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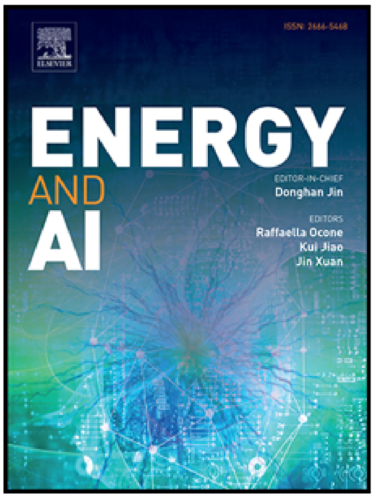

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Ocean energy applications for coastal communities with artificial intelligence—a state-of-the-art review

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Highlights

- Ocean energy supply, transmission, distribution and end-user side services
- Ocean thermal/electrical energy conversions with multi-energy synergies
- Pumped hydroelectric, compressed air and hydrogen storage for stable power supply
- Power controls and energy management with high efficiency and resilience
- Challenges and future perspectives of ocean energy in seashore communities

Abstract

Ocean energy plays essential roles in reducing carbon footprint and transforming towards carbon neutrality , with cleaner power production, whereas the vertical cascade ocean energy systems with spatiotemporal power supply characteristics might lead to fluctuated power frequency, disruptive disturbance and grid shock. Hybrid renewable energy dispatch, coordinated demand-side management, and electrical energy storages for grid ancillary services provision with different response time-durations are effective solutions to integrate ocean energy with stable and grid-friendly operation. This study is to review advanced ocean energy converters with thermodynamic, hydrodynamic, aerodynamic, and mechanical principles. Power supply characteristics from multi-diversified ocean energy resources are analysed, with intermittency, fluctuation, and spatiotemporal uneven distribution. Hybrid ocean energy storages with synergies are reviewed to overcome the intermittency and provide grid ancillary services, including pumped hydroelectric energy storage, ocean compressed air energy storage, and ocean hydrogen-based storage in different response time durations. Applications of diversified ocean energy systems for coastal residential communities are reviewed, with energy

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management and controls, collaboration on multi-carrier energy networks. Furthermore, application of artificial intelligence is reviewed for sustainable and smart ocean energy systems. Results indicated that, effective strategies for stable and grid-friendly operations mainly include complementary hybrid renewable system integrations, synergies on hybrid thermal/electrical storages, and collaboration on multi-carrier energy networks. Furthermore, depending on the geographical location, flexible on-shore and off-shore installation of transformers can provide large-scale ocean energy system integrations for long-distance transmission, with low transmission losses, low resistive losses, and simple system configuration. Research results can provide a heuristic overview on ocean energy integration in smart energy systems, providing alternatives for solar and wind energy resources and paving path for the carbon-neutrality transition.

Keywords: Ocean Energy; District Residential Community; Energy Conversion, Storage and Management; Multi-energy Synergies; Techno-economic-environmental Performance

1. Introduction

Ocean energy resource, with a large amount of quantity and diversified energy forms (such as thermal, kinetic, mechanical, gravitational energy) can address the global energy shortage crisis and associated global warming issues. Following thermodynamic, hydrodynamic, aerodynamic, and mechanical principles, a series of cascade ocean energy systems along the vertical axis, can be designed for capturing the dynamic ocean energy resources with advanced energy conversion devices, for sustainable energy supply. However, the energy supply characteristics are spatiotemporally different for various ocean energy systems. For example, compared to the ocean wind resource with a density of around 1.2 kg/m^3, the wave-current shows a much higher density at 1000 kg/m^3, leading to the much higher power supply of the current turbine than the wind turbine for a similar rated capacity. Integrating ocean energy systems in energy districts can promote the carbon-neutral district transition with cleaner power production, whereas the frequency fluctuation and the appearance of power spikes will lead to instability and power interruption of the grid. Demand-side management from perspectives of energy districts, hybrid energy storages with different response time-durations, can regulate demand profiles with high correspondence with the power supply profile and improve the matching performance.

Depending on different energy forms, ocean energy conversion technologies can be mainly classified into ocean thermal and electrical conversions. Ocean thermal systems include a direct sea-source heat exchanger and heat pumps. Ocean electrical conversion systems mainly include current turbine/wave energy converters, tidal stream generators, floating PV panels, off-shore wind turbines, and ocean thermo-electric generators (OTEG). Sources for various ocean energy forms can be mainly classified into gravity, solar radiation, and atmospheric heat. Driven by gravity, the tidal potential can be applied in fixed, kite and flow-induced turbines. Generated by ocean heat, different types of turbines can be designed for power generation, such as saline water turbine for the utilization of salinity gradients, the vapor turbine driven by thermal gradients, and the ocean current turbine. The wave energy can drive the waver energy converter. Furthermore, ocean wind energy can drive offshore wind turbines for electrical power generation. The utilization of various ocean energy forms can provide guidelines for the cascade ocean energy system design. Due to the diversity of various ocean energy resources, differences can be noticed, in terms of prediction capability and spatiotemporal intermittency. Compared to spatiotemporal fluctuations of solar and wind energy, the periodic tidal current energy is less variable for longer time horizons, and ocean wave energy is more stable for short time scales, and thus the ocean wave energy is predictable [1].

In order to accurately predict the dynamic performance and estimate the energy potentials of ocean energy systems, researchers developed mathematical models and prediction tools based on historical data. Based on the historical database, Esteban and Leary [2] predicted that the power supplied from ocean energy can cover 7% of the world electric demand in 2050. Penalba et al. [3] comprehensively reviewed nonlinear approaches for mathematical model development of wave energy converters. Results showed that CFD models are the most popular approach, but with a high computational load. Garrido et al. [4] developed a mathematical model of Oscillating Water Columns. High accuracy between simulation and experimental measured data can be noticed. Windt et al. [5] comprehensively reviewed CFD models on ocean wave energy. The high-performance computing technique can promote the development of CFD-based numerical models. Barnier et al. [6] indicated that the available power can be overestimated by more than 80% with modelling simplifications and assumptions on flow-driven turbine power and wind-driven ocean currents.

Considering the intermittency and power spikes of ocean energy supply systems, ocean energy storage techniques can provide stable and reliable power supply services, which will be critical for district demand coverage and power grid decarbonization with ocean energy integration. Chen et al. [7] provide technical guidelines and future prospects for multi-diversified energy storage techniques in the future. Synergies between battery, supercapacitor and flywheel can effectively address long-period and short-period power fluctuations, with stable power supply [8]. The flywheel energy-storage [9] and supercapacitor storage [10] can mitigate the power fluctuation and enhance the dynamic power stability enhancement, for integrating offshore wind and marine-current farm in local power grid.

Ocean energy management and controls have been studied for renewable energy penetration, grid flexibility, and techno-economic performance improvement. Renewable energy dispatch strategies have been explored. The overall performance can be enhanced through the dynamic dispatch on power generation and demand profile [11]. Furthermore, the power dispatch strategy [12], simulation-based optimization [13] and optimal control [14] can improve the energy efficiency of ocean energy utilization.

Nowadays, due to the self-learning capability through multiple linear regression, support vector regression and backpropagation, artificial intelligence has been applied in renewable energy, energy storage [15], energy demand in buildings [16] and smart energy management [17]. Chen et al. [18] applied AI in energy demand and carbon footprint modeling. Shaqour et al. [19] studied short-term load forecasting using deep learning technologies. Training time and prediction accuracy need to be well balanced, especially with the increase in aggregated dwellings. Huseien et al. [20] comprehensively reviewed 5G technology for smart buildings. Kausika et al. [21] applied GeoAI method to size solar photovoltaic installation through aerial imagery. Note that, there are a few studies focusing on AI in ocean energy systems.

However, scientific gaps are identified below:

1) along with the vertical cascade ocean energy systems with spatiotemporal power supply characteristics, a review on ocean energy systems is rare, in terms of advanced ocean energy converters with thermodynamic, hydrodynamic, aerodynamic and mechanical principles. The integration of ocean energy in the power grid might lead to fluctuated power frequency, disruptive disturbance and grid shock;
2) strategies for power fluctuation mitigation and dynamic stability enhancement in ocean energy supply have been rarely reviewed, in respect to renewable energy dispatch and hybrid energy storages with different power response time-durations;
3) ocean energy systems for applications in coastal residential communities are quite few, especially for complementary hybrid renewable system integrations, synergies on hybrid

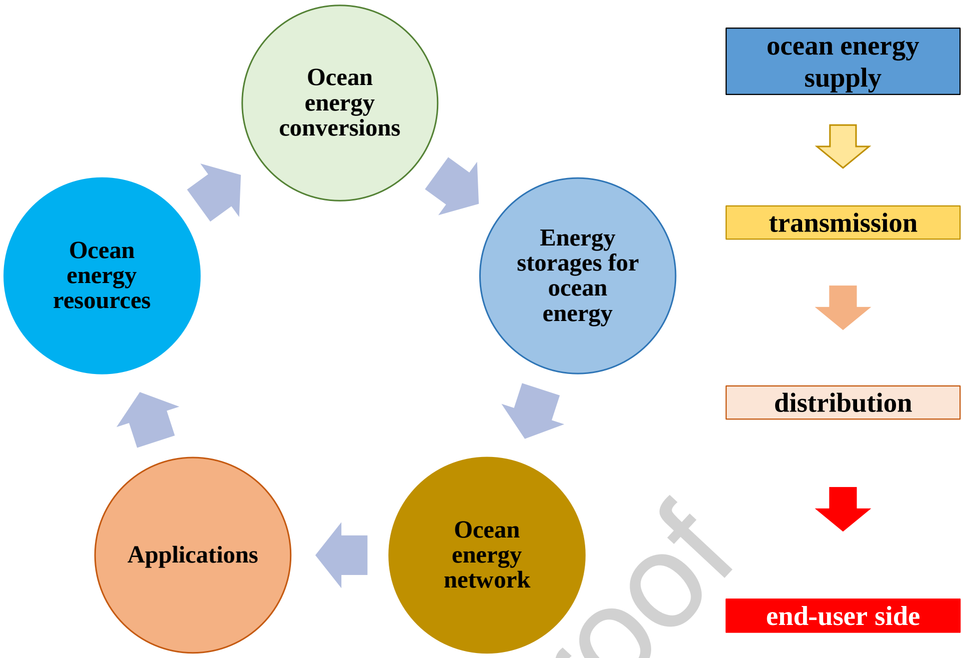
thermal and electrical energy storages, energy management and controls, and collaboration on multi-carrier energy networks.

A state-of-the-art review on global ocean energy resources and multi-diversified ocean energy systems, is quite necessary, to report the current status, development, challenges and future prospects. The integration of ocean energy resources in the power grid can promote the clean power and the carbon-neutrality transition, whereas the spatiotemporal intermittency will lead to grid power fluctuation and instability. The originality and novelty of this study include:

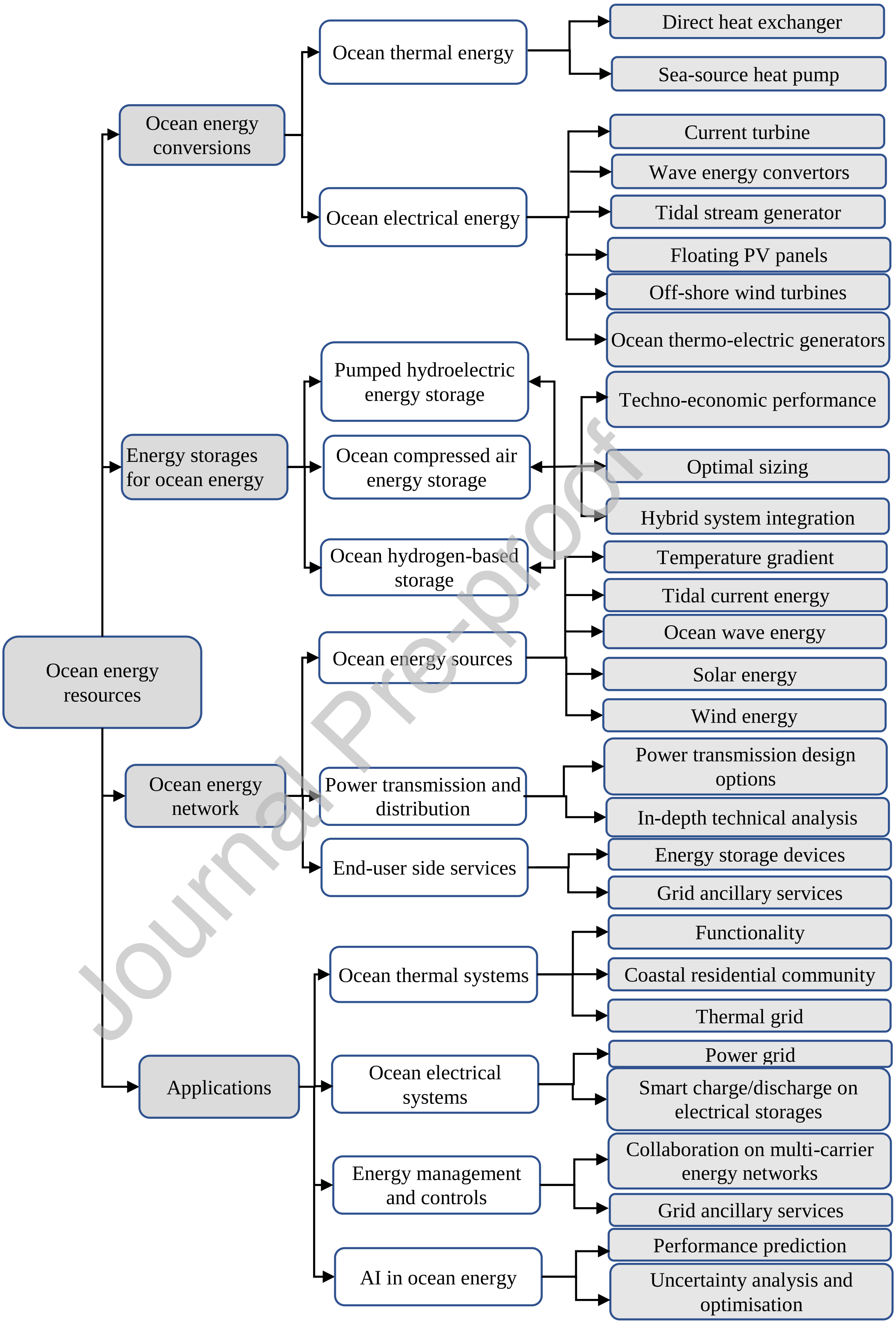
1) along the vertical axis of the sea with different types of ocean energy resources (such as solar energy, wind energy, wave energy, current energy and so on), a comprehensive and systematic literature review on vertical cascade ocean energy systems is provided, in terms of thermal/electrical energy forms and advanced ocean energy conversion principles;
2) in order to address associated issues from the ocean energy integration, such as fluctuated power frequency, disruptive disturbance and grid shock, strategies have been rarely reviewed for power fluctuation mitigation and dynamic stability enhancement, in respect to renewable energy dispatch, hybrid energy storages and demand-side management in energy districts;
3) ocean energy systems for applications for coastal residential communities are reviewed, with complementary hybrid energy supply, synergies on hybrid thermal and electrical energy storages, energy management and controls, and collaboration on multi-carrier energy networks.

The paper is organized as follows. The methodology is in Section 2. Section 3 shows the global ocean energy resources. Thermal and electrical energy conversion technologies are comprehensively reviewed in Section 4. Afterwards, in Section 5, electrical energy storages are introduced to stabilize the ocean energy supply with power fluctuation mitigation, in different power response time-durations. Energy networks are reviewed in Section 6, for ocean energy sources, generation, transmission, distribution and end-user side service provision. Advanced energy management strategies with ocean energy systems, coastal community and utility grids are introduced in the Section 7. Challenges and future trends are shown in the Section 8. Last but not the least, research conclusions are drawn in Section 9.

2. Methodology



(a)


Ocean energy resources
Ocean energy conversions
Ocean thermal energy
Direct heat exchanger
Sea-source heat pump
Ocean electrical energy
Current turbine
Wave energy convertors
Tidal stream generator
Floating PV panels
Off-shore wind turbines
Ocean thermo-electric generators
Energy storages for ocean energy
Pumped hydroelectric energy storage
Ocean compressed air energy storage
Ocean hydrogen-based storage
Techno-economic performance
Optimal sizing
Hybrid system integration
Ocean energy network
Ocean energy sources
Temperature gradient
Tidal current energy
Ocean wave energy
Solar energy
Wind energy
Power transmission and distribution
Power transmission design options
In-depth technical analysis
End-user side services
Energy storage devices
Grid ancillary services
Applications
Ocean thermal systems
Functionality
Coastal residential community
Thermal grid
Ocean electrical systems
Power grid
Smart charge/discharge on electrical storages
Energy management and controls
Collaboration on multi-carrier energy networks
Grid ancillary services
AI in ocean energy
Performance prediction
Uncertainty analysis and optimisation

(b)

Fig. 1 A holistic overview on research methodology in ocean energy and applications: (a) overall framework; (b) structural configuration.

Ocean energy, with a huge of renewable energy potentials, will contribute to carbon-neutral transition of coastal district communities. A review was conducted, to report the current status, technical challenges and future outlooks, as shown in **Fig. 1**. The overall framework, as shown in Fig. 1(a), includes ocean energy supply, transmission, distribution and end-users. There are four main parts in structural configuration as shown in Fig. 1(b), including the ocean energy conversions, hybrid energy storages, energy network and real applications. Ocean energy conversions mainly include ocean thermal and electrical energy conversions. Systems for ocean thermal energy utilisation include direct heat exchanger and sea-source heat pump. Devices for ocean electrical energy conversion include current turbine, wave energy convertors, tidal stream generator, floating PV panels, off-shore wind turbines and ocean thermo-electric generators. In the second part, hybrid ocean energy storages are reviewed, including pumped hydroelectric energy storage, ocean compressed air energy storage and ocean hydrogen-based storage. Response time-duration of different energy storages are shown and compared, to provide grid ancillary services. In the third part, ocean energy networks have been reviewed, from perspectives of ocean energy sources, power transmission and distribution, end-user side services. Ocean energy sources mainly include temperature gradient along the sea depth, tidal current energy, ocean wave energy, solar energy and wind energy. Afterwards, the real applications are reviewed in the fourth part, in terms of ocean thermal systems, ocean electrical systems, energy management and controls. Collaboration on multi-carrier energy networks and grid ancillary services with the integration of ocean energy systems are prospected. Challenges and future trends of integrated ocean energy systems in community seashore residential zero-energy communities are presented, including the system protection under extreme weather conditions (e.g., hurricane and typhoon), chemical corrosion on deep ocean energy systems, intermittent and unpredictable ocean energy sources, operational unreliability and thermal–electrical-chemical storages with synergies of interactive energy sharing networks.

3. Global ocean energy resources

Global ocean energy potentials have been studied in different coastal regions. Table 1 lists the ocean energy resources in 2007. An increasing tendency on ocean energy resources can be noticed. In 2018, Melikoglu et al. [22] provided a holistic overview on global ocean energy sources. Results indicated that, the global annual potentials for different ocean energy systems are: tidal nearly 1000 TWh, wave up to 93,000 TWh, temperature gradients/thermal up to 87,600 TWh and salinity gradients/osmotic between 2000 and 5200 TWh or maybe even up to 27,700 TWh [22].

Table 1. A holistic overview on ocean energy resources of a few representative countries worldwide [23]

Ocean Energy Forms	Annual generations
Tidal energy	>300 TWh
Marine current power	>800 TWh
Osmotic power Salinity gradient	2,000 TWh
Ocean thermal energy Thermal gradient	10,000 TWh
Wave energy	8,000–80,000 TWh

The global ocean energy resources from the worldwide perspective are demonstrated in Table 2, in respect to ocean wave energy [24][25], ocean wind energy [26][27][28][29], Ocean Thermal [30] and electrical Energy [31]. In Thailand, Kompor et al. [24] explored the optimal location for wave power generation by developing a Waves Nearshore (SWAN) model. The wave power increases from the north to the south along the China's coastlines [25]. Ocean wind energy shows promising potentials in power density, energy supply, wind energy storage and stability. Researchers are mainly focused on ocean wind energy potential [27][29], power generation [28], and levelized cost of energy [26]. In Spain, Schallenberg-Rodríguez and Montesdeoca [28] indicated that the offshore wind energy cost is much lower than the current electricity cost, and the total power generation from offshore wind farms is much higher than the yearly electricity demand. Compared to the wave energy, the LCOE is much lower for the wind energy system in Australia [26]. The ocean thermal [30] and electrical energy [31] have also been studied.

Table 2. A worldwide overview of global ocean energy resources

Energy forms	Studies	Geographical location	Methodology	Results
Wave energy resource	Kompor et al. [24]	Thailand	Simulated Waves Nearshore (SWAN) model for wave potential assessment	In respect to all selected locations, the station P5 is the best station for wave power generation, and stations P4 and P11 also provide the peak wave power.
	Qiu et al. [25]	China	Resources, governmental policies, and financial support	Wave power increases from the north to the south coastline in China.
Ocean Thermal Energy	Souza et al. [30]	Brazilian	Ocean Thermal Energy Conversion	The South Atlantic Ocean can provide electric power of 41.36 GW, and ocean heat remove 60.16 GW.
Ocean Power Energy	VanZwieten et al. [31]	Florida	Ocean thermal energy conversion	HYCOM is accurate for the OTEC potential prediction.
Ocean Wind energy	Hemer et al. [26]	Australia	Ocean renewable energy application	Compared to the wave energy, the LCOE is much lower for the wind energy system. Moreover, the LCOE is dependent on the rated capacity of the system.

	Olaofe [27]	Africa	Offshore wind energy resource map	Annual and seasonal capacity factors of ocean wind farms are between 17.6 and 51.2%.
	Schallenberg-Rodríguez and Montesdeoca [28]	Canary Islands, Spain	Spatial planning	The total power generation from offshore wind farms is high with low cost.
	Zheng and Pan [29]	Global	Grade classification map based on wind field data for the period 1988–2011	Global ocean wind energy resource is abundant, in terms of wind power density, wind energy levels, effective wind speed, wind energy storage and stability

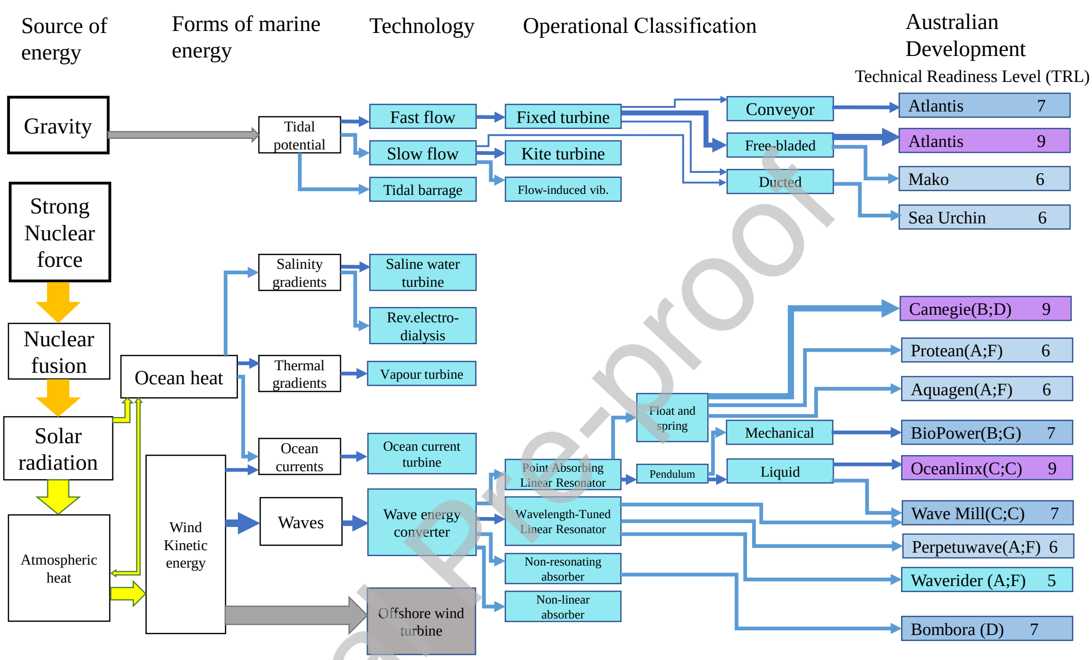


Fig. 2. Australian marine renewable energy developments [26].

Fig. 2 shows a roadmap for ocean energy utilisation in Australia. Sources for various ocean energy forms can be mainly classified into gravity, solar radiation and atmospheric heat. Driven by the gravity, the tidal potential can be applied in fixed, Kite and flow-induced turbines. Generated by ocean heat, different types of turbines can be designed for power generation, such as saline water turbine for the utilization of salinity gradients, the vapor turbine driven by thermal gradients, and ocean current turbine. The wave energy can be used to drive the waver energy converter. Furthermore, the ocean wind energy can drive the offshore wind turbine for electrical power generation. The utilization on various ocean energy forms can provide guidelines for the cascade ocean energy system design.

4. Systematic review on energy generation technologies

In order to efficiently utilize various ocean energy forms for power generation, a summary is listed in Table 3, for mathematical tools for energy potential estimation on various ocean energy technologies. Along the different depth along the sea, different ocean energy technologies can be applied. In the sea level above the sea surface, off-shore wind turbines can convert the kinetic energy to power, following the aerodynamic principle [32]. In the sea surface, the floating PV panels can convert the solar radiation into the electricity [33]. Based on the hydrodynamic [34] and aerodynamic [35], the wind energy can be converted into wave energy with kinetic energy for power generation. In the region beneath the sea surface, the gravitational potential energy can drive the tidal stream generator [36].

Based on various available ocean energy resources, Hernández-Fontes et al. [37] comparatively studied the ocean energy alternatives for isolated communities. Results showed that, wave and thermal gradient energy harvesting technologies are suitable for Michoacan, together with identified potential sites for ocean energy production.

Table 3. Summary of various ocean energy technologies and mathematical tools for energy potential estimation

Ocean Energy technologies	Studies	Energy sources	Mechanisms	Mathematical calculation
Wave energy convertors (WECs)	Viet and Wang [38]	Wind energy is converted into water waves with huge kinetic energy	Hydrodynamic [22][34] and aerodynamic [23][35]	$y = a\sin(\frac{2\pi x}{\lambda} - \frac{2\pi t}{T})$
Tidal stream generator	Markus et al. [36]	Maximum gravity on ocean waters	Gravitational potential energy	$E = \rho g \int_{h=0}^{h=R} hAdh$
Floating PV panels	Sahu et al. [39]	Solar resources	Solar-to-power conversion [26][33].	E=$\eta \cdot I \cdot A$
Off-shore wind turbines	Pan and Shao [32]	Wind energy	Conversion of kinetic energy to power	$P = \frac{1}{2}\rho\pi r^2 \cdot C \cdot V^3$
Ocean thermo-electric generators (OTEG)	Khanmohammadi et al. [40]	Temperature difference	Temperature gradient for electron densities.	$V = a\ (T_H - T_C)$

4.1. Ocean thermal energy conversions

Due to the abundance in ocean thermal energy, applications include heating and cooling energy supply for district communities. Hu et al. [41] studied cooling performance of an absorption refrigeration system with ocean thermal energy. Results indicated that, primary energy rate ratio can be improved with the increase in seawater temperature or decrease in cold seawater temperature. Wang et al. [42] reviewed technical challenges for ocean thermal energy in unmanned underwater vehicles, including low heat transfer rate, energy conversion efficiency, energy storage density without synergy between motion and heat transfer. Yuan et al. [43] experimentally tested thermal efficiency of an ammonia-water based ocean thermal energy system. Results indicated that temperature difference in generator and absorber significantly restrained further performance improvement. Hunt et al. [44] studied ammonia district cooling to cover cooling load of a coastal region. 1-GWt cooling load can be obtained with 17 m^3/s seawater flow. In addition to cooling/heating energy supply, ocean energy is mainly applied for electrical energy supply.

4.2. Ocean electrical energy conversions

In addition to ocean thermal energy conversions, the ocean electrical energy conversions have also been studied. Techniques for ocean electrical energy conversions mainly include current turbine/wave energy convertors, tidal stream generator, floating PV panels, off-shore wind turbines and ocean thermo-electric generators (OTEG). Weeks et al. [45] proposed an offshore multi-purpose platform for coastal areas, consisting of off-shore wind turbines, wave converter and tidal stream generator. Results can provide strategic offshore location planning for offshore renewable energy systems. Bahaj [46] studied ocean energy for electricity generation, and the economic analysis highlights the promising application prospects.

4.2.1. Current turbine/ Wave energy convertors (WECs)

Wind energy is converted into water waves with huge kinetic energy. Compared to the energy density of solar parks (0.1–0.2 kW/m^2) and wind farms (0.4–0.6 kW/m^2), wave farms energy density is much higher at 2–3 kW/m^2. Furthermore, from the time-duration perspective, compared to the availability of solar and wind power at 20–30% times, the wave energy is available 90% of the time. Uihlein et al. [47] studied the wave and tidal current energy utilization, and provide the up-to-date research gaps and technical barriers to the designers and researchers. Life cycle assessments with fluctuation of power output, storage, or grid interaction are worthy to be investigated. Furthermore, the impact of increased demands and integration of fluctuated renewable systems on the system reliability and stability needs to be investigated. Viet and Wang [38] designed a smart ocean wave energy pitching harvester based on the piezoelectric effect, with minimized components and space. Through the design on geometrical dimensions, distances and material properties, the generated power of the harvester can be 900 W. With the triboelectric and piezoelectric effects, Jurado et al. [48] designed a hybrid device for coastal wave energy harvesting. Results shows that compared to the single triboelectric and piezoelectric nanogenerator, the hybrid devices can improve the energy conversion efficiency by 30.22%.

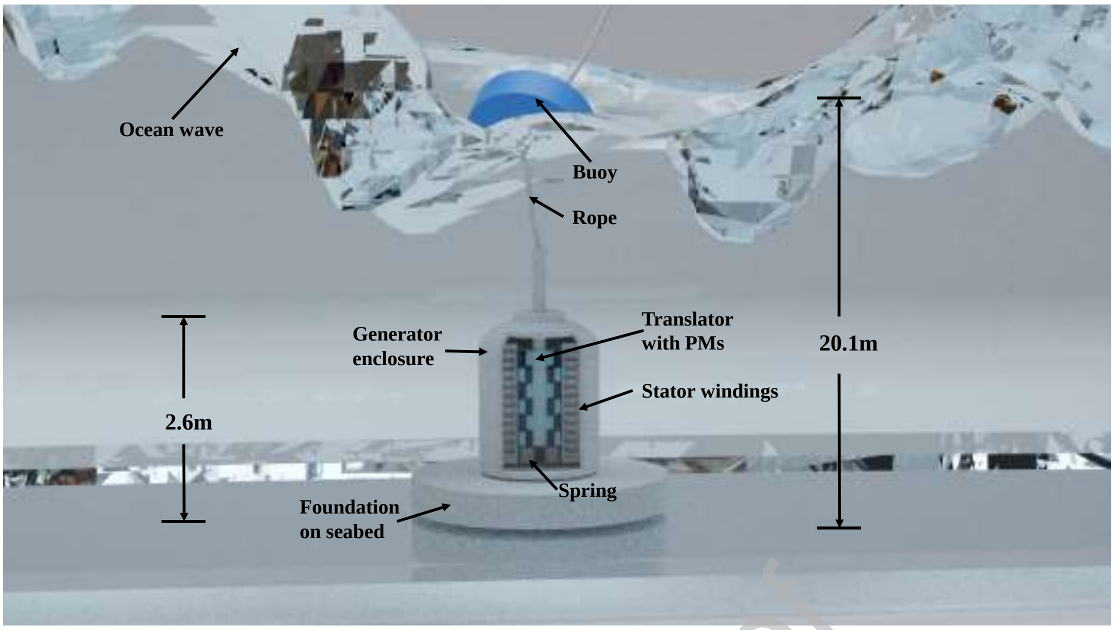


Fig. 3. Ocean Wave Energy Converter [49].

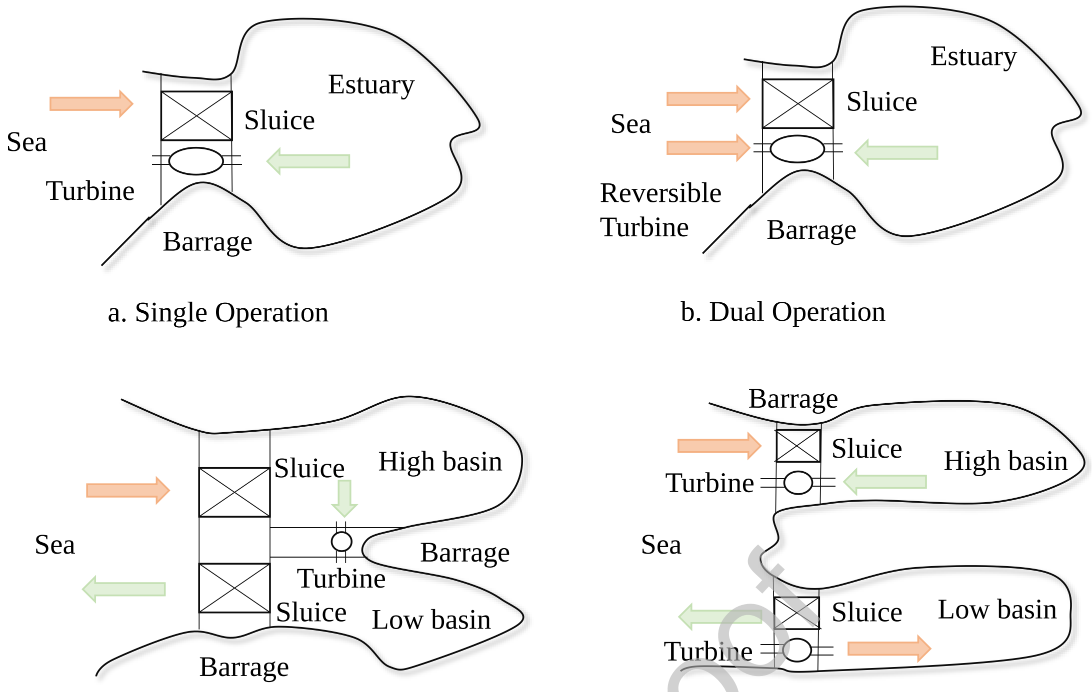
Wave energy convertors (WECs) are designed based on hydrodynamic [34] and aerodynamic [35] models. Fig. 3 shows the typical design of an Ocean Wave Energy Converter. Considering the vertical and horizontal motions of wave energy, wave energy converter (WEC) needs to be designed with both vertical and horizontal power extraction devices. Börner and Alam [50] systematically reviewed the modeling development of wave energy converters, in terms of each sub-domain model. Results indicated that, the model needs to be re-developed, whenever at least one experimental subdomain is to be used. Furthermore, the advancement of computational and experimental techniques can promote the practicability and acceptance of the hybrid simulation. Shahriar et al. [51] developed a dynamic model on a Searaser wave energy converter based hydroelectric power generation. By converting the kinetic energy into power, the Searaser can provide about 35 m of water-head, and the estimated capacity was about 144 kW for the decentralized Mini Hydroelectric Power Plant (MHPP).

4.2.2. Tidal stream generator

The spring tides were created with maximum gravity on ocean waters when a solar month earth and moon twice become aligned. The water springs are as high as 11.4 m (Penzhinsk, Russia) to 12.4 m (Cobequid, Canada). The calculation of the tidal power generation potential can be calculated as follows:

$$E = \rho g \int_{h=0}^{h=R} hAdh$$

where ρ is sea water density (kg/m^2) and g is gravitational constant (9.81 m/s^2).



a. Single Operation

b. Dual Operation

c. Double basin linked operation

d. Double basin paired operation

Fig. 4. Categories of tidal power stations: (a) single operation, (b) dual operation, (c) double basin linked operation, (d) double basin paired operation.

Depending on the geographical situation of the tidal power stations, four categories of single, double linked and paired tidal power stations can be designed, as shown in Fig. 4. The single operation sluice, as shown in Fig. 4(a), is turned on during high tides, but becomes closed during emptying process. Double operation reversible turbine and sluice, as shown in Fig. 4(b), function during high tide, but the sluice remains closed during emptying process. In the double basin linked operation, as shown in Fig. 4(c), the turbine is placed on Tied barrage. As shown in Fig. 4(d), in the case of double paired barrages, upper sluice opens during filling and the lower sluices during emptying process.

4.2.3. Floating PV panels

By converting the solar radiation into power, Sahu et al. [39] systematically reviewed the application of floating PV panels. Compared to land-based PV system, the floating PV system has numerous advantages, including space saving, fewer obstacles to block sunlight, convenient, higher power generation efficiency due to a lower cell temperature. Additionally, the PV plant can prevent excessive water evaporation, limit algae growth and improve water quality. Further studies are required, in terms of the flexible thin film under harsh water environment, solar tracking system with changeable tilt and azimuth angle, advanced anchoring system for fixing the buoyancy PV system, remote sensing and GIS based technique. Ates et al. [52] evaluated the power potential of a hydroelectric power plant using remote sensing. The case study indicates that, a 2.03-GWp floating photovoltaic solar power plant can provide 3,328.33-GWh annual energy, and prevent 28,231,026.90-m^3 water from evaporating. Zhang et al. [53] studied the semitransparent polymer solar cells (ST-PSCs) on water. Trapani and Millar [54] studied a-Si floating PV for power supply. Results showed that, a 250 MW installation can realise equivalent to a 25% reduction on the embodied carbon emission. In addition to the renewable energy supply and carbon emission reduction, the impact of floating PVs on the algal growth has also been studied. Zhang et al. [53] firstly validated that the semitransparent polymer solar cells can avoid the algal growth in water. Haas et al. [55] studied the impact of floating PV covered area on microalgal growth and hydropower revenue. The further increase of the covered fraction can eradicate algal blooms completely, whereas economic hydropower will be decreased.

4.2.4. Off-shore wind turbines

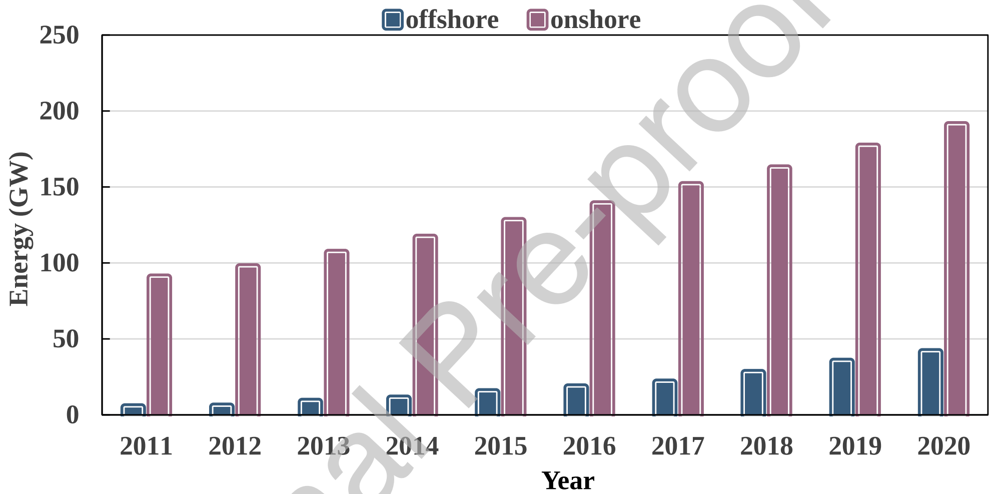


Fig. 5. Evolution of onshore and offshore wind turbine from 2011 to 2020 [56].

Wind turbine, for the conversion from kinetic energy to electric energy, has been studied for the utilisation of ocean wind resources. Researchers are mainly focused on the estimation on offshore wind energy potentials [27][57] and reliable operation [58]. The evolution of onshore and offshore wind turbine, as shown in Fig. 5, indicates that, both the onshore and offshore wind energy harvesting systems are increasing, while the increasing magnitude of the onshore wind turbine is much higher than the offshore wind turbine. Elsner [57] analyzed the African offshore wind energy potential based on explicit models and long-term satellite data. Results indicated that, the integrated development on the power pools is promising to utilise offshore wind energy in Africa. Olaofe [27] assessed the offshore wind energy resource along the coastal lines of Africa.

The spatial planning for off-shore wind turbines has attracted widespread interests in coastal regions and islands. Díaz and Soares [59] adopted the Geographic Information System for marine spatial optimization of floating offshore wind farms. With the locations and legislative considerations, the research can provide guidelines to eliminate unsuitable areas and to identify the most suitable position. Abdel-Basset et al. [60] developed a hybrid MCDM (AHP-PROMETHEE II) approach to select optimal offshore wind power station. The proposed approach can provide rigorous methodological support for site selection with benefits in coastal management. Total power generation from offshore wind farms is much higher than the yearly electricity demand, and the offshore wind energy cost is much lower than the current electricity cost [28].

In terms of the geotechnical and structural issues of deep-water floating wind farms, Wu et al. [61] comprehensively reviewed offshore wind turbine foundations and anchorages of mooring systems, as shown in Fig. 6. The review calls for the further study on standard design codes for offshore wind turbine foundations, advanced numerical modelling on structure-foundation-soil system, geotechnical engineering of offshore anchors and hydrodynamics of mooring systems.

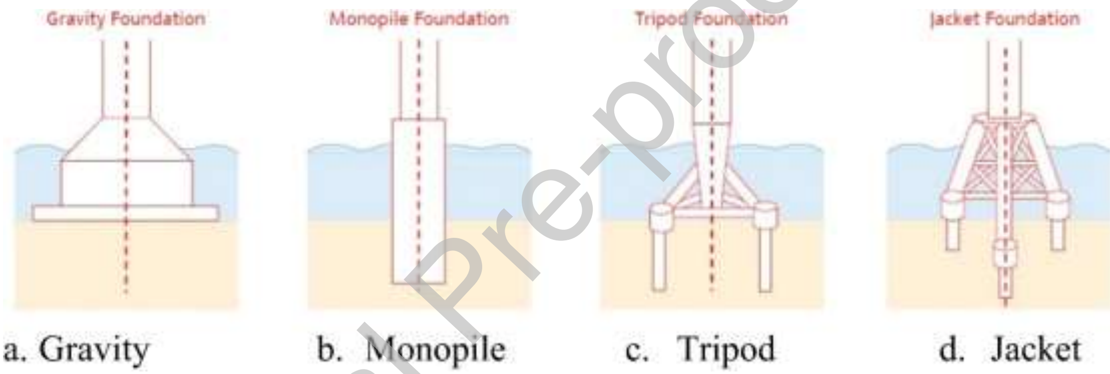


Fig. 6. Schematic diagram for bottom-fixed offshore wind turbine foundations [67].

4.2.5. Ocean thermo-electric generators (OTEG)

The temperature difference between deep ocean water and warm surface water can drive the ORC to generate electricity [62]. Osorio et al. [62] initiated an Ocean Ecopark in a small tropical island. Zereshkian and Mansoury [63] studied the power supply through the utilization of thermal gradient along the ocean depth. Through the historical data from 2005 to 2014, the power generated by the ocean thermal energy conversion can be used in the southern basin during July–September.

In the academia, researchers mainly focused on optimal geographical location of ocean thermal energy plants [64], dynamic model development for estimation on power potential [31], economic performance analysis [65][66]. Zhang et al. [64] developed a novel multi-criteria decision-making framework for ocean thermal energy plant site selection. The robustness and effectiveness of the proposed method were demonstrated through the case study in Guangdong and Guangxi Provinces. VanZwieten et al. [31] studied the Florida's ocean thermal energy conversion (OTEC) resource via a dynamic model, i.e., HYCOM. Results indicated that, the maximum net power production potential is

152 MW in August and the minimum is 78 MW in February. In terms of the economic performances of OTEC, Langer et al. [65] clearly identified gaps on life-cycle based analysis. Results showed that, current studies are mainly on individual plants. Furthermore, the Levelized Cost of Electricity (LCOE) was analyzed, while other economic metrics are ignored, such as payback period and Internal Rate of Return (IRR).

Temperature difference between the surface water and deeper well head is high enough to drive thermo-electric generators [68]. OTEG can supply 1–10 W to subsea control electronics for oil wellheads. As depicted in Fig. 7, temperature gradient leads to high densities of electrons in n-type materials and holes in p-type materials. A TEG can convert waste heat from thermal power plants, engine exhaust and flue gases into power. Thermoelectricity (V) produced by thermo-electric materials having Seebeck coefficient α(μV/K) under temperature gradient (ΔT) may be given by:

$$V = a\,(T_H - T_C)$$

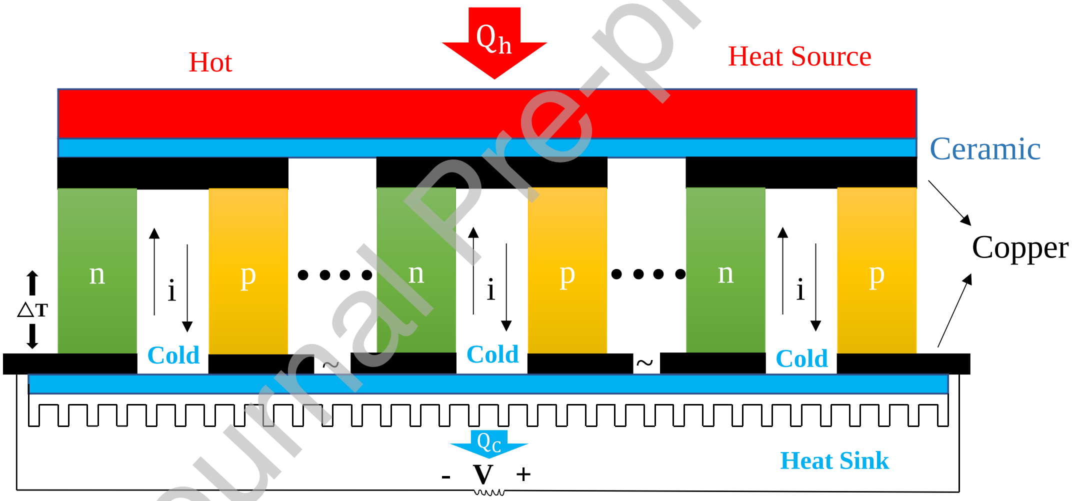


Fig. 7. A model of cascaded TEG units thermally in parallel and electrically in series.

4.3. System integration with synergistic operation

Synergies of hybrid energy system are important for the reliability and flexibility of the power supply systems, in terms of the intermittence and fluctuance of renewable energy systems [69]. Khosravi et al. [69] studied the techno-economic performance of a hybrid ocean thermal/photovoltaic system with integrated hydrogen. The structural configuration of the integrated system is shown in Fig. 8, consisting of power supply systems (i.e., an OTEC, solar PV arrays and fuel cells), electrolyser for power-to-H_2 conversion and a H_2 tank. Results indicated that, the exergy efficiency of the hybrid system was 18.35% and the payback period was around 8 years. The unit electricity cost was 0.168 $/kWh. Jahangir et al. [70] designed a hybrid system, consisting of PV/Wind turbine/Wave energy converter, for the stand-alone power supply. The economic analysis indicates that, the cost of energy for the hybrid system is between 0.233 and 0.348 $/kWh. Hu et al. [71] designed a synergistic wave and wind energy system on a floating platform. The optimisation method can provide guidance on optimum number and layout of wave energy converter.

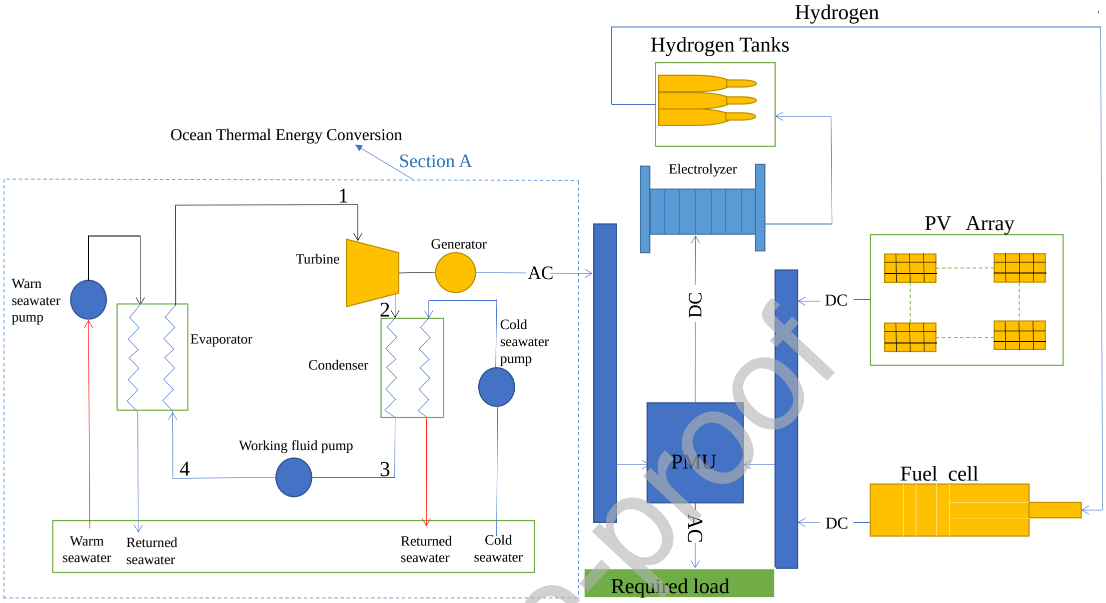


Fig. 8. A hybrid ocean thermal/photovoltaic and hydrogen integrated system [69].

5. Electrical energy storage (EES) system in coastal regions

To enhance the matching between intermittent renewable energy and stochastic energy demand, energy storages are critical components. Chen et al. [7] systematically reviewed progresses in electrical energy storage systems. The comprehensive review can provide technical guidelines and future prospects for multi-diversified energy storage techniques in the future.

5.1. Pumped hydroelectric energy storage (PHES)

Through the exploitation of the pressure difference between the seafloor and the ocean surface, electricity storage at the bottom of the ocean is firstly proposed by Rainer Schramm [72] with an efficiency of around 80%. The general working principle is that, the current turbine turns the generator to produce the electricity whenever the power is insufficient. The pumped storage power station can complement the intermittent solar power generation with constant electricity supply to improve the reliability and reliance of power grid.

Table 4 shows a worldwide overview on pumped hydroelectric energy storages. A seawater pumped storage power project was designed [74], with the plant capacity of 800 MW, the maximum discharge of seawater at 242 m^3/s and the effective head at 389.4 m. Kotiuga et al. [75] studied the technical feasibility of a seawater pumped storage system with the capacity at 1000 MW, to replace the fuel oil-based 1000 MW thermal plants. The identified number of potential sites with different priorities can assist the engineers for the system planning.

Economic performance analysis on ocean energy storages has also been studied. Cazzaniga et al. [76] studied techno-economic performances of an ocean energy storage. Results showed that, the system cost is low with a cost of € 400 per kWh storage capacity with a life cycle of at least 5 years. Furthermore, due to the linear increase of stored energy along with the sea depth, the apparatus is cheap only when depth is greater than 500 m. Loisel et al. [77] integrated the tidal range energy with undersea pumped storage for techno-economic performance enhancement with constraints of the grid and high-power curtailment rates. Results showed that, the LCOE is decreased to 0.17 €/kWh under the grid constraints.

Table 4. A worldwide overview of pumped hydroelectric energy storages of a few representative countries worldwide

Location	Studies or Projects	Capacity	System
Japan	Shibuya and Ishimura [78]	Okinawa 30 MW capacity sea water pumped storage plant	The maximum depth is 25 m with storage capacity at 564,000 m^3.
JORDAN	[79]	1500 to 2500 MW	The penstock from the reservoir to the Dead can provide 800 cm/s flow.
Ireland	[80]	480 MW seawater pumped-storage hydro plant	Through the storage of primarily excess wind power, the imported fossil fuels can be reduced.
Germany	Schramm [81]	300 MW power generation for a time period of about 7–8 h	Underwater plant can cover demands of 200,000 British households
Indonesia	[74]	800 MW	the maximum discharge of seawater at 242 m3/s and the effective head at 389.4 m.
Saudi Arabia	Kotiuga et al. [75]	1000 MW	4 turbines with 250 MW for each turbine

5.2. Ocean compressed air energy storage (OCAES)

Ocean compressed air energy storage (OCAES) beneath the ocean has also been designed for electrical energy storage. A conceptual schematic of OCAES system is demonstrated in Fig. 9. The renewable energy is supplied to the compressor to compress the air into high pressure, which is stored in the CAS. The high-pressure air passes through the expander for power generation and supply to the utility grid.

In the academia, researchers mainly focused on the system design [82][83][84][85], technical performance [12][86] and optimal energy management strategy [87]. Patila and Ro [82] studied the design specifications of a 2-MWh CAES. Results showed that, the increase of the ocean depth can decrease the storage volume. Furthermore, by designing the compressor/expander operation under near-isothermal conditions, the roundtrip efficiency of OCAES can be improved. A 1-GWh storage at 1000 m depth requires length of the tubular bag between 1 km (Kevlar) and 15 km (nylon) [83]. Pimm et al. [84] experimentally tested the cost-effective storage and supply of high-pressure air for offshore and shore-based compressed air energy storage plants. Results indicated that, the 5 m diameter bag can be cycled for 3 months in 25 m of seawater. Moradi et al. [85] designed an underwater compressed energy storage to provide the collaborative operation with wind energy resources. The coordinated operation can mitigate the risk of commitment in the electricity market and protect the high prices of the spot market. Sant et al. [88] evaluated an integrated compressed air energy storage with MW floating wind turbine system. Results indicated that, the increased mass of the floating spar, due to the integration of the compressed air energy storage (CAES), results in reduced wind turbine motions.

In terms of technical performance, compared to the underground storage, the underwater Compressed Air Energy Storage shows isobaric containment and improved roundtrip efficiency [86]. Sheng et al. [12] studied a tidal turbine farm and an ocean CAES to reduce the reliance on conventional diesel generators. By storing the heat during the air compression process and releasing the stored heat during the discharging process, as shown in Fig. 10, the cycle efficiency can be about 60.6%. Furthermore, compared to wind energy system, the marine current turbine and CAES are more economically competitive. In addition, Maisonnave et al. [87] developed an optimal energy management strategy for the storage of marine energy, stabilizing power interaction with grid.

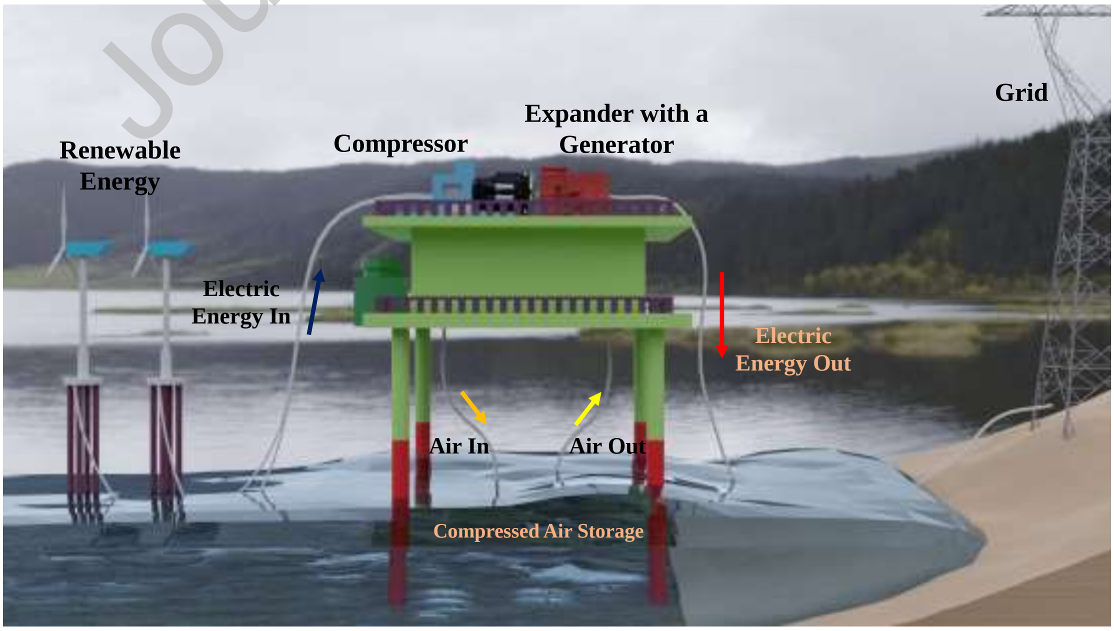


Fig. 9. Conceptual schematic of Ocean Compressed Air Energy Storage (OCAES) system [89].

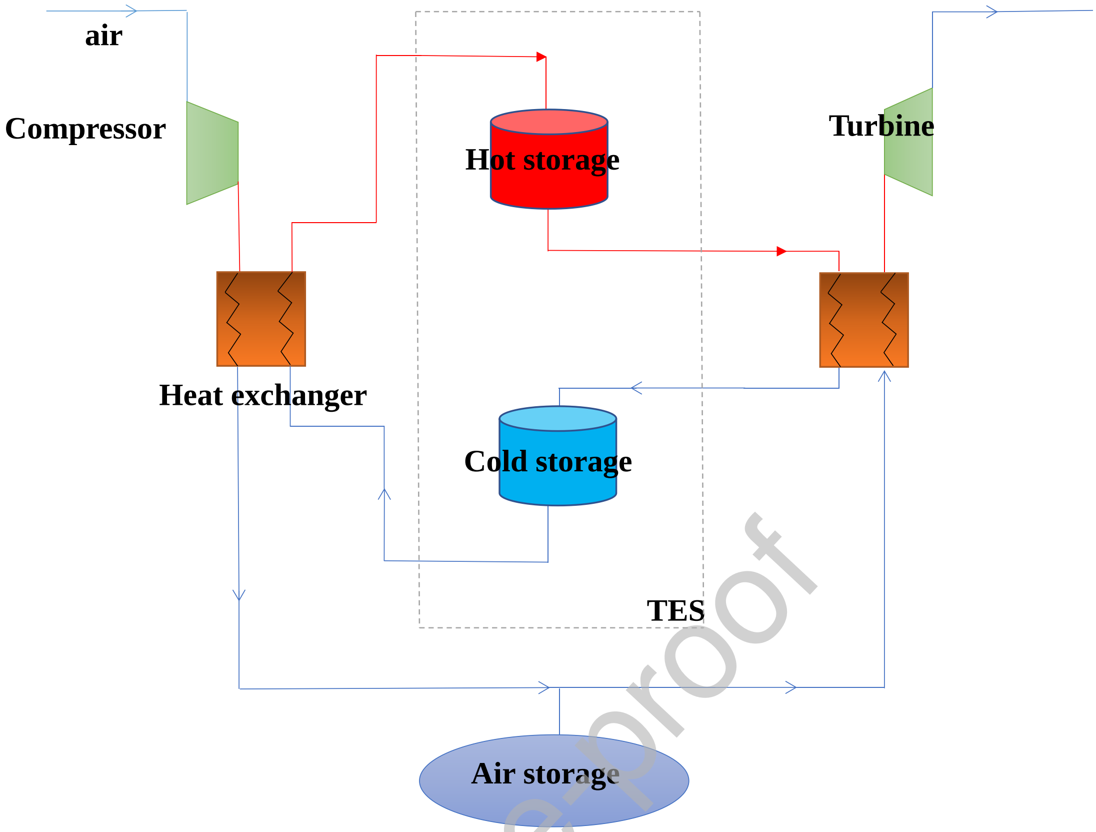
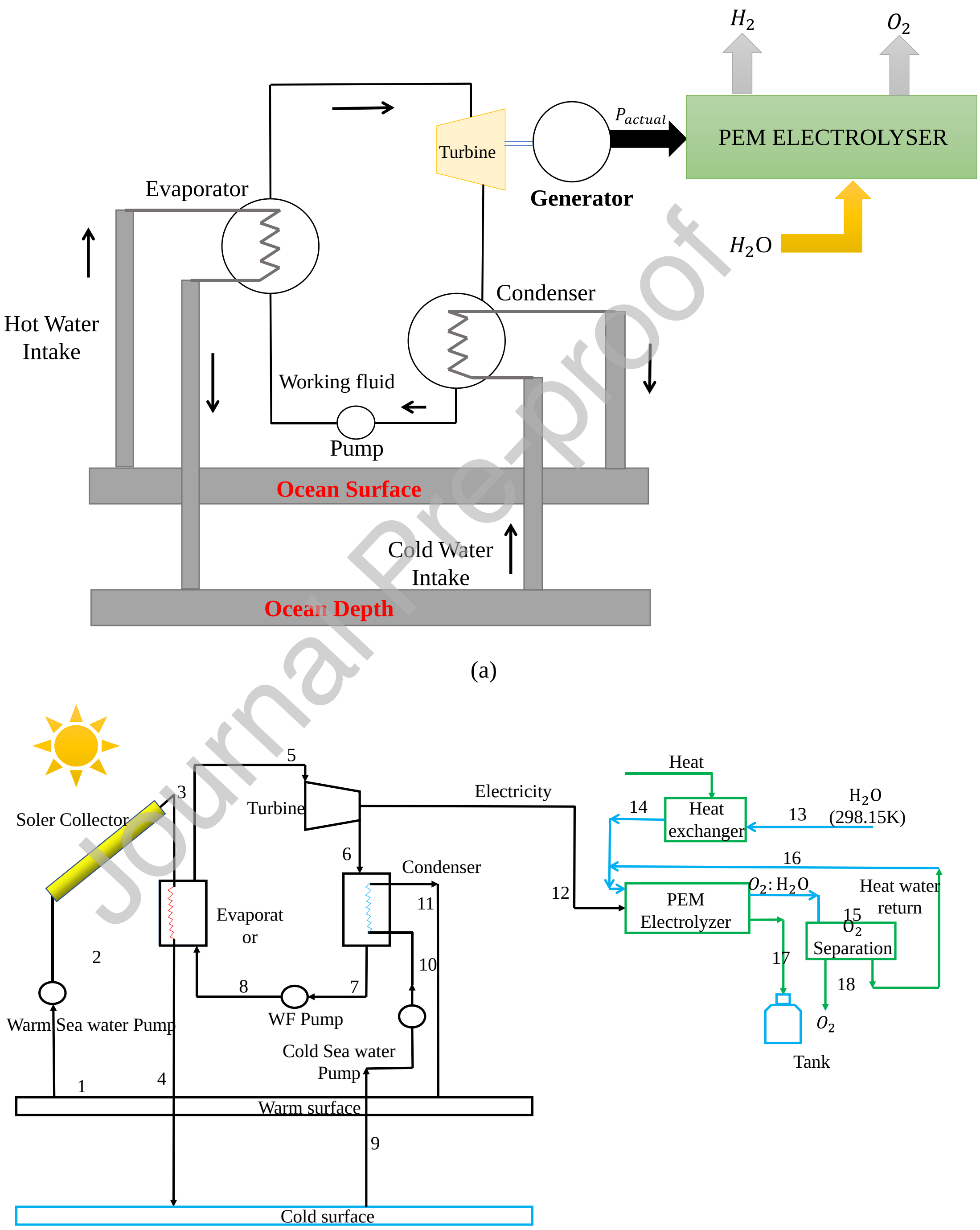


Fig. 10. Diagram of the Ocean Compressed Air Energy Storage [12].

5.3. Ocean hydrogen-based storage

By driving the electrolyzer, the renewable energy can be converted into hydrogen, which can be stored in the H_2 tank after being compressed by the compressor. During the energy demand shortage or power emergency period, the stored H_2 can be discharged to cover the energy demand [90]. Compared to the direct power-to-power storage in the electrochemical battery storage with the efficiency at around 90%, the efficiency of the power-chemical-power conversion in the H_2 system is relatively lower at around 45%. Strategies for energy efficiency improvement include the exhaust heat recovery from the electrolyzer, micro-thermophotovoltaic integration [91], and advanced materials integration [92]. Tarkowski [93] studied the prospects and barriers of underground hydrogen storage. Results showed that, the decrease of hydrogen production is a dominant factor for the widespread application. Due to high energy storage density and clean byproduct without pollution to the environment, the hydrogen-based storage shows promising prospects in ocean energy systems.

In the academia, Nazir et al. [94] comprehensively reviewed the H_2 storage, transportation, and distribution, including the road, pipelines, and ocean transmission mediums. The results concluded that, the compressed H_2 and its transportation by road are common technologies. Researchers are maingly focused on techno-economic performance analysis [69], parametrical analysis on temperature difference [95], energetic and exergetic efficiencies [96]. As shown in Fig. 11(a), the increase of the temperature difference between the surface and deep-sea water from 5 °C to 25 °C will improve the hydrogen production rate from 2.5 to 60 N m^3/h. Yilmaz et al. [96] conducted the parametrical analysis with energetic and exergetic efficiencies at 43.49% and 36.49%, respectively.



(b)

Fig. 11. Schematic diagram: (a) an OTEC system for H_2 production with a PEM electrolyser [95]; (b)an integrated ocean thermal energy conversion (OTEC) and a flat plate solar collector for hydrogen production [98].

In addition to only OTEC system, the integrated solar thermal and OTEC system has also been studied for H_2 production. A schematic diagram of an integrated OTEC and a flat plate solar collector is shown in Fig. 11(b) for hydrogen production. Ahmadi et al. [97] analysed the energy and exergy performances of an integrated solar thermal and OTEC system. Furthermore, Ahmadi et al. [98] adopted the evolutionary algorithm NSGA-II for the multi-objective optimisation to optimise design parameters, in terms of the minimal total cost rate and the maximal cycle exergy efficiency. Critical parameters can thereafter be identified for optimal system design.

5.4. Comparison between different energy storages

Based on the above-mentioned literature review, comparison between various electrical energy storages is necessary, in terms of technical maturity, response time, storage capacity and efficiency, initial capital cost, life-time and environmental effect. In terms of the energy production, storage, transmission and distribution in the clean energy network, Li et al. [99] comparatively studied the renewable energy carriers between hydrogen and liquid air/nitrogen. Results showed that, although the hydrogen has a higher volumetric energy density than cryogen, the hydrogen is less competitive than the liquid air/nitrogen, due to the expensive cost of fuel cell, impurities of hydrogen and relatively short service time.

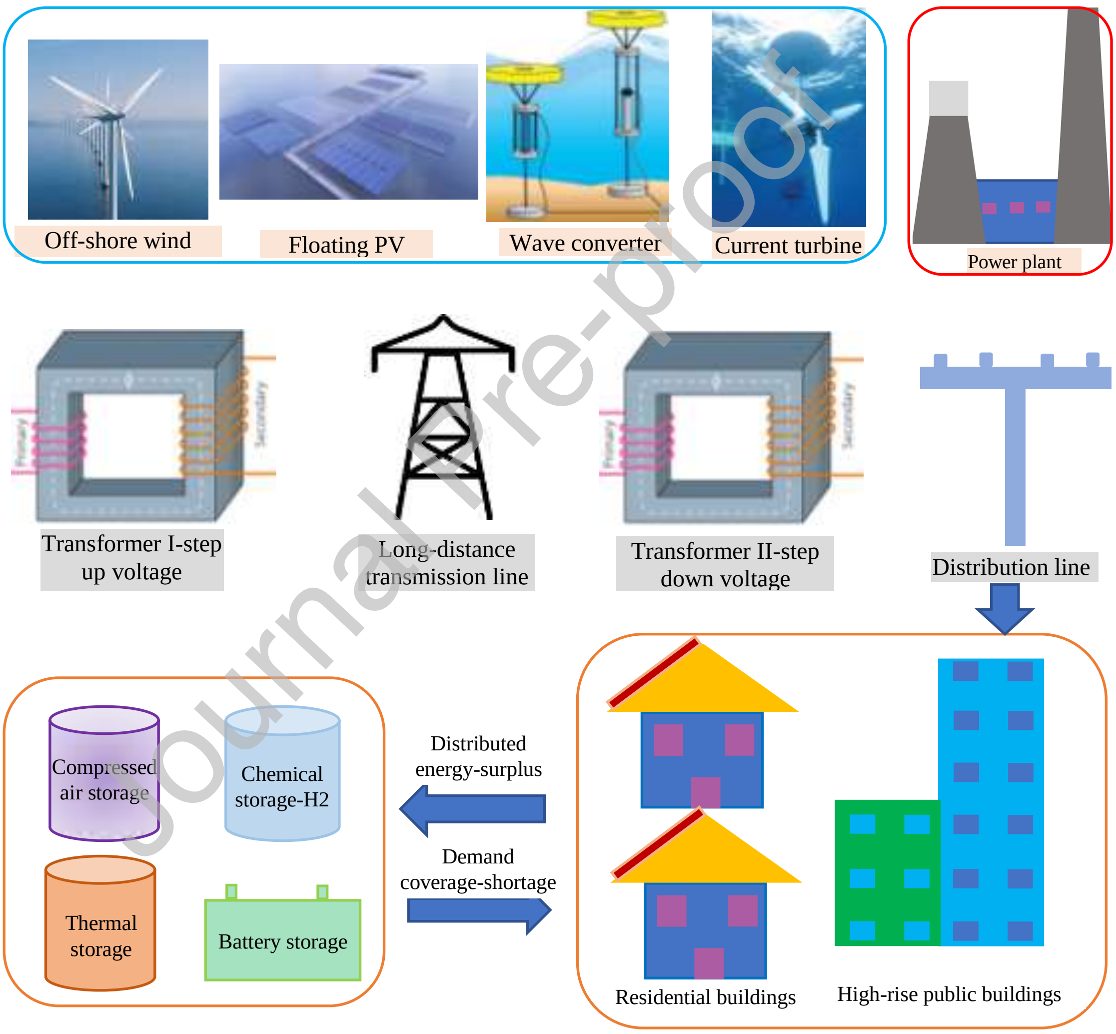
Table 5 shows the comparison between different energy storage systems. The pumped hydroelectric and electrochemical battery storages show the highest efficiency, nut with relatively high cost and long payback time. Ocean compressed air energy storage can avoid the reliance on favourable geography, whereas the practical application is restrained by fossil fuel combustion, carbon emission and safety issues. Furthermore, the ocean hydrogen-based storage shows high energy density and clean byproduct water, whereas the main disadvantages include the low efficiency at around 45% and safety issues.

Table 5. Comparison between different energy storage systems and future prospects.

Energy storages	Advantages	Disadvantages	Future prospects
Pumped hydroelectric energy storage	High energy efficiency (between 70% and 80%), stabilised power supply	Scarcity of available sites for large reservoirs; long payback time (around 10 years); high cost and remove of trees and vegetation fields	Low cost on product for widespread acceptance in the market
Ocean compressed air energy storage	Avoidance of the reliance on favourable geography	Limited application due to the associated gas turbine; fossil fuel combustion and emission; Safety issue	Advanced Adiabatic CAES with Thermal Energy Storage; Compressed Air Storage with Humidification

Electrochemical battery storages	High efficiency at around 90%	Low energy densities; high maintenance costs; cycling aging; ecological impact due to toxic materials in the battery;	Batteries for large-scale community application
Ocean hydrogen-based storage	High energy density and clean byproduct	Low efficiency at around 45%; Safety issue	Strategies for energy efficiency improvement, such as the exhaust heat recovery from the electrolyzer, micro-thermophotovoltaic integration [75], and advanced materials integration [76]; Advanced materials for high-pressured H_2 storage

6. Energy network for ocean energy sources, generation, transmission, distribution and end-user side services



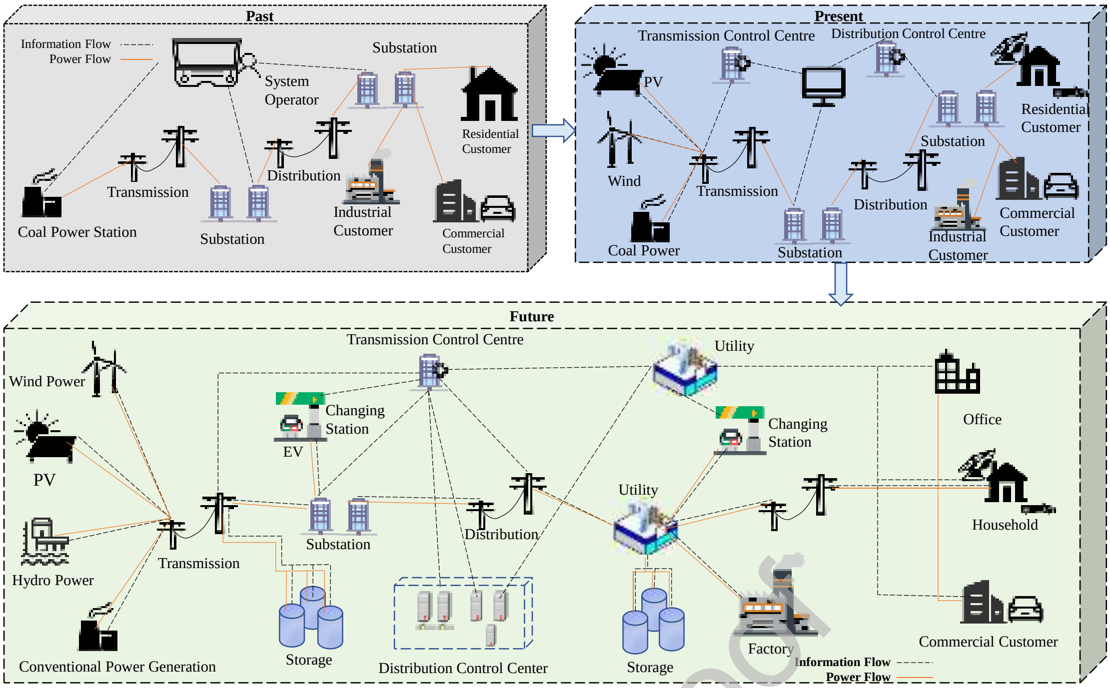


Fig. 12. Blockchain for ocean energy sources, generation, transmission, distribution and end-user side services [100].

Fig. 12 demonstrates an energy network, consisting of ocean energy sources, generation, transmission, distribution and end-user side service. Energy supply sources include off-shore wind turbine, floating PV panels, wave converters, current turbines and back-up power plant. In order to realise the long-distance transfer for power supply to the end-user side, a long-distance transmission line is designed, consisting of transformer I-step up voltage, power transmission device, and transformer II-step down voltage. Afterwards, the distribution line is applied to distribute the power to end-users. The function of the power grid is to dynamically balance the difference between renewable supply and energy demand. In addition, hybrid energy storages are designed to balance the building integrated renewable energy supply (such as from BIPVs or micro wind turbines) and energy demands. In this section, a systematic review was conducted on ocean energy sources, generation, transmission, distribution and end-user side services.

6.1. Ocean energy sources and power generations

Compared to the spatiotemporal fluctuation of solar and wind energy, the periodic tidal current energy is less variable from longer time horizons. Considering the resource variability for the grid interaction, several strategies have been studied to improve the stability and reliability of power grid, such as the wind energy source forecasting, advanced energy management strategy between intermittent generation and stochastic load, and hybrid energy storage (e.g. pumped hydro, battery storage). Qiu et al. [25] comprehensively reviewed ocean wave energy in the coastline in China.

Furthermore, the wind-wave synergy system is promising, but more studies need to be conducted for realizing the maturity of the hybrid system. Furthermore, advanced simulation techniques have also been explored. Draycott et al. [101] studied the advanced ocean methodology to simulate the dynamic ocean environment for offshore renewable energy.

As a popular technology, OTEC with temperature difference between the ocean surface and deep ocean has been applied for power generation. The working principle of the OTEC can be briefly summarized as follows. As shown in Fig. 13, the low working fluid with low boiling temperature, such as ammonia, freon or propylene, is vaporized by warm seawater from the surface. The vaporized steam drives the generating turbine to generate electricity. The cold water from the deep ocean can condensate the working fluid in the condenser.

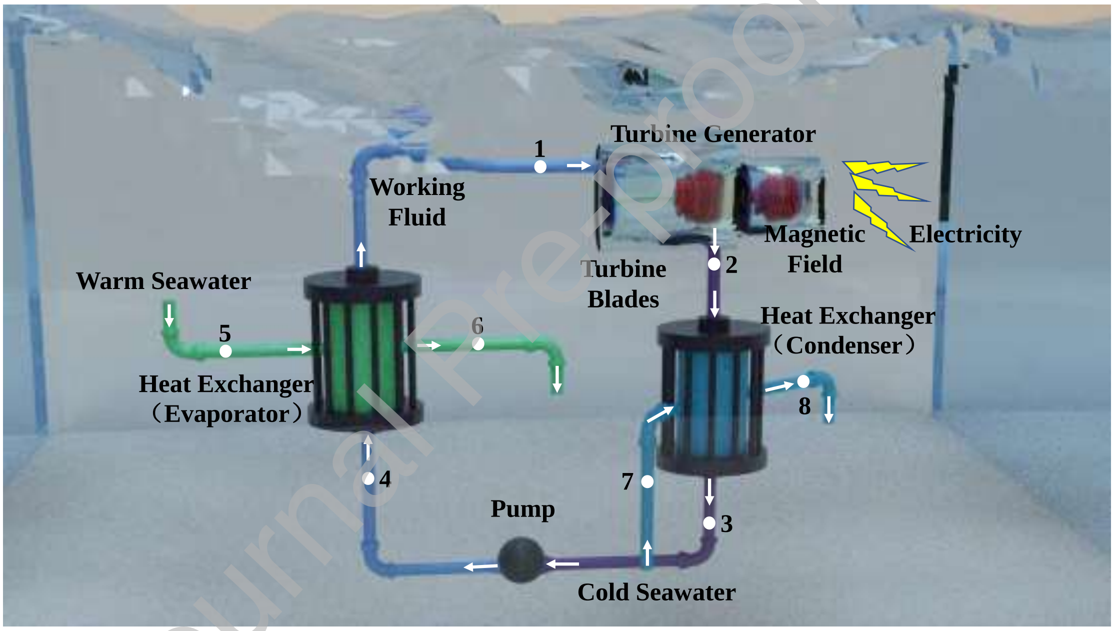


Fig. 13. Thermodynamic and power generation devices of an OTEC plant [30].
(Note: 1, 2, 3, and 4 refer to Rankine cycle. Heat exchangers inlets and outlets are indicated by numbers 5, 6 (evaporator), 7 and 8 (condenser).

6.2. Transmission and distribution

Energy transmission with low power loss and high efficiency, and distribution to end-users require the grid network optimisation. Before the realization of a large-scale offshore wind energy system, the upgrade of the existing grid network is necessary with the requirement on substantial investments in the regional transmission line network (like submarine cable) [102]. The seawater pumped storage power system in East Java [74] can transmit the generated power to Paiton–Kediri through a newly constructed 80 km transmission line.

In respect to the design of power transmission line, several design strategies can be applied as shown in Fig. 14. Depending on the geographical location of converter, on-shore and off-shore installations in design strategies I and II are proposed, as shown in Fig. 14(a) and (b). Depending on the geographical location of transformer, on-shore and off-shore installation of transformer in Design strategies II and III are proposed, as shown in Fig. 14(b) and (c). Due to the step-up of voltage in the transformer, the Design strategy III shows lower resistive losses than that of the Design strategy II, and therefore the Design strategy III is more suitable for long-distance power transmission. Furthermore, the inclusion of converters in both off-shore and on-shore sides can become useful for large -scale system for long-distance transmission, as shown in the Design strategy IV.

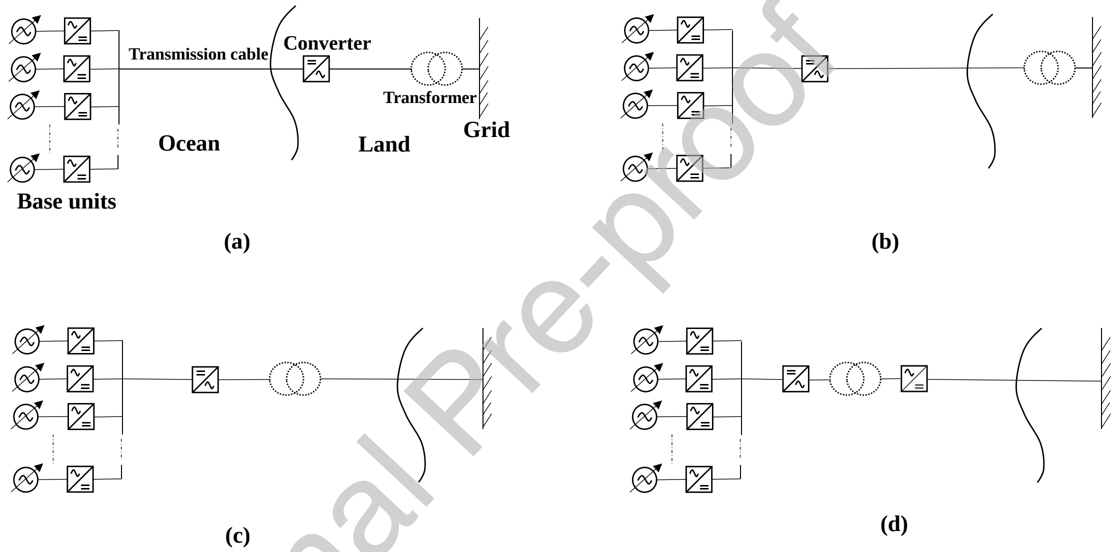


Fig. 14. (a) Power transmission designs: Design strategy I (without transformer, 1.1; with transformer, 1.2); (b) Design strategy II (without transformer, 2.1; with transformer, 2.2); (c) Design strategy III; (d) Design strategy IV [103].

Table 6 summarises the advantages and disadvantages of the proposed power transmission designs. The Design strategy I and II show a few components and low complexity but with a high transmission loss. The Design strategy III shows low resistive losses and simple components, but complex components with transformer are offshore. In addition, the Design strategy IV shows extremely low transmission losses, but the complex installation offshore can be noticed with many converters. In terms of the installation intervals, the Design strategies I and II are suitable for small system close to grid, and the Design strategy III is suitable for medium to large system close to grid. The Design strategy IV is suitable for large-scale systems with long-distance transmission.

Table 6. Summary of advantage and disadvantages of different power transmission designs

Power transmission design options	Design strategy I	Design strategy II	Design strategy III	Design strategy IV
Advantages	Few components and low complexity	Simple components	Lower resistive losses and simple components	Very low transmission losses
Disadvantages	High transmission losses	Complex components offshore and High transmission losses	Transformer and complex components offshore	Many converters; Complex installation offshore
Possible installation interval	Small system close to grid	Small system close to grid	Medium to large system close to grid	Large -scale system for long-distance transmission

6.3. End-user side services

In respect to challenges for ocean energy integration in power grid, due to the instability and fluctuation of ocean energy resources, energy flexibility can be provided from the end-user side, through demand-side management, forecasting on stochastic energy demands and distributed renewable generations. Lund et al. [104] reviewed energy flexibility measures for high renewable penetration, including the demand-side management, supply-side flexibility, grid ancillary services, energy storage, together with advanced energy conversion technologies. With the consideration of fluctuation and intermittence of renewable energy, Pina et al. [105] exploited the demand-side management to promote the renewable penetration and to reduce the standby power. The load shifting strategies can increase the effective capacity factor and delay the installation of renewable generation systems. Zhou and Cao [106] proposed the surplus renewable recharging strategy to enhance the renewable penetration in thermal energy storage systems. Results indicated that, the proposed demand-side strategy can improve the surplus renewable energy penetrated in the building energy system and reduce the grid reliance for demand coverage. Furthermore, the grid ancillary services can provide flexibility through contingency service with spinning reserves and frequency regulation. Depending on response time-duration, grid ancillary services for different storage devices are summarized in Table 7.

Table 7. Grid ancillary services with different response time-durations.

Response time-duration	Technologies	Grid ancillary services
1 ms–5 min	Flywheels, DSM	Power quality, regulation
5 min–1 h	Flow batteries, PHES, DSM	Spinning reserve, contingency reserve, black start
1 h–3 d	CAES, PHES, DSM	Load leveling/peak shaving/valley filling
months	CAES, PHES	Seasonal shifting

7. Advanced energy management strategies with ocean energy systems, coastal community and utility grids

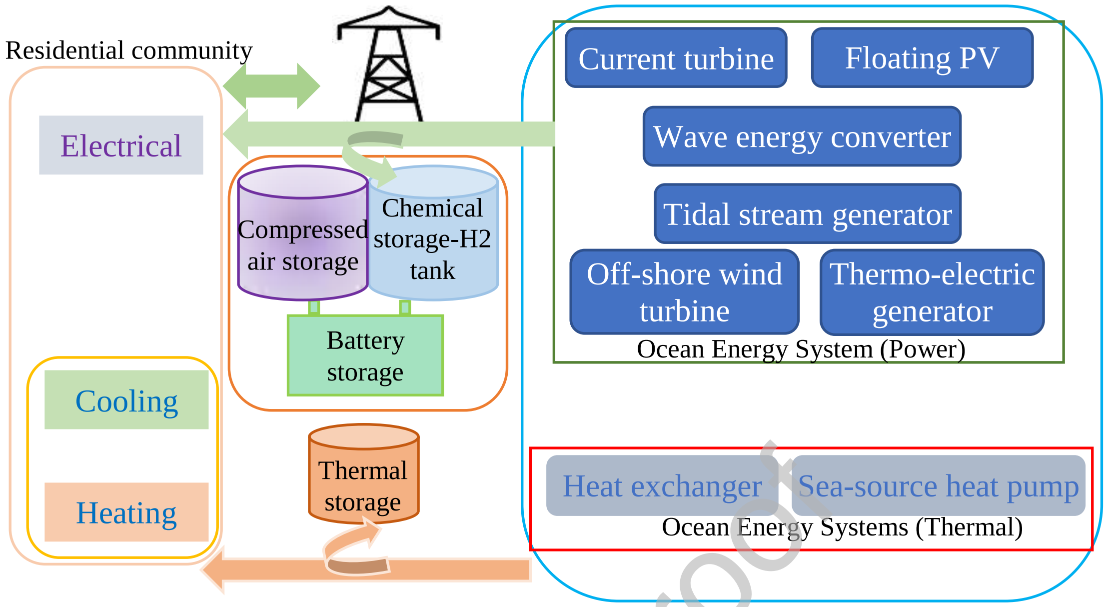


Fig. 15. A schematic diagram on ocean energy systems for a coastal community.

Fig. 15 demonstrates the hybrid ocean energy systems for a coastal community. The utility grid is operated to dynamically balance the ocean energy supply and energy demands in the community, through the bi-directional energy interactions. The surplus electricity can be stored in the compressed air storage (through a high-pressure compressor and a blade turbine), high-pressure H_2 tanks (through the electrolysis process) and electrochemical battery. The discharge of the storage during the demand shortage period can simultaneously reduce the electrical energy imported from the grid and the peak grid import power, relieving the grid burden for district demand coverage. In respect to the thermal energy demands, sea-source heat pumps can be designed to cover the cooling and heating loads through the vapor compression refrigeration cycle process. Thermal energy storages can shift the peak load with buffer effect.

7.1. Functionality of ocean thermal energy for coastal residential community and thermal grid

The depth-dependent temperature difference in ocean water layer provides the possibility for ocean thermal energy utilization. In the cooling dominated coastal regions, the condenser of the heat pump can be connected with the heat exchanger, which is connected to the ocean water for the heat dissipation. In heating dominated coastal regions, the evaporator of the heat pump can be connected with the heat exchanger, which is connected to the ocean water for heat source.

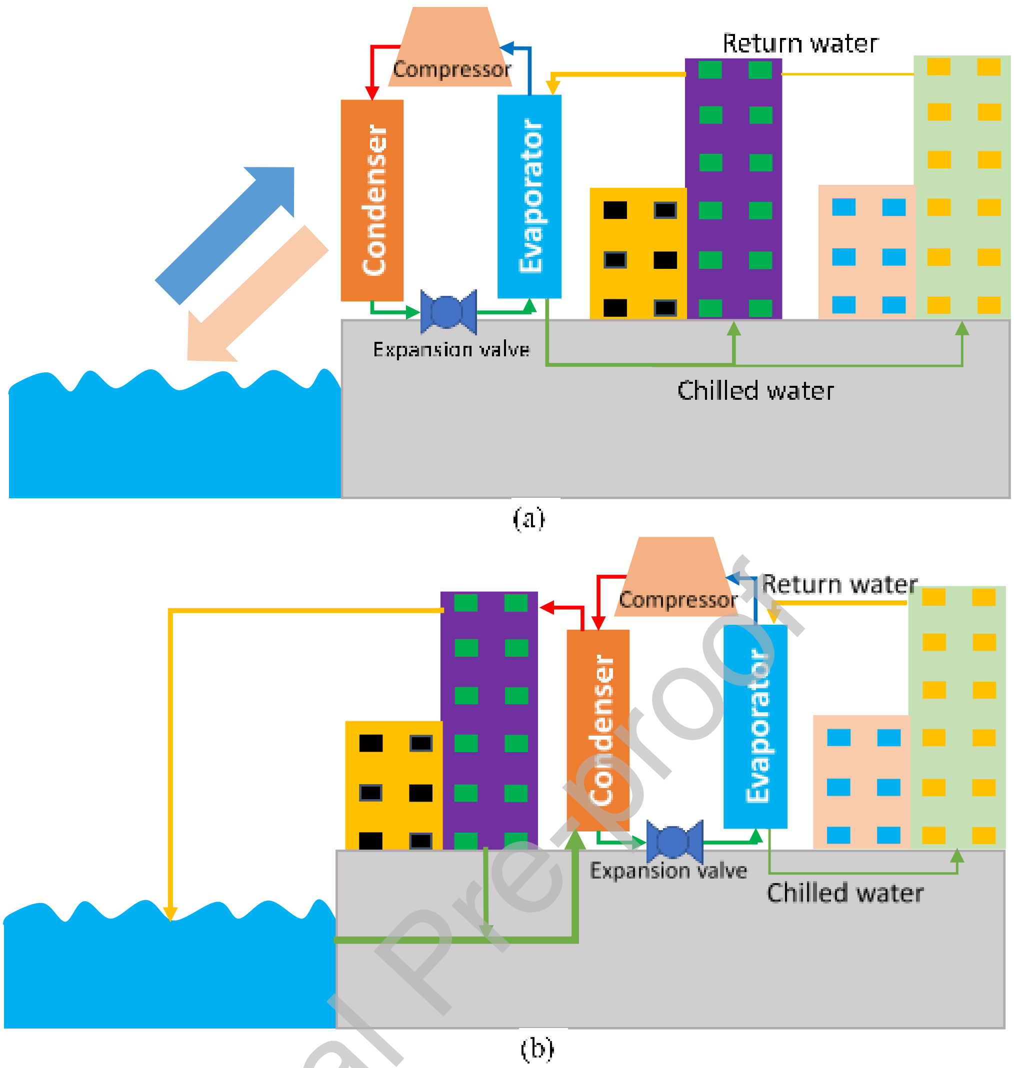


Fig. 16. Diagram of the sea-sourced district cooling and heating systems: (a) sea-sourced cooling system; (b) sea-sourced cooling and heating system.

Fig. 16 demonstrates the working mechanism of the sea-sourced district cooling and heating systems. Fig. 16(a) shows the sea-sourced chiller for cooling applications. Instead of releasing the exhaust heat to the surrounding environment, the exhaust heat in the condenser will be cooled down by the sea water. Depending on multi-diversified types of building energy demands (such as the cooling, heating and electric demands), Fig. 16(b) shows the sea-sourced heat pump. In subtropical regions, the cooling energy demand is normally much higher than the heating demand. The main function of the sea is to realise the dynamic energy balance of the system. The heat released from the condenser is partially applied to cover heating demands of buildings (such as the domestic hot water and space heating), and the rest heat is released to the sea.

In addition to thermal energy supply, the ocean thermal energy can be converted into electricity through the Organic Ranking Cycle (ORC) [107]. Dincer and Hasan [108] studied the ocean thermal energy conversion (OTEC) system for district cooling, ammonia and power production, as shown in

Fig. 17. The ocean surface warm water passes through the evaporator to generate the high-pressure vapor, which will flow through the expander for power output with the release of the high pressure. The deep cold seawater passes through the condenser first and then to the district cooling coil to support the cooling load, before returning back to the sea.

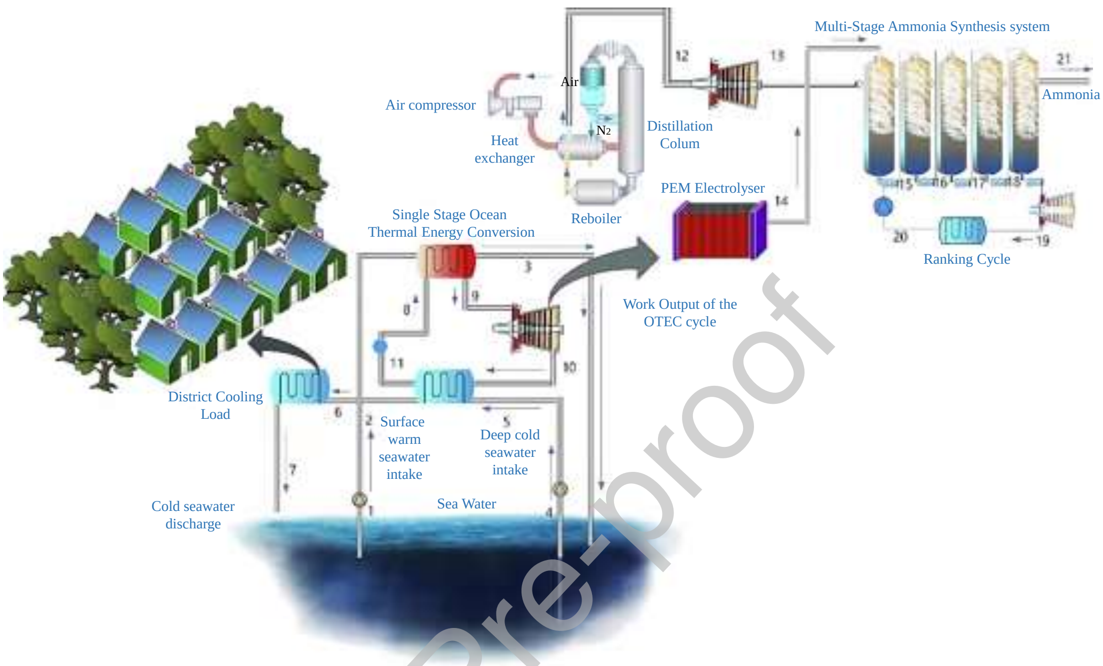


Fig. 17. Schematic diagram of a single stage OTEC cycle with a district cooling and ammonia production [108].

7.2. Functionality of ocean electrical energy for coastal residential community and power grid

The ocean power energy systems can support the coastal residential community and power grid. Wilberforce et al. [109] reviewed ocean power technologies with grid and power transmission and losses. Beatty et al. [110] studied the power supply from wave energy converter to support the community electric demand of a remote Alaskan island, and quantified the capacity as 100 kW. Ahmed et al. [111] studied advanced power electronics for ocean energy integration in the power grid. The ocean energy integration can reduce the power output fluctuations and improve the power efficiency. From the perspective of the power sources, Pearre et al. [112] studied the optimal combination of hybrid renewable systems (i.e., wind, solar and tidal stream generator), for the optimal grid integration, with respect to energy, power and ramp rate. The optimal capacity is identified as 61% wind, 27% solar, and 12% in-stream tidal. In order to reduce the power fluctuation from ocean wave energy converter, Parwal et al. [113] designed energy storages (battery and supercapacitors) and smart dynamic controls, to provide stable and smooth power integrations with grid. Nezhad et al. [114] assessed the technical and environmental performances of wave energy converters in an off-grid system. Robertson et al. [115] comparatively studied the technical performance among hydro, solar and wave energy systems. The wave energy will provide economic benefits and reduce the diesel consumption by 40%.

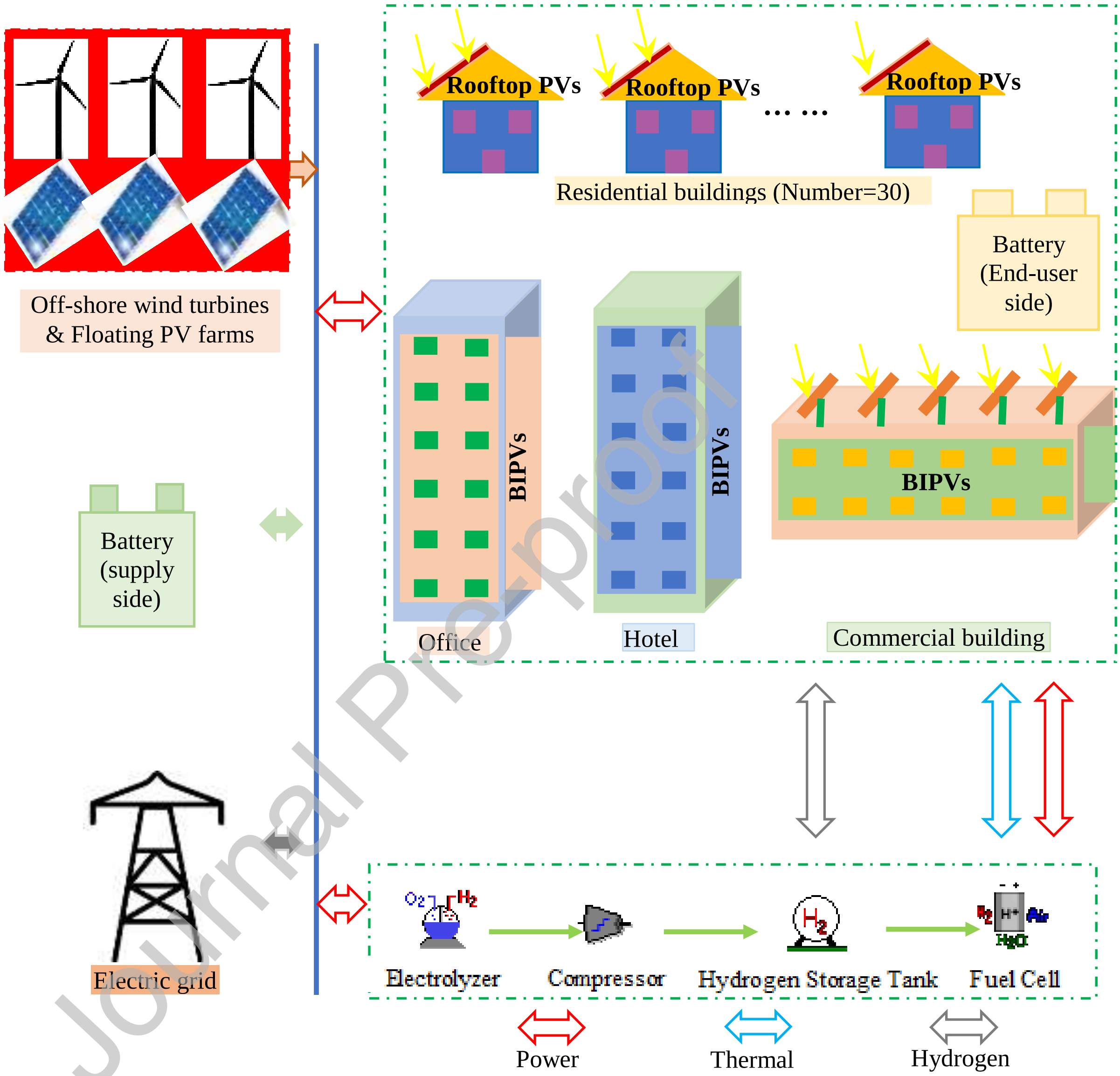


Fig. 18. Schematic diagram of a sustainable community with off-shore wind turbine, floating PV and power-to-hydrogen conversion.

Fig. 18 demonstrates an integrated sustainable community with off-shore solar-wind energy systems and power-to-hydrogen conversion. Renewable power can be either used to cover electric demands or converted into hydrogen through the electrolysis process. The produced H_2 can be original fuels and the waste heat from fuel cells can be recovered for heating. However, the power-to-hydrogen and hydrogen -to-power conversions are with low efficiency at around 80% and 50% [116], respectively. Compared to the direct power utilisation, advantages of power-to-hydrogen conversion include spatiotemporal power shifting and clean by-product water.

7.3. Energy management and control strategies

Energy management [117] and optimization [11] have been studied on offshore wind and marine current energy systems. Furthermore, the ultracapacitors can prevent the deep discharge of batteries, and the required power can be shifted for the continuous load demand coverage, over the hybrid energy storage system. Nazari-Heris et al. [118] studied the collaborative operation of the multi-carrier energy networks, consisting of gas-fired power plants, heat buffer tank storage, gas storage and wind turbines. Results indicated that, the interconnections among different energy carriers can minimize operation cost. An energy management controller [119] on wave energy converters can stablise the power supply to the utility grid. Sheng et al. [12] studied the power dispatch strategy for a tidal turbine farm and an ocean compressed air storage. The proposed system can decrease the fossil fuel consumption and CO_2 emission. Garrido et al. [120] applied a sensorless control in an Oscillating Water Column. Results showed that the control can improve the power extraction and overall system performance. In order to smooth the power production from wave energy converter, Kovaltchouk et al. [121] comparatively studied the centralized and decentralized controls, and indicated that the centralized control showed a smaller capacity, but higher cables losses.

In order to achieve the optimal design and smart control, Li et al. [13] optimized installation capacity and operation strategy on offshore wind energy systems, and reduce the annual total cost by around 35%, and carbon emissions by around 75%. Mohanty et al. [122] applied genetic algorithm and particle swarm optimisation algorithm to stabilize the output voltage of a hybrid wind-diesel-tidal system. The optimal STATCOM controller can improve the power stability and reactive power compensation of the hybrid system. Topper et al. [123] developed a DTOcean software tool to quantify the variability of ocean energy systems. The simulation platform can provide strategies for power reliability improvement and reduce the levelised cost of energy.

8. Application of artificial intelligence in sustainable ocean energy systems

The rapid development of machine learning techniques promotes the intelligence of ocean energy systems. Fig. 19 summaries the application of artificial intelligence in ocean energy, in respect to performance prediction, uncertainty analysis and optimisation. In order to process the historical database, Masoumi [124] applied unsupervised machine learning for data classification, following the wave height, wave period, and wind speed features. Bento et al. [125] applied a Deep Neural Network for short-term wave energy prediction, and the prediction results are more accurate than statistical and physics-based approaches. Ali et al. [126] predicted peak wave energy period based on advanced extreme learning machines (ELM) and deep learning models. Results showed that, the ELM is accurate in forecasting peak wave energy period.

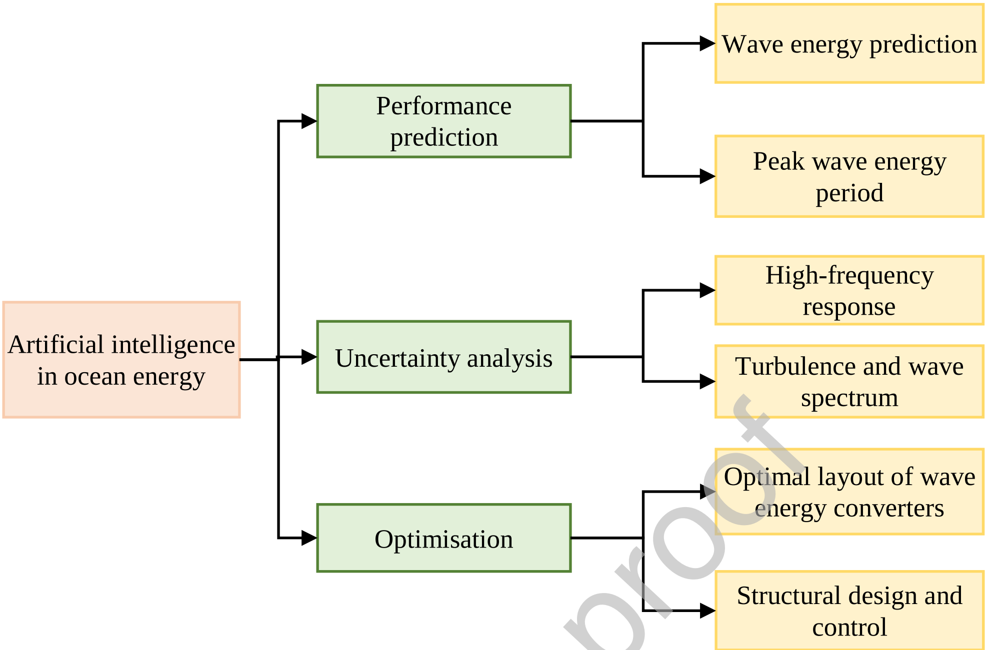


Fig. 19. A summary of artificial intelligence in ocean energy.

Nowadays, with the rapid development of artificial intelligence (AI) and robotics, ocean energy exploitation with bio-inspired intelligence has been widely studied. Generally, studies are mainly on performance prediction, uncertainty analysis and structural optimization. In terms of AI-based performance prediction, Mitchell et al. [127] reviewed AI in offshore wind energy systems and identified symbiotic digital architecture on offshore wind farms. Avila et al. [128] predicted wave energy potentials with AI. Research results can significantly reduce onsite measuring costs for long-term resource predictions based on database from limited buoys. Li et al. [129] applied feedforward artificial neural networks to establish straightforward mathematical associations between free surface elevation and future wave force. Research can provide an advanced control for enhancing power capture efficiency. Lee and He [130] reviewed the historical evolution of AI in wind power innovation, highlight the significance in wind energy prediction and wind farm optimisation. Kagemoto et al. [131] predicted both actual and numerically reproduced irregular wave trains with AI, using recurrent neural networks. Based on iterative calculations through dynamic learning processes, nonlinearity of the training data can be captured and accurate predictions on motion responses can be achieved. In terms of freak waves, Kagemoto et al. [132] explored AI-assisted prediction approach to accurately analyse frequencies and amplitudes of freak-like waves. Results indicated that, the peak heights of prediction results are slightly lower than actual heights.

In terms of parametrical and uncertainty analysis, under the impact of turbulence and wave spectrum, Jiang et al. [133] developed AI models to provide qualitative analysis on the thrust force and concluded that high-frequency response is dependent on wave change, and low-frequency response is dependent on wind change. Li et al. [134] applied neural networks trained by machine learning algorithms to control the wave energy converter, together with sensitivity and uncertainty analysis. Results showed that the phase deviation will lead to the decrease in energy absorption.

Regarding optimization, Teixeira-Duarte et al. [135] comprehensively reviewed optimal layout of wave energy converters, including analytical, semi-analytical and computational intelligence methods. Based on the applied different approaches, computational costs and reliability can be achieved. Cuadra et al. [136] reviewed applications of computational intelligence in wave energy, in terms of resource estimation, structural design and control. Li et al. [137] applied deep learning to maximise the power supply of wave energy converter.

9. Challenges and future trends of integrated ocean energy systems and storages in community seashore residential zero-energy communities

9.1. Technical challenges for hurricane and typhoon

However, the above-sea energy systems, such as the floating PV panels and wind turbines, will be destroyed under extreme weather conditions, such as hurricane and typhoon. Researchers mainly focused on working mechanisms [138], power performance, stability of structural foundation [140], and safety measures [141] on off-shore wind turbines under extreme weather conditions. Wang et al. [138] studied the working mechanisms of typhoon-induced vibration of wind turbine systems during different travelling stages of typhoon. Results can make preparations for anti-typhoon safety measures with respect to multi-stage typhoon effects. Nowadays, with the rapid development of artificial intelligence, smart controls on wind turbines have been developed, for the maximum power generation and operational reliability under large wind speed, such as passive stall control and active pitch control strategies. When wind speed is high, in the stall regulated wind turbines, the designed blades fully utilise the rotational speed or the aerodynamic torque to decrease the power production. In the pitch control, a blade pitch mechanism will be received and the rotor blade immediately pitches (turns) slightly out of the wind. By adopting the ANN-based active pitch control to control the pitch angle, overloading or outage of the wind turbine can be avoided, when the wind speed is high [141]. The controlling mechanism is that, multi-layer perceptions with backpropagation learning algorithm in radial basis function network are adopted for pitch angle controllers.

9.2. Challenges, expensive initial, maintenance cost and chemical corrosion on deep ocean energy systems: metering and remote sensing

In order to analysis the dynamic thermal and electrical performance of ocean energy systems, smart metering and remote sensing technologies are required, whereas great challenges are imposed, such as expensive costs (initial, maintenance and replacement costs), corrosion of sensors, testing accuracy and uncertainty under high-pressure condition, and etc. Smart metering and remote sensing technologies need to be developed and applied in deep ocean energy systems. Furthermore, autonomous wireless sensors [142] to collect the real-time data and information, communication and technology (ICT) need to be developed for the smart energy internet.

9.3. Intermittent and unpredictable ocean energy sources

Due to the intermittency of different ocean energy resources, such as daily solar and wind energy, wave energy and periodic tidal current energy, challenges are proposed for ocean energy utilization, such as mismatch between power supply and demand and power fluctuation on electric grid. Compared to the spatiotemporal fluctuation of solar and wind energy resources, the periodic tidal current energy is less variable from longer time horizons. Driven by ocean thermal energy, and temperature difference between sea surface and deep-sea layer, ocean power generation based on ORC is dependent on solar energy and specific heat capacity of sea water. Furthermore, the tidal energy is relatively stable, due to the gravity effect.

Accurate performance prediction and smart energy dispatch strategies are critical, for high energy matching and stable grid operation. Advanced performance prediction tools include mathematical models [143] and data-driven models [144]. Compared to mathematical models with complicated modeling and computational processes, the data-driven models are more simplified and computational efficient, but with a huge amount of database for training, testing and cross-validation. In addition, demand-side management in district community to adjust the demand profiles, in accordance with the ocean power supply profiles, is effective to improve the energy matching with reduced import/export pressure on the power grid. Demand-side management strategies include battery and pumped hydro energy storages [145], smart appliances [146], adjustable HVAC systems [106], and so on.

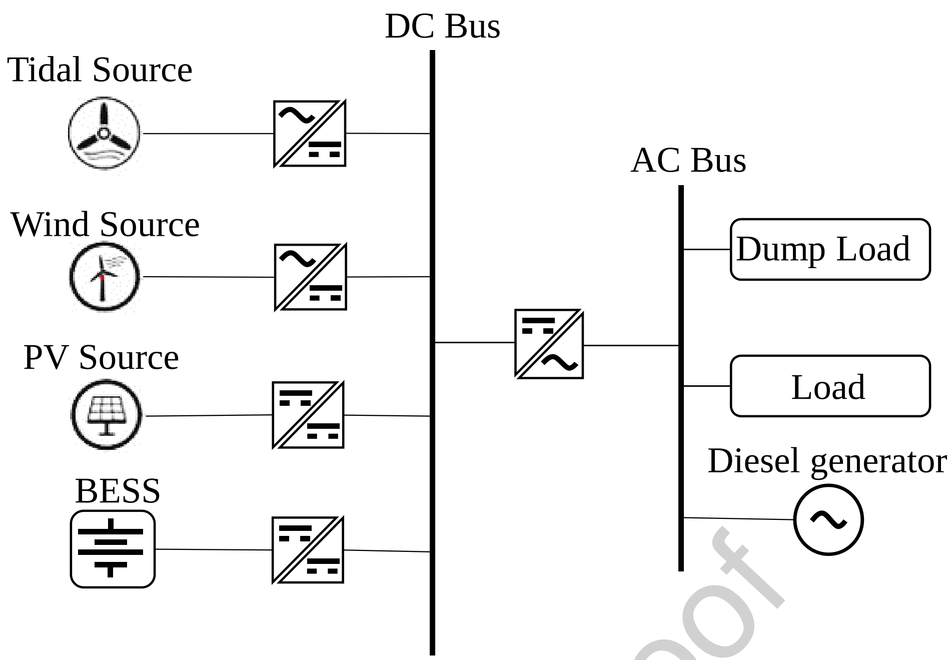
9.4. Efficiency improvement and operational unreliability with faults

In order to ensure the high efficiency of ocean energy systems with high operational reliability, researchers are mainly focused on optimal parameter design [147], synergistic system integration [71] and reliable operation with fault detection [139][148]. Sun et al. [147] conducted the structural optimization on a wave energy converter (WEC) to maximize the power efficiency. Based on the developed mathematical model, effective strategies include the increase of the buoys spacing, the vertical buoys and the staggered lengths of buoy actuating arms. Hu et al. [71] studied the optimal parameter design on a WEC to maximize ocean energy through synergies. A larger diameter to draft ratio can improve the wave power efficiency. Furthermore, the integration of WEC can reduce the maximum horizontal force and pitch moment on the wind turbine platform. Furthermore, fault detection techniques for reliable system operation have also been explored.

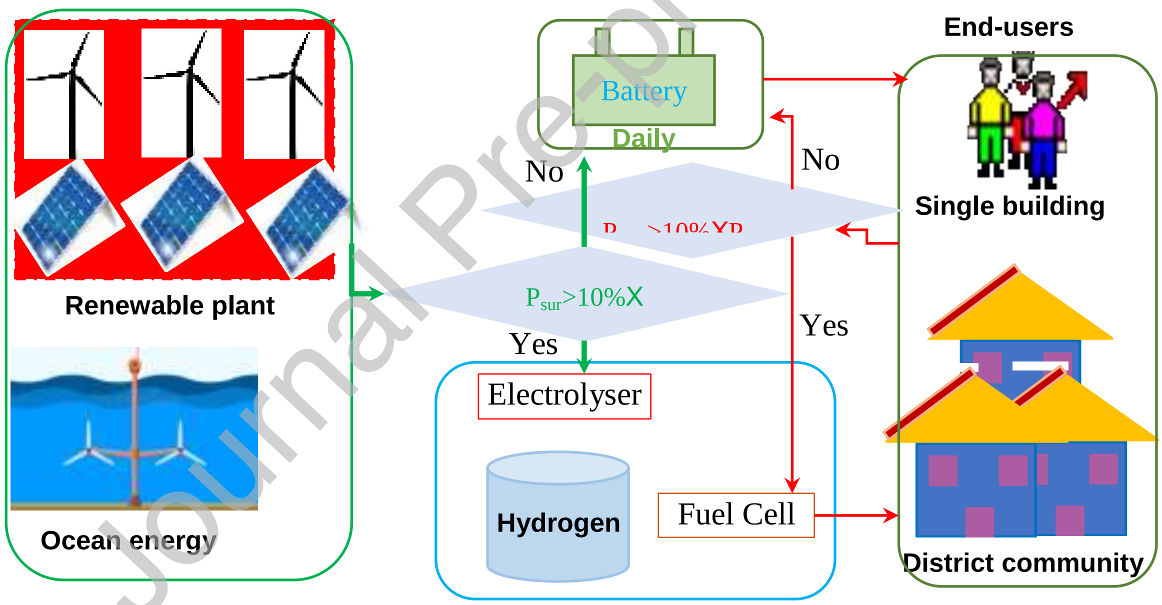
Li et al. [139] designed Bayesian Networks for reliability analysis on and offshore wind turbine, with the identification of failure probability, failure rate, mean time to failure. Research results can provide recommendations on corrective and preventive operations on wind turbine systems. Xie et al. [148] systematically reviewed current turbine blade faults and associated detection technologies. They concluded that, the built-in sensor-based methods are superior for blade fault detection.

9.5. Synergies on solar-wind-ocean energy sharing networks with hybrid energy storages

The complementary between hybrid renewable sources can effectively overcome the spatiotemporal intermittency of renewable energy supply. Multi-energy complementary energy systems with ocean energy have been studied, with a series of advantages, such as high renewable penetration [149], stable power supply [150] and mitigated pressure on grid integration, as shown in Fig. 20(a). Furthermore, synergistic functions provided by hybrid energy storages with different power supply characteristics can further improve the energy storage efficiency. For instance, as shown in Fig. 20(b), considering the idling power of electrolyser and fuel cell (normally 10% of the rated power), the integration of an electrochemical battery for the absorption of low surplus renewable energy (lower than the idling power of the electrolyser) and the coverage of the low district demand (lower than the idling power of the fuel cell), will simultaneously reduce the dumped power, increase the renewable penetration in hybrid storages, and improve the load coverage.



(a)



(b)

Fig. 20. (a) Isolated microgrid with complementary renewable energy sources [150]; (b) complementation and synergy of hydrogen and other integrated systems for daily and seasonal storages in district community.

10. Conclusions

In this study, a comprehensive literature review on ocean energy systems has been conducted, in terms of energy conversions, hybrid ocean energy storages, energy supply network, together with advanced energy management and control strategies. Underlying mechanisms for advanced ocean energy conversions are investigated, with classifications on ocean thermal (such as direct heat exchanger and sea-source heat pump) and electrical energy conversions (such as current turbine, wave energy convertors, tidal stream generator, floating PV panels, off-shore wind turbines and ocean thermo-electric generators). Power supply characteristics from multi-diversified ocean energy resources are identified as intermittency, fluctuation and spatiotemporal uneven distribution, leading to great pressure on local microgrid. In order to mitigate the grid pressure due to the ocean energy integration, hybrid ocean energy storages with synergies are reviewed, including pumped hydroelectric energy storage, ocean compressed air energy storage and ocean hydrogen-based storage, in respect to different response time-duration and provision of grid ancillary services. Ocean energy networks have been formulated, including ocean energy sources, power transmission and distribution, end-user side services. Last but not the least, applications of diversified ocean energy systems for coastal residential communities are reviewed, with energy management and controls, collaboration on multi-carrier energy networks. Challenges and future trends of integrated ocean energy systems in community seashore residential zero-energy communities are proposed. Key conclusions are summarized below:

1) Due to the characteristics of different energy sources, complementary hybrid renewable system integrations can overcome the intermittency and improve the power supply reliability. Depending on the spatiotemporal power supply characteristics, hybrid solar-wind-ocean energy supply systems can enhance the power supply reliability with reduced power fluctuation on the electric grid.
2) Electrical energy storages in coastal regions mainly include pumped hydroelectric energy storage, ocean compressed air energy storage and ocean hydrogen storage. The pumped hydroelectric and electrochemical battery storages show the highest efficiency, nut with relatively high cost and long payback time. Ocean compressed air energy storage can avoid the reliance on favourable geography, whereas the practical application is restrained by fossil fuel combustion, carbon emission and safety issues. Furthermore, the ocean hydrogen-based storage shows high energy density and clean byproduct water, whereas the main disadvantages include the low efficiency at around 45% and safety issues.
3) The integration of multi-diversified ocean energy sources requires the upgrade of existing grid networks and substantial investments in the regional transmission line network. Depending on the geographical location, flexible on-shore and off-shore installation of transformers can provide

large-scale ocean energy system integrations for long-distance transmission, with low transmission losses, low resistive losses and simple system configuration.

4) Collaboration on multi-carrier energy networks and grid ancillary services can provide more opportunities and flexibilities for the integration of ocean energy systems. Advanced energy management and control strategies are necessary, in respect to minimizing power loss, voltage fluctuation, controlling the charge/discharge status of storages, and so on. Artificial intelligence-based model predictive controls in nonlinear systems are critical for system reliability, robustness and flexibility.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: