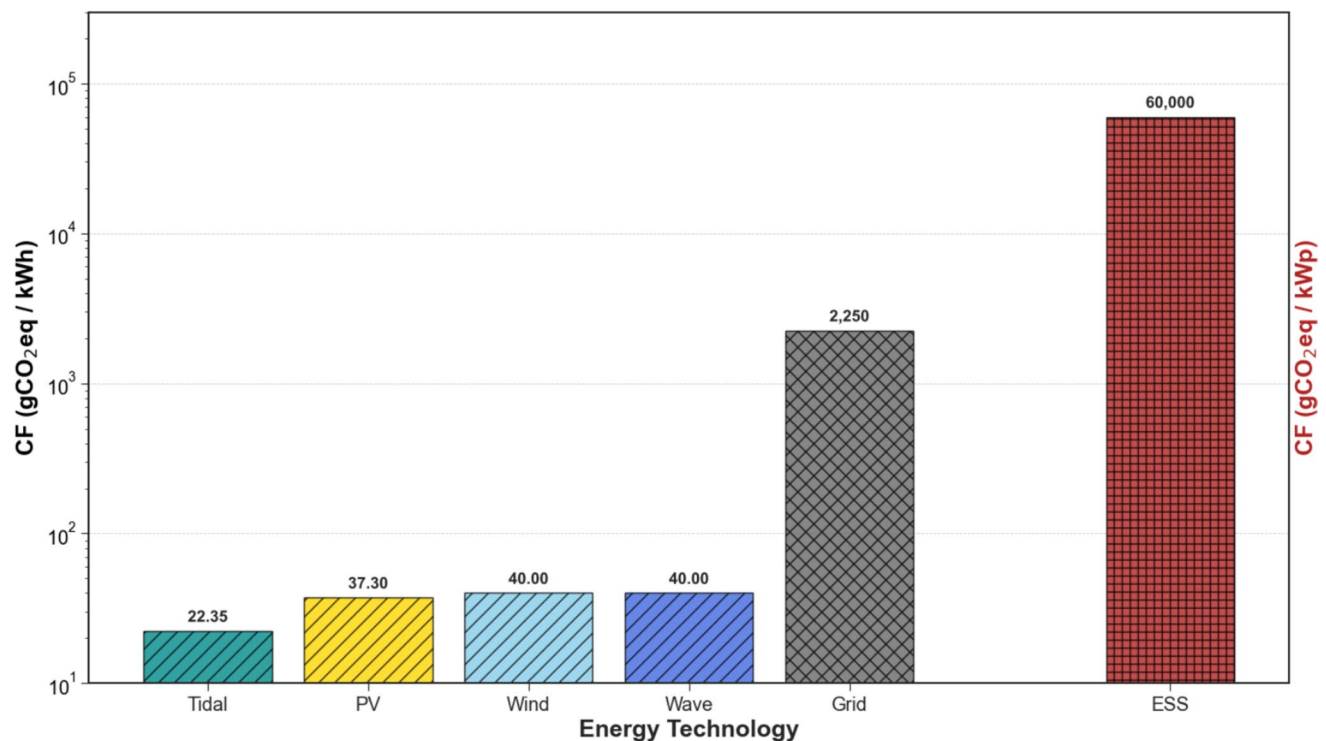


Fig. 7 Comparative analysis of emissions, grid integration efficiency per kWh and ESS per installed capacity among common RES, including tidal and wave technologies

- While the conceptual application of this case study is the port of Chania, the analysis utilizes tidal energy data from the port of Messina, Italy. This assumption was made to test the system's capabilities with a more substantial tidal resource, as the tidal potential in Chania is negligible.
- Despite the integration of Messina's tidal resource data, this research is definitively classified as a 'Souda-based case study.' This is because the optimization model is entirely grounded in the exact, empirically validated, high-resolution energy demand profile of the Port of Souda, as well as its specific infrastructure layout and spatial constraints. By superimposing a high-potential tidal resource onto Souda's actual operational load, the study successfully validates the transferability and resilience of the mathematical framework under optimal marine conditions. However, because the resource inputs are a hybridized theoretical archetype rather than a reflection of Souda's local hydrodynamics, the resulting optimal configurations are indicative of the framework's overarching capabilities.
- The study employs a GA for optimization. While effective for complex problems, GAs have inherent limitations, including the risk of converging on a locally optimal solution rather than the true global optimum. The results are also sensitive to the algorithm's parameter settings.
- The mathematical equations used to simulate the system are simplified representations of highly complex physical and electrical interactions. This study does not model real-time grid integration challenges, power quality issues, transient effects, or component degradation.
- The multi-objective analysis uses a weighted-sum approach to balance the competing goals of minimizing LCOE and CF. This method, while standard, simplifies a complex decision-making process. The final "optimal" solution is highly dependent on the specific weights chosen, which may not fully capture the nuanced priorities of all stakeholders.
- The use of tidal data from Messina means the results, particularly for scenarios involving tidal power, are not directly transferable to Chania. A dedicated, site-specific study would be required to accurately assess the feasibility of such a system in Crete.

5.4 Business model for the proposed system

The proposed port energy business model integrates a marine-based HRES comprising tidal and wave energy technologies coupled with an ESS, configured via scenario-based, dual-objective optimization. The primary aim is to minimize both LCOE and CF through a two-stage strategy: economic optimization followed by cost–emissions trade-off

analysis. Six system configurations are evaluated to identify the most viable hybrid architecture. The model aligns with regulatory and funding mechanisms, including NECP, ESEK, EU ETS, and CEF, while its operational design is consistent with energy management standards (ISO 50001) and sustainable community development frameworks (ISO 37101). Implementation is assumed through a PPP involving the port authority, marine technology providers, and regulatory stakeholders, enabling technical feasibility and financial de-risking. This collaborative arrangement reflects the emerging paradigm of localized energy communities and industrial clusters, wherein port stakeholders collectively participate in the energy transition through shared infrastructure and coordinated resource management. The framework is transferable to similar coastal and island environments facing space constraints and energy transition targets, offering a replicable blueprint for low-carbon, marine port energy systems under blue economy strategies.

6 Results

After the simulation of the six scenarios conceptualized, a detailed assessment of the proposed systems is conducted. The study aims to provide insights into how wave and tidal energy can operate on their own and complement each other in a hybrid implementation while at the same time depicting the difference between single and multi-objective optimization towards a conventional port transition towards a nZEP using maritime energy.

The results of the research are summarized in Table 4 where the most important economic indicators are demonstrated, each technology contribution in the total energy mix as well as the CF reduction when compared to the initial base case scenario. The table columns provide specific data for each scenario. Tidal capacity and wave capacity report the optimal installed electrical generation capacities for tidal and wave energy converters, respectively, as determined by the GA. Economic metrics include the LCOE, the NPC* and the PP*. For energy contributions, RES contribution shows the percentage of total annual energy demand met by the combined RES, while tidal contribution and wave contribution specify the individual percentages supplied by each technology. Lastly, CF reduction illustrates the environmental benefit by quantifying the percentage decrease in GHG emissions from integrated renewable systems compared to the baseline.

6.1 Single-objective approach

For the initial category assessed under single-objective optimization, scenario 3 emerges as the optimal solution. This scenario integrates an HRES distinguishing itself

Table 4 Economic and environmental performance of all proposed HRES configurations

Scenario	Tidal capacity (kWp)	Wave capacity (kWp)	LCOE (€)	NPC (€)*net present cost	PP (years)*payback period	RES contribution %	Tidal contribution %	Wave contribution %	CF reduction %
1	0	420	0.1953	3,042,004	8.28	77.70	0	77.7	67.74
2	250	0	0.2160	3,311,399	9.38	73.80	73.8	0	66.43
3	117	261	0.1784	2,631,980	7.56	87.76	30	57.3	82.90
4	0	420	0.1953	3,042,004	8.28	77.70	0	77.7	67.74
5	250	0	0.2160	3,311,399	9.38	73.80	73.8	0	66.43
6	139	239	0.1791	2,650,595	7.64	87.96	41.34	46.62	88.33

from scenarios 1 and 2, which rely solely on separate tidal or wave energy installations to meet the port's demand. The hybrid and complementary approach of this optimization, leveraging both maritime renewable technologies, demonstrably achieves the lowest LCOE, as each technology effectively mitigates the limitations of the other.

The specific configuration yielding this optimal LCOE incorporates 117 kW of capacity for tidal energy and 261 kW for wave energy, collectively achieving a RES penetration of 87.76%. As depicted in Fig. 8, the winter months provide the most robust energy production, followed by late autumn, primarily attributed to the increased wave energy implementation within the HRES. Furthermore, the HRES output histogram reveals that the selected system predominantly operates at low energy output levels; however, it does occasionally attain higher, specific production thresholds, with instances of very high output remaining rare.

The total energy production per technology compared to the energy demand is demonstrated in Fig. 8 that depicts a radar chart that demonstrates the annual HRES production in kw per month which verifies the previous findings about the HRES output seasonality with tidal being more productive in the summer months (Fig. 9).

As depicted in Fig. 10, the ESS discharge is concentrated during high-demand periods in the morning and evening, while remaining minimal or zero for the majority of the day. This is confirmed by a discharge histogram showing that the ESS is mostly idle, resulting in a total annual throughput of 402,813 kWh/year. This pattern demonstrates the battery's primary role is for peak shaving and providing supplemental power when primary generation is insufficient.

The average daily energy profile of the port (Fig. 11a), characterized by consistent discharge in the early morning and late afternoon/evening, serves to bridge the gaps in supply throughout the year, as seen in the monthly energy profile. For the monthly profile (Fig. 11b), the HRES energy production, which totals 932,969 kWh per year, is visibly higher in the winter months.

The analysis reveals a substantial reduction in total CF when transitioning from a grid-only system, which recorded 1,967.90 tons CO₂eq, to a HRES integrated with the grid, with a footprint of 335.50 tons CO₂eq and a CF percentage reduction that reaches up to 82% (Fig. 12). This underscores the significant environmental benefits of renewable energy adoption.

To understand the individual contributions of each marine technology, two standalone scenarios were simulated:

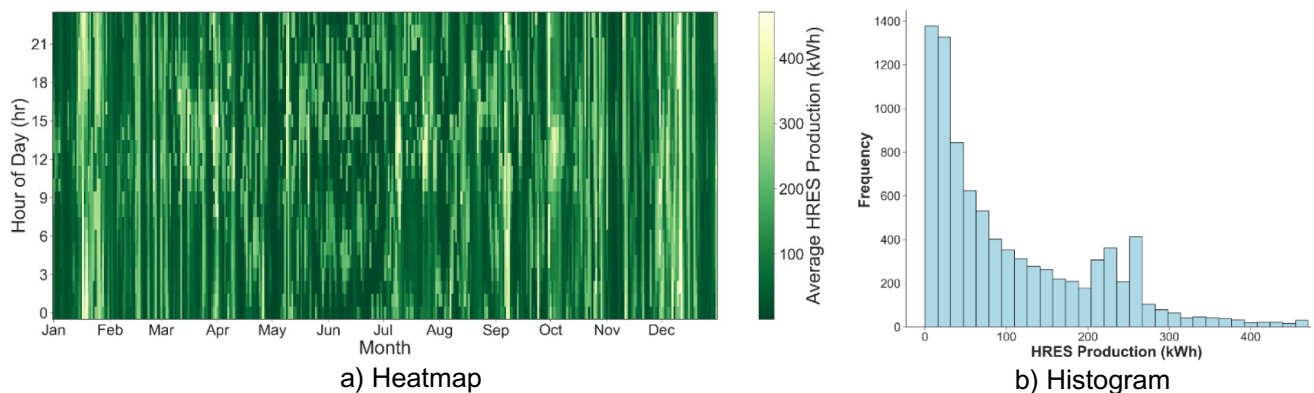
**Fig. 8** HRES energy output (Scenario 3)

Fig. 9 Radar chart of HRES monthly output in comparison to the energy demand (Scenario 3)

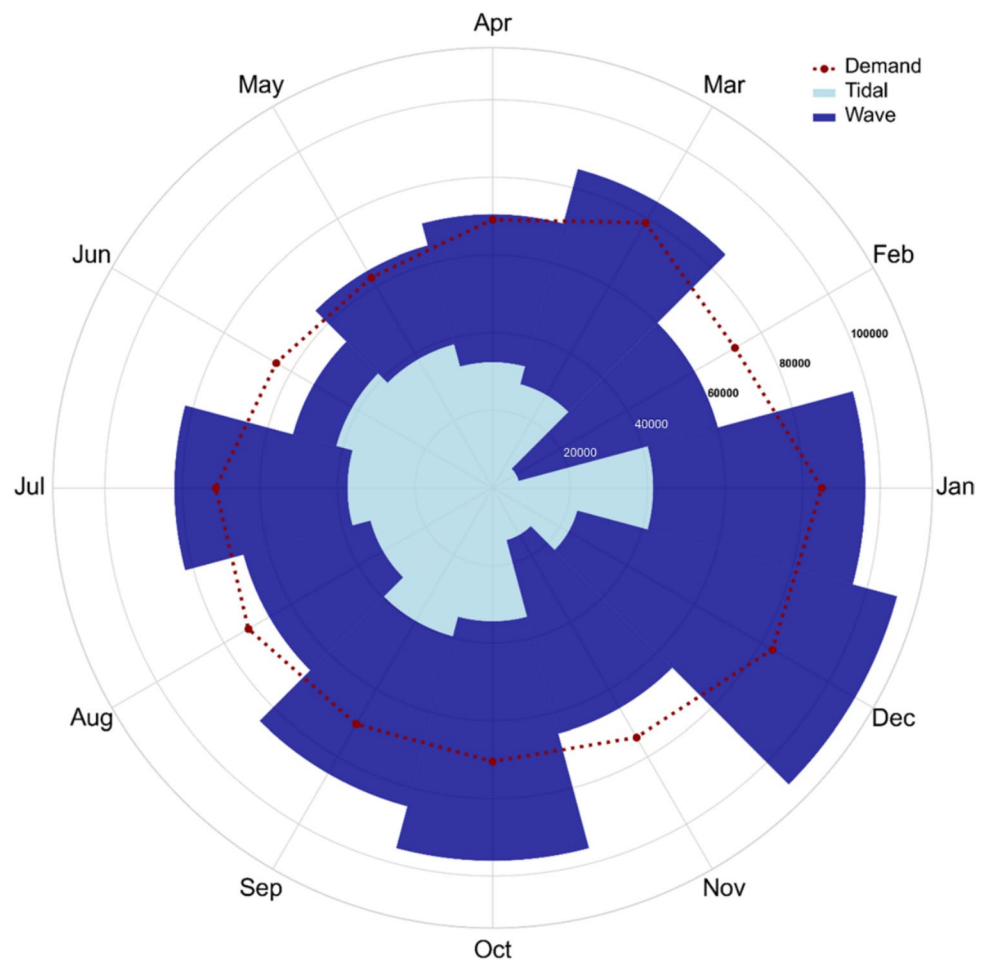
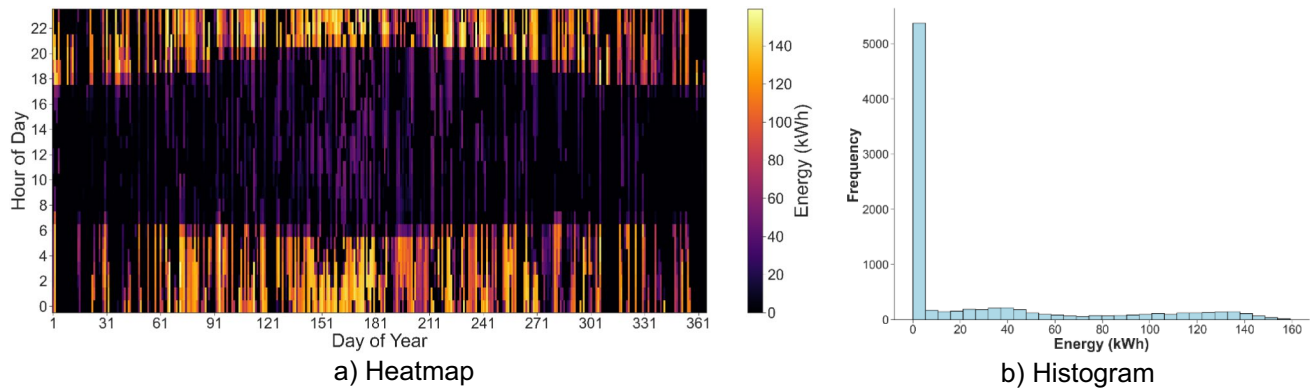


Fig. 10 ESS energy discharge (Scenario 3)

wave-only and tidal-only, with their monthly energy profiles shown in Fig. 13.

The wave-only system (Fig. 13a) exhibits strong seasonal dependency, with high generation in winter and very low output in summer, leading to significant grid reliance

during summer months. In contrast, the tidal-only system (Fig. 13b) provides more consistent and predictable year-round generation driven by lunar cycles, which, while more stable, may require steady grid supplementation to meet demand.

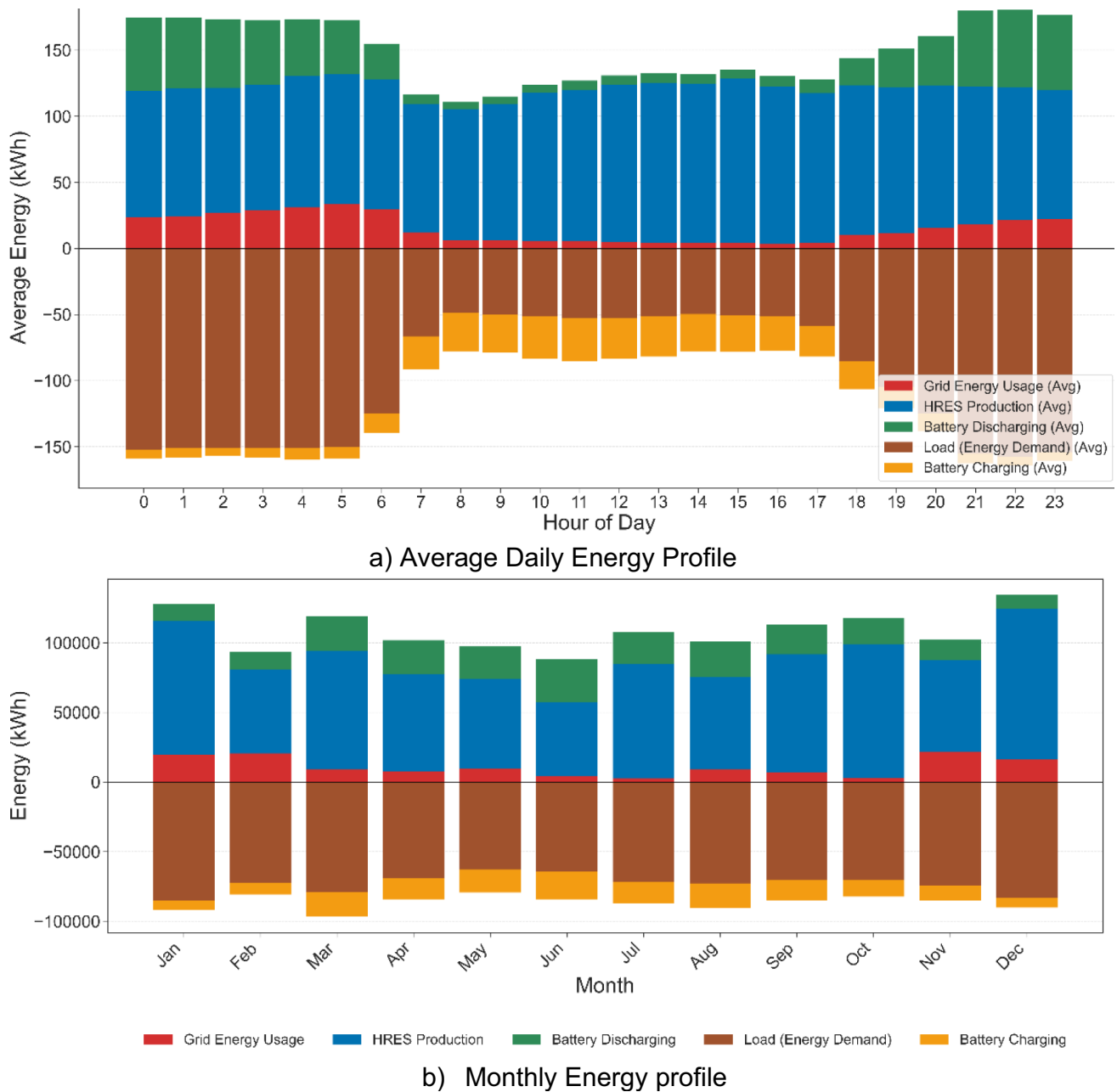


Fig. 11 Energy profile (Scenario 3)

6.2 Multi-objective approach

Scenario 6 demonstrates multi-objective optimization, which strategically reconfigures the system to balance both economic cost (LCOE) and environmental impact (CF). This approach prioritizes emissions reduction, resulting in a different HRES composition: an increased tidal capacity (139 kW) complemented by a slightly reduced wave capacity (229 kW). As shown in Figs. 14 and 15, this shift towards higher tidal integration, while accepting a marginal cost increase, yields a more consistent and evenly distributed

energy output throughout the year compared to the single-objective scenarios.

The ESS maintains a consistent operational strategy, as illustrated in Fig. 16. Its discharge pattern remains concentrated during high-demand periods in the mornings and evenings, while the system is mostly inactive at other times. The total annual throughput is 433,202 kWh/year, representing a 7.5% larger use of the battery compared to the single-objective scenario.

The energy profile in this multi-objective scenario (Fig. 17) reveals a strategic seasonal shift. The monthly

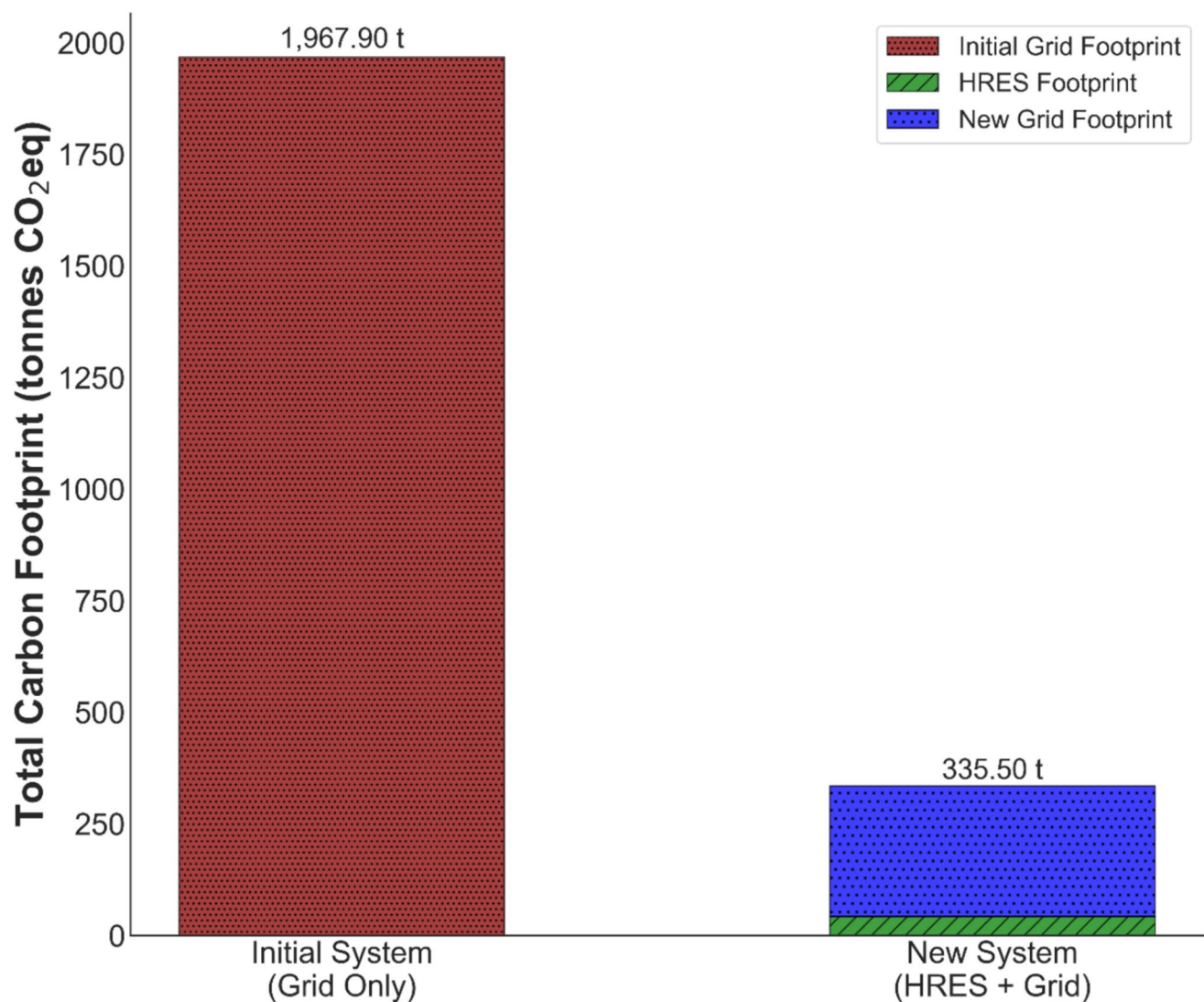


Fig. 12 Initial and new system's CF (Scenario 3)

profile now shows higher HRES output in summer and slightly lower output in winter trade-off from the increased tidal energy used to balance emissions with energy yield. Despite this seasonal reallocation, the daily profile aligns consistently with port demand, and the combined HRES and ESS system effectively ensures a stable, year-round energy balance with reduced grid reliance.

The analysis indicates a significant decrease in overall carbon emissions when shifting from a fully grid-dependent system, which produces approximately 327.97 tons of CO₂eq, to a hybrid configuration integrating RES, resulting in a reduced footprint of tons of CO₂eq with a percentage reduction reaching up to 83% (Fig. 18). This outcome highlights the considerable environmental advantage offered by the adoption of marine-based RES.

Scenarios 4 and 5 yield identical outcomes to scenarios 2 and 3, respectively. This is because applying a multi-objective framework does not change the optimal configuration when only a single technology is used. This result underscores the inherent inflexibility of standalone systems and highlights the added value of hybrid configurations in balancing multiple objectives.

6.3 Discussion

The comparative evaluation of six modeled configurations reveals that hybrid marine-based HRES architectures (scenarios 3 and 6) outperform single-technology systems in both techno-economic and environmental dimensions. Scenario 3, optimized solely for cost, achieves the lowest

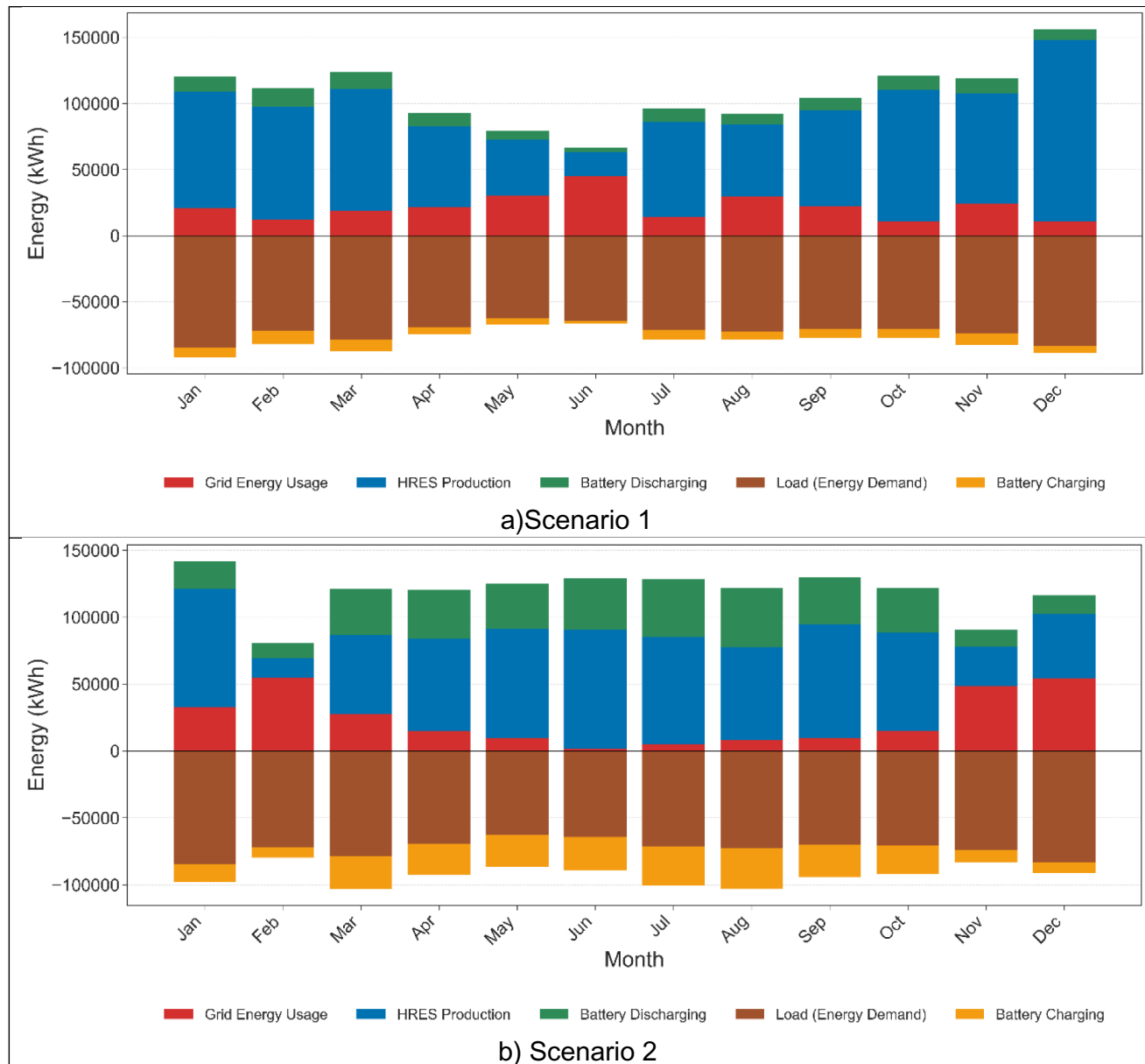


Fig. 13 Monthly energy profile

LCOE (€0.1784/kWh) and a 7.5-year payback period, making it the most economically favorable configuration. In contrast, Scenario 6, derived from multi-objective optimization, incurs only a marginal increase in LCOE (€0.1795/kWh) while delivering a superior CF reduction (88% vs. 82%). This demonstrates that substantial environmental benefits can be achieved at minimal additional cost. The performance divergence is rooted in system architecture: Scenario 3 emphasizes wave capacity (249 kW), whereas Scenario 6 increases tidal capacity (139 kW) and slightly reduces wave input, yielding a more stable annual output and improved emissions profile. Scenario 6 also increases ESS utilization

(433,202 vs. 402,813 kWh/year), highlighting its role not only in economic load shifting but also in enhancing emissions mitigation by decoupling the system from the grid. Scenario 3 may suit applications focused on rapid capital recovery, while Scenario 6 supports longer-term sustainability objectives aligned with integrated decarbonization planning.

To provide a direct visualization of the trade-off between LCOE and CF, Fig. 19 maps the distribution of the evaluated solutions under the two different objective weighting schemes. By plotting the performance of all scenarios based on their relative reductions compared to the grid-only

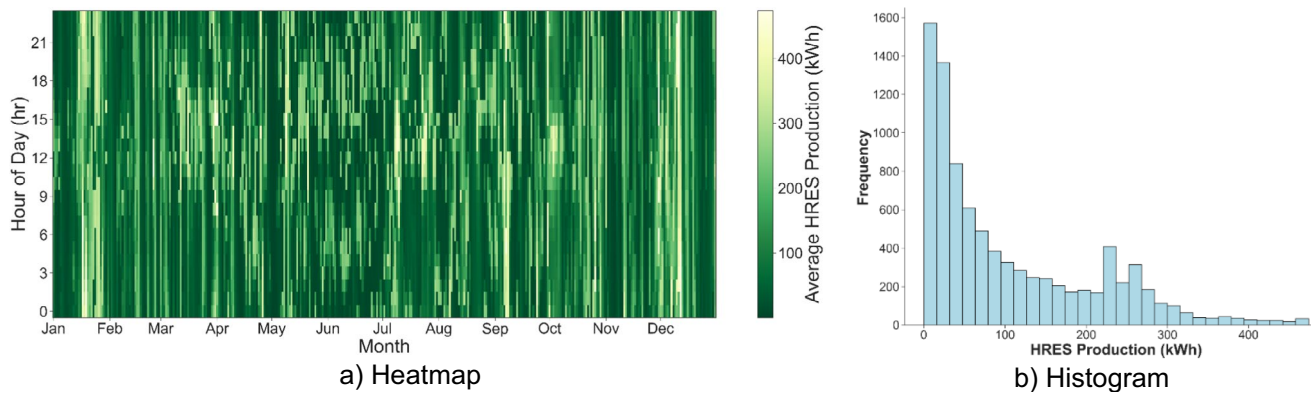
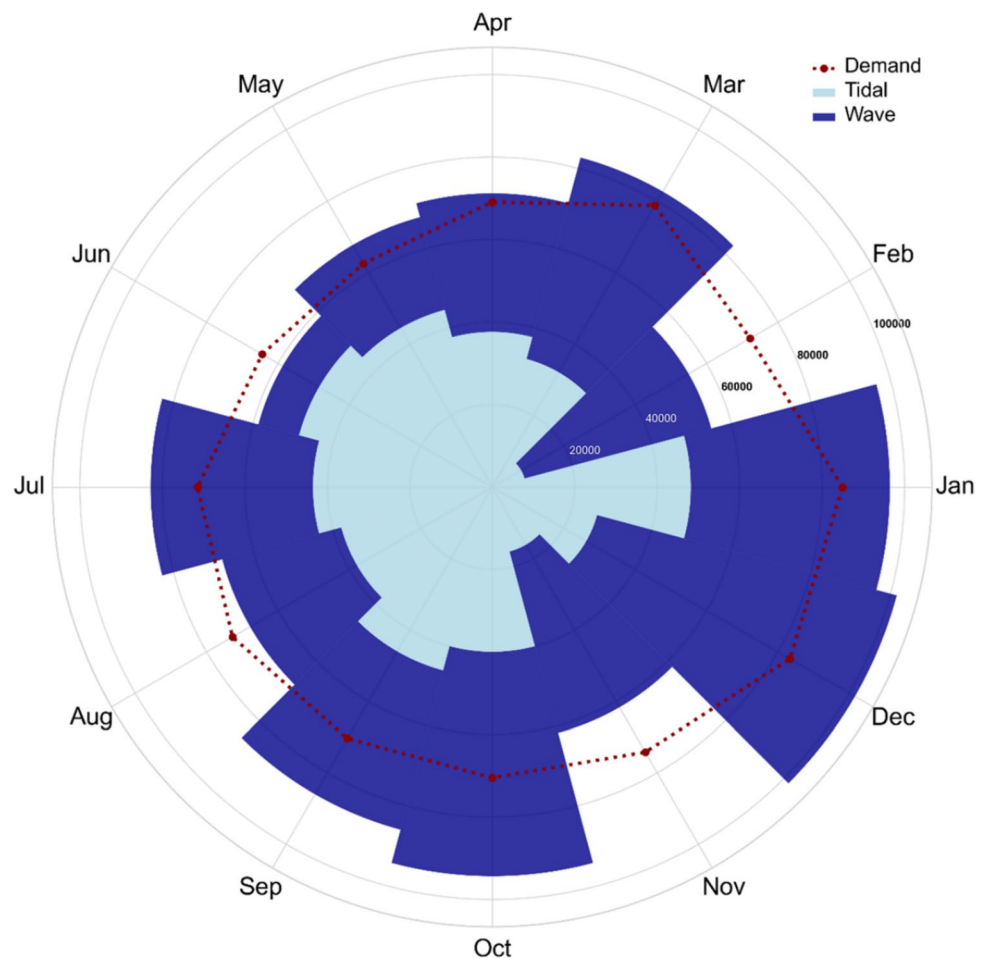


Fig. 14 HRES energy output (Scenario 6)

Fig. 15 Radar chart of HRES monthly output in comparison to the energy demand (Scenario 6)



baseline, the optimal solutions naturally cluster toward the top-right quadrant. The scatter plot clearly demonstrates the performance gap between the standalone systems and the highly efficient hybrid configurations. Furthermore, the visualization highlights a key characteristic of the GA's performance: optimization, whether guided by a single- or multi-objective weighting scheme, functions with high precision

and consistency in single-component configurations. This is evidenced by the exact identical reduction percentages achieved when optimizing the wave-only architectures (Scenarios 1 and 4) and the tidal-only architectures (Scenarios 2 and 5). Most importantly, the plot visually validates the strategic value of the multi-objective approach (Scenario 6): by sacrificing a negligible fraction of economic savings (a

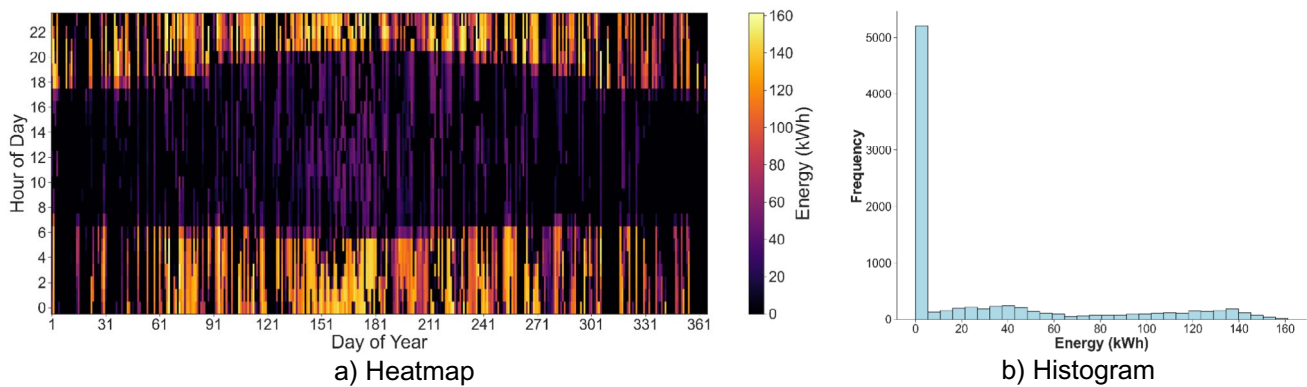


Fig. 16 ESS energy discharge (Scenario 6)

shift from a 50.44% to a 50.25% LCOE reduction compared to the purely cost-focused Scenario 3), the system secures a substantial leap in environmental performance, elevating the CF reduction from 82.90% to 88.33%.

To directly visualize the internal trade-off mechanics of the multi-objective optimization, Fig. 20 presents the Pareto front generated from the extensive iterations evaluated by the GA for the multi-objective hybrid system (Scenario 6). The scatter plot illustrates the vast distribution of system configurations explored by the algorithm as it navigated the solution space. The lower-left boundary of this distribution cloud represents the non-dominated solutions, the true Pareto front, which clearly demonstrates the inverse relationship between minimizing costs and reducing emissions. The specific optimal configuration selected for Scenario 6 is highlighted on this curve, visually validating its strategic position as a balanced compromise that secures maximum environmental benefits without incurring prohibitive economic penalties.

These results carry significant implications for the decarbonization of coastal infrastructures, particularly ports where land constraints often limit deployment of large-scale PV or wind installations. By relying solely on marine-based renewables, this study provides a viable alternative pathway for port energy autonomy. Although the achieved LCOE values may exceed those of some land-based PV–wind systems, the strategic advantages of marine HRES, such as harnessing local ocean resources, improving resilience, and operating within spatially constrained environments, offset these differences. Beyond their minimal land footprint, marine renewables offer unique operational and environmental benefits. Tidal energy, in particular, provides highly predictable generation governed by astronomical cycles, reducing reliance on fossil-fueled spinning reserves and enhancing grid stability. Additionally, the high power density of water allows for compact, less visually intrusive installations compared to wind turbines of equivalent capacity, reducing visual impact and increasing social acceptability. As such,

the environmental case for marine HRES extends beyond direct emissions reduction to encompass improved reliability, esthetic integration, and system-level sustainability. Realizing these benefits at scale will require supportive institutional frameworks and socio-technical instruments, including standardized energy management protocols, collaborative governance models, and structured technology maturation pathways, to operationalize the energy transition within port and coastal planning contexts.

6.4 Sensitivity analysis

The sensitivity analysis separates the system's influencing factors into two clear categories. Figures 21, 22, and 23, which analyze financial variables, show that changes in capital cost, grid cost, or discount rate only affect the economic outcome. In these figures, plot (b) shows a direct rise in LCOE, while plot (a) and the CF remain completely flat, indicating that the system's physical operation and environmental impact are independent of these costs.

In contrast, Figs. 24, 25, and 26 demonstrate high sensitivity to physical parameters. The figures for energy demand show that as demand increases, grid imports (Plot a) rise, causing a detrimental increase in both LCOE and CF (Plot b). Conversely, the figures for wave and tidal resources show that increased availability improves self-sufficiency (Plot a) and delivers a dual benefit: a reduction in both LCOE and emissions (Plot b). Notably, the figures reveal the system is most sensitive to changes in the wave resource, leading to more significant performance variations.

The sensitivity analysis reveals distinct system behavior under economic versus physical parameter variations. Financial factors such as capital cost, grid tariffs, and discount rate affect only the LCOE, leaving CF and energy flows unchanged. This decoupling confirms that the system's structural configuration and energy dispatch are insensitive to economic input shifts. Across all cases, the stability of RES-to-demand and grid reliance demonstrates that

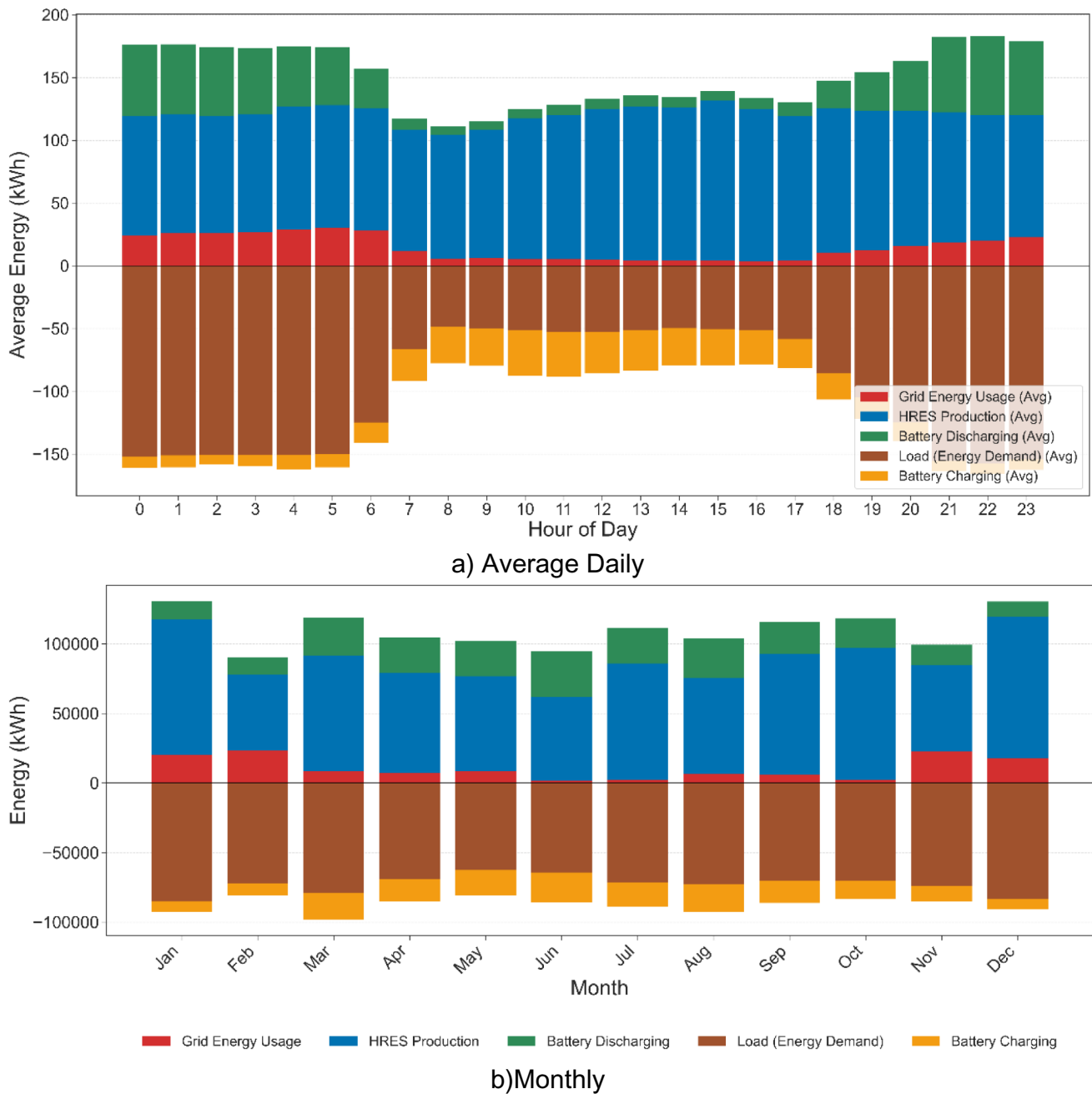


Fig. 17 Energy profile (Scenario 6)

financial stressors do not compromise system performance, affirming its economic robustness and viability under varying cost environments.

In contrast, the system responds strongly to changes in physical conditions. Increases in energy demand or reductions in marine resource availability (wave or tidal) lead to deteriorated performance in both LCOE and CF. Enhanced wave or tidal inputs improve self-sufficiency, reducing grid dependence and emissions. However, the system exhibits greater responsiveness to wave conditions, suggesting that

wave resource variability exerts more influence on performance outcomes. Export energy patterns confirm that higher marine input scenarios lead to greater renewable surplus, reinforcing the importance of accurate site-specific marine resource characterization. The baseline configuration (multipliers = 1.0) emerges as the most balanced scenario, achieving an optimal trade-off between cost and emissions. It performs reliably under expected average conditions but reveals diminishing returns or penalties when stressed by unfavorable physical shifts.

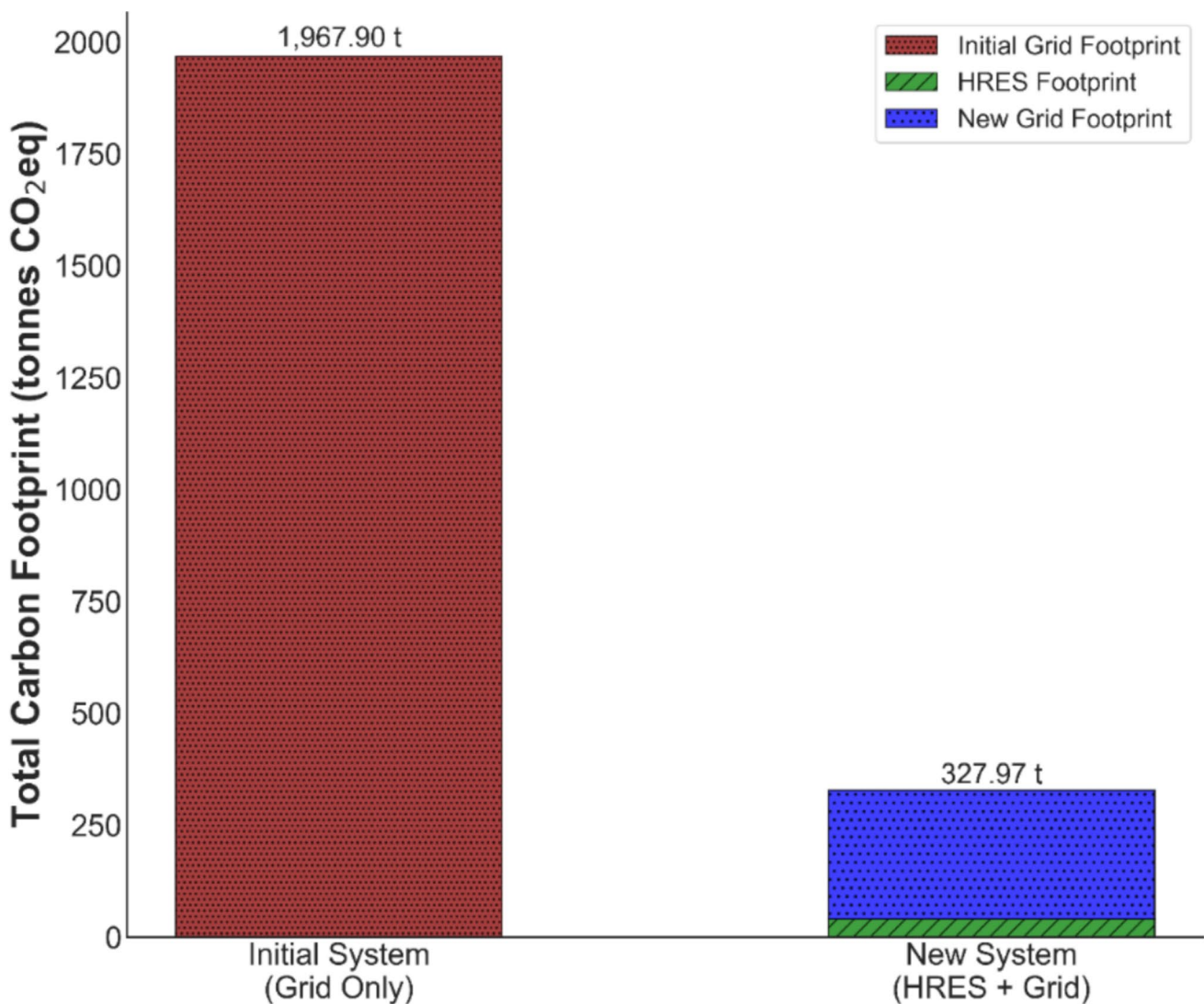


Fig. 18 Initial and new system's CF (Scenario 6)

6.5 Comparative analysis with past studies

The findings of this study demonstrate competitive techno-economic performance when evaluated against comparable HRES configurations in the literature (Table 5). The achieved LCOE reduction of 50.25% situates the proposed system within the upper performance tier of studies that utilize less conventional renewable energy sources. While some references report higher LCOE reductions, e.g., exceeding 65% and (Cholidis et al. 2025a, b) reaching 53%, these results are primarily associated with mature and widely deployed technologies such as PV and wind. In contrast, the current study achieves its reduction using exclusively marine-based inputs (wave and tidal), which remain in early-stage deployment and are characterized by higher capital costs and limited commercial experience. Therefore, the observed economic performance is notable and validates

the viability of marine HRES even under current cost constraints. The PP of 7.64 years further confirms the economic soundness of the proposed configuration. It outperforms most studies where PP exceeds 8.5 years (Wang et al. 2019; Rehman et al. 2020) or remains unreported. Notably, only a few configurations, such as with 3.17 years, report faster returns, but again, these are based on more conventional systems with mature deployment economics. Relative to this context, the reported PP reinforces the system's investment potential, especially for port authorities and stakeholders seeking medium-term cost recovery within infrastructure lifecycles.

This research also diverges methodologically from prior works. As highlighted in Table 5, most comparative studies either apply mono-objective optimization or lack integrated assessment of environmental trade-offs. By contrast, the present framework employs a dual-objective GA minimizing

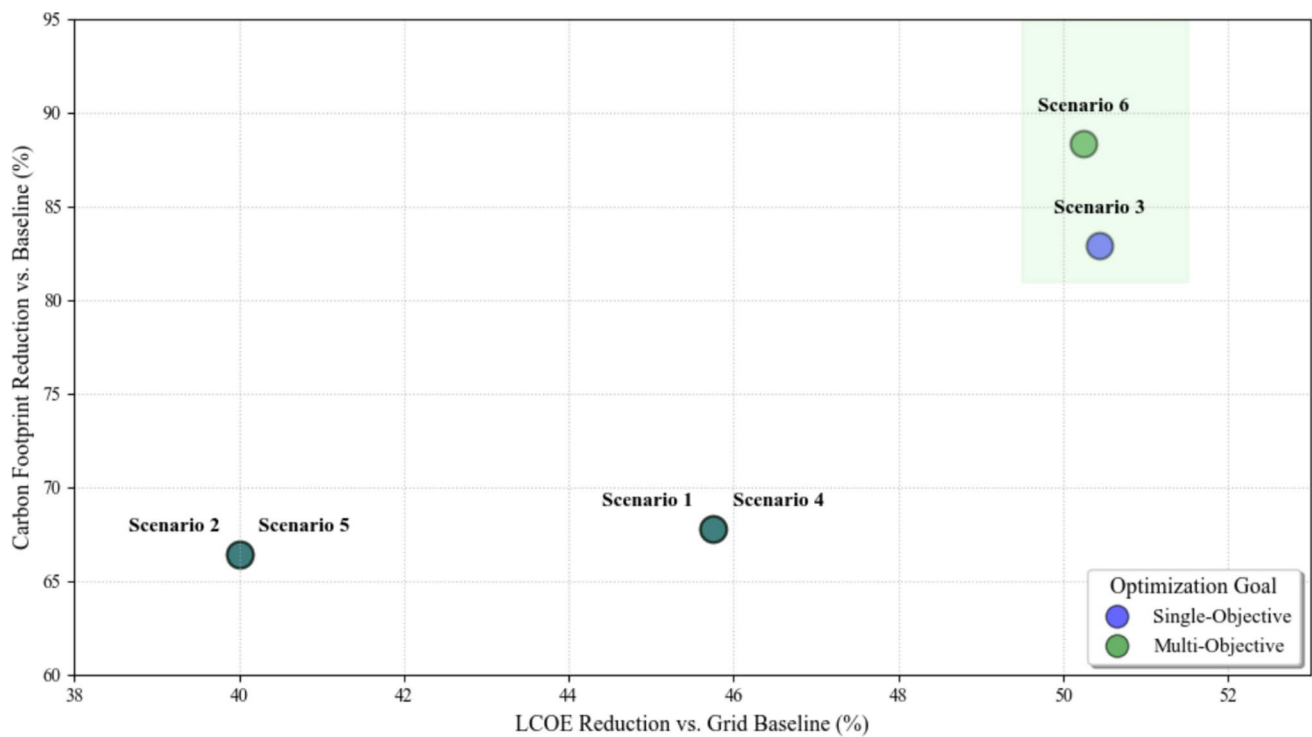


Fig. 19 Distribution of optimal solutions among the six evaluated scenarios

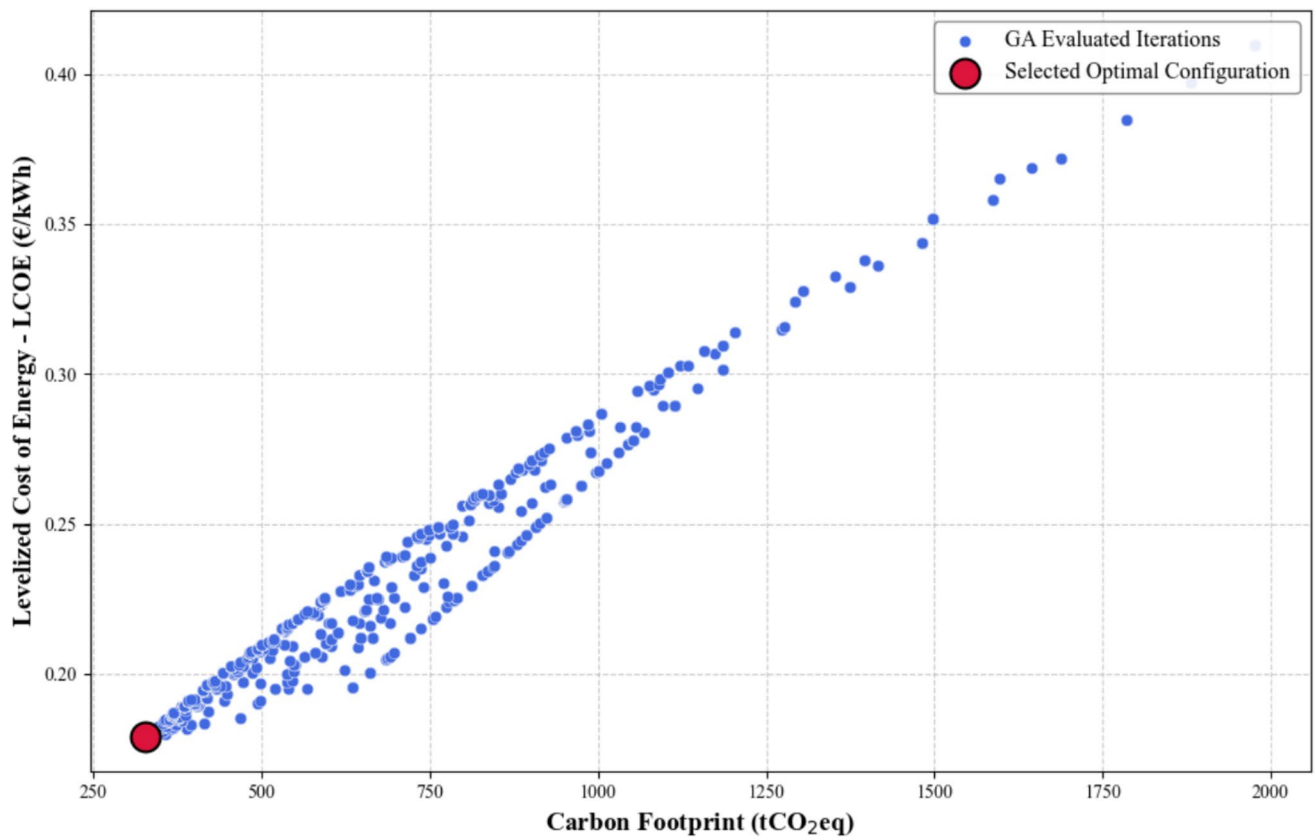


Fig. 20 Distribution of all solutions in the hybrid multi-objective analysis (Scenario 6)

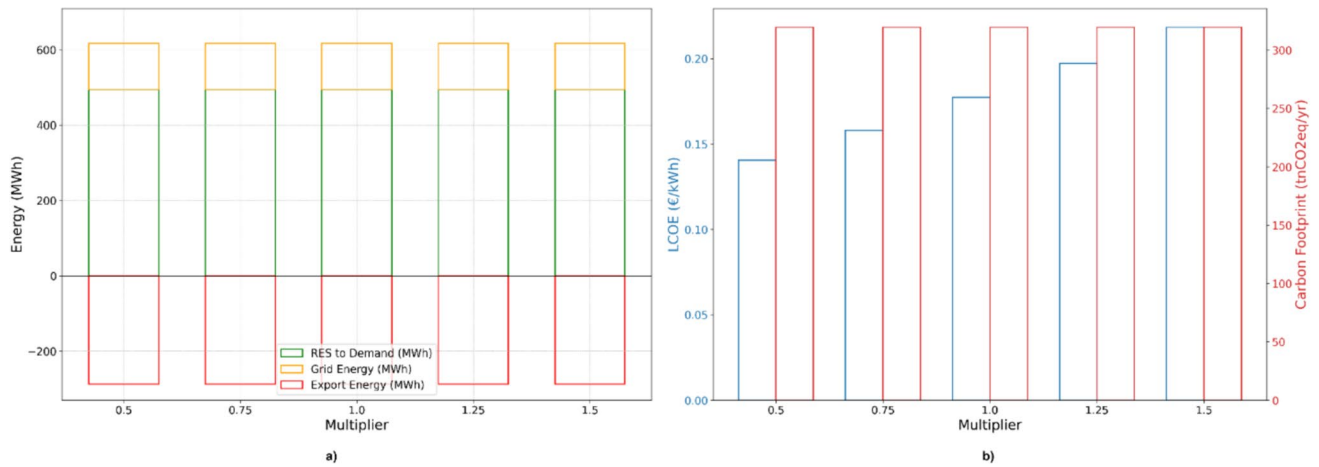


Fig. 21 Sensitivity analysis of the discount rate showing the impact on **a** the energy profile and **b** the LCOE and carbon footprint

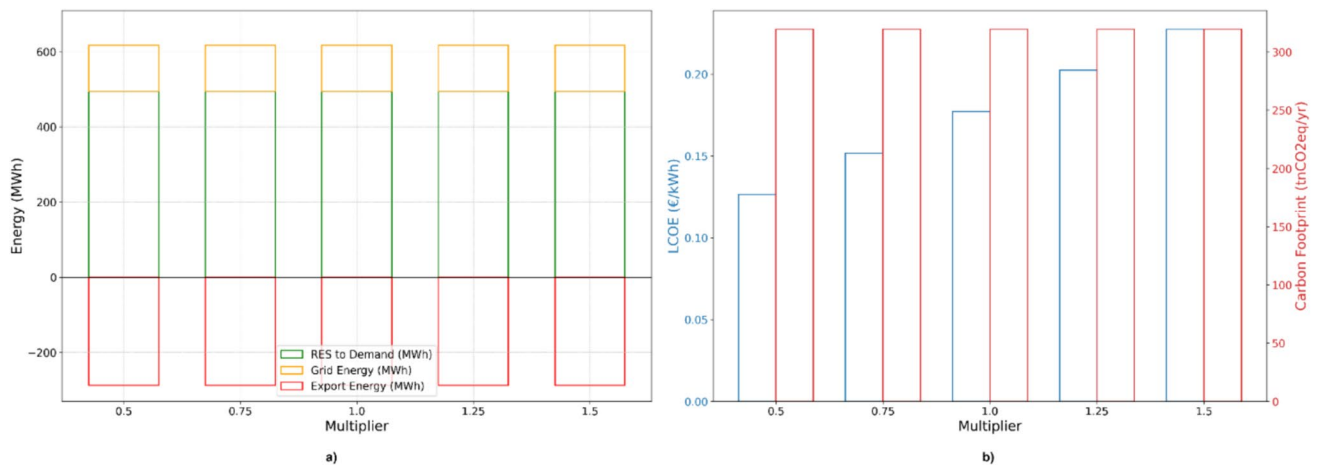


Fig. 22 Sensitivity analysis of the capital cost showing the impact on **a** the energy profile and **b** the LCOE and carbon footprint

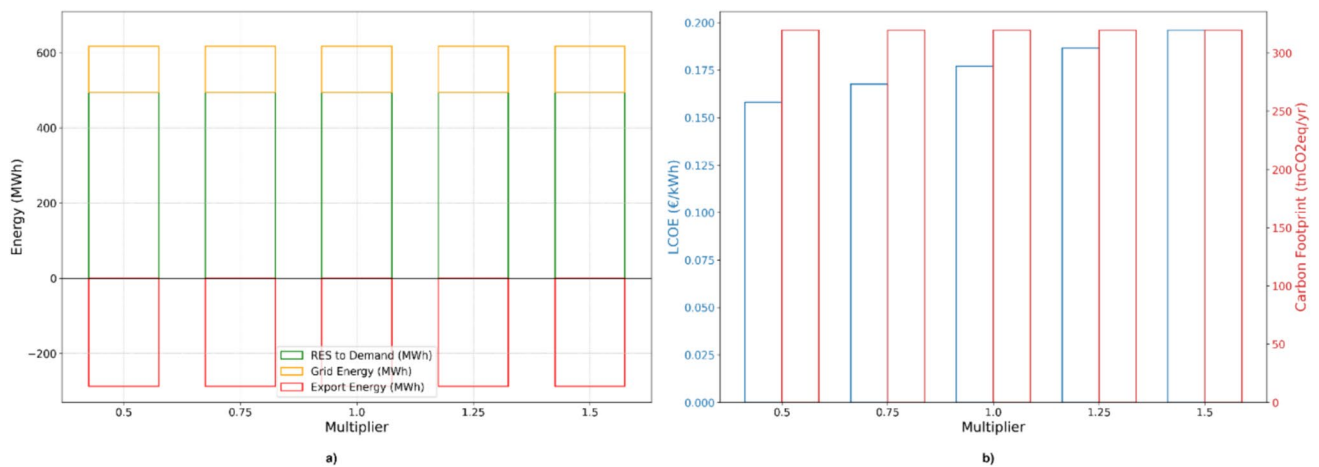


Fig. 23 Sensitivity analysis of the grid cost, showing the impact on **a** the energy profile and **b** the LCOE and carbon footprint

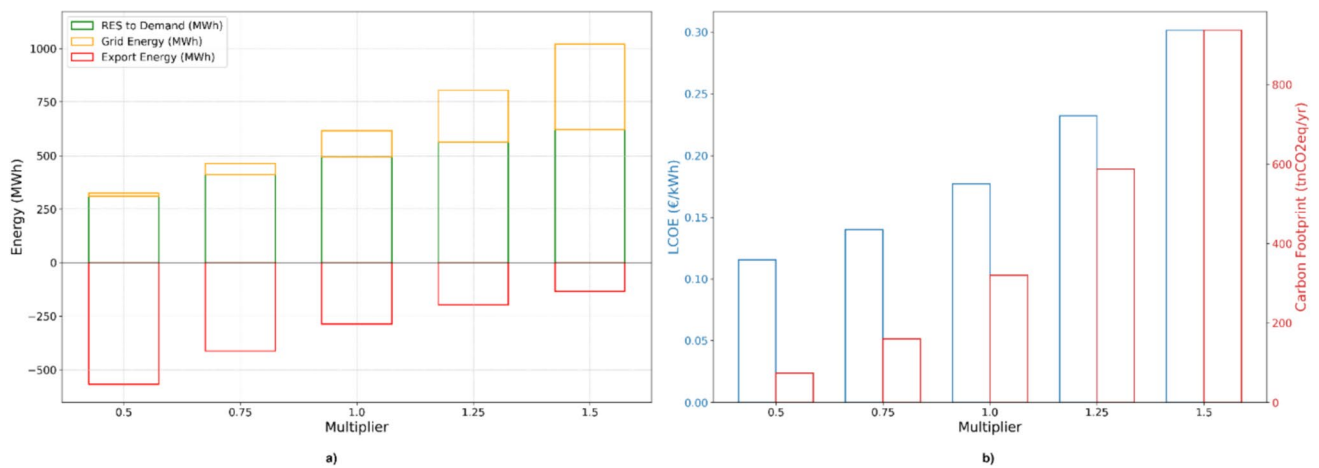


Fig. 24 Sensitivity analysis of the energy demand, showing the impact on **a** the energy profile and **b** the LCOE and carbon footprint

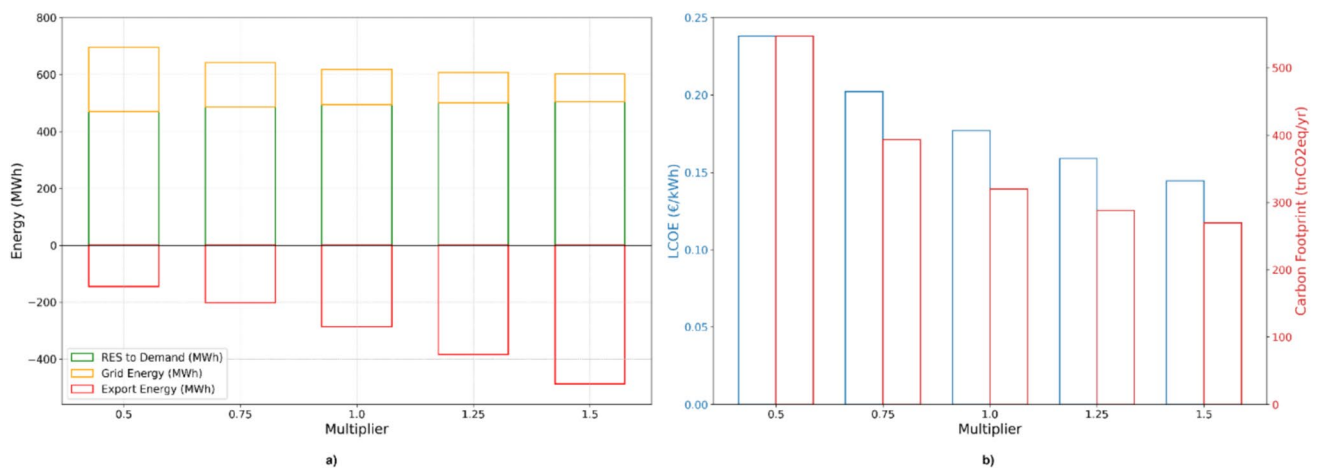


Fig. 25 Sensitivity analysis of the tidal potential, showing the impact on **a** the energy profile and **b** the LCOE and carbon footprint

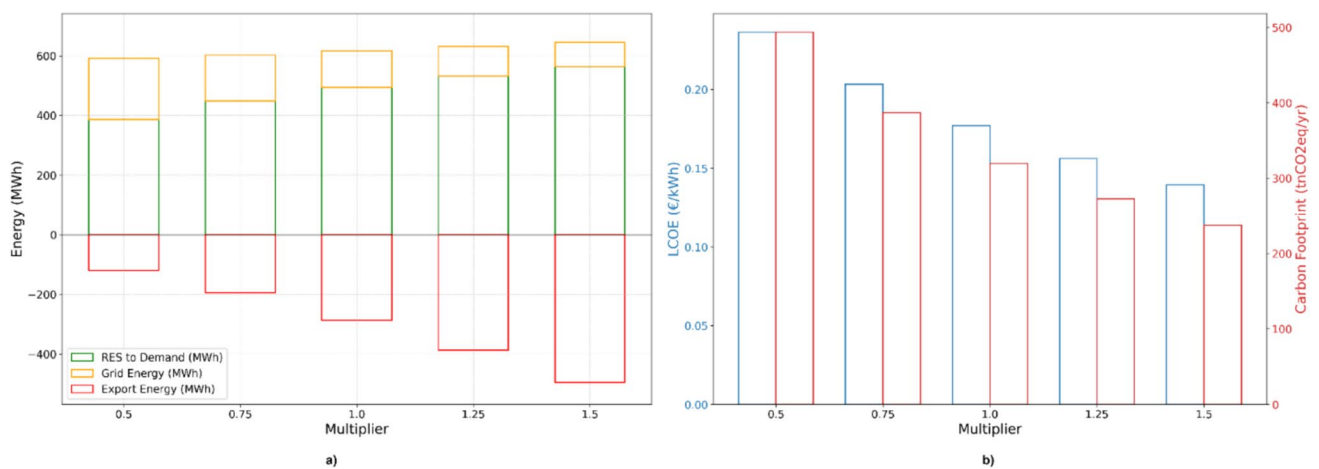


Fig. 26 Sensitivity analysis of the wave potential, showing the impact on **a** the energy profile and **b** the LCOE and carbon footprint

Table 5 Benchmarking HRES performance

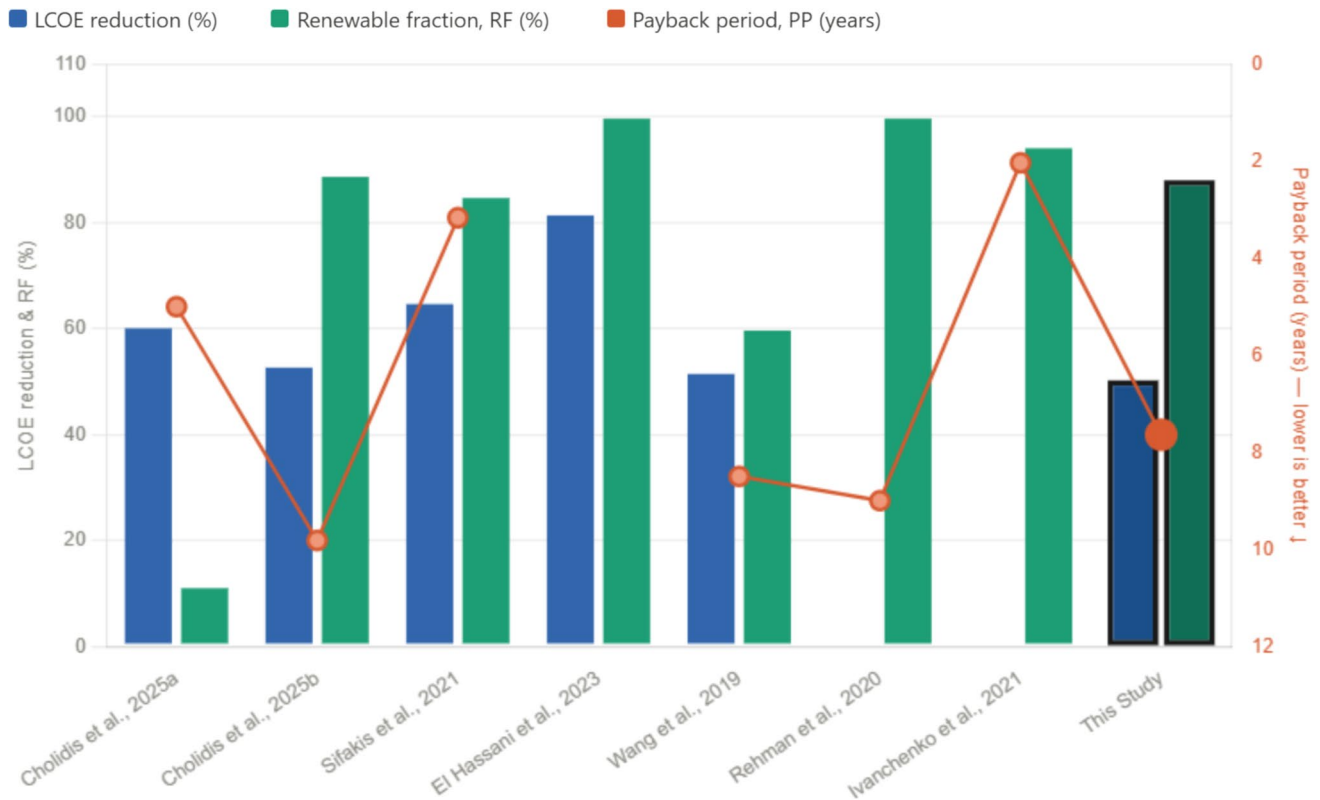
Study	LCOE (% reduction)	RF	PP
Cholidis et al. (2025a, b)	60.44	11.32	5
Cholidis et al. (2025a, b)	53	89	9.82
Sifakis et al. (2021)	> 65	85	3.17
Savvakis et al. (2023)	N/G	N/G	N/G
El Hassani et al. (2023)	81.7	100	N/G
Wang et al. (2019)	51.8	> 60	> 8.5
Rehman et al. (2020)	N/A	100	> 9
Yadav et al. (2024)	N/G	> 75	N/G
Chowdhury and Bohre (2023)	N/G	95	N/G
Konneh et al. (2023)	N/G	N/G	6.9
Chowdhury et al. (2020)	N/G	N/G	N/G
Ivanchenko et al. (2021)	N/G	94.4	2.04
Kumar et al. (2022)	N/G	100	N/G
This Study	50.25		7.64

*N/G stands for not given

**N/A stands for not available

both LCOE and lifecycle CF, a methodological advancement that aligns cost-efficiency with decarbonization objectives. In addition, this study introduces a transferable port archetype rather than a site-specific feasibility model. This approach, combining validated load profiles with high-resolution marine resource data, yields a replicable planning tool suitable for broader application across spatially constrained coastal infrastructures. The explicit incorporation of full lifecycle GHG emissions, including embodied impacts, further distinguishes this work from conventional models that overlook indirect environmental costs. As such, the study contributes both quantitatively and methodologically to closing key gaps in marine HRES optimization literature.

Figure 26 benchmarks the performance of this study against 13 comparable HRES deployments reported in the literature, across 3 key indicators: LCOE reduction, renewable energy fraction (RF), and payback period (PP). The results confirm that while this study operates within the competitive range of existing works, it is distinguished by the simultaneous optimization of both economic and environmental objectives, a dual-objective capability that most benchmarked studies do not address (Fig. 27).



N/G = not given; N/A = not available. This Study highlighted with bold border. PP axis inverted: lower is better.

Fig. 27 Benchmarking of HRES performance across selected literature

7 Conclusion

This study developed and validated a data-driven, dual-objective optimization framework for the design and assessment of marine-based HRES in port environments. Integrating wave and tidal energy with an ESS, the framework was applied to a Cretan Port to explore how the simultaneous minimization of LCOE and lifecycle CF can guide strategic energy planning under operational, spatial, and environmental constraints. The optimization results underscore the technical feasibility and environmental merit of marine renewables for coastal infrastructures. Specifically, the hybrid wave–tidal configuration (Scenario 6), derived from the multi-objective optimization, achieved an 88.3% reduction in CF, decreasing annual emissions from 1,967.9 tCO₂eq (grid-only baseline) to 230.1 tCO₂eq, while maintaining a competitive LCOE of €0.179 /kWh and a payback period (PP) of 7.64 years. This represents a 50.25% reduction in LCOE relative to conventional grid-supplied energy costs. The hybrid configuration reached an 87.96% renewable energy penetration, supplying over 765,000 kWh/year from marine sources, thereby demonstrating that environmental and economic objectives can be achieved concurrently with minimal trade-off.

The negligible economic penalty (0.6% LCOE increase) observed when transitioning from a single-objective to a multi-objective optimization reveals a critical strategic insight: sustainability does not inherently compromise profitability in marine-based HRES. The multi-objective approach (Scenario 6) strategically adjusted the technology mix to provide a more stable generation profile, which optimized the duty cycle of the ESS. This synergy suggests that for early-stage technologies, the environmental benefits of diversification far outweigh the marginal financial costs, aligning directly with the EU Green Deal and IMO decarbonization targets for 2030 and 2050.

Comparatively, Scenario 3 (single-objective, cost-focused optimization) achieved the lowest LCOE at €0.178 /kWh and a slightly shorter PP of 7.56 years, but delivered a lower CF reduction of 82.9%, reaffirming that the multi-objective configuration enhances sustainability with only a marginal 0.6% cost increase. ESS utilization also improved in Scenario 6, with an annual throughput of 433,202 kWh/year, a 7.5% increase over the single-objective case, highlighting its role in balancing supply–demand fluctuations and stabilizing port operations during high-load intervals. The combined system achieved 8 h of autonomous operation, enhancing reliability and resilience in case of grid outages. From an investment standpoint, these figures demonstrate that marine-only HRES, even with early-stage technologies, can achieve payback periods under 8 years and substantial emission cuts exceeding 85%, positioning

them as viable contributors to the blue economy and nZEP transitions, particularly where collaborative paradigms such as energy communities and localized industrial networks provide the institutional basis for deployment. The sensitivity analysis further revealed robust performance across financial variables, with LCOE stability under capital cost fluctuations, while confirming the strong dependence of system efficiency on wave resource variability, underlining the importance of accurate site-specific resource characterization.

Beyond technical metrics, this research positions marine energy as a primary pillar for the nZEP transition. By demonstrating that a marine-only HRES can achieve an 88% CF reduction, this study provides a concrete pathway for ports to transition from passive energy consumers to active 'Blue Energy' hubs. This is particularly vital for Mediterranean ports where land scarcity or historical protections often render traditional solar and wind farms unfeasible.

Practically, the proposed framework provides a replicable decision-support tool for port authorities and coastal planners, enabling quantitative trade-off analysis between cost-efficiency and carbon mitigation under realistic marine and demand conditions. Theoretically, it extends multi-objective optimization in HRES design by embedding wave–tidal coupling, lifecycle emissions, and ESS dynamics into a unified model, a gap previously unaddressed in port energy research. Certain limitations of this study should be acknowledged. Tidal resource data were sourced from the Strait of Messina due to the absence of long-term in situ measurements in Cretan waters, which constrains direct applicability to engineering deployment at Souda; the resulting optimal configurations are therefore indicative of the framework's capabilities rather than a site-specific deployment prescription. Additionally, real-time electricity pricing and policy incentives were not incorporated into the current optimization model. Future research should pursue dedicated tidal stream assessments in the Cretan region to validate and refine resource assumptions and expand the economic model to incorporate full lifecycle costing, including operation, maintenance, degradation, and decommissioning. Extending the optimization to include real-time grid dynamics, power quality effects, and cold-ironing synergies would further strengthen system integration insights and enhance the policy relevance of marine HRES planning.

Finally, the introduction of the transferable port archetype serves as a standardized decision-support roadmap. While this case study focused on Souda, the methodological framework is designed to be modular, allowing port authorities globally to 'stress test' their own coastal hydrodynamics before capital investment. This significantly de-risks the deployment of early-stage marine technologies in spatially constrained industrial zones.

8 Appendix

Mathematical formulas table

WT and TT	P_{wt}, P_{tt}	WT, TT adjusted power output
	V	Actual windspeed
	V_{cut-in}	Minimum wind speed for power production
	$V_{cut-out}$	Maximum wind speed the turbine shuts down
	P_r	Rated power
	V_r	Rated windspeed
	V_i	Wind speed at reference height H_i
	H	WT hub height
	H_i	Reference height
	$\alpha\rho$	Power law exponent
	ρ	Actual air density
	ρ_0	Air density under standard temperature and pressure
ESS	B_{soc}	Available battery capacity
	c	Energy storage system's capacity ratio
	I_{ess}	Energy storage system's current
	I_{max}	Energy storage system's maximum charge current
	k	Constant for storage
	N_{ess}	Number of energy storage systems
	$\eta_{ess,c}$	Charge storage efficiency
	$P_{ess,max,kbm}$	Kinetic battery model
	$P_{ess,max,mcr}$	Maximum charge rate
	Q	Initial available energy
	Q_1	Energy storage system's available energy
	$Q_{ess,0}$	Initial ESS charge
	$Q_{ess,max}$	Total maximum available energy stored
	V_{ess}	Energy storage system's voltage
	V_{nom}	ESS's nominal voltage
	αc	Energy storage system's maximum charge rate
	Δt	Time step duration
WEC	P	Wave energy potential
	d	Density
	g	Earth's gravitational force
	H	Wave height
	T	Wave period
	P_{owc}	Wave power output
	w	Width of OWC chamber
	η_{owc}	OWC's total efficiency
	η_p	Chamber efficiency
	η_t	Turbine efficiency
	η_g	Generator efficiency
	P_{max}	Maximum theoretical power
	L_{max}	Absorption width at maximum power

ω	Angular frequency
Φ	Real velocity potential
Sb	Control parameter for the wetted section of the WEC
B	Characteristic dimension of the WEC
η_1	Hydrodynamic efficiency
C_g	Group speed parameter
ε	Coefficient that depends on the characteristics of the wave field
λ	Waves wavelength
k	Wave number
h	Bed depth

Technologies specifications table

Parameter	Value
TT	<i>GEMSTAR</i>
Rated power (kW)	50
Depth (m)	9.8–10
Rated rotation speed (rpm)	65
Rotor efficiency (%)	0.8
Nominal water speed (m/s)	2.6
Maximum water speed (m/s)	3
Minimum sufficient water speed (m/s)	1–1.5
Lifetime (y)	25
WV	<i>REWEC3</i>
Generator rated power (kw)	20
Significant wave height (m)	2.5–3
Mean wave period (s)	5.5–6
Wave energy absorption efficiency (%)	80
Turbine efficiency (%)	55
Generator efficiency (%)	95
Chamber width (m)	3.87
Lifetime (y)	25
ESS	<i>Galaxy 3420</i>
System capacity per unit (kwh)	3421
Efficiency (%)	86
Cycles	≥ 8000
Rated voltage (V)	3.2
Charging current (A)	150
Discharging current (A)	150

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Author contributions George Arampatzis contributed to Project administration, methodology, and supervision, providing strategic oversight

and academic guidance throughout the research process. Nikolaos Sifakis was responsible for conceptualization, formal analysis, validation, data curation, methodology, and supervision, overseeing the research execution and contributing to the design, analysis, and verification of results. Dimitrios Cholidis led the writing—original draft and contributed to investigation, data curation, and visualization, preparing the manuscript and managing the underlying data and visual outputs.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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