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Integration of solar, wind, and wave energy for sustainable hotel operation in coastal regions: optimization of a building with hydrogen-supported hybrid renewable energy system

Mohsen Fathi [a], Zahra Mohammadi [b], Sevda Allahyari [c], Shayan Rahimi [d], Abolfazl Ahmadi [a,*], Alireza Zahedi [a]

[a] School of New Technologies, Iran University of Science and Technology, Tehran, Iran
[b] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran
[c] School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran
[d] Mork Family Department of Chemical Engineering and Material Science, University of Southern California, Los Angeles, USA

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ABSTRACT

This study proposes and optimizes a novel hybrid renewable energy system (HRES) designed for achieving near-zero energy performance in coastal buildings. The selected case is a large hotel located on Kish Island, Iran, where electricity demand is supplied through a synergistic combination of photovoltaic (PV) panels, vertical-axis wind turbines (VAWTs), and oscillating water column (OWC) wave energy converters (WECs) integrated with a hydrogen-based energy storage system (HESS). The system is modeled using TRNSYS for dynamic simulation and coupled with a multi-objective optimization framework employing genetic algorithm. The optimization minimizes the total cost rate, loss of power supply probability (LPSP), and CO_2 emissions simultaneously. The main innovation of this study lies in the comprehensive integration of solar, wind, and wave energy with hydrogen storage within a single building-scale system, which has not been previously explored in such detail for coastal environments. The results reveal that the optimized configuration, consisting of 500 PV modules, 13 VAWTs, and 35 OWCs, achieves a CO_2 emission of 84.45 tons per year, an LPSP of 0.179, and an operational cost rate of 472 EUR/hour, representing an 81% reduction in annual carbon emissions compared to grid-dependent operation. The findings demonstrate that combining diverse renewable resources with hydrogen storage not only enhances system reliability and autonomy but also offers a scalable framework for developing cost-effective and low-carbon near-zero energy buildings in coastal and island regions.

Nomenclature

Symbol		GHG	Greenhouse gases
CW	Capture width	GWO	Grey wolf optimizer
G	Gravity acceleration	HESS	Hydrogen-based energy storage system
H	Wave height	HRES	Hybrid renewable energy system
I	Interest rate	HVAC	Heating, ventilation, and air condition
N	Operation years	IEA	International energy agency
N	Annual operation hours	LCOE	Levelized cost of energy
P_w	Wave power	LPSP	Loss of power supply probability
T	Wave period	MED	Multi-effect desalination
Z	Purchase cost	MGT	Micro-gas turbine
Ż	Cost rate	NSGA	Non-dominated sorting genetic algorithm

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Greek symbols		nZEB	Near zero energy buildings
Φ	Maintenance factor	OWC	Oscillating water column
η_{w2w}	Wave to wire efficiency	PEM	Proton exchange membrane
ρ_w	Sea water specific mass	PSO	Particle swarm optimization
Acronyms		PV	Photovoltaic
ACO	Ant colony optimization	PV/T	Photovoltaic/thermal
AEP	Annual energy production	RE	Renewable energy
CRF	Capital recovery factor	TOPSIS	Technique for order preference by similarity to an ideal solution

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* Corresponding author.
E-mail address: a_ahmadi@iust.ac.ir (A. Ahmadi).

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DOE	Department of energy	VAWT	Vertical axis wind turbine
ESS	Energy storage system	WEC	Wave energy converter
GA	Genetic algorithm	ZCC	Zero carbon community

1. Introduction

Conventional power plants, such as those utilizing oil, gas, and coal, encounter significant environmental challenges due to their substantial CO_2 emissions [1]. As global demand for energy continue to rise [2], the world faces even more difficulties. In addition to dealing with the negative effects of climate change, it is necessary for addressing the developmental discrepancies caused by energy constraints. Respectively, the development and utilization of clean renewable energies like wind, solar, and hydrogen have become an important field of investigation in residential energy [3].

1.1. Near zero energy building

A near zero energy building (nZEB) is a residential or commercial building that generates as much as energy as it uses annually. In other words, it can offset its own annual grid energy usage by producing equivalent amount of renewable electricity onsite. In major cities, 40% of the power used is related to the building sectors [4]. According to the International Energy Agency (IEA) statistics, buildings have higher global energy consumption in residential sector than commercial sector. In fact, the residential buildings are responsible for 25 % of the world energy usage and 17 % of the world CO_2 emissions [3]. Since hotels are some of the most electricity-intensive buildings, one of the main targets of the European Union's energy strategy is to convert the current hotels to nearly zero-energy condition by 2050 [5]. When trying to achieve indoor comfort, hotels use a lot of energy due to consumer desire differences. There are two ways to handle electricity use in buildings: either building new structures according to energy-efficiency rules, or putting environmentally friendly features to existing structures [6]. Thus, installing green power systems for buildings to achieve the required energy of the building using green energy is the primary focus of current studies. Numerous studies are trying to model and simulate nZEB, primarily electrical power. Gholamian et al. [7] developed a system consisting of an absorption chiller, a micro-gas turbine (MGT), and photovoltaic/thermal (PV/T). We et al. [8] proposed a strong constructed energy assessment methodology for assessing the potential use of hydrogen storages in residential buildings to meet the electrical power, heating, and cooling demands of the building. Additionally, Guo et al. [9] investigated standard routine energy schedule, and how energy storage affect the system use of energy when it provides power to a nearly-zero energy community, when installing Li-ion batteries, the annual self-sufficiency rate of PV and wind energy production of distinct and local combined energy systems improved by 23.3% and 11.0%, respectively. The difficulty of energy conservation and minimizing emission makes the energy management research for zero carbon communities (ZCC) quite crucial, for this aim for general communities, Gao et al. [10] established a multi-objective optimization planning model of the energy storage systems (ESS) with the maximum economic cost and the minimum carbon emission. Also, Liu et al. [11] for a practical office building presented a grid-protective energy management method of the solar PV power and storage system, results indicated that the nZEB achieves minimum emission with the architecture of sizing of 300 electric vehicles and 450 kWh batteries.

1.2. Renewable energy systems

21.3×10^9 tons of CO_2 are released into the environment annually by petroleum and coal. unburned fossil fuels additionally contributing significantly to the emission of CO and other dangerous particles. The environmentally friendly building reduces greenhouse gases (GHG) emissions from the consumption of fossil fuels. The Statistical Review of World Energy 2020 stated that fossil fuels provide 84% of the worldwide power needs [12]. Furthermore, incorporating a renewable component into the energy system enhances its effectiveness and exergy effectiveness [13–15]. Clean energy sources consisting of solar, wind, and etc. could be used to generate electricity in building sector. Solar power is considered to be the most economical and sustainable approach to addressing global warming. Izadi et al. [16] presented the designing and optimizing of hospital wards to produce electricity and oxygen utilizing PVs and hydrogen storing systems. The cost and demand for grid electricity for the specified system design are 18.930 €/hour and 469.07 MWh/year, respectively. Zarei et al. [17] examined the thermodynamic and economic properties of an innovative PV/T multi-generation system compared to a PV system for building applications. Performance increased by 11% as a result of the PV/T generation of electricity and heat. Le et al. [18] analyzed the effects on the environment of multiple microgrids that include the PV arrays and a hybrid hydrogen and battery storage in a grid-connected building, the effects of climate change initially decreased to its minimum values but then increased again towards reaching full self-sufficiency. Also, numerous forms of clean energy, including tidal and wave energy, are stored in the ocean. Furthermore, offshore wind turbines and other ocean-integrated renewables are great choices [19–22]. It is necessary to noted that while the majority of oceanic power devices, such as wave energy converters, are used in simulation tests or analytical research, only a few are used in practical applications. Given the great potential of ocean waves for the generation of green energy, it is desirable to research WEC devices, which uses wave energy generated on the sea surface [23]. Seawater air conditioning is one of the most attractive devices to reduce the utilization of fossil fuels, particularly on tropical islands, Dinesh and Abba [24] evaluated the technical and economic viability of seawater air conditioning for hotels near the shore in Mauritius. The results indicated a major decrease in electrical usage and a relatively shorter payback time employing the recently developed method. Tolga et al. [25] also investigated a hotel in Antalya, Turkey, that replaced its air-conditioned system with a seawater-sourced cooling system, demonstrating a significantly higher overall air conditioning efficiency. To increase the energy converting, a number of changes were made to the structural and operational elements of the WECs. For instance, Doyle and Aggidis [26] compared the OWC of three arrays with a single chamber and a three-chambered modular system demonstrates that the modular device that received the airflow from three chambers would operate at more than three times the power of the three OWC devices operating alone.

1.3. Hydrogen storage

When the amount of renewable energy produced surpasses the amount of energy required, ESSs are used for preserving power [27]. Hydrogen is a sustainable energy carrier with zero carbon properties, great power density, minimum leakage rate, multiple storage kinds, and long-distance transportability, in contrast to batteries and hydro pumps. Hydrogen is therefore an attractive form of energy to deal with seasonally imbalances. Additionally, hydrogen is able to consumed and transformed into power to meet a variety of requirements for residential buildings, including heating, electricity, and domestic hot water [28]. Thus, combining PV systems with a HESS for residential communities is a practical and efficient way to create large-scale and long-term zero carbon buildings. The usage of hydrogen has been the subject of numerous studies as a clean and zero carbon fuel [29]. The technical and

economic feasibility of employing renewable energy systems with battery and hydrogen storage for building energy supply has been investigated through case studies and parametric calculations [30]. Izadi et al. [31] considered wind turbines and PV cells to meet an office building electrical loads. A HESS was incorporated into the building to minimize fuel costs and CO_2 emissions. HESS could improve the building energy-supplying capacity from 48.9% to 87.5% since it is in charge of providing 38.6% of the demand for electrical power. Apart from examining the use of the HESS, the impact of four distinct fuel types is also taken into account. Izadi et al. [32] investigated a HRES, Simulated HRES included of PVs, VAWTs, and hydrogen storage in four distinct climate conditions has been considered, Bandar abbas, Tabriz, Tehran, and Yazd in Iran. Results indicated by considering HESS, 8.5% less energy was exported to the grid than in the absence of EES. Additionally, Mohammad et al. [33] examined urban apartment buildings with a microgrid powered by solar PV and hydrogen storage, the extended results showed using hydrogen system was very efficient, and there were no GHG emissions throughout operation. Mohammadi et al. [34] studied the incorporation of PV panels into buildings in order to develop zero-energy buildings. Comparing two distinct storage technologies (battery and hydrogen storage) was the main objective of this case study. The energy system was modeled utilizing TRNSYS, an accurate transient simulating software. According to the conclusion, PV panels can produce 39% and 37% of the building electrical demands in technologies with battery and H_2 storage, respectively. Deymi et al. [35] analyzed a hybrid system to meet a building load for water, power, and heating. The main power system of the building is solar power to integrate with HESS, and multi-effect desalination (MED). Hot water storage and HESS are utilized to storage solar power as heating and electric power, respectively, at peak solar irradiation. Total amount of freshwater produced was equal to 351857.4 kg, which 81.7% of it consumes in the HESS. Finally, Table 1 reviewed the hotel building energy systems and storages studies.

Hybrid renewable energy systems integrating solar, wind, wave, and hydrogen technologies have gained increasing attention for sustainable and resilient energy generation in coastal and island regions. A comprehensive review of hybrid renewable systems in offshore environments highlighted the rapid growth of solar-wind-wave configurations over the past two decades, emphasizing their complementary resource characteristics and the use of optimization techniques such as genetic algorithms (GA) and particle swarm optimization (PSO) for system design and cost reduction. However, the review also noted that the practical deployment of such integrated systems remains limited and requires further feasibility studies and cost assessments under real marine conditions [46]. In parallel, a detailed review of building energy optimization methods compared conventional linear programming with modern metaheuristic algorithms, showing that the latter especially memetic algorithms offer superior adaptability and efficiency in solving nonlinear and multi-objective energy management problems, making them ideal for optimizing complex renewable systems in buildings [47]. Jin et al. [48] investigated hydrogen-supported hybrid systems to enhance reliability and long-term storage capability. A mixed-integer linear programming (MILP)-based framework integrating PV panels, lithium-ion batteries, and alkaline electrolyzers demonstrated that maintaining electrolyzers at constant rated operation prevents degradation, achieves full load coverage, and reduces annual CO_2 emissions by up to 0.83 tons per user, although battery costs remain dominant. Meanwhile, studies on wave energy emphasize its growing role as a complementary renewable source. Said et al. [49] presented a comprehensive review of WEC technologies outlined challenges related to power quality, converter control, and grid integration while noting that combining wave energy with other renewables can reduce overall energy costs and enhance grid stability. Case studies further validate wave energy integration potential. On the Adriatic island of Vis, optimized coupling of PV systems with Wavestar and Wavebob converters achieved near net-zero power exchange with the mainland and improved voltage stability [50]. Similarly, a Puerto Rico maritime microgrid study found that incorporating WECs into solar-based systems reduced required battery capacity and PV land area, improving resilience and sustainability for coastal microgrids [51].

Table 1
Related studies in hotel building energy systems.

Reference	Year	Energy system	Energy storage	Location	Key findings
[36]	2024	PV, Heat pump, Biomass	-	Turkey	PV panels are the top choice for hotel buildings using multi-criteria decision-making methods and initial investment cost is the most important factor.
[37]	2015	Solar thermal	-	Greece	Solar thermal systems are effective for sanitary hot water and swimming pools in Greek hotels.
[38]	2011	PV, Biomass	Battery	Portugal	Hybrid system with solar PV and biomass gasification reduces energy demand, costs, and emissions.
[39]	2018	PV, Solar thermal, Ground-source heat pump, Biomass	-	Cyprus	Several measures of energy efficiency to improve the current situation have been recommended.
[40]	2018	PV, Solar thermal	Battery	Italy	Solar energy systems and building automation control technologies can effectively manage energy consumption in isolated hotel locations.
[41]	2024	PV	Battery	Crete	Algorithm increases hotel energy self-sufficiency to 99% using PV power and battery storage.
[42]	2024	PV	Battery	Sanya	PV-battery systems reduce electricity purchases and increase hotel profits by up to 31.4.
[43]	2014	PV, Wind, Diesel	Battery	Iran	Wind-diesel hybrid system with battery is the most effective for medium-size hotel energy loads.
[44]	2024	PV	-	Indonesia	Combining PV with building envelope renovations can reduce energy use by up to 32.2% annually.
[45]	2009	PV, Biomass	Battery	Portugal	The payback NPV and IRR metrics were advantageous for making the investment after the economic viability was determined.

1.4. Contribution of the recent study

Upon recent advances in integrated renewable systems, this study aims to address a critical gap between high-performance energy simulation and deployable building-scale solutions for coastal hospitality facilities. While prior research has explored the individual or dual integration of solar, wind, and wave energy, comprehensive building-scale hybrid renewable energy systems that simultaneously integrate solar, wind, and wave resources with hydrogen-based storage remain largely unexplored, particularly for coastal and island hotels with high, continuous, and seasonally variable energy demands. Existing studies predominantly focus on PV–wind or PV–battery configurations, community-scale microgrids, or standalone wave energy systems, without capturing the combined techno-economic–environmental interactions of multi-source renewable integration at the building level. Moreover, the strategic role of hydrogen-based storage in enhancing reliability and autonomy for coastal hotels operating under grid constraints has received limited attention. To address these gaps, this study designs, simulates, and optimizes a HRES tailored to a large hotel on Kish Island, Iran, aiming to achieve near-zero energy performance. The proposed system integrates PV panels, VAWTs, OWC energy converters, and a HESS. By coupling dynamic simulation using TRNSYS with a multi-objective optimization framework based on NSGA-III, this research captures seasonal energy dynamics and identifies optimal system configurations that minimize cost rate, LPSP, and CO_2 emissions. The findings provide a scalable and transferable decision-support framework for the design of low-carbon, reliable, and near-zero energy coastal buildings in island and maritime regions. The overall methodology adopted in this study is illustrated in Fig. 1, which presents a four-step roadmap involving system definition, weather data gathering, energy system and building modeling using TRNSYS and EnergyPlus, and multi-objective optimization via NSGA-III.

Finally, the objectives of this study are to.

- Develop a building-scale HRES integrating PV, VAWT, OWC, and hydrogen-based storage for coastal hotel applications.
- Quantify the seasonal and dynamic performance of the integrated system using TRNSYS simulation.
- Identify optimal system configurations using NSGA-III multi-objective optimization with respect to cost rate, reliability (LPSP), and CO_2 emissions.
- Evaluate the environmental and economic viability of the proposed system as a pathway toward near-zero energy coastal hotels.

2. System explanation

2.1. Building explanation

Examined in this paper, the large hotel is a prototype building modeled according to the latest ASHRAE standards and derived from the most recent U.S. Department of Energy (DOE) reference building library [52,53]. The DOE prototype building dataset, available at the official repository [52], was last updated in 2023–2024 and reflects the ASHRAE 90.1-2022 framework, ensuring realistic and contemporary energy performance representation. This building (look at Fig. 2) includes a broader range of functional spaces such as guest suites, administrative offices, multiple meeting and banquet rooms, commercial kitchens, laundry facilities, fitness areas, service zones, staff areas, storage, mechanical rooms, corridors, and restrooms. Simulations were performed using EnergyPlus in conjunction with OpenStudio. The main objective of this study is to evaluate the performance of the proposed energy system under the climatic conditions of Kish Island, located at 88.55°E longitude and 89.29°N latitude in southern Iran. Local weather data was obtained from the nearest meteorological station using Meteonorm. EnergyPlus calculated the building hourly energy demands, covering space cooling, heating, domestic hot water, and electrical load, over an entire year. Electricity loads account for heating, ventilation, and air condition (HVAC), pump operation, lighting systems, and all internal equipment across different zones.

The building has a total conditioned floor area of approximately 11,345.5 m^2, with window-to-wall ratio set at about 20%. The overall building volume is estimated at 34,120.2 m^3, assuming a uniform zone height of 3.04 m. Design occupancy density is assumed to be five persons per 93 m^2. Infiltration is modeled at a constant rate of 0.2 cfm/ft^2, and

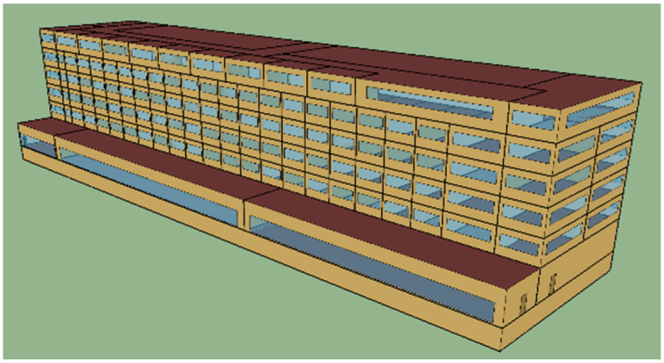


Fig. 2. The DOE prototype small hotel examined in this study [52].

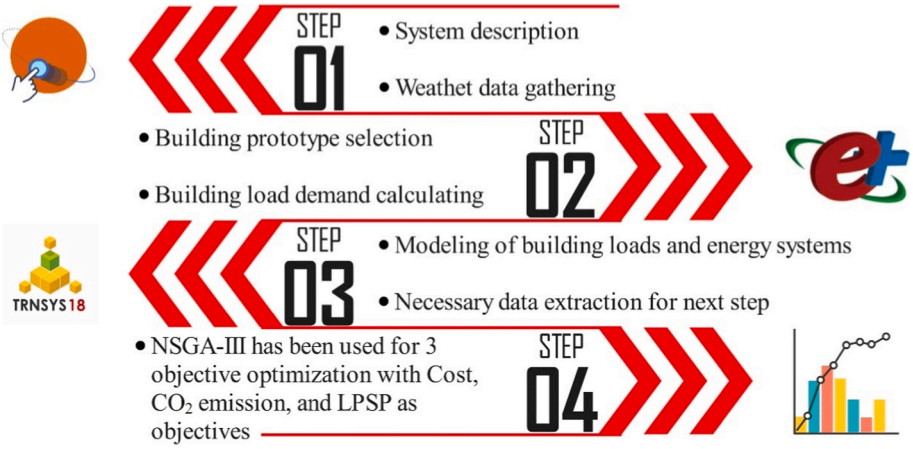


Fig. 1. Step-by-step roadmap of the proposed methodology.

ventilation systems are designed in compliance with ASHRAE 90.1-2004 and ASHRAE 62 (1999 edition). Further details on construction assemblies, internal loads, schedules, and system configurations are available in Reference [52].

2.2. System explanation

The primary goal of the suggested HRES is to introduce a consistent and sustainable source of power for a grid-connected structure in a coastal area, while also allowing the storage of extra energy in the shape of hydrogen. This setup is meant to provide energy independence, improve system flexibility, and enable integration with clean hydrogen-based storage options. Using a thorough simulation technique that links OpenStudio 3.4.0, EnergyPlus 9.2, and TRNSYS 18.02 environments for load assessment and performance evaluation, respectively, the system is created and examined under transient situations. The architecture of the HRES includes three main renewable energy generation units: PV panels to harness solar irradiance, VAWTs to capture wind energy, and OWC devices to convert ocean wave energy into electricity. These renewable subsystems operate in parallel to collectively satisfy the dynamic load demand of the building throughout the year. The energy generated by these components is routed to a centralized controller that manages the flow of electricity in real time based on supply-demand conditions. The energy storage and conversion section of the system comprises a proton exchange membrane (PEM) electrolyzer, a multi-stage hydrogen compressor, pressurized hydrogen storage tanks, and a fuel cell stack for electricity regeneration.

2.3. Control algorithm

The energy management strategy prioritizes renewable energy use and hydrogen storage operation. During periods of surplus renewable generation, the system prioritizes the operation of the electrolyzer. If the available power exceeds the idle threshold of the electrolyzer and the hydrogen tanks have sufficient capacity, excess electricity is converted into hydrogen and stored for future use. If either of these conditions is not met, i.e., if the excess power is below the idle load threshold or the storage tanks are full, the system exports electricity to the grid. Conversely, in periods when the total renewable generation is insufficient to meet the building electrical energy, the system switches to backup operation. In this case, stored hydrogen is used by the fuel cell to produce electrical power. The controller evaluates the availability of hydrogen in storage and the energy requirements of the building. If the combination of renewable sources and fuel cell output cannot meet the load, the remaining deficit is covered by electricity purchased from the grid. This multi-stage logic ensures operational reliability while maximizing the use of clean and renewable resources. All of this logic is performed by a controller, which Table 2 summarized all key controller setpoints and operational thresholds and Fig. 3 illustrated in detail the logic of this controller.

Overall, this integrated system enables year-round autonomous energy supply, enhances the efficiency of renewable resource utilization, and facilitates the generation and consumption of green hydrogen. An overview representation of the full system configuration is shown in Fig. 4.

Table 2
Key controller setpoints and operational thresholds.

Parameters	Setpoints
Electrolyzer idle power	24 kW
Fuel cell idle power	12 kW
Minimum allowed H_2 tank level	0.5 m^3
Maximum allowed H_2 tank level	4.5 m^3
Start buying electricity from grid	$P_{PV} + P_{WT} + P_{OWC} + P_{FC} < P_{load}$
Start selling electricity to grid	$P_{PV} + P_{WT} + P_{OWC} - P_{electrolyzer} > P_{load}$

3. Methodology

3.1. Study objective and site description

The objective of this study is to examine the system efficiency in Kish Island, an area with high radiation and also with suitable wind and having sufficient potential for using wave energies. The high diversity of renewable energy sources in this climate raises a challenging question. Which energy system and why? this question can be answered from different aspects such as environmental factors, economic analyses, energy supply capability, investor attraction, consumer satisfaction, and etc.

With these descriptions, this study attempts to consider a building and its loads such as cooling and heating loads, lights, hot water consumption and electrical device. Meteorological conditions data of the island has been obtained from Meteonorm at main weather station. Afterward, hourly electricity and gas consumption of the building have been computed in EnergyPlus for a year.

3.2. Hybrid energy system modeling

Next step, a HESS is modeled in conjunction with solar PVs, VAWTs, and OWCs to develop a hybrid energy system. This system is considered to be connected to the grid to provide electricity through the grid after the hydrogen storage fully discharged, or to sell the grid extra electricity after the hydrogen tank fully charged.

3.3. Solar PV and VAWT design

Solar PVs and VAWTs are installed to meet the building electricity load. PV panels with VAWTs can take up to 65% of the roof area, according to a study by Melius et al. [54]. VAWTs are positioned at least 2.5 times the rotor diameter apart from another [55]. Thus, a maximum of 14 VAWTs are put around the building roof. 70% of the remaining space is used for PV arrays implementation in order to mitigate the shadowing of VAWTs and other PVs. Therefore, a maximum of 510 PV arrays could be positioned on the rooftop. The number of PVs is determined from Eq. (1).

$$Number\ of\ PV = \frac{(roof\ area \times 0.65 - turbines\ area) \times 0.7}{area\ of\ PV} \quad (1)$$

3.4. Wave energy conversion systems

WECs are technologies made to capture and transform ocean waves kinetic and potential energy into electrical energy. This form of renewable energy is gaining attention due to its potential to offer a sustainable power source, particularly in coastal areas where wave energy is abundant [56]. There are several types of WECs, each utilizing different mechanisms to capture wave energy. Point Absorbers devices, often in the form of buoys, float on or just below the water surface and capture energy from the vertical motion of waves. They are typically deployed in arrays to maximize energy capture [57,58]. OWC systems utilize the rise and fall of water within a chamber to drive air through a turbine, generating electricity. OWCs can be integrated into breakwaters or standalone structures [59]. Overtopping Devices capture water as waves break over a structure, storing it in a reservoir and then releasing it through turbines [60]. Oscillating Body technologies use the motion of waves to move a body, which in turn drives a generator. Examples include heaving plates and surge converters [61].

The fixed OWC model has been considered and used in this study. The bidirectional rotation of the air turbine is a simple way to convert the oscillating power from waves. Fig. 5 illustrated that how an OWC device work. To calculate the output power, Eqs. (2) and (3) are used, as well as wave characteristics such as height, period, and availability [62,63].

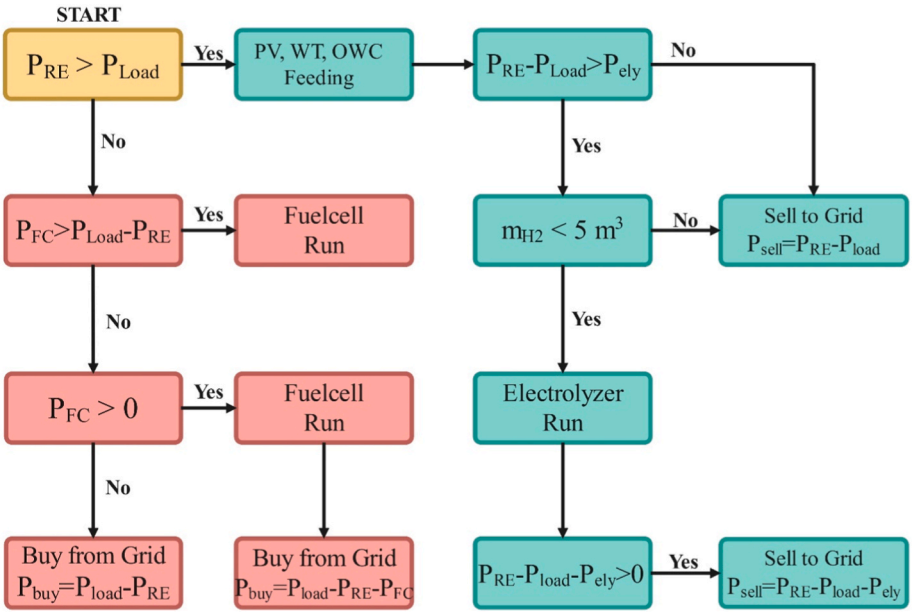


Fig. 3. The flowchart of the controller logic.

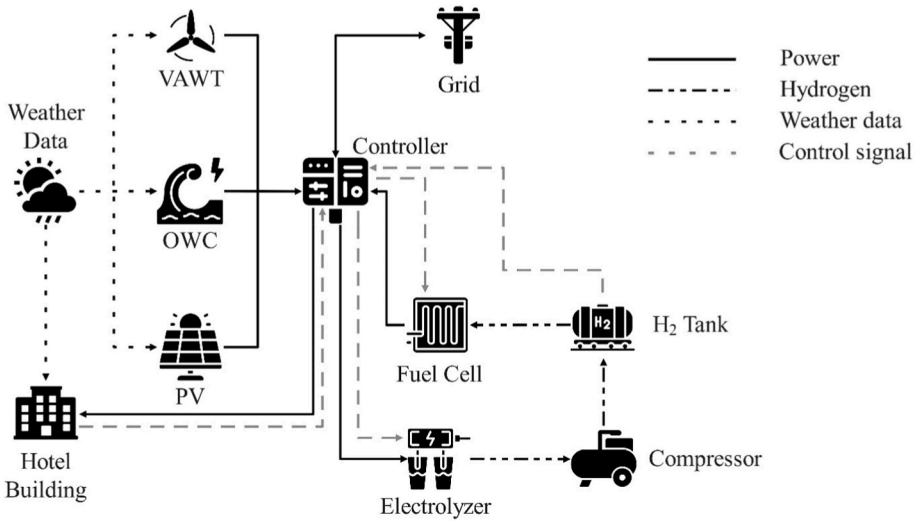


Fig. 4. Overview of the multigeneration configuration.

$$P_w = \frac{1}{32\pi} \times \rho_w \times g^2 \times H^2 \times T \quad (2)$$

$$AEP = P_w \times CW \times \eta_{w2w} \times wave\ availability \times annual\ hours \quad (3)$$

where P_w, ρ_w, g, H and T are wave power, sea water specific mass, gravity acceleration, wave height, and wave period, respectively. In Eq. (3) also AEP is annual energy production, CW is capture width, and η_{w2w} is wave to wire efficiency.

3.5. System components and specifications

Proposed PV panels, VAWTs, and OWC systems have a nominal power of 375 W, 9.8 kW, and 200 kW, respectively. 210 alkaline electrolyzer cells with a maximum current density permitted of 680 mA/cm^2 are installed in order to generate hydrogen. The produced hydrogen is stored at 20 °C in a 5 m^3 hydrogen tank after passing through a 3-stage compressor. For energy producing from hydrogen storage, 1024 fuel cells with an electrode area of 100 cm^2 are installed. The controller coordinates the storage operation by keeping an eye on the fuel cell and electrolyzer nominal power and keeping an eye on the hydrogen tank level. Table 3 lists all of the solar PVs, VAWTs, OWC systems, Alkaline Electrolyzer, Alkaline fuel-cell, hydrogen tank, compressor, and controller technical specifications.

4. Optimization

Present study utilized multi-objective optimization that improving the performance of energy technologies by considering multiple objectives simultaneously, such as cost, efficiency, and environmental impact.

4.1. Multi-objective optimization principles and problem formulation

Techniques like Pareto optimality are often used to find the best trade-offs between conflicting objectives. In this regard, various algorithms inspired by natural phenomena, such as Grey Wolf Optimizer (GWO), PSO, Ant Colony Optimization (ACO), and Genetic Algorithm (GA), are employed to solve complex optimization problems in energy

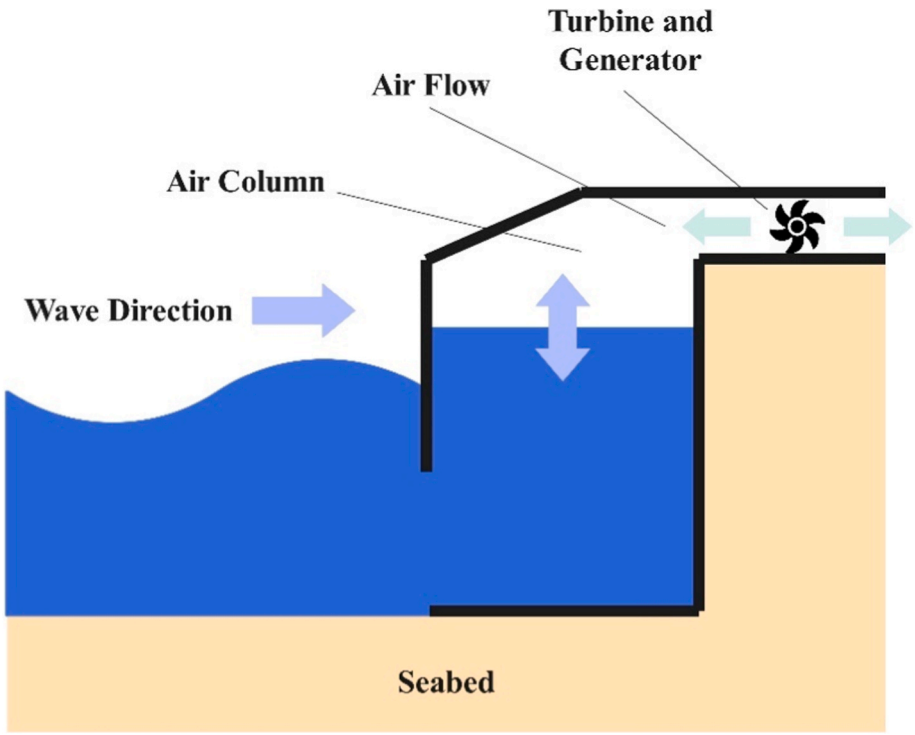


Fig. 5. OWC device working mechanism.

systems [64]. So, one of this paper primary objectives is to develop an architecture with the least operational cost rate, CO_2 emission and LPSP. LPSP or grid power usage are used here as a measure of efficiency and calculated from Eq. (4).

$$LPSP = \frac{hour\ of\ required\ grid\ power}{total\ hour\ of\ year} \tag{4}$$

Carbon emission is another objective that can be calculated with two separate criteria for renewable sources and fossil sources through Eq. (5).

$$Total\ CO_2 = \left(CO_{2\ grid} \times P_{grid}\right) + \left(CO_{2\ renewable} \times P_{renewable}\right) \tag{5}$$

where Table 4 lists the life cycle CO_2 emission for each kWh of grid and renewable energy.

In this study, the cost rate was employed as the economic evaluation metric. While levelized cost of energy (LCOE) is a common index for broadly comparing the costs of electricity generation from various sources, the cost rate was deemed more suitable for this research due to its focus on project cash flows, the possibility of more detailed sensitivity analysis, and assess the impact of changes in key project parameters. Each component cost rate is calculated using an accurate equation that takes into account each potential economic factor. This equation includes purchase cost of the device, maintenance cost (as a coefficient), annual operating hours and capital recovery factor (CRF), which automatically incorporates replacement costs by taking the base currency interest rate into account. Eqs. (6) and (7) using for CRF and cost rate, respectively [65].

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

$$\dot{Z} = \frac{Z \times CRF \times \Phi}{N} \tag{7}$$

where i, n, Z, Φ, and N are interest rate, operation years, purchase cost, maintenance coefficient, and number of operation hours in one year, respectively. All parameters and component costs are represented in Table 5.

With the technique of optimization, an effective estimate for the cost rate, carbon emission, and LPSP can be found. So, number of PV (N_{PV}), number of VAWT (N_{VAWT}), and number of OWC (N_{OWC}) are introduced as decision variables that range of each decision variable is provided in Table 6.

4.2. NSGA-III method

The NSGA-III is an advanced evolutionary algorithm designed to solve multi-objective optimization problems, particularly those with three or more objectives. NSGA-III significantly outperforms NSGA-II in three-objective problems, particularly in terms of achieving a complete and well-distributed pareto front and replaces the crowding distance measure in NSGA-II with reference points to ensure diversity of the converged solutions [67,68].

The total hyperparameter tuning, summarized in Table 7, was performed to optimize the performance of NSGA-III. NSGA-III utilizes a set of well-distributed reference points in the objective space to maintain diversity among solutions. These reference points guide the population towards a diverse set of pareto-optimal solutions [69]. The reference points help in spreading the solutions across the pareto front, ensuring that the trade-offs between the objectives are well-represented. Similar to its predecessor NSGA-II, NSGA-III relies on pareto-dominance to rank solutions [70]. This approach ensures that the algorithm can effectively push the population towards the pareto front while maintaining a diverse set of solutions. NSGA-III employs a sophisticated environmental selection mechanism that uses reference points to select the best solutions for the next generation. This helps in balancing the trade-offs between the competing objectives by ensuring that a wide range of solutions is considered. The selection process is designed to maintain a balance between convergence towards the pareto front and diversity among the solutions [71].

Finally, Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) could be integrated with the algorithm output to generate and rank pareto-optimal solutions. TOPSIS is a widely utilized

Table 3
Technical specifications of the components.

Parameter	Value	Unit
Wind turbine		
stan height	1.5	m
turbine height	5.6	m
rotor diameter	4.3	m
rated power	9.8	kW
rated speed	12	m/s
Photovoltaic panel		
short-circuit current at reference conditions	11.4	A
open-circuit voltage at reference conditions	41.9	V
reference cell temperature	25	°C
module area	1.822	m
rated power	375	W
Oscillating water column		
length	12	m
width	12	m
capture width ratio	30	%
wave to wire efficiency	20	%
rated power	200	kW
Alkaline electrolyzer		
maximum allowable current density	680	mA/cm^2
maximum allowable operating temperature	85	°C
electrolyzer pressure	7	bar
operating temperature	80	°C
electrolyzer rated power	100	kW
Alkaline fuel cell		
area of electrode	100	cm^2
Faraday efficiency	98.7	%
voltage of open circuit	5.6	V
minimum permissible voltage of cell	0.4	V
stack operating temperature	70	°C
fuel cell rated power	60	kW
Hydrogen tank		
minimum pressure	7.1	bar
maximum pressure	250	bar
volume of tank	5	m^3
Compressor		
compressor stage numbers	3	-
pressure of gas inlet	7	bar
Controller		
idling power of fuel cell	12	kW
electrolyzer idling power	24	kW
H_2 tank lower limit	10	%
H_2 tank upper limit	90	%

Table 4
Environmental impact values [32].

Parameter	Value ($g-CO_2/kWh$)
Renewable emission	5.9
Grid emission	653

Table 5
Economical parameter values [16,32,66].

Component price	
photovoltaic panel	$Z_{PV}(EUR) = 165 \times N_{PV}$
vertical axis wind turbine	$Z_{WT}(EUR) = 22133 \times N_{WT}$
oscillating water column	$Z_{OWC}(EUR) = 433000 \times N_{OWC}$
electrolyzer	$Z_{Elz}(EUR) = 1200 \times P_{Elz}$
fuel cell	$Z_{FC}(EUR) = 3000 \times P_{FC}$
compressor	$Z_{Cmp}(EUR) = 81490 \times \left(\frac{P_{Cmp}}{455}\right)^{0.67}$
H_2 tank	$Z_{Tnk}(EUR) = 300 \times m_{H_2}$
Economic parameter	
operation hours in one year (N)	8760
interest rate (i)	12%
maintenance coefficient (Φ)	1.06
years of operation (n)	20

Table 6
Decision variables range.

Parameter	Minimum	Maximum
N_{PV}	1	510
N_{WT}	1	14
N_{OWC}	1	70

Table 7
Optimization hyperparameter values.

Parameter	Value
Number of populations	50
Number of reference points	55
Crossover ratio	0.9
Mutation ratio	0.33
Maximum number of generations	200
Convergence criterion	Over 20 consecutive generations

method in multi-objective optimization and multi-criteria decision-making. In this way, after the algorithm found a set of non-dominated solutions, TOPSIS is applied to rank the solutions [72]. Also, TOPSYS ranking requires weight adjusting. In this study, the TOPSIS weight for the three objective functions is considered equal to 0.33 to consider equal importance of objectives.

To optimize the HRES dynamically, a closed-loop co-simulation framework is employed, coupling TRNSYS with NSGA-III via Python. In this framework.

- TRNSYS executes the dynamic building-scale energy simulations, computing hourly outputs such as PV generation, wind and wave contributions, and hydrogen storage states.
- Python acts as the optimization controller, reading TRNSYS outputs at each hourly time step and computing the multi-objective fitness function.
- NSGA-III updates the decision variables (e.g., number of PVs, VAWTs, OWCs) and sends them back to TRNSYS for the next simulation iteration.
- This iterative feedback loop continues until convergence is achieved, defined as either stabilization of the pareto front over 20 consecutive generations or reaching the maximum of 200 generations.

This coupling ensures that TRNSYS is not just a passive evaluation tool but actively informs the optimization trajectory by reflecting the impact of changing system configurations on hourly performance metrics. The framework thus enables reproducible, adaptive, and data-driven multi-objective optimization for building-scale hybrid renewable systems. Moreover, in python, libraries such as *pymoo*, *scipy*, *mpl*, *seaborn*, *sklearn*, *pandas*, *numpy*, and *matplotlib* are used to obtain accurate results in optimization.

5. Results and discussion

5.1. Building energy simulation

As stated in the earlier section, Open Studio and Energy Plus tools are used to simulate the building. To obtain the building energy demand, the building load must be earned, the presented energy system is modeled in the TRNSYS 18 program which is a reputable tool and its components are already valid. Solar irradiation is collected by PV panels and generates electricity. Thus, renewable energy supplies a portion of the building load demand. Moreover, for the WEC, gained the hourly wave height and period from Ref. [73] database. Also, results of building model in Openstudio and energyPlus show that the total load for the hotel building in Kish for one year is 693,255 kWh (2495 GJ). Fig. 6 presents the monthly cooling and heating loads of the simulated hotel

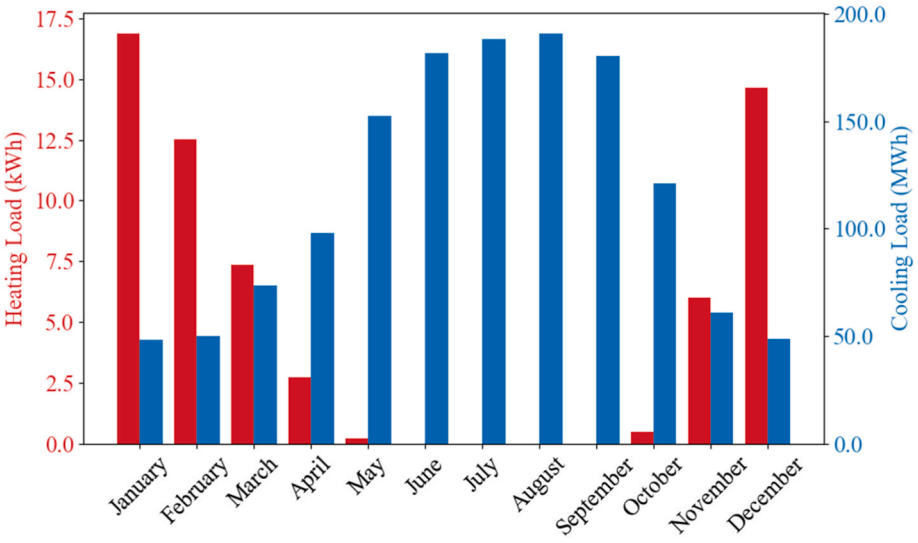


Fig. 6. Monthly load of the building cooling and heating.

located on Kish Island. The results clearly reflect the island distinct climatic conditions. Kish Island lies near the Tropic of Cancer and is influenced by subtropical high-pressure systems and the surrounding warm, shallow waters of the Persian Gulf. These geographic and atmospheric factors create a hot and humid environment for the majority of the year. As illustrated in Fig. 6, the building experiences a substantial cooling load from May through September, with peak demand occurring during the summer (especially July and August) that cooling requirements exceed 190 MWh. In contrast, the heating demand is minimal and occurs only during the cooler months, with the highest heating load appearing in January and December. Even in those months, the heating demand remains relatively low compared to cooling. This sharp contrast highlights the dominant role of cooling in the building energy profile. The simulation confirms that due to the island tropical climate, the building requires significantly more energy for cooling purposes than for heating, emphasizing the importance of designing energy systems that prioritize cooling efficiency and renewable integration tailored to hot-climate performance.

5.2. *Weather and ocean data*

To accurately calculate the building hourly energy demand, comprehensive weather data was obtained using Meteonorm software. This dataset includes essential climatic variables such as hourly ambient temperature, solar radiation, and wind speed specific to Kish Island. These parameters, shown in Appendix (Figure A1), play a critical role in determining the dynamic thermal and energy performance of the building across different hours and seasons. In addition to meteorological inputs, oceanic data was sourced from the ERA5 dataset [73] to support the analysis of wave energy potential. As presented in Appendix (Figure A2), this dataset provides detailed information on the wave height and wave period along the coastline of Kish Island. These parameters are fundamental for assessing the viability and output of WECs, which form part of the hybrid renewable energy system designed for the building. By integrating both terrestrial and marine environmental data, a more holistic and accurate simulation of the building energy behavior and renewable energy generation potential is achieved.

Moreover, the preprocessing is essential step to do well data collection process. Preprocessing causes the clean input data to be easily used in building and energy system modeling and affects the accuracy and results. Therefore, for both meteorological and oceanic hourly data (for one year), the average of each hour was used to fill out the missing data in that hour to clear dataset from data lacking.

5.3. *Electricity consumption by end-use*

The building electricity consumption is driven by several end-uses, including cooling systems, fans, exterior and interior lighting, pumps, and other electrical device. As illustrated in Fig. 7, these components contribute differently to the total monthly electricity demand throughout the year for the case study building located in Kish. Among these, cooling systems are the most dominant contributor, accounting for approximately 46% of the building total annual electricity consumption. This is particularly evident during the warmer months, specifically from May to September, when cooling demand surges due to elevated outdoor temperatures. In fact, around 36% of the total electricity usage occurs during this warm period alone. The seasonal variation is clearly observable that the electricity demand in the summer months is more than double that in the cold months such as January, February, and December. This underscores a significant impact of the cooling load on overall energy consumption. It also suggests that effective cooling strategies, such as energy-efficient HVAC systems, passive cooling design, and integration of renewable energy, can greatly influence the building energy performance and sustainability. Therefore, optimizing cooling-related energy use should be a primary focus in energy management strategies for buildings in hot and humid climates like Kish.

5.4. *Optimization results using NSGA-III and TOPSIS*

In the final stage of the study, a NSGA-III was employed to identify the most efficient system configuration for minimizing three key performance indicators: cost rate, LPSP, and CO_2 emissions. This multi-objective optimization technique allows for a comprehensive exploration of trade-offs between conflicting goals and is particularly suitable for complex energy system modeling. The outcomes of this optimization process are visualized in Fig. 8, which displays the Pareto frontier generated by the NSGA-III algorithm. Because this study simultaneously considers three different objectives, the optimization results are best provided in a three-dimensional space. In Fig. 8, the left-hand side illustration displays only the 3D Pareto frontier, which showcases the set of non-dominated solutions, those that offer a balance among the three objectives without being outperformed in all criteria by any other solution. Meanwhile, the right-hand side diagram includes the entire solution population, highlighting the Pareto-optimal points within the broader dataset. These visualizations help to clearly distinguish between average and high-performing configurations.

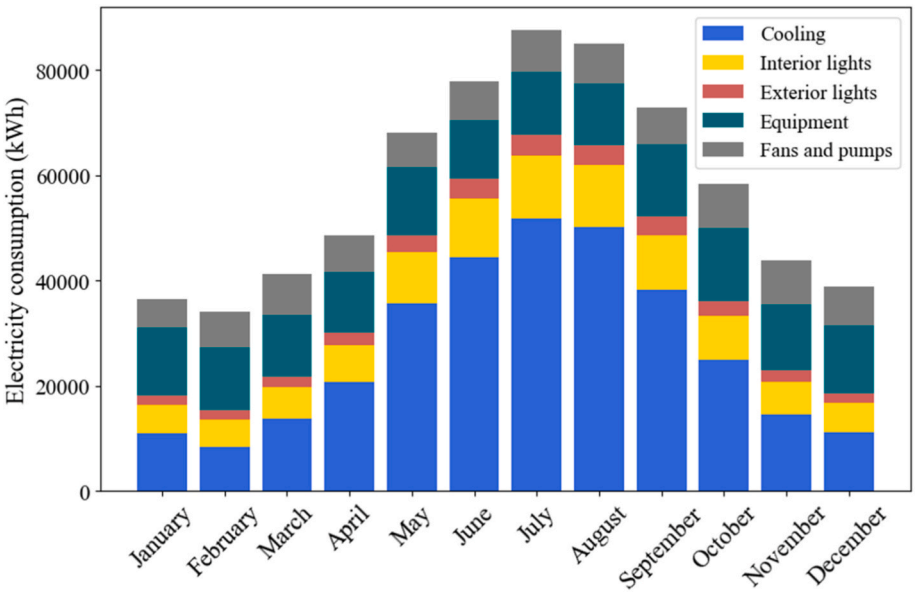


Fig. 7. Monthly electricity consumption.

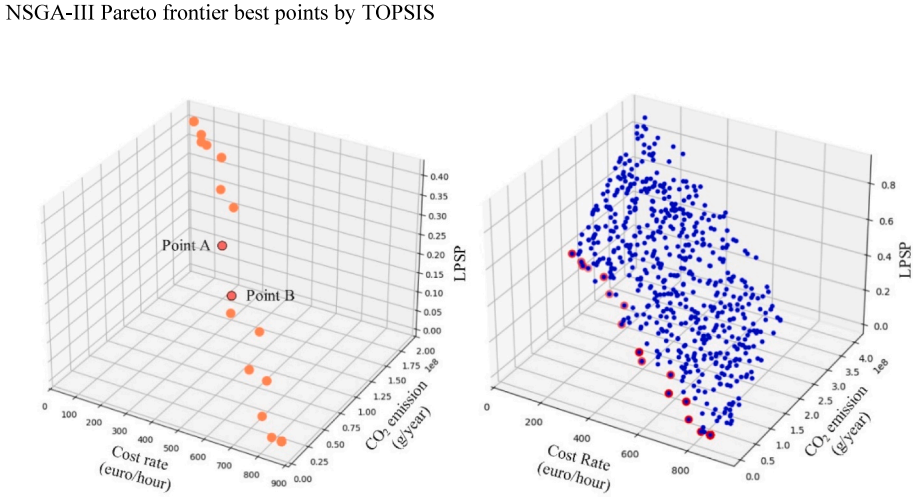


Fig. 8. Output 3D plots of pareto frontiers with the best points (A and B) of TOPSIS technique and the entire solution population.

To further refine the selection process and pinpoint the most appropriate solutions from among the Pareto-optimal set, the TOPSIS method was used. TOPSIS allows for decision-making based on assigning relative weights to each objective, which helps identify solutions closest to the ideal point while farthest from the worst-case scenario. Within this framework, Points A and B are identified in Fig. 8 as two of the most favorable configurations. Although both points are close in performance, there is a slight trade-off. Point A demonstrates a lower cost rate, while Point B offers better performance in terms of both CO_2 emissions and LPSP. Depending on the specific priorities of the project, whether minimizing cost or environmental impact, either point could be selected as the optimal solution. Further insights into the relationships between each pair of objectives are presented in Fig. 9, which contains 2D plots showing the correlations among: cost rate vs. CO_2 emissions, LPSP vs. cost rate, and CO_2 emissions vs. LPSP. Points A and B are clearly marked in these plots for comparison. Additionally, Point C emerges as the best solution on the CO_2 emissions vs. LPSP plot, suggesting it strikes the most favorable balance between environmental performance and power supply reliability. The link between grid electricity usage and CO_2 emissions is particularly evident here. Since LPSP quantifies the reliance on grid power to meet demand when renewable generation falls short, and grid power typically comes with significant emissions, there is a direct correlation between LPSP and CO_2 output. In fact, using grid electricity alone would result in an annual emission of approximately 452.7 tons of CO_2.

However, by implementing the optimized HRES configuration identified in this study, CO_2 emissions can be reduced to just 84.45 tons per year, equivalent to an 81.34% reduction in emissions. This substantial decrease highlights the environmental advantage of the proposed hybrid system. Also, the optimized system yields an LPSP of 0.179 in point B, indicating that the hybrid renewable system supplies over 82% of the annual electrical demand autonomously. For hotel applications, this reliability level is operationally acceptable when the system is deployed as a near-zero energy solution rather than a fully off-grid configuration. From a planning perspective, the selected LPSP range reflects a realistic compromise between reliability, capital investment, and decarbonization goals, making the proposed system suitable for decision-makers targeting substantial emission mitigation in coastal and island regions without incurring the high costs associated with near-perfect autonomy. Detailed specifications and performance metrics for

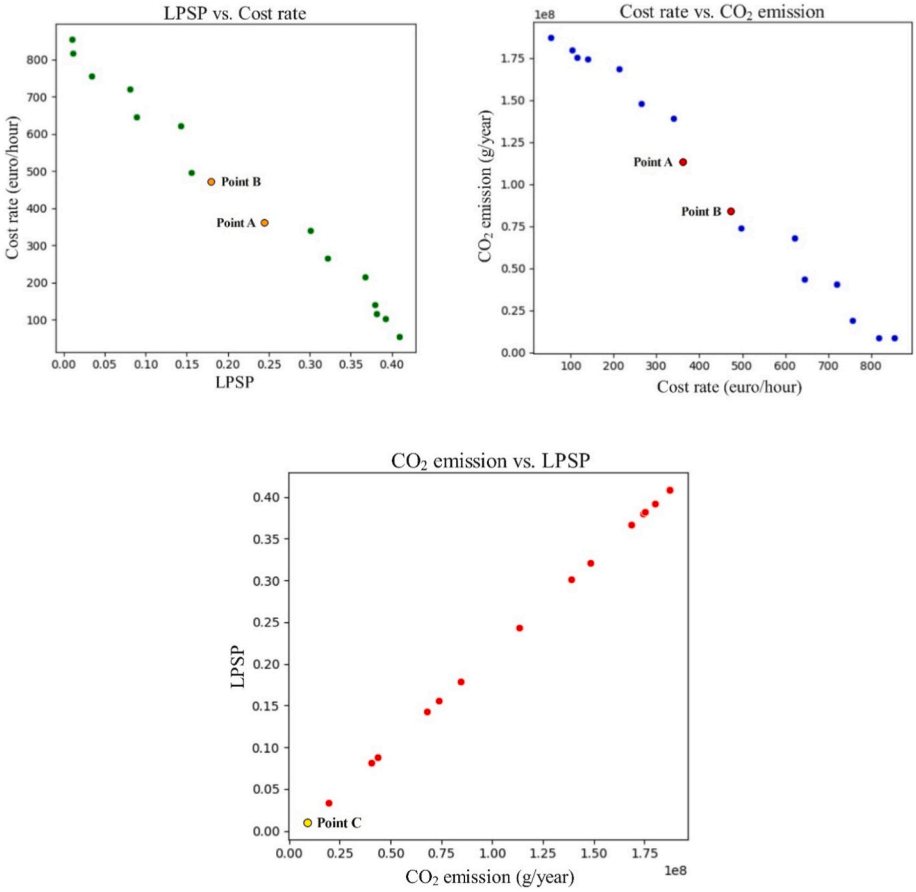


Fig. 9. 2D pareto frontiers plots of LPSP vs. cost rate, cost rate vs. CO_2 emission, and CO_2 emission vs. LPSP with the best points (A, B, and C) of TOPSIS technique.

Points A, B, and C are provided in Table 8 for reference.

Finally, A sensitivity analysis was conducted to evaluate the impact of ±10% variations in key input parameters: solar irradiation, wind speed, wave height, and component efficiencies on the hybrid renewable energy system performance. As illustrated in Fig. 10, all parameters exhibited noticeable but varied effects on the system key performance indicators (LPSP, CO_2 emission, and cost rate). Among them, solar irradiation showed the highest sensitivity, with a ±10% change resulting in approximately ±5% variation in all three indicators. This highlights the dominant role of solar energy in the overall hybrid configuration due to the region high solar potential. Wind speed and wave height had moderate impacts, inducing roughly ±2% to ±3% variations, while component efficiencies had a comparatively lower influence, below ±2%. Overall, the results confirm that the proposed system maintains stable performance against moderate parameter fluctuations, indicating robust design and reliable operation under typical environmental uncertainties.

5.5. Renewable energy contributions in optimum condition

PV panels, VAWTs, and OWC devices each contribute differently to meeting the building load demand across the seasons. As shown in Fig. 11, the share of renewable energy generated in the optimum condition, by PV panels ranges from 36% in winter to a peak of 58% in summer. This variation reflects the seasonal dependency of solar energy production, with higher efficiency and longer daylight hours in summer compared to winter. Conversely, the contribution of OWCs and VAWTs shows an inverse seasonal trend. OWCs, which harness energy from wave motion, provide their highest output during the fall (43%) and winter (40%) seasons when ocean activity tends to be more vigorous. Similarly, VAWTs demonstrate their strongest performance in winter (24%), benefiting from increased wind speeds typically associated with colder months. These complementary generation patterns highlight the advantages of combining multiple renewable sources into a hybrid energy system. Specifically, the inclusion of OWCs and VAWTs enhances system reliability during periods when solar energy is less abundant, primarily in fall and winter. This diversification ensures a more consistent and dependable renewable energy supply throughout the year, effectively addressing the variability of each individual source.

Table 8
NSGA-III Pareto frontier best points by TOPSIS.

Point	Cost Rate (EUR/hour)	Carbon Emission (ton/year)	LPSP	Number of PV	Number of VAWT	Number of OWC
A	361.2	113.40	0.243	493	13	26
B	472	84.45	0.179	500	13	35
C	854.8	8.57	0.010	495	10	66

5.6. Impact of hydrogen storage

The efficiency of the suggested renewable energy system can be thoroughly assessed by comparing its operation with and without a HESS. As depicted in Fig. 12, integrating hydrogen storage significantly enhances the system capability to utilize renewable energy sources. Specifically, renewable energy utilization increases by approximately 77% when hydrogen storage is included, highlighting the role of HESS in reducing dependency on the electrical grid. Without hydrogen storage, a substantial portion of the generated renewable energy remains underutilized, necessitating a higher reliance on grid-supplied electricity, especially during peak demand periods. However, with the

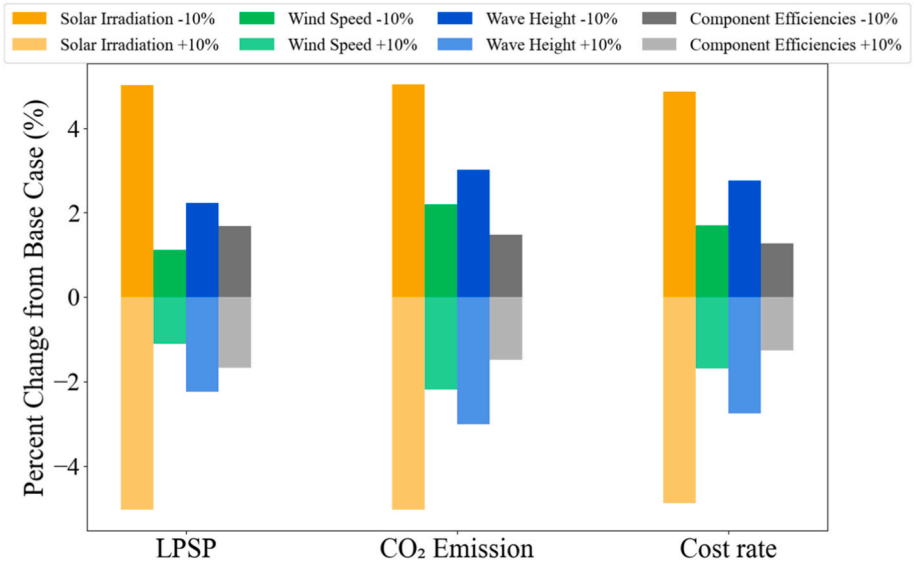


Fig. 10. Sensitivity analysis of the solar radiation, wind speed, wave height, and component efficiency for each objectives.

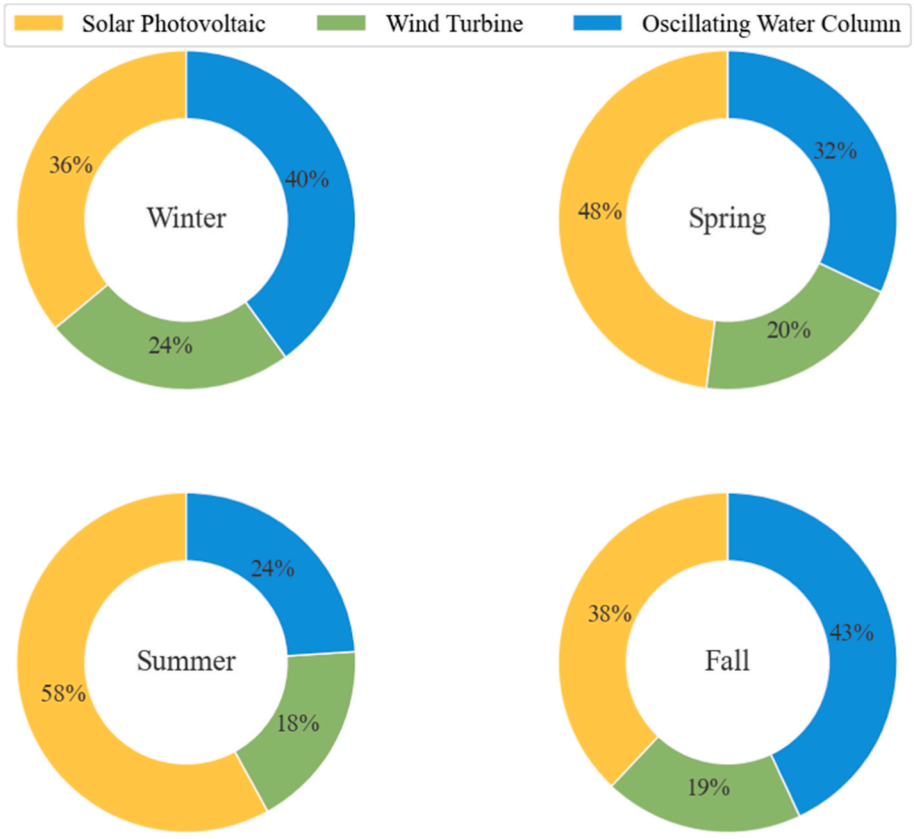


Fig. 11. Percentages of generated energy by solar PV, VAWT, and OWC in different seasons.

addition of HESS, surplus renewable energy generated during high-production months (e.g., June to August) can be stored and later used during periods of lower generation (e.g., December to February), thereby improving overall system efficiency and reliability. Moreover, the inclusion of hydrogen storage enables the renewable energy system to cover up to 38% of the building annual electricity load directly from stored renewable energy, substantially reducing the building carbon footprint and grid dependence. This demonstrates that hydrogen storage not only enhances energy autonomy but also ensures better load balancing and energy resilience. Overall, integrating hydrogen storage significantly improves the operational effectiveness of the renewable energy system by maximizing renewable energy capture and minimizing energy wastage.

5.7. *Strategic implications for energy planning in coastal buildings*

Although this study focuses on a specific hotel on Kish Island, the findings provide transferable planning and design insights for hybrid

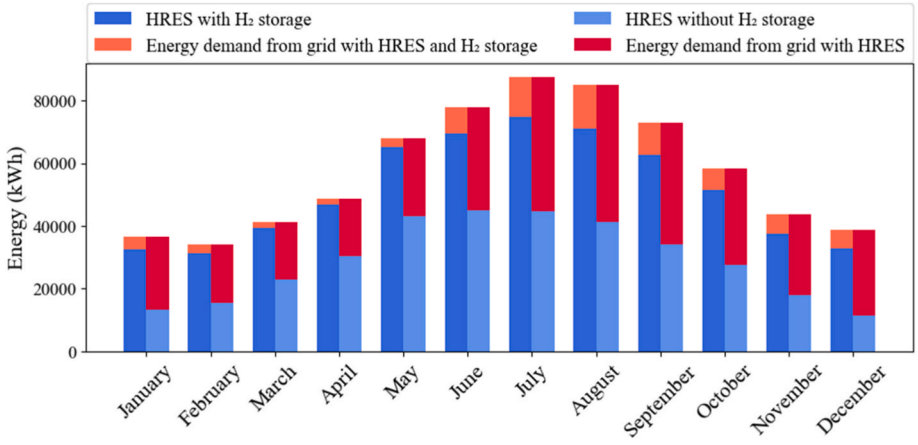


Fig. 12. Comparison of monthly energy consumption from renewable energies and grid electricity with H_2 storage and without H_2 storage.

renewable energy systems in other coastal and island hotels. The results demonstrate that integrating multiple renewable resources with complementary temporal characteristics can substantially reduce carbon emissions and grid dependence in large, energy-intensive hospitality buildings, particularly in regions with diverse coastal energy potentials.

From a strategic perspective, the analysis highlights the conditions under which hydrogen-based energy storage becomes most valuable, namely when long-duration or seasonal energy balancing is required to support near-zero energy objectives without imposing the high costs associated with fully off-grid operation. In such contexts, hydrogen storage complements solar-, wind-, and wave-based generation by enhancing system flexibility and resilience rather than merely increasing short-term reliability.

For planners, designers, and policymakers, the proposed modeling and optimization framework enables early-stage evaluation of trade-offs between cost, reliability, and decarbonization targets, allowing system configurations to be adapted to local resource availability, energy prices, and policy priorities. Accordingly, the study is intended to serve as a scalable decision-support reference for coastal energy planning rather than a site-specific design prescription.

6. Conclusion

The growing global emphasis on sustainable development and carbon neutrality has intensified the need for nZEBs, particularly in regions with abundant renewable energy resources. Coastal and island environments, while offering significant solar, wind, and wave energy potential, present unique challenges such as high cooling loads, variable resource availability, and reliance on grid electricity. Addressing these challenges requires advanced modeling and optimization to ensure energy efficiency, economic feasibility, and environmental sustainability. In this study, a hybrid nZEB system integrating PVs, VAWTs, and OWCs was modeled for a hotel building on Kish Island. To enhance reliability and reduce grid dependency, a HESS was incorporated. A feedback-based framework combining TRNSYS simulations with NSGA-III multi-objective optimization was employed to identify the most cost-effective and environmentally sustainable configuration. The inclusion of HESS substantially improved system autonomy, reducing reliance on grid electricity from approximately 40–50% to less than 12%. This demonstrates that energy storage is critical for enhancing the resilience of hybrid renewable systems in locations with variable resource availability. The optimal configuration, comprising 500 PV modules, 13 VAWTs, and 35 OWCs, achieved a LPSP of 0.179, an annual CO_2 emission of 84.45 tons, and a cost rate of 472 €/h. These results indicate that the hybrid system successfully balances sustainability, reliability, and cost efficiency. The analysis also highlighted the significant impact of local climatic conditions on energy demand. In the hot and humid environment of Kish Island, nearly 47% of annual electricity consumption is devoted to cooling.

The integration of OWC-based wave energy, which is both carbon-free and site-specific, proved particularly advantageous. Its dual functionality as an energy generator and coastal breakwater further enhances its environmental and infrastructural value. This study explores beyond traditional single-source or simpler hybrid energy systems by simultaneously integrating solar, wind, and wave energy with a hydrogen-based storage system.

The methodological advancements not only demonstrate the practical applicability of the system for real-world deployment but also highlight its innovative contribution to the design of nZEBs in challenging climatic and geographic contexts. From a broader perspective, the findings underscore the potential of hybrid renewable systems to achieve nZEB objectives in coastal regions. The synergistic operation of solar, wind, and wave energy sources not only reduces carbon emissions but also strengthens energy security through diversified energy inputs. All of these are in line with the energy strategies to developing the coastal hotels in accordance with nZEB for occupants comfort and also energy availability in island regions.

Nevertheless, the study is limited to simulation-based analyses without experimental validation and based on one geographic location, which limits the generalizability of the results. Also, simplified modelling assumptions are used for WECs, and component efficiencies are assumed to be constant and do not account for degradation or ageing effects, which may affect accuracy. Interannual variability of weather and wave resources is not considered, as the analysis is based on a single typical meteorological year.

Future research should focus on field implementation, component degradation modeling, and the development of advanced operational control strategies. In addition, the integration of thermal energy systems, such as solar collectors and phase change materials, could provide more effective management of cooling and heating loads.

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.

Appendix

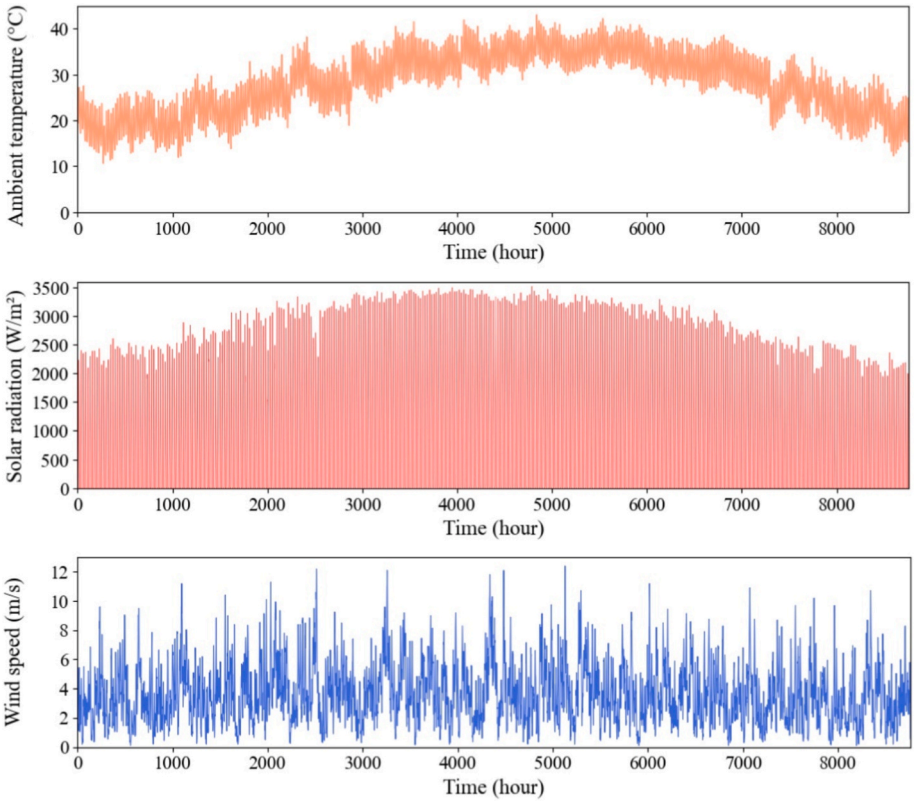


Fig. A1. Hourly data for Kish ambient temperature, solar irradiation and wind speed.

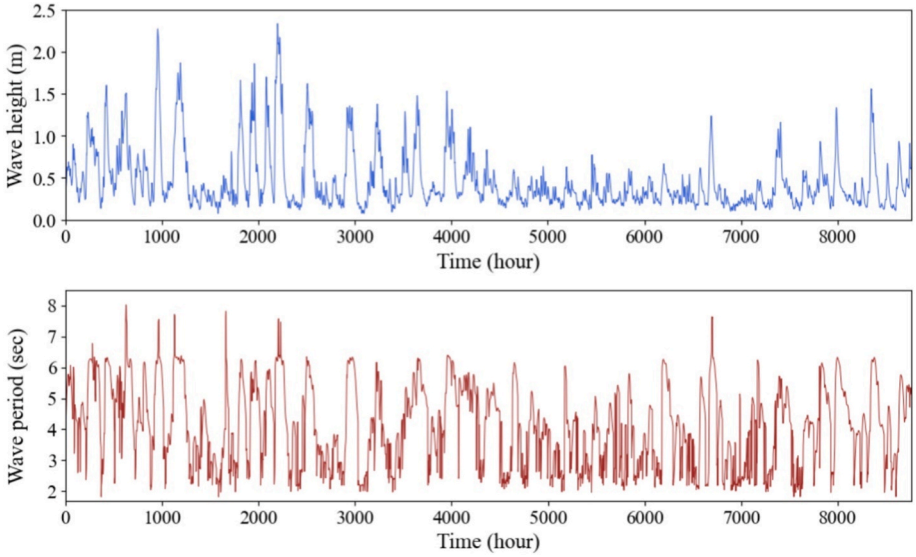


Fig. A2. Hourly data for wave height and period in Kish.

Data availability

Data will be made available on request.

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