Fundamental Research 5 (2025) 2161–2179

Contents lists available at ScienceDirect

Fundamental Research

journal homepage: http://www.keaipublishing.com/en/journals/fundamental-research/

Review

Optimisation of island integrated energy system based on marine renewable energy

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A R T I C L E I N F O

Article history:
Received 10 July 2024
Received in revised form 17 November 2024
Accepted 26 November 2024
Available online 15 December 2024

Keywords:
Marine renewable energy
Energy conversion and storage
Island integrated energy system
Process systems engineering
Process integration

A B S T R A C T

Integrating marine renewable energy (MRE) with conventional energy sources and logically constructing island energy systems is crucial for alleviating island energy supply challenges and helping coastal energy systems achieve a sustainable, low-carbon transition. In this study, the status of marine energy utilisation technologies is reviewed, with a focus on advancements in energy conversion equipment, grid integration, and energy storage. The economic feasibility and environmental sustainability of marine energy systems are comparatively analysed to enhance the development and utilisation of marine energy technology while reducing the economic cost of power generation. Suitable equipment is highlighted for islands, with efficient energy generation strategies proposed to achieve cleaner, localised, and cost-effective island integrated energy system (IIES) design. Island energy facilities vary, and integrated development is crucial for building new energy systems. Based on the types and resources of island energy, IIESs are constructed for hierarchical energy utilisation and multi-energy coupling, coordinating resources to achieve source–grid–load–storage integration. The optimisation of IIESs is reviewed, with a focus on modelling methods, intelligent algorithm development, and system simulation. This study differs from previous research as it considers the integration of marine energy into existing systems to achieve comprehensive integration of multiple energy sources. Additionally, optimisation and solution methods for IIES models are summarised. To integrate complex, multivariable energy systems and create stable and predictable outputs, marine energy and load forecasting methods are explored. Overall, this study supports the advancement of marine energy utilisation, focusing on its progressive integration into island energy systems as the efficiency of marine energy improves. This work aims to inspire the development of new functions and modules based on existing system optimisation and forecasting techniques.

1. Introduction

The latest International Energy Agency report highlights that global energy demand is increasing, rebounding following a brief dip during the COVID-19 pandemic in 2020, as shown in Fig. 1a. This trend is expected to continue, with the annual growth in global electricity demand rising from 2.6% in 2023 to an average of 3.2% in 2024–2025, surpassing the pre-pandemic rate of 2.4%. As the largest electricity consumer globally (31% of global energy in 2022), China experienced slower energy demand growth in 2022 due to economic factors but is nonetheless expected to see an average annual growth of 5.2% from 2023 to 2025 [1]. As shown in Fig. 1b, despite this growth, most of the world's energy is still derived from fossil fuels, and about three-fifths of it is used to generate electricity [2]. Relying heavily on fossil fuels is not sustainable in the long term due to the inherently limited nature of these resources, there is a crucial need to transition to renewable energy sources (RES) [3]. In China, coal remains a significant part of the electricity system, representing over 62% of power generation in 2022. Hydropower ac-

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https://doi.org/10.1016/j.fmre.2024.11.022
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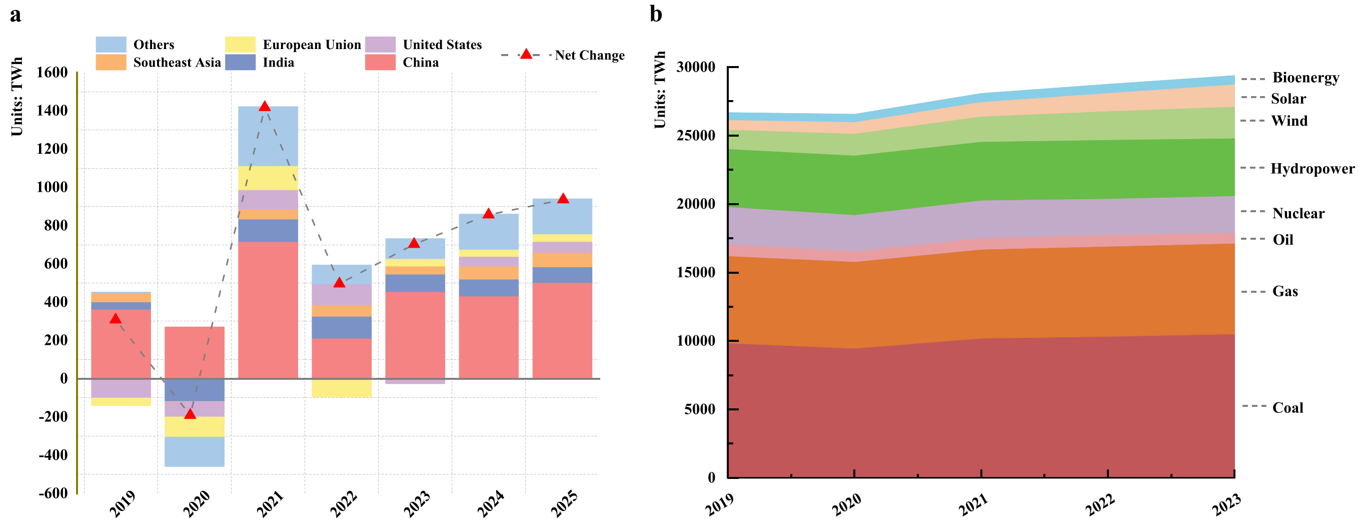


Fig. 1. (a) Year-on-year variations in electricity demand by region from 2019 to 2025 [1], (b) electricity production by source, World. In 2023, the proportion of energy generation by source (Coal: 35.5%, Gas: 22.5%, Hydropower: 14.3%, Nuclear: 9.1%, Wind: 7.8%, Oil: 2.7%, Solar: 5.5%, Bioenergy: 2.3%). In addition, other renewables: 0.3% (including waste, geothermal, tidal and wave) [2].

counts for half of the renewable electricity generation, followed by wind at 29% and solar photovoltaic (PV) energy at 15% [1].

The current outlook predicts that renewable power generation will grow significantly, with an annualised growth rate exceeding 9% surpassing that of all other sources combined, making up over one-third of the global power generation mix by 2025 [1]. Energy transitions are not just technological shifts but are also closely linked to societal, economic, and political structures [4]. Reducing global dependence on fossil fuels, addressing energy demand, overcoming design and governance challenges, and generating reliable electricity are all essential to achieving an environmentally friendly energy portfolio that offers socio-economic and environmental benefits [5]. As a part of this energy mix, marine renewable energy (MRE) is a promising low-emission resource. The energy potential of oceans and seas is well recognised and could help promote a shift from a fossil fuel-based energy system to a more sustainable and flexible mix, with greater reliance on indigenous, clean, renewable, predictable, and reliable energy resources. The term MRE typically includes energy from waves, tides, ocean currents, salinity, and temperature differences, with the relevant power generation equipment installed and operated at sea, while a broader definition also encompasses marine biomass, offshore wind, and offshore solar energy that utilise the ocean's surface [6]. Among the current globally installed capacity of RES, hydropower represents a major component with an installed capacity of 1170 GW, followed by solar PV at 760 GW, wind power at 743 GW, and bioenergy at 145 GW [7]. The strengths, weaknesses, opportunities, and impacts of MRE were analysed by Molla et al. [7], with the main findings of this analysis summarised in Table 1.

Alternative energy technologies such as MRE devices can provide green power, thus aiding decarbonisation; for example, oil and gas companies can use MRE devices to supply green power to offshore platforms and sub-sea facilities [13]. While renewable electricity forms a crucial part of any sustainable future energy mix, its lack of flexibility to meet grid demands and the continued need for emissions-free thermal energy and fuels represent notable challenges [14]. The volatility of MRE and the need for improved grid flexibility have become key focuses recently. As the share of power generated from intermittent renewable sources rises along with electricity demand, integrating these intermittent sources will become a challenge to power system flexibility.

Islands are a key example of an area affected by challenges related to renewable power generation. Due to their remote locations and lack of freshwater resources, islands often struggle to meet essential water demands. Seawater desalination effectively utilises renewable energy and enhances the flexibility of system controls in these areas [15]. The instability of microgrid renewable sources such as PV and wind energy, along with their dynamic power loads, complicates the economic and safe operation of these technologies. Energy storage (ES) technology can help address these issues by storing excess electricity and providing power during shortages [16]. Green hydrogen generation in far-offshore locations has also been proposed for decarbonisation efforts, especially in regions aiming for energy independence [17]. According to Lüth et al. [18], connecting near-shore wind farms directly to the electricity system can provide greater benefits, whereas, for distant islands, electrolysis can offer higher value by avoiding the need for costly long-distance cable infrastructure. Combining ES and electric vehicles can also enhance renewable energy integration and reduce infrastructure requirements [19]. Interest in integrating distributed energy into microgrids has also increased, with solutions including ES, microgrid development, hybrid systems, demand management, distributed generation (DG), and smart grids [20]. In MRE-based island integrated energy systems (IIESs), the energy equipment capacity is configured to avoid heterogeneous energy flows, with grid and natural gas network scheduling used to coordinate user demand changes. As energy supply technology, storage, and demand-side loads evolve, traditional integrated energy system (IES) strategies are becoming less effective due to increased complexity; thus, IES scheduling must be optimised via multi-objective and coordinated approaches involving various energy sources [21].

In particular, in challenging locations such as islands, there is an urgent need to exploit island resources and develop innovative energy supply models to meet the energy demands of residents. Meschede et al. [22] reviewed 100% renewable energy systems for islands, focusing on transition plans, the sectors involved, and regional differences; however, they did not address specific system integration. Liu et al. [19] analysed energy demand, forecasting techniques, and hybrid renewable systems for isolated regions, emphasising the potential of solar and wind. They suggested developing complex models tailored to isolated areas. Recent research has focused on optimising system configuration and operation [23]. Simulation platforms have been used to generate scenarios for island decarbonisation, while Yang et al. [24] proposed a reinforcement learning method to optimise energy management in island clusters. Cabrera et al. [25] planned island energy–water infrastructure to maximise renewable energy contribution, balancing fuel use and excess electricity. Previous reviews have examined the flexibility [26] and feasibility [27] of coastal marine energy technologies; however, comparative analyses of specific marine energy technologies for

Table 1
SWOT analysis of marine energy technologies.

MRE	Strengths	Weaknesses	Opportunities	Impacts	Refs
Tidal Range Energy	Predictable output power (120–400GW). High energy density.	High initial investment. Limited suitable locations globally. High construction time and cost.	Can be utilised as bridges, enhancing land accessibility and visual aesthetics.	Disrupts bird habits and aquatic migration. Affects ship movement and creates construction noise.	[8]
Tidal Current Energy	450 GW global resource.	Reduced power due to turbine placement.	Supports marine life migration and ecosystem balance.	Impacts fisheries, aquatic migration, fish schools, coral reefs, and sport fishing.	[9]
Wave energy	Abundant resource (1–10TW). Highest power density among RES. High availability.	High installation and maintenance costs. High transmission cost. Less effective in calm seas.	Abundant untapped resource. Does not occupy residential or agricultural land. No emissions.	Complex maintenance. Water eutrophication and toxification. Hampers ship movement. Affects marine habitats. Recycling wave energy devices is challenging.	[10]
Ocean thermal energy	Abundant resource (30 TW). High power density and availability.	Low efficiency. Far from shore.	Promotes biodiversity.	Water pollution and toxification from ammonia leakage. Affects marine habitats and pH balance.	[11]
Salinity gradient energy	Requires a small land area. High efficiency.	Requires shut down for maintenance. High investment required for multiple cells.	Can be linked with desalination plants, reducing environmental impacts.	Water toxification, salinity changes, eutrophication, fish decline, noise during installation and operation.	[12]

island energy complementarity to date are limited, as most technologies are still experimental. Accordingly, most research on marine energy systems has focused on evaluating and introducing renewable energy sources to energy-poor islands without considering how marine energy can be integrated into existing multiple energy systems. Applying this approach can enhance the development and utilisation of marine energy technologies while also reducing the economic cost of power generation.

To address these limitations, this paper summarises the latest developments in marine energy technologies and analyses suitable energy conversion equipment to allow marine energy technologies to be integrated into island energy systems. In this paper, the integration of marine energy with other clean energies in island energy systems is analysed along with the complex, multidimensional modelling and solution processes involved in IIES optimisation, and predictive methods for optimising IIES scheduling are discussed. In addition, future research prospects are summarised. The framework of the study is shown in Fig. 2. The key points of the current review include:

- Design and integration of coupled marine energy systems.
- Economic and environmental benefit assessment.
- Optimisation and solution methods.
- Energy and load forecasting methods.

2. Marine renewable energy

This section provides a brief introduction to the technological advancements in MRE, along with an analysis of how to improve efficiency in addressing technical challenges. Specific examples of applications and system integration are also provided.

2.1. Salinity gradient energy

Among the various RES available today, salinity gradient power (SGP), although relatively rarely used, is particularly suitable for coastal countries. In this technique, clean energy is generated from the chemical energy produced when two solutions with different salinities come into contact. Freshwater from rivers mixes readily with saltwater, seawater, or more concentrated solutions. The most efficient SGP technologies implemented at a pilot scale for harvesting osmotic energy are pressure retarded osmosis (PRO) and reverse electrodialysis (RED) [12], which are both based on membrane science. RED relies on the transport of ions across selectively charged ion-exchange membranes, categorised as anion-exchange membranes and cation-exchange membranes, with chemical energy converted into electrical power through electrochemical reactions at electrodes. In contrast, PRO is driven by water permeation across salt-rejecting membranes, with electrical power mechanically generated through turbine rotation, as illustrated in Fig. 3a and b [28].

The multivalent ions of seawater impact its osmotic power. River water reduces the osmotic power by half due to the presence of divalent ions and low ion concentration [29]. Biomimetic materials enhance osmotic power density by blocking river water cations [30]. Thermal considerations are also significant in these systems, with reverse electrodialysis systems using low-grade heat for power generation [31]. Enhancing the concentration and temperature and selecting an appropriate initial concentration are critical for maximising the efficiency of osmotic power. The membrane design must also account for surface charge, thickness, and pore density effects. One approach is to reduce the pore size to below 2 nm to enhance the ion selectivity, while advanced membrane engineering should be applied to mitigate adverse effects on ion permeability.

In terms of power densities, Sharma et al. reported that PRO outperforms RED, with 22–32 times higher values for engineered salinity gradients [32]. Ju et al. [33] also confirmed higher power densities for PRO (1.09–3.24 W/m^2) compared to RED (0–1.66 W/m^2) under conditions without fouling. RED exhibited a smaller decrease in power density due to fouling (0–11.2%) than that observed in PRO (14.2%–58.7%). The use of wastewater reverse osmosis brine as the low-salinity solution resulted in reduced power densities for both methods. Despite the superior performance of PRO, this approach involves challenges such as the requirement for high-performance pumps, pressure exchangers, and membranes; thus, technological advancements are needed for both PRO and RED to become feasible sources of renewable energy [34]. Compared to PRO, RED is deemed the more suitable approach for low-salinity power generation at river estuaries due to its advantages such as high energy density, low membrane pollution, and low investment cost [35]. Integrating renewable energies with desalination has also been proposed as a practical solution to water scarcity, thereby enhancing water supply sustainability [36]. Integrating a salinity gradient energy generation system into seawater desalination involves using high-concentration seawater output from desalination as the draw solution, with seawater as the feed solution. This expands the application scope of salinity gradient energy, increases osmotic pressure to enhance power density, reduces energy costs for desalination, and adds economic value.

Traditional salinity gradient energy-based power generation methods may be unsuitable for large-scale applications. Instead, more viable alternatives may include optimising systems to power them using batteries or applying hybrid approaches such as RED combined with elec-

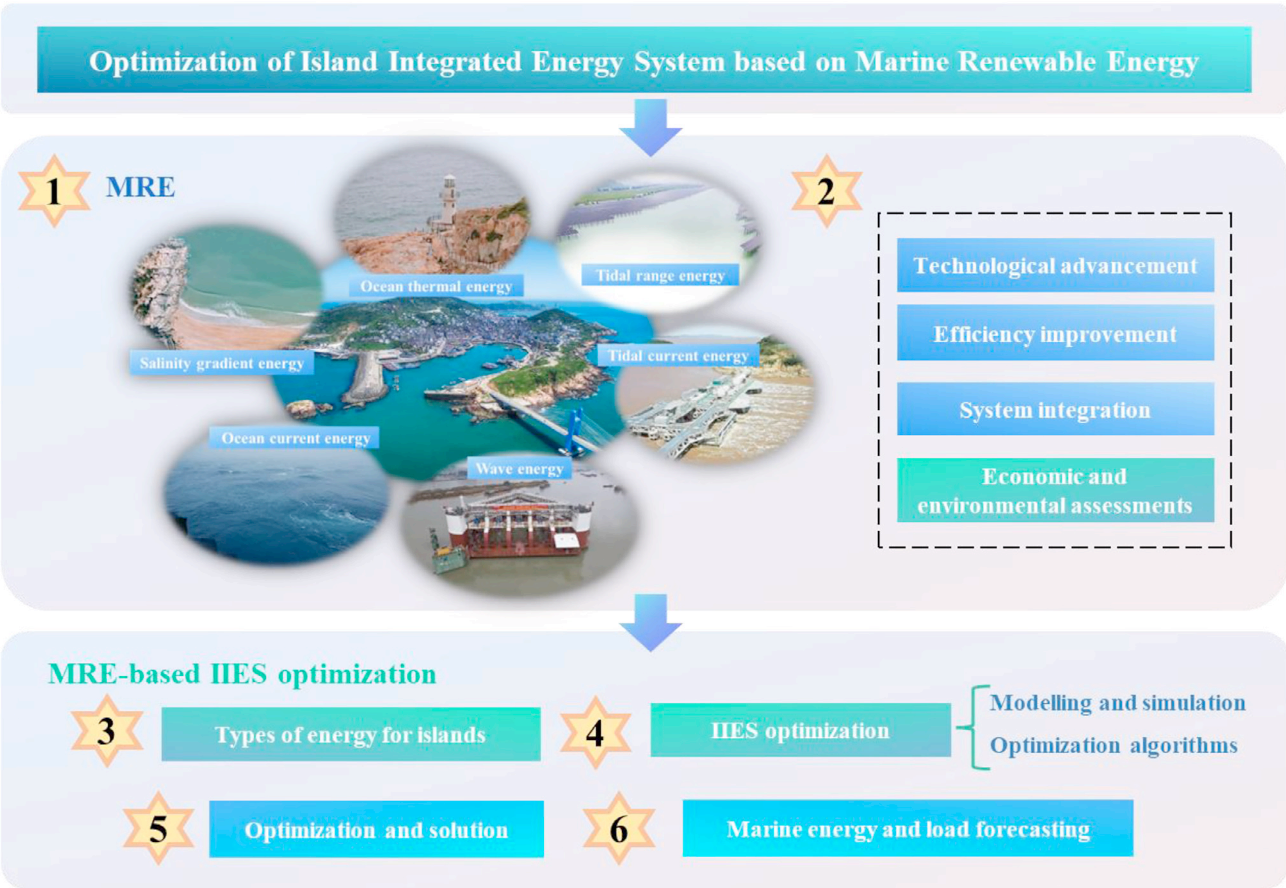


Fig. 2. Paper framework.

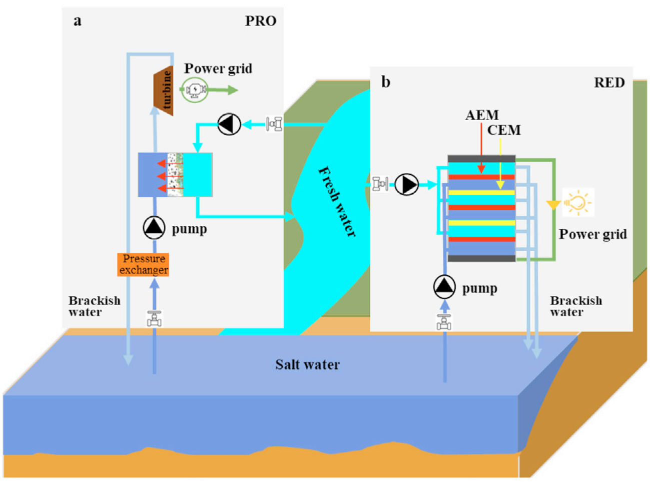


Fig. 3. (a) Process layout for a typical PRO power plant and (b) schematic of a typical RED system [28].

trodialysis, reverse osmosis, or nanofiltration [37]. Significant research has also focused on using RED for hydrogen generation. Since directly integrating salinity gradient energy into the power grid is challenging, instead converting it into storable hydrogen energy represents a feasible option [38]. Salinity gradient energy can be harnessed for hydrogen production through the integration of RED and water electrolysis, as demonstrated by Fonseca et al., who showcased the potential of coupling water desalination with hydrogen generation [39].

2.2. Ocean thermal energy

Ocean thermal energy conversion (OTEC) is a renewable energy technology that harnesses thermal energy stored between the ocean's surface and deep water to generate electricity. The efficiency of this approach is based on global sea surface temperatures, with the tropics experiencing the highest temperatures, which decrease towards higher latitudes. OTEC plants can provide continuous energy generation 24 h a day year-round, thus making them ideal and eco-friendly choices for distributed generation applications in remote tropical islands [40]. The research using the CESM-H model suggests that under high carbon emission scenarios, global OTEC power potential could increase by 46% by the end of this century [11]. Major design aspects of OTEC systems include location selection (which affects the temperature difference and sea temperature changes), thermodynamic cycles, and system positioning. The efficiency of the cycle is significantly impacted by the water temperature gradient, where higher temperature differences lead to improved efficiency. Notably, the relatively limited temperature difference available in the sea (typically approximately 20 °C) results in generally low thermodynamic cycle efficiency. OTEC systems comprise heat exchangers (evaporators and condensers), turbines, generators, seawater pumps, and working fluids. In this technique, thermodynamic cycles are used to extract heat from the sea surface to vaporise a low-boiling-point fluid in the evaporator, which then drives a turbine for electricity generation. There are two primary types of OTEC systems: open cycle (OC–OTEC) systems, depicted in Fig. 4a, and closed cycle (CC–OTEC) systems, which integrate a desalination process, as illustrated in Fig. 4b [41]. Due to its closed working fluid circulation system, CC–OTEC systems can effectively reduce environmental pollution, improve system stability and efficiency, and be used in a wider range

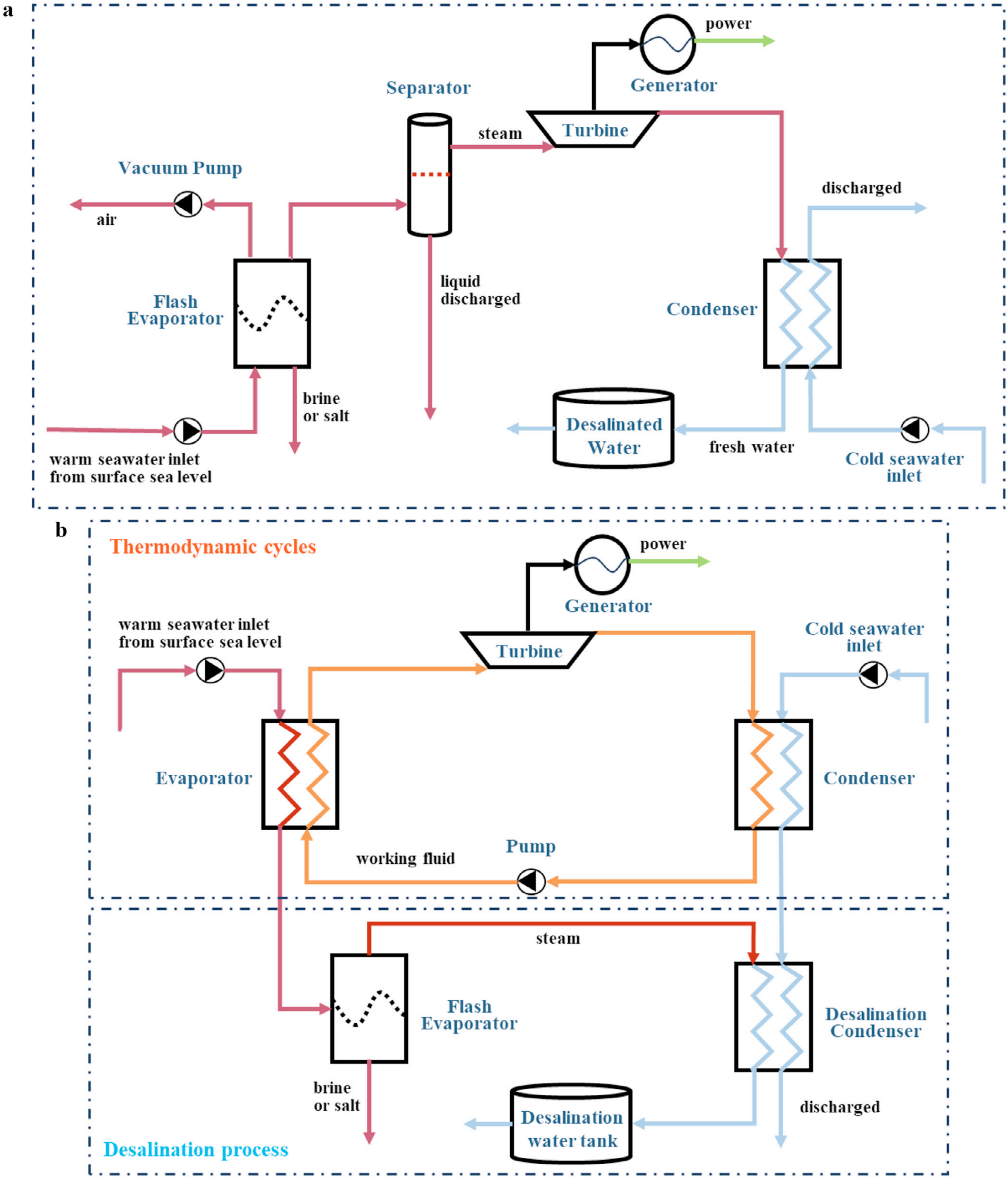


Fig. 4. (a) Diagram of a conventional open-cycle OTEC system, (b) conventional OTEC systems with closed cycle with desalination process [41].

of applications. In contrast to OC–OTEC systems, which need larger turbines for low-pressure seawater vapour and face mechanical resistance issues, CC–OTEC systems use different fluids to minimise their component sizes, thus offering a significant advantage [41]. Ammonia is commonly used as a working fluid due to its low boiling point, enabling condensation at low pressure and evaporation at high pressure [42]. The theoretical Carnot cycle efficiency is approximately 6.7%, whereas more practical cycles, such as the organic Rankine cycle, Kalina cycle, and Uehara cycle, achieve efficiencies in the range of 3%–4% [42].

OTEC research aims to maximise energy extraction using closed-cycle systems, primarily by employing the Rankine cycle. An analysis conducted by Abbas et al. [43] revealed that the primary challenges in OTEC technology are the selection of circulating fluid and types of heat exchangers, thus emphasising the need for steam turbines to be optimised to enhance the efficiency of this approach. Zhang et al. [44] suggested that various energy sources, such as solar power, can be integrated to increase temperature differences and improve system performance while simultaneously reducing costs. They proposed a temperature-lifting OTEC cycle, achieving a 40% average thermal efficiency improvement and significant increases in energy efficiency. The optimal cost was reduced by 38%, thus resulting in a decrease in the levelised cost of energy from 0.18 $/kWh to 0.13 $/kWh. Vera et al. [45] investigated a theoretical model and optimisation of an OTEC system, which was integrated with an organic Rankine cycle generator for small-scale applications in the San Blas archipelago (Panama). Onshore OTEC can be used to simplify operations by locating most of the required equipment on land, thereby eliminating the need for complex mooring systems or ship interfaces [46]. This setup also enables the export of desalinated seawater and nutrients from deep seawater, which has significant promise for advancing fisheries and sustainable aquaculture in tropical regions. The applications of OTEC may include not just power plants for green electricity generation but could also include district heating and cooling (to meet the refrigeration needs for freezing and preserving seafood), seawater desalination, hydroponic cultivation, aquaculture, and mineral extraction from seawater [47].

2.3. Wave energy

Wave energy boasts a higher energy density (3 kW/m^2) compared to wind and solar (500 W/m^2 and 170 W/m^2, respectively) [48], and energy predictions for this source show lower errors, thus making it highly suitable for grid integration. Wave energy systems are categorised based on factors such as position, construction, operational principle, size, orientation, and power take-off (PTO) system, as illustrated in Fig. 5a. Wave energy conversion comprises three stages: (1) initial conversion from wave energy into mechanical, pneumatic, or potential energy, (2) subsequent conversion of the absorbed energy into useful mechanical energy using specific PTO systems, and (3) final conversion of the mechanical energy to electricity by linking PTOs to generators [49]. As shown in Fig. 5b, these stages are interconnected and sequential. Improving the efficiency of energy conversion across these stages is essential for enhancing the power generation efficiency of the process overall. With advancements in wave energy conversion technology, various wave power generation devices, referred to as wave energy converters (WECs), are emerging [10]. Classified by their operational principles, PTO systems employ control strategies such as torque, airflow, current, power, or valve control, thus enabling WECs to adapt to varying wave conditions and enhance energy capture efficiency. The economic feasibility, efficiency, and complexity of different WECs are heavily dependent on the design of their PTO systems [50]. To achieve commercial applications of wave energy, two challenges must be addressed: improving energy efficiency through the development of reliable WECs and conducting spatiotemporal reliability assessments of wave energy [51].

Wave energy development focuses on areas with resources ≥ 25 kW/m. North America and Western Europe have stronger waves than East and Southeast Asia. In China, waves mainly originate from the north in the winter due to cold winds and from the south in summer due to warm currents. However, wave power along China's coastline is relatively limited, averaging < 10 kW per meter of wave front [52]. The ocean wave power of China varies along its coastline, with higher density in the East China Sea compared to the Bohai and Yellow Seas. In northern Zhejiang Province's Zhoushan archipelago, the wave power exceeds 2 kW/m, whereas further south, in locations such as Dachen Island, it surpasses 3 kW/m [53]. A methodology combining geographic information systems, multi-criteria decision-making, and artificial neural network (ANN) techniques found that approximately 1.36% (1427.93 km^2) of Hainan Island was suitable for wave power plant deployment, with optimal sites on the island are Wanning, Wenchang, and Qionghai area [54]. Selecting sites suitable for both wind and wave energy production can reduce installation costs and enhance renewable energy exploitation efficiency. Electricity demand and production integration from wave energy, along with other renewables, was pursued to achieve energy independence in an archipelago.

Wave energy for kilowatt-scale niche applications has experienced rapid development in the past decade. Unlike megawatt-scale utility applications, these smaller-scale, niche applications have received significant support due to their potential to reduce or eliminate cabling, mooring, and grid connection costs [55]. These smaller-scale applications include powering aquaculture platforms and integrating WEC devices into breakwater structures or artificial reef farms, such as the semi-submersible wave-energy-powered aquaculture platform in China's Penghu islands, which has been operational for six years [56]. Embedding WEC devices into breakwater structures can help reduce costs, enhance structure reliability, and provide green power to nearby facilities or artificial reef farms to safeguard coastlines and improve marine ecosystems [57]. Another related technology involves using WECs for navigation buoys, in which they are used to power lights, air horns, radar reflectors, and other navigational aids [58]. Studies have demonstrated the feasibility of using wave energy to meet the energy demands of large desalination plants, although the outcomes of this application vary based on wave technology and hourly analysis [59].

2.4. Tidal energy

The gravitational pull of the moon and sun induces the natural rise and fall of seawater, known as tides, which can be harnessed to generate energy. Two primary types of tidal energy technologies exist: tidal current (or tidal stream) energy and tidal range (or tidal barrage) energy. Different tidal energy technologies were reviewed and their respective technology readiness levels (TRLs) were tested and reported in IRENA [60].

Tidal current technologies harness the flow of water in open seas, analogous to wind turbines but in water; however, tidal current energy boasts high energy density, around 832 times greater than that of wind energy [61]. Extracting energy from ocean currents has received limited attention due to deployment challenges in deep offshore locations. Ocean currents, driven by wind, temperature, and salinity differences, are vast, continuous, and unidirectional, although slower than tidal currents. Their large volume makes them a promising approach for baseload power generation, with technologies such as tidal kites showing potential [62].

Tidal barrage technology operates by harnessing the kinetic energy generated by the movement of tides, similar to the principles of hydroelectric generation systems. This method utilises the tidal range, which represents the actual height difference between high and low tide, to capture potential energy [63]. Efficient tidal energy generation requires careful consideration of several main factors, including identification of suitable sites for tidal power plants, effective component design (e.g. turbines, generators, converters, and batteries), and determining the desired output to develop corresponding control mechanisms.

2.4.1. Tidal current energy

Marine current turbine (MCT) structures typically consist of a turbine, a generator (either a permanent magnet synchronous generator (PMSG) or a doubly fed induction generator), and a power converter. The corrosive nature of seawater poses a significant challenge in MCT systems, as seawater is a strong electrolyte. To address this issue, additional reliability measures must be introduced, including special coatings to prevent biofouling and corrosion, as well as the use of sealing and insulation materials suitable for saline environments [64].

There are two main configurations of MCT: (1) horizontal axis tidal turbines (HATTs), which are efficient but require high flow velocities that may not be met in deep water [65], and (2) vertical axis tidal turbines (VATTs), which generate lower power coefficients but can sus-

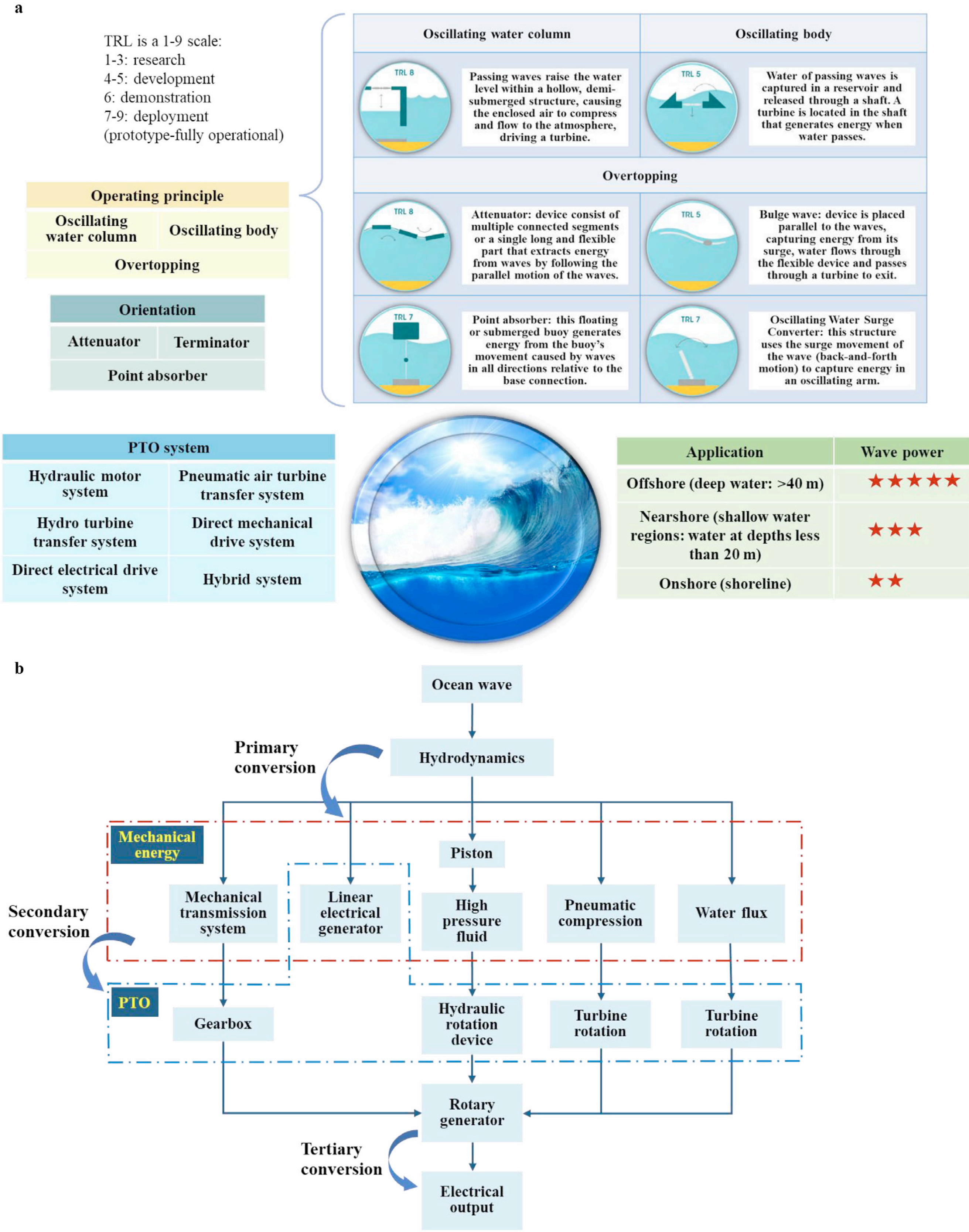


Fig. 5. (a) Wave energy classification system, (b) three stages of wave energy conversion [49].

tain continuous power under low flow conditions, making them suitable for deep-water environments [66]. Compared with VATTs, HATTs offer many advantages, such as higher efficiency and lower torque fluctuation. Type 4 MCT generators with full converters [67], including PMSGs [68], are utilised in AC microgrids to harness renewable energy from marine currents. The currently industrialised MCTs, primarily for tidal rather than oceanic currents, are all HATTs with sea-bottom supporting structures. Most of these turbines have fixed-pitch blades. For upcoming pilot oceanic current turbine farms, the preferred design is a three-blade, open rotor, axial flow turbine, anchored to the ocean floor [69]. Optimal tidal energy sites have strong, stable currents, shallow floors, and are situated close to shore. For example, the waters of the Zhoushan archipelago, one of the strongest tidal estuaries in China, show high power densities, especially in the Guishan, Guanmen, Xihoumen, and Luotou channels, with tidal stream power densities up to 6.79 kW/m^2 [70].

There are two main types of tidal current energy converter: (1) large-scale turbines intended for grid connection and (2) small-scale turbines designed for diverse applications in marine environments. The large-scale configurations primarily focus on supplying power to grids or islands [9]. Previous research has found that reducing the spacing between turbines across the stream (i.e. increasing local blockage) can significantly enhance power extraction performance. A staggered sub-array layout was implemented in a case study in Orkney's Hoy Sound to achieve optimal energy yield, involving two stages: power output regulation and integration of energy generation into Orkney's grid system, resulting in a 42.5% improvement in system efficiency and an expected 33% reduction in capital costs [71].

Tidal energy, though predictable, may not always align with demand. With proper optimisation and storage, this approach can offer reliable base-load power without disrupting grid operations. Key considerations include optimising conversion devices, managing costs, and ensuring structural integrity. Exploring multi-energy systems for applications such as in situ power supply, desalination, and mariculture is essential.

2.4.2. Tidal range energy

Tidal power plant feasibility depends on resource and basin size, tidal range, and environmental conditions [8]. In China, notable estuaries and bays with tidal power generation potential include Qiantang River, Hangzhou Bay, Yong River, Xiangshan Harbor, Sanmen Bay, Taizhou Bay, Jiao River, Yueqing Bay, Wenzhou Bay, Ou River, Feiyun River, and Ao River. The tidal range varies in these locations, with the range in the southern bay exceeding 5 m annually, while the tidal range in the Zhoushan Islands is 3–3.5 m [72]. Tidal range electricity schemes are designed to last at least 120 years to accommodate changes such as sea-level rise. While barrages in estuaries have historically been preferred for tidal range energy, coastal lagoons in bays are now increasingly popular due to the lower environmental impact of tidal schemes in these areas [73]. These two schemes were analysed by Vandercruyssen et al. [74] using the Lancaster 0-D Tidal Range Model, with barrages and lagoons compared in terms of energy generation, flood protection, navigation, and environmental impacts. Impoundments in barrages are generally shorter than those in lagoons, resulting in lower civil engineering costs, and barrages also typically experience slightly higher tidal ranges. Both barrage and lagoonal impoundments were found to foster diverse ecosystems, while two-way operation can match the tidal range while preserving intertidal areas.

Single-basin power plants are designed with turbines and sluice gates distributed along a reservoir. In this configuration, the reservoir exchanges water with the sea through the turbines for power generation. The plant's operation can be one-way (either ebb-generation-only or flood-generation-only), as depicted in Fig. 6a, two-way (bidirectional generation), as shown in Fig. 6b, or may include pumping intervals for storage purposes. Linked-basin systems, illustrated in Fig. 6c, consist of two internally connected lagoons or basins, with turbines positioned at an internal barrier that divides the impounded area into two lagoons [75]. Single-basin tidal power plants provide predictable energy outputs but have periods without generation in each tidal cycle due to turbine capabilities and significant variability over spring–neap cycles [76]. Athanasios et al. [77] considered the hypothetical case of a linked-basin system at the UK's Severn Estuary, which generated energy 80%–100% of the time over a spring-neap cycle but captures only about 30% of the energy of an equivalent single-basin design. So linked-basin tidal power systems offer more consistent energy generation than single-basin designs but may capture less energy overall. A run-of-river hydroelectric plant generates electricity using the natural flow of a river without requiring large reservoirs, thus making it suitable for coastal cities or islands. By integrating this type of hydroelectric plant with a tidal range power station in the same estuary or bay area, both water resources can be utilised to enhance overall power generation capacity and ensure a stable electricity supply.

To harness tidal potential energy more effectively in the future, there is a need to update the generating units (hydro–pumps), enhance construction skills, and optimise operations to reduce costs and minimise their environmental impact [72]. Exploring construction methods for medium to large-scale tidal power plants will also help accelerate the utilisation of tidal energy resources in coastal areas. Wave energy devices positioned along the tidal stream units situated near outfalls can capture additional energy while potentially reducing wave forces and harnessing extra energy to dissipate high-velocity water streams. The excess energy generated in this way can be converted into hydrogen for long-term storage or compressed air for short-term storage, or can be used in hybrid energy systems for desalination [74]. Repurposing disused infrastructure, such as historic docks, offers cost-effective and environmentally friendly options for the implementation of tidal energy systems, often with a focus on energy provision for waterfront housing and commercial development [78]. Tidal power plants (TPPs) have additional functions beyond energy generation. As eco-friendly solutions for coastal regions, TPPs clean up water, control flooding, and emit far less carbon dioxide than traditional (e.g. coal-fired) power plants. The proportion of CO_2 emissions displaced in the life cycle of a TPP is 100 times lower than that of a coal-fired power plant [79]. As an example of a successful TPP implementation, the Shihwa TPP generates energy and has revived a polluted area, transforming it into a flourishing ecosystem [80].

Overall, the current state of marine energy utilisation technology integrates multiple fields including oceanography, energy storage, geotechnics, hydraulics, mechanical engineering, materials science, power generation, power transmission, and reliability engineering. Although research and development in this sector have made steady progress, with a certain level of technical proficiency and production potential now accomplished, many challenges remain. These include the high cost of marine energy generation (high investment, small scale, and low profitability), potential risks of ecosystem disruption, technical issues, and the lack of market competitiveness. Table 2 summarises the primary technical challenges, applications, and system integration potential of MRE.

3. Economic and environmental assessments

The economic efficiency of ocean power generation is mainly reflected in the levelised cost of electricity (LCOE). Given the early stage of development across all marine energy technologies, predicting and stabilising the LCOE values of these systems remain challenging and uncertain. Extensive advances will be necessary in terms of research, development, demonstration, and validation to enhance the performance and reliability of marine energy systems and, ultimately, reduce their LCOE [26]. As wave and tidal capacity expand, their costs may decrease through economies of scale, streamlined supply chains, and device improvements. Government support, such as feed-in tariffs and clear renewable energy targets with dedicated deployment zones, would further

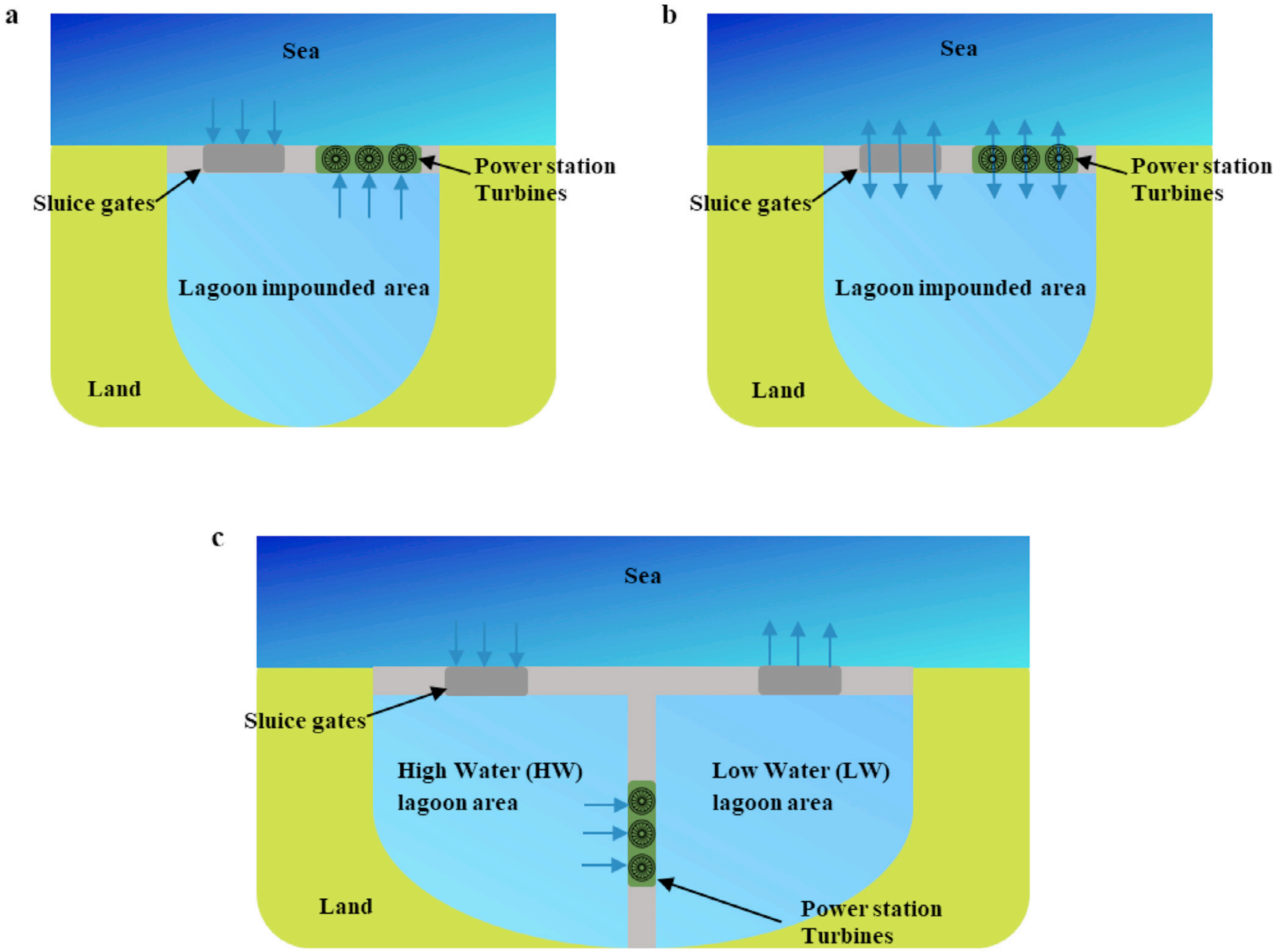


Fig. 6. Tidal range power plant designs consist of (a) single-basin ebb-only operation, (b) single-basin two-way operation, and (c) linked-basin operation [74].

Table 2
Technical challenges and system integration of MRE.

MRE	Primary technical challenges	Applications and system integration
Salinity gradient energy	Design of high-efficiency, anti-fouling membranes	Seawater desalination, wastewater utilisation, hydrogen production
Ocean thermal energy	Optimisation of cycle fluids and heat exchangers	Green electricity, mixing systems, district heating and cooling, desalination, hydroponics, aquaculture, mineral extraction from seawater.
Wave energy	Optimisation of power take-off systems	Green electricity, aquaculture, navigation buoys
Tidal current energy	Enhancement of marine current turbine and determination of optimal array configurations	Green electricity, aquaculture, seawater desalination
Tidal range energy	Dependency on environmental conditions and tidal power plant design	Green electricity, mixing systems (wave energy, run-of-river hydroelectric plant), reuse of abandoned docks
Ocean currents energy	Advancements in low-tide energy turbine technology	Green electricity

drive down costs, mirroring the reductions seen in onshore and offshore wind and solar PV energy. Globally, onshore and offshore wind energy costs have dropped to 0.05 $/kWh and 0.12 $/kWh, respectively [27]. Marine energy conversion efficiency is directly tied to the maturity of power generation technology, with the efficiency and costs of various marine energy conversion technologies listed in Table 3.

Before installing MRE farms in specific areas, each case study requires a thorough investigation of a range of variables and parameters. Effective preliminary field studies are essential, including multidisciplinary analyses involving fields such as oceanography, taxonomy, ecological impact assessment, and toxicology. These efforts can be used to anticipate environmental risks associated with developing MRE projects, minimise their impacts, and prioritise conservation efforts for key ecosystem elements. Martínez et al. [85] used multivariate analyses to assess the effects of various energy devices and frequently mentioned receptors in the literature. Their analysis highlighted that the main impacts of wave and tidal energy devices are likely to include noise, collision risks, wave or tidal alterations, and habitat changes. For salinity gradient devices, water quality effects are the most commonly mentioned issues, while OTEC systems may experience entrapment and entrainment issues. Fig. 7a illustrates the multivariate analysis based on frequently mentioned keywords, showing a high variance explained by the first principal component (95.2%). Fig. 7b indicates that receptors commonly mentioned for wave and tidal energies include benthic

Table 3
The efficiency and cost of various marine energy conversion technologies.

MRE	Efficiency	LCOE ($/kWh)	Refs
Tidal Range Energy	VATTs up to 35% Bidirectional HATTs up to 42%	0.20–0.45	[27]
Tidal Current Energy	35%–45%	0.67–0.80 (individual turbine)	[27]
Ocean Current Energy	15.06%	0.86–1.00 (tidal farms)	
Wave Energy	15%–20%	0.30–0.55	[27]
Ocean Thermal Energy	6%–10%	0.10–0.18 (long-term cost) 0.03 (100-MW scale)	[81–83]
Salinity Gradient Energy	47.3%	0.935	[84]

communities, marine fauna, marine mammals, birds, shoreline characteristics, and invertebrates. In contrast, fish and plankton are most frequently cited as affected by OTEC systems, while receptors for salinity gradient devices remain unclear.

A broad spectrum of environmental criteria must be considered when assessing the sustainability of different energy technologies. The environmental impacts of natural gas and RES are shown in Fig. 8 [86]. The bar charts compare the environmental impacts per megawatt-hour (MWh) of energy production across various sources using nine key metrics, including acidification, ecotoxicity, global warming, and respiratory effects. The analysis reveals that natural gas, while cleaner than some fossil fuels, exhibits significantly higher impacts than the studied RES across several metrics, particularly in terms of its global warming potential, ozone depletion, and respiratory health effects caused by particulate emissions. Solar energy (both rooftop and ground-based) demonstrates moderate to high impacts in ecotoxicity, carcinogenic, and non-carcinogenic, reflecting the potential environmental challenges associated with PV technologies, such as photochemical oxidation and eutrophication due to the materials and chemicals used in the production and disposal of solar panels. To minimise these effects, improvements in manufacturing and waste management will be essential as solar adoption grows. Hydropower and wind energy have low environmental impacts across all metrics and represent the most environmentally sustainable options. Tidal, wave, OTEC, and salinity gradient energy sources have extremely low operational emissions, with their lifecycle emissions mainly derived from manufacturing, installation, and maintenance and still far lower than those of fossil fuels. Overall, marine energy technologies are crucial to achieving sustainable and eco-friendly energy systems, with each kW of installed marine energy capacity capable of reducing CO_2 emissions by 1.67 t annually [60].

4. MRE-based island integrated energy system optimisation

In this section, the typical applications of MRE in existing islands are described, and a framework for constructing IIESs is introduced. The system optimisation is reviewed primarily from the perspectives of modelling methods, optimisation algorithms, and system simulation.

4.1. Types of energy for islands

RES such as hydropower, wind, and solar are commonly used on island power grids. Some islands also tap into biomass, geothermal, and marine energy resources. Energy facilities on islands vary; however, most of the aforementioned marine technologies still face techno-economic and techno-environmental challenges. Technologies like salinity gradient energy and ocean thermal energy are still in the early stages of research and development, as detailed above, whereas tidal energy is relatively mature and has been widely deployed. Integrated development is central to developing new and efficient energy systems, as different energy combinations can yield additional economic benefits. In a study by Ibrahim et al. [87], the cost and power production performance of 11 off-grid energy combinations were compared for application to an economic seawater treatment system without a grid. Their study reported that the PV/wind/diesel and PV/hydro turbine/diesel combinations were economically viable solutions with energy costs of 0.2252 $/kWh and 0.1216 $/kWh, respectively. Rad et al. [88] considered the use of fuel cells in hybrid energy systems. Their analysis found that despite the potential 33% –37% increase in energy prices caused by introducing fuel cells, this approach can help maintain energy balance and enhance reliability during periods of high electricity demand. Xu et al. [89] performed an economic parameter consideration of the abandonment rate, showing that when the power abandonment rate is 5%, the energy cost of PV/wind/hydropower hybrid pumped storage systems can be reduced to 0.091 $/kWh while ensuring reliable power supply to meet local demands and reducing initial capital costs.

In island resource-rich regions, marine energy should be used based on the local conditions, in combination with aquaculture, seawater desalination, liquefied natural gas (LNG) receiving stations, and repurposing abandoned docks. Integrating marine energy into existing energy systems can reduce the burden on the power grid, increase the energy supply to islands to meet the needs of their inhabitants, and minimise the transportation and consumption of fossil fuels. By combining MRE with other offshore technologies and implementing innovative business models, there is a notable potential for decreasing the levelised energy costs. This can be achieved by creating economies of scale and generating additional revenue streams. Such integration could pave the way for accessing new markets, exemplified by the island regions listed in Table 4, thus representing an important advance for marine energy. These integrated approaches not only provide economic benefits but also contribute to enhancing the reliability of energy systems.

4.2. Island integrated energy systems

IIESs leverage energy cascade utilisation and multi-energy coupling, coordinating various energy resources and integrating source–grid–load–storage. This approach can smooth out power load fluctuations, optimise the usage of multiple energy sources, and achieve high energy efficiency. These systems can also meet cooling, heating, and electricity demands while effectively absorbing any surplus resources generated. IESs share a common physical structure and equipment for the generation, transmission, storage, and usage of electrical, thermal, cooling, and gas energy. Typical equipment units used in IIESs and their physical indexes are listed in Table 5. Project specifics, local conditions, and technological advancements heavily influence the pricing and capacity of the energy system equipment. Electricity and gas prices play pivotal roles in shaping these parameters, where higher electricity prices make distributed generation and storage solutions such as solar PV and batteries more economically viable, thus encouraging their deployment. Meanwhile, fluctuations in gas prices impact the operational costs for natural gas-based technologies such as generation, combined heating and power, and combined cooling, heating, and power systems, potentially driving demand towards more efficient alternatives such as electric heat pumps and hydrogen production via electrolysis. Integrating these price dynamics enables optimal system configurations, thereby allowing

Table 4
Integrating marine renewable energy with other renewable sources in island regions.

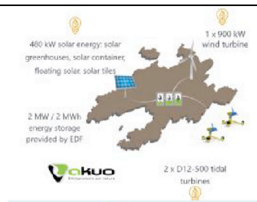
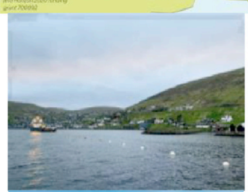
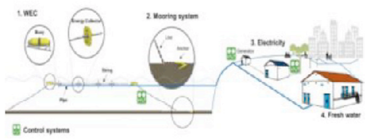
Islands	Energy type	Mode of operation and project scale	Energy application	Refs
Ushant Island in the French Channel Islands	Solar, wind, energy storage, tidal	Solar energy (solar greenhouses, solar container, floating solar, solar tiles: 480 kW); wind turbine (1 x 900 kW); energy storage (2 MW / 2 MWh); tidal turbines (2 x D12-500)		[90]
Orkney Island in the north of Scotland	Tidal, wind, solar, energy storage	Solar PV (0.5 MW); tidal (Sabella D12 x 21 MW); wind (0.9 MW); energy storage		[71]
Estmanna Faroe Islands in Sweden	Tidal Energy Kite delivers	Dragon12 (1.2 MW); main subsea cable (3.4 km)		[91]
Reunion Island, French overseas region located in the Indian Ocean	Water, wind, solar, wave, ocean thermal energy	Hydroelectricity (133.6 MW); photovoltaic solar energy (186.6 MW); wind farms (14.8 MW); wave energy (2 MW); ocean thermal energy conversion (15 kW)		[92]
Isola Piana, Italy, 0.21 km^2	Wave to energy and water	Wave energy utilizing an Attenuator (100- 150 kW); Reverse Osmosis desalination (capable of processing 1,500-30,000 cubic meters); water storage.		[93]

Table 5
Typical equipment units used in IIESs and their physical indexes.

Equipment type	Main physical index
Electric power equipment: DG, transmission and distribution network grid, energy storage (battery), charging pile	Voltage, current, phase angle difference (AC), power (active power, reactive power), transmission and storage losses, charge and discharge power and efficiency
Thermal equipment: Heat network (pipeline, pump), thermal storage tank, heat pump	Temperature, pressure, transmission and storage efficiency
Natural gas equipment: Gas network (pipeline, station), gas storage tank, gas station	Pressure, flow, transmission and storage efficiency
Gas–electricity coupling device: micro-combustion power generator, hydrogen fuel cell	Electrical output power, gas consumption, gas-electric conversion efficiency
Gas–thermal–electricity coupling device: combined heating and power units (CHP)	Gas consumption, electrical output power, thermal output power, gas–electric conversion efficiency, gas–thermal conversion efficiency, etc.
Gas–cold–thermal–electricity coupling device: combined cooling heating and power units (CCHP)	Gas consumption, electrical output power, thermal output power, cold output power, gas–electric conversion efficiency, gas–thermal conversion efficiency, etc.
Gas–thermal coupling device: gas-fired heating boiler	Gas consumption, thermal output power, gas–thermal conversion efficiency
Electricity–gas coupling device: electric hydrogen production system	Hydrogen production, electrolytic voltage, electrolytic current, hydrogen storage capacity
Electricity–thermal coupling device: electric boiler, electric heating, heat pump	Power consumption, thermal output power, electric–thermal conversion power
Heat–cold coupling device: absorption refrigerator	Input thermal power, output cold power, thermodynamic coefficient
Electricity–cold coupling device: absorption refrigerants, ice storage, etc.	Temperature, cooling efficiency, cold storage efficiency

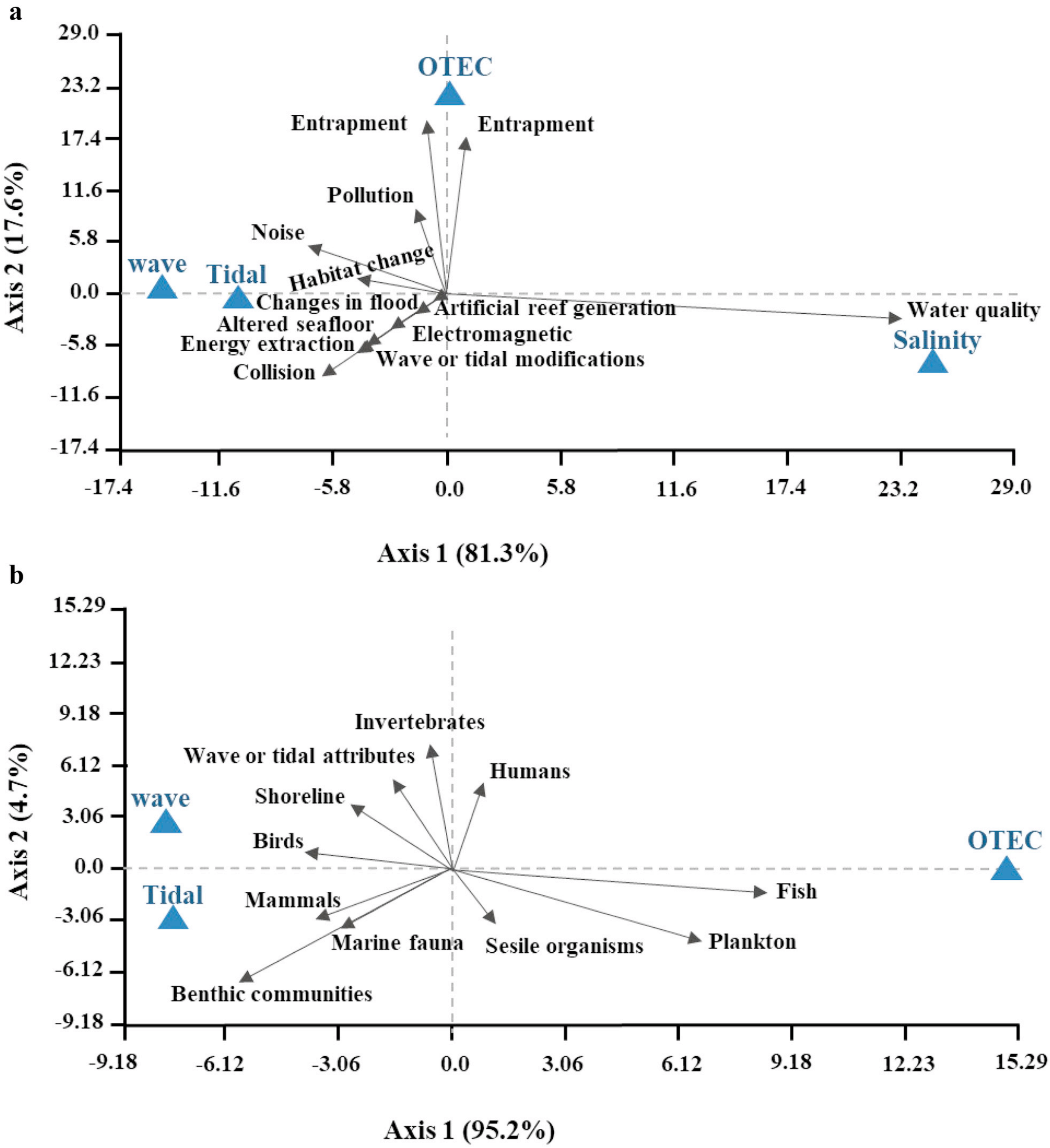


Fig. 7. Multivariate analysis (PCA) examined how often environmental stressors (a) and environmental receptors (b) are affected by different marine energy devices (tidal, wave, OTEC, and salinity gradient), based on the reviewed scientific literature [85].

the most cost-effective technologies to be selected for the economic and technical optimisation of energy systems.

Energy hubs connect and manage different energy resources; virtual power plants utilise advanced intelligent computing technology, communication, and control systems to aggregate various distributed energy resources, storage, and flexible loads. Fig. 9 illustrates the basic framework of an IIES based on existing research. IIESs can be categorised into two main types: system planning (SP) and system operation (SO). The SP approach, also known as system design, aims to achieve the optimal system configuration, whereas the SO approach focuses on reducing short-term operational costs. The optimisation models can be categorised into basic models and models that incorporate energy flow variations, system flexibility, and system randomness. The basic models consist of general and unified models, where the former type individually models each energy system and coupling component. In contrast, the unified models employ theoretical equations such as energy hubs or

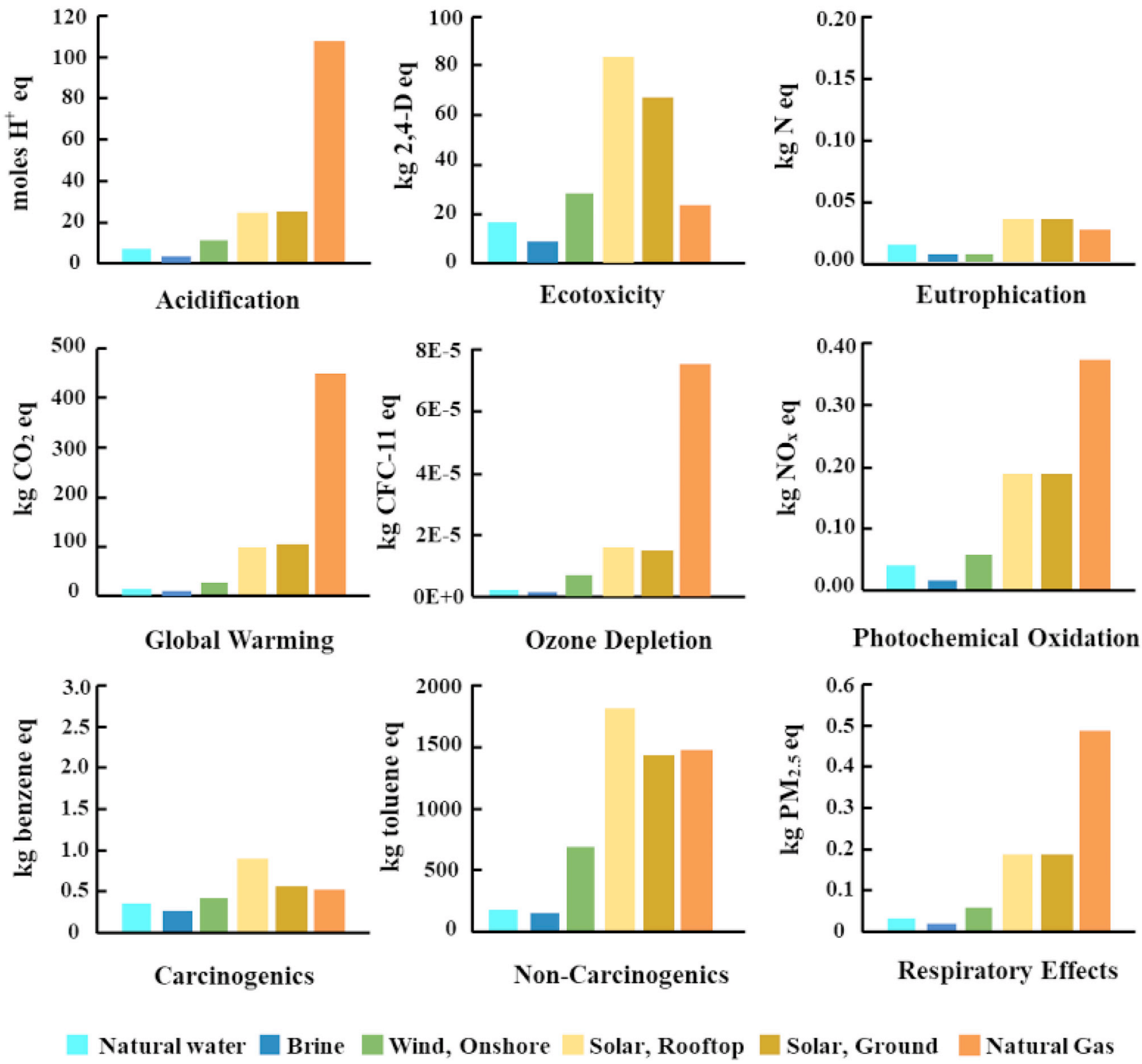


Fig. 8. Impact per MWh for nine metrics assessed using TRACI, with comparative technology values sourced from Ecoinvent [86].

circuits to uniformly express multiple energy relationships [94]. Models considering energy flow variations address time-scale differences in system optimisation, ensuring energy transmission speeds are matched and balanced [95]. Models considering system flexibility enhance economic viability and renewable energy integration capacity through resource conversion, coordination, and the addition of coupling components and energy storage devices, leveraging pipeline storage characteristics and building thermal properties [96]. Models addressing system randomness focus on uncertainties arising from renewable energy integration and electricity price-induced load fluctuations, with stochastic optimisation approaches used for decision-making [97].

IIES optimisation is inherently a multi-objective, multi-constraint, nonlinear mixed-integer optimisation problem with uncertain factors. It involves a stochastic, complex dynamic optimisation process. The optimised coordination of an IIES encompasses the energy production, transmission, transformation, distribution, and consumption stages, thus significantly influencing island development. The initial optimisation requires objective functions to be constructed based on an island's specific policies and socio-economic needs. These objective functions include the system's economic efficiency, environmental protection, utilisation efficiency, energy quality, and reliability. These targets can be met by managing renewable resources, traditional DGs, ES units, and adjustable loads in response to potential issues, changes in utility grid status, and intermittent renewable energy supply [98].

Load fluctuations, energy/communication issues, and inter-network interactions impact the operational stability of IIESs. Renewable energy relies on distributed microgrids, thus facing stability challenges due to variable output and consumption [99]. Integrating variable renewable energy sources and balancing technologies, storage, and demand-side management requires high temporal resolution to ensure accurate behaviour capture (hourly time steps in energy system modelling represent the current highest resolution) [100]. The major technical challenges in this process include the following: coordinating control among the system's devices for overall optimisation across multiple periods, accurately modelling diverse circuit topologies in energy optimisation, managing different operational requirements in grid-connected and island modes, and addressing device limits and operational constraints such as generator capacity, start-up time, costs, energy efficiency, and line voltage/current limits [101].

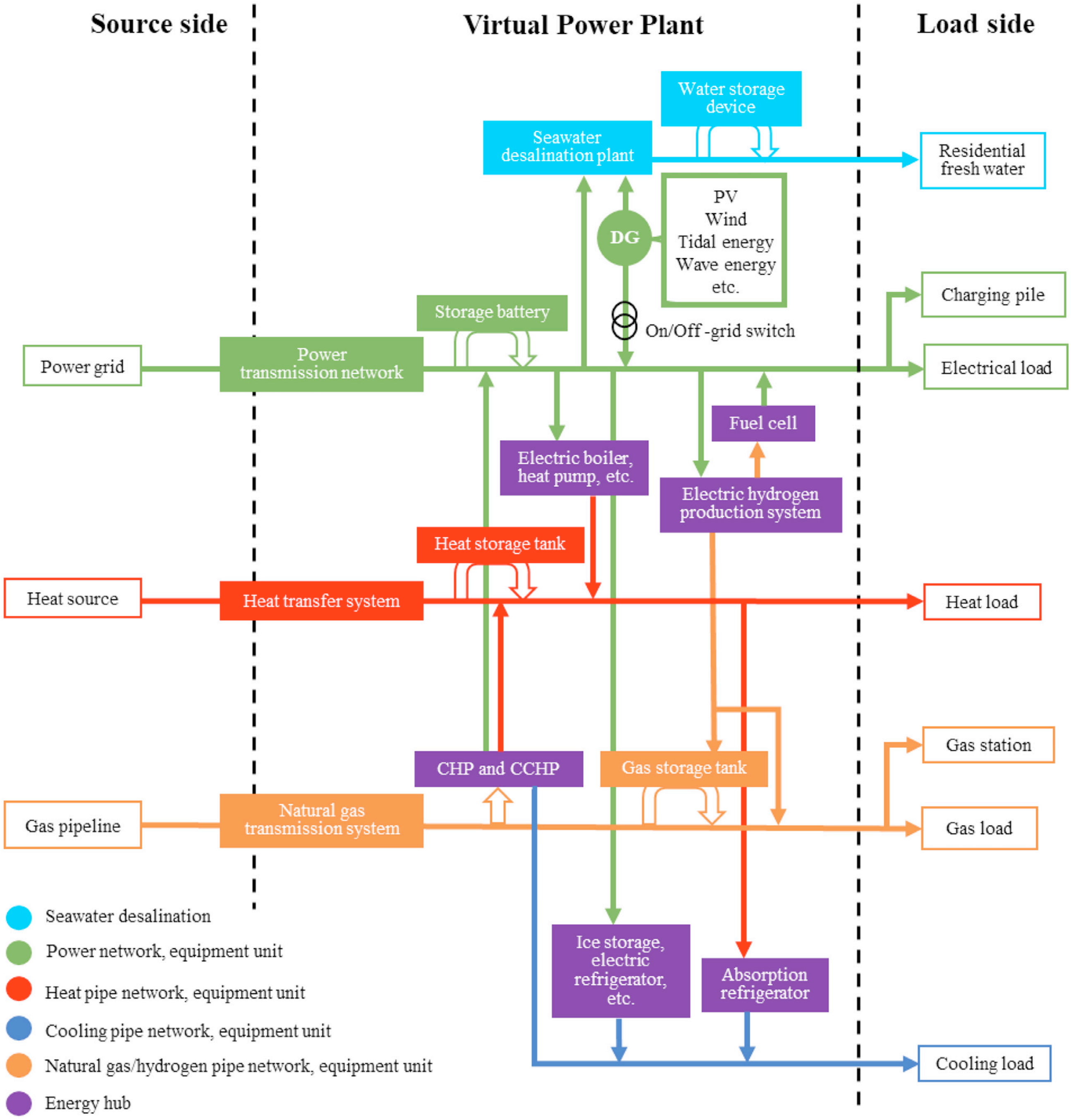


Fig. 9. Framework schematic diagram of IIES.

4.3. Modelling and simulation

Modelling methods for energy systems include dispatch (or operational) optimisation and single-objective (or multi-objective) investment (or expansion capacity) optimisation [102]. Dispatch optimisation follows merit-order logic – in this approach, a useful tool for evaluating energy systems is the P-Graph [103], which is based on physical models. This approach can provide clear process insights to enhance engineering decision-making for cleaner production and sustainability. Some previous studies have determined optimal energy system configurations and operations based on this tool; for example, Xu et al. [104] developed a P-Graph model to evaluate the most economically feasible option between exporting renewable electricity or hydrogen from a virtual island. Their model integrated solar, wind, wave, and biomass sources and found electricity export to be a more cost-effective option than hydrogen. A P-Graph-based multi-period energy model was introduced by Ji et al. [17] to manage fluctuating electrical and thermal demands on an island using hydrogen storage. The authors conducted economic and carbon footprint analyses, comparing pure renewable energy systems with those incorporating hydrogen and battery storage. Compared to pure renewable energy systems, their study reported cost savings of 21.5% and 5.3% for systems with hydrogen storage and battery storage, respectively, with corresponding CO_2 equivalent emissions of 1717 t/year and 1680 t/year. Additionally, an optimised energy system for islands, integrating fossil and renewable sources, was presented by Shi et al. [105]. Using a P-Graph, these authors found that the lowest cost could be achieved using a mix of 59% wind, 3% mainland grid, 28% fossil fuels, and 10% natural gas. The study also demonstrated that energy costs overall are significantly affected by fluctuations in electricity and gas prices and the variability of wind and natural gas sources.

In contrast, investment optimisation focuses on expanding capacity. Compared to continental systems, island electricity systems have greater vulnerability to power quality, reliability, and resilience issues. Addressing these challenges requires capacity-planning models specifically tailored for island systems. An optimisation model for long-term planning in island electricity systems was developed by Barrera-Santana and Sioshansi [106]. Based on the technical constraints specific to island systems, this model identifies the best mix of generation and transmission capacity to meet energy demand at a minimum cost. Bi-level frameworks are often used to solve multi-objective problems by either converting multiple objectives into single objectives or using different stages. Ma et al. [21] developed a two-layer optimisation strategy for island energy systems, focusing on resilience and economic efficiency. A Pareto-based multi-objective optimisation model was applied by Cabrera et al. [25], in which production and treatment systems were modelled as flexible loads and various water supply infrastructures and combinations of PV/wind power were explored to identify the optimal energy–water setup. Additionally, a stochastic optimisation framework integrating uncertainties, AC and HVDC transmission, renewable generators, and energy storage was proposed by Boffino et al. [107]. This approach focuses on two main decision types: investments (i.e. generation, transmission, and storage infrastructure) and operations (i.e. how assets are used to meet energy needs and operational requirements).

Simulation software packages are specifically designed to execute these models and generate simulation results. These packages typically include functionalities such as model input, parameter setting, running simulations, analysing results, and visualisation. In the simulation of IIESs incorporating renewable energy, the most used bottom-up energy system models are EnergyPLAN, HOMER, unit commitment models, MATLAB/Simulink, TRNSYS, and P-Graphs. These tools allow models of IIESs to be established and the impacts of different energy combinations to be evaluated in terms of system performance and economic viability [102]. EnergyPLAN, documented on the website www.energyplan.eu, applies the Smart Energy System concept and can simulate the entire energy system, connecting different sectors [108]. Although EnergyPLAN is user-friendly, it limits subsequent executions. To vary the decision variables in a specific energy system model, the MATLAB Toolbox for EnergyPLAN was developed, which includes functionality to call and manage EnergyPLAN models from MATLAB [109]. Ye et al. [100] used the HOMER hybrid optimisation model to assess the feasibility of meeting energy demand and applied the model to an isolated 2.8 km^2 island in the South China Sea to confirm its technological and economic feasibility. Additionally, many specialised marine energy simulation software packages can be used to assist with integrating marine energy into IIESs, such as WEC-Sim for wave energy simulation and TELEMAC-3D for tidal energy simulation. For example, using TELEMAC-3D to simulate tidal hydrodynamics, Almoghayer et al. [71] explored the most economical approach to incorporate tidal energy into the Orkney energy system.

4.4. Optimisation algorithms

Notably, the modelling and optimal operation of island energy systems tend to be complex, nonlinear, and uncertain due to the highly complex structures of island energy systems. Gao et al. [15] studied the optimisation of a desalination system with 12 motors, considering water flow and pressure constraints. Three control strategies were proposed, with the aim of minimising costs while meeting practical requirements. The grey wolf optimisation (GWO) algorithm was utilised, achieving precise control and economic improvements compared to other algorithms such as particle swarm optimisation (PSO) and moth–flame optimisation (MFO). Szilagyi et al. [110] investigated a hybrid energy microgrid integrating photovoltaic, geothermal, and biomass resources with a storage system. They introduced a new smart management method (day-ahead scheduling) based on support vector regression (SVR), artificial neural networks (ANN), and random forest (RF) decision trees. The study utilised day-ahead solar power prediction and compared four cost-optimisation methods (mathematical models such as mixed integer linear programming (MILP) or nature-inspired optimisation algorithms such as the genetic algorithm (GA), PSO, and harmony search optimisation to minimise microgrid operating costs. MILP was found to be the most effective energy management strategy among the tested approaches.

Energy management strategies are crucial for optimising renewable energy systems. Traditional rule-based approaches use predefined flowcharts, whereas optimised strategies ensure ideal operation through real-time optimisation. An emerging technology called deep reinforcement learning also shows promise in ensuring optimal operation without the need for frequent re-optimisation [23]. Due to variable load and the timeliness of energy transmission, the model has discrete variables; however, many of the important equipment parameters are continuous variables. Traditionally, when solving an optimisation model with hybrid actions, the model must be simplified. This represents one of the challenges involved with achieving accurate results from optimisation models of IIESs containing discrete–continuous hybrid actions. Yang et al. [96] proposed a MILP formulation focused on enabling flexibility provision on IESs. Their model targeted independent sizing of power and energy capacities for simultaneous generation and storage expansion planning. Future research may explore dynamic models for multi-stage investment decisions; for example, the distributed model predictive control (DMPC) method is a powerful approach for ensuring dynamic stability in various systems. A novel DMPC consensus algorithm using second-order cone programming for stable operation of IESs was proposed by Han et al. [111], which identified optimal solutions for regulating multiple variables and meeting consensus objectives. Yang et al. [112] investigated multi-timescale indirect multi-energy transactions using distributed proximal policy optimisation, and Duman et al. [113] introduced the multi-objective adaptive guided differential evolution (MOAGDE) algorithm, designed to excel at solving complex multi-objective optimisation problems. MOAGDE combines non-dominated sorting with crowding distance and was demonstrated to be effective in finding Pareto optimal solutions across diverse decision spaces.

5. Summary and discussion

Commonly used mathematical planning models for IIESs include MILP and mixed-integer nonlinear programming methods. These models are suitable for solving combinatorial optimisation problems, which involve comprehensive optimisation methods for system composition, equipment capacity, and operation strategies. Optimising IIESs for island environments involves a complex, multidimensional modelling and solving process that can be summarised as follows:

- Multi-stage optimisation: given the long-term nature of IIES optimisation, the process is divided into stages to address growing energy demands over time. Each stage involves decisions based on the current conditions, with the earlier-stage solutions informing later ones. This dynamic programming-like approach ensures the optimal solutions meet evolving load requirements throughout the system's lifespan, thus minimising equipment depreciation costs and avoiding capacity shortages.
- Multi-objective optimisation: under normal operating conditions, optimisation schemes are evaluated using economic efficiency, emissions reduction, and energy efficiency metrics. In multi-objective scenarios, conflicting goals require compromise solutions represented by Pareto optimal sets. Additionally, dual-level optimisation

models are utilised for IIESs, in which equipment types and capacities within the IIES are optimised in the first level, while the second level focuses on operational strategies. This approach mitigates the local optima issues often encountered in segregated planning and achieves superior outcomes.

- Uncertainty optimisation: incorporating distributed energy forecasting and addressing uncertainties in MRE and fluctuating load demands makes IES optimisation challenging. Stochastic programming uses probabilistic distributions of variables, employing methods such as expectation, chance-constrained, and scenario-based approaches. Robust optimisation considers parameter uncertainties within known fluctuation ranges, ensuring the obtained solutions are resilient to worst-case scenarios, thus enhancing the system's reliability. Overall, balancing economic considerations with reliability metrics is crucial when managing uncertainty in IIES models, as overly conservative approaches may affect the economic optimisation of the system.

5.1. Optimisation

IIESs are characterised by complexity and numerous parameters, which are typically optimised in the existing literature using mathematical programming approaches or heuristic algorithms. Mathematical programming involves linearly simplifying the mathematical models of each device and optimising them using methods such as linear programming and 0/1 integer programming. Complex mixed-integer nonlinear programming problems can be simplified into easier-to-solve linear problems, which can be resolved via mathematical optimisation algorithms like branch-and-bound, column generation, and cutting-plane methods. For complex planning models, rational decoupling can decompose large-scale problems into multiple sub-problems, which are then solved iteratively between the main and sub-problems. Multi-objective optimisation effectively seeks the optimal solutions among different objectives (which are often nonlinear, conflicting, or immeasurable) by utilising Pareto optimal solution sets. The Pareto solutions represent compromises across different objectives, with decision-making performed based on Pareto fronts and specific objective requirements, thereby avoiding the need to convert multi-objective problems into single-objective ones. Given the uncertainty in load forecasting, the K-means method is utilised to reduce scenario complexity.

In contrast, heuristic algorithm optimisation employs nonlinear modelling of IIESs and uses intelligent algorithms such as GA, ant colony optimisation, and PSO. These algorithms, which do not rely on gradient information of the objective function, are particularly suitable for solving large-scale complex optimisation problems that cannot be resolved with traditional methods, contributing to the discovery of global optimal solutions. Heuristic algorithm approaches suffer from inaccuracies in optimisation results and long computational times. Given these limitations, there is a pressing need to develop an optimisation method that balances computational efficiency with result accuracy. To handle the complexity of models containing multiple variables and nonlinear constraints, heuristic algorithms require improvements in fitness functions, selection operators, and adaptive crossover adjustments to avoid local optima. The complexity of IIES models also leads to long optimisation times, which researchers have aimed to address using optimisation software like GAMS and LINGO with solvers such as CPLEX and GUROBI. For convex optimisation, solvers like CPLEX and Mosek are integrated with tools including YALMIP and CVX in MATLAB. To reduce model computation time, some studies only optimise the system for three typical days, representing summer, transitional seasons, and winter; however, this approach cannot guarantee the accuracy of the results under a diverse range of scenarios. Overall, further research is needed on IIES optimisation methods that can simultaneously meet both accuracy and computation speed requirements.

5.2. Forecasting

Marine energy can be categorised into stable and unstable sources. Stable sources include ocean thermal energy, salinity gradient energy, and ocean current energy, while the unstable sources can be further subdivided into those with regular variations (e.g. tidal range and tidal current energy) and those with irregular variations (e.g. wave energy). Tidal range and tidal current energy sources, which are characterised by predictable fluctuations, allow detailed daily and hourly forecasts of tidal heights and current strengths to be constructed. These forecasts enable tidal range and tidal current power stations to optimise their power generation schedules. In contrast, wave energy is inherently unstable and lacks predictable patterns. Most MRE derives from dynamic aspects of the oceanic environment that vary both temporally and spatially, posing challenges for stable energy production. Key technologies are being developed to overcome critical challenges in marine energy, including site selection, design, manufacturing, and operation.

Marine energy forecasting can be categorised into two main modelling principles: physical methods (see Table 6) and statistical methods. The physical methods require minimal historical data and are ideal for newly established marine energy power plants; however, solving these models is time-consuming and resource-intensive, restricting their application to individual power plants. Statistical methods typically rely on extensive historical data to establish patterns for power prediction. These methods involve time series analysis, regression analysis, or machine learning (ML) algorithms such as neural networks or support vector machines (SVMs) to build predictive models for short-term marine energy parameters. These methods leverage large datasets and statistical techniques to handle complex nonlinear relationships and data noise. Their prediction times are less affected by spatial scales, thus making them suitable for both individual and regional-scale modelling of power plants.

Short-term load forecasting methods typically rely on historical load data and relevant meteorological data to establish mappings between driving factors and load, thereby obtaining forecast results. Depending on whether the forecasting model is a black-box model, these methods can be categorised into mathematical equation forecasting and artificial intelligence forecasting. Mathematical equation-based load forecasting uses non-black-box models, with common methods including regression analysis, exponential smoothing, and load derivation. In contrast, artificial intelligence-based load forecasting employs black-box models, with common approaches including ANN, SVM, and fuzzy forecasting. Mathematical equation forecasting requires the model type to be specified before forecasting, whereas artificial intelligence forecasting does not require prior specification of the mapping between input variables and load. This allows the model to be adjusted based on results, which is currently a commonly used approach in load forecasting.

ML and deep learning (DL) methods are particularly suitable for multi-energy forecasting due to their strong generalisation capabilities and excellent ability to handle complex data structures. Techniques such as SVMs, long short-term memory networks, convolutional neural networks, and capsule networks have proven effective in analysing the complex features of load data, significantly improving forecasting accuracy. Additionally, IIESs involve multiple energy load types, and a single predictive model cannot adequately model all the required types of load data, resulting in insufficient generalisation capabilities. Multi-task learning promotes inter-task learning through weight-sharing mechanisms and can be effectively applied to complex problems. IIES multi-energy load data exhibit strong nonlinearity and non-stationarity, thus making thorough data preprocessing crucial. Signal decomposition techniques such as time-varying filter empirical mode decomposition and complete ensemble empirical mode decomposition with adaptive noise have been widely used. Despite yielding significant results, these models face challenges in embedding key information in the pre-model data identification, insufficiently comprehensive analysis methods, limitations in handling abrupt signals with time-domain decomposition, ex-

Table 6
Physical methods of marine energy forecasting.

MRE	Forecasting
Wave	Based on wave dynamics equations and oceanographic principles, models predict parameters such as wave height and period, considering factors such as wind fields and seabed topography.
Tidal	Involves forecasting tidal currents (tidal streams) and tidal ranges (water level changes) using astronomical tidal theory, tidal flow equations, and observational data.
Ocean Current	Uses ocean dynamics theory and numerical simulations to forecast velocities and directions of ocean currents, considering factors like wind-driven currents and the Earth's rotation.
Salinity and Thermal Gradient	Predicts distributions of salinity and thermal gradients using environmental models and observational data, simulating physical processes to forecast future conditions.

cessive reliance on single factors in reconstruction methods, and a lack of effective data processing techniques to ensure reliable data sources.

6. Conclusions and future directions

Through an examination of the technical challenges, economic feasibility, and environmental sustainability of MRE (i.e. wave energy, tidal energy, ocean currents, salinity gradient energy, and ocean thermal energy), this study emphasises the importance of integrating marine renewable energy with traditional energy sources in the construction of rational IIESs. By discussing advancements in energy conversion devices, grid integration, and energy storage technologies, this research provides insights and guidance for designing cleaner, locally adaptable, and cost-effective energy systems in the future. Future research efforts are needed to improve the efficiency and performance of equipment, investigate measures to reduce capital investment and lifecycle costs, and address lifecycle performance and environmental impacts.

This paper also analyses the current research status in IES optimisation from the perspectives of models and methods, proposes the development of new functionalities and modules based on existing technologies, and provides references and insights for sustainable energy development in island regions. Promising research directions include hybrid energy storage systems, energy management strategies based on deep reinforcement learning, sustainability and resilience indicators, and scale methods based on distributed robust optimisation. With the continuous development and application of new technologies and equipment, the basic architecture of IESs is also evolving. The power models of distributed energy rely on environmental parameters, and predictive methods based on forecasted parameters such as wind speed and sunlight can be employed to schedule systems in advance to ensure economic efficiency and stability. The technologies of wave energy, tidal energy, and biomass energy generators are also continuously improving, and their power models should be updated accordingly. Future research could focus on coordinating electricity with other forms of energy (such as LNG cold energy) on islands.

Future IIESs will involve the integrated operation of source, grid, load, and storage. Synchronous scheduling of these elements must be integrated into the design of the IIES to ensure a unified planning and operation model. Current planning models lack high coupling and do not fully consider operational patterns, thus requiring improvements with adaptive and distributed dynamic planning methods to ensure the development of optimal IIES solutions. IIESs also face many uncertainties, requiring models that can account for these factors in terms of planning and operation. In particular, IIESs integrate power, natural gas, and thermal systems: as multi-energy coupling deepens and energy trading prices and incentives evolve, flexibility in demand for gas and thermal energy will increase; hence, future planning should incorporate integrated demand response for electricity, gas, and heat. Energy market reforms have replaced the old integrated management model. Generation and transmission rights are now increasingly separate, altering stakeholder interests. Including natural gas and heating systems expands the pool of IIES participants, all aiming to maximise benefits. Energy price fluctuations and company investment strategies will also significantly influence IIES planning. Considering market factors can significantly save investment costs and promote efficient energy use. With IoT and big data technologies, vast data resources are available that reflect IIES operational states. Data-driven intelligent algorithms, such as DL, will increasingly aid IIES planning and scheduling. These algorithms can also construct more accurate uncertainty sets from historical data. Overall, algorithms leveraging big data will be crucial for future IIES planning.

In conclusion, most existing studies optimise IIES from an electrical engineering perspective without fully considering thermodynamic performance, multi-energy complementarity, and the energy interconnections between distributed systems. Collaborative optimisation methods for IIES system configuration and operation are needed to ensure computational accuracy and speed. Additionally, given the ongoing reforms in the energy market, numerous emerging market organisations have intensified competition, thus necessitating research into managing conflicting interests among multiple stakeholders in this type of system.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2024YFE0100800), the Strategic Research and Consulting Project of the Chinese Academy of Engineering (2024-HZ-32), the National Natural Science Foundation of China (52302420), and the Major Industry and Technology Project of Zhoushan (2024C03009).

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