

Technological feasibility and challenges of hybrids: wave, hydro, offshore-wind and floating solar energy harnessing



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Abstract Approaches to harnessing energy from renewable sources, such as wind, water, oceanic waves, and solar, are garnering heightened attention. Although these technologies are often discussed in isolation, the hybrid approach holds great promise and represents a revolutionary advancement in energy generation. Integrated energy systems of this nature not only facilitate zero-emission power generation but also foster synergies among different approaches, ultimately enhancing power generation efficiency. In this paper, we provide a comprehensive overview of renewable energy technologies, encompassing wind, hydro, oceanic wave, and floating solar energy systems. We delve into both the advantages and disadvantages of floating photovoltaic (PV) technology, as well as the intricacies of integrated offshore wind and wave technology.

Keywords: energy, renewable, ocean, zero emission

1. Introduction

Sustainable energy technologies are key to economic prosperity and environmental quality worldwide. Over the past decades, there have been major developments in harnessing renewable energy. Hybrid renewable technologies that combine distinct sources may help increase the overall potential of renewables by forming synergies. These synergies include effective space utilization, cost sharing, multiple functionalities and uninterrupted operation. As such, the widespread floating offshore platforms help create ground space on the ocean for various uses, such as the erection of airways, aquaculture, seaports and residential areas. A floating PV-based power unit can be employed not only in an ocean but also in a large hydroelectric power reservoir. On the other hand, these hybrid energy systems feature few technical difficulties and may induce environmental impacts. Evaluation of each technology should consider both the benefits and costs they bring.

Our analysis suggests that the benefits associated with such integrated systems (along with the prime benefit of power generation) may help mitigate land-power conflicts, reduce land possession/site developmental costs, enhance PV performance due to regulated temperature over the water surface, diminish the growth of algae, control water surface evaporation losses, decrease shading losses in offshore systems and reduce capital expenses when floating PV systems are integrated with other renewable power generators. Such collocated systems may enhance the use of existing power transmission infrastructure due to additional power generation capability. The intermittent power generation of solar power systems would be effectively compensated by other power source alternatives, e.g., ocean waves, hydro and wind power. Additionally, the impacts of one renewable resource on power generation by another resource, e.g., the impact of wave power on offshore wind power, are also discussed. A review of turbine designs that could be employed to extract energy from offshore wind as well as hydroenergy is also presented.

2. Technologies

In the present section, we discuss the benefits associated with floating PV technology (FPV), the limitations or drawbacks of conventional PV technology, and the classification of offshore renewable systems (wind cum oceanic wave turbines). We present benefits associated with integrated wind and offshore wave power systems, practical feasibility of such systems, schematics of probable arrangements of such integrated systems, and the challenges being faced while erecting these energy systems offshore.



2.1. Floating PV Technology

2.1.1. Overview

The floating type of photovoltaics comprises connectors, mooring systems, pontoons, cabling structures and photovoltaics. This technology is a ground saving technology. The floating structures could adapt to water level fluctuations in the ocean. The material used for floating structures is nontoxic and recyclable. It should bear salty as well as alkaline ambience. It should endure temperatures ranging from -60 to 80°C. The structural materials suitable for it are high-density polyethylene, which is durable, reliable and cost effective. The very first floating PV power generating system was established by SPG Solar on a pond at Far-Niente-Winery in California (Krishnaveni, 2016).

The power generation capability of a floating solar power system is approximately 11% of the average capability of a PV system erected on the ground. It has been reported that approximately 40% water loss occurs due to evaporation. Spreading floating PV panels over 30% of the water surface mitigates the evaporation loss by 49% (Yousuf et., 2020). The sequence of installations of floating PV technology is presented in Table 1 as follows.

Table 1 Sequence of installations of FPV.

Sr. No.	Location	Capacity	Year
1	Aichi, Japan	20 kW FPV (Floating PV)	2007
2	California	175 kW	2008
3	Spain	24 kW	2015
4	China	40 MW	2018
5	Yamakura, Japan (Largest)	13.8 MW	2018

The roof-mounted PV plant capacity is restricted to 100 kW. Such a limitation is not present in the case of floating-type PV plants. Before discussing the drawbacks or limitations associated with land-mounted conventional PV technology, the benefits associated with this technology are briefly discussed.

2.1.2. Benefits

Benefits associated with FPV (Cazzaniga and Rosa-clot, 2021):

- 1) It decreases the land usage,
- 2) This type of PV technology checks the greenhouse effect and reduces the albedo effect. In the case of land, the albedo effect is approximately 20-30%, while the PV module reflection is below 5%. PV converts the visible radiation band into IR bands, which diminishes the greenhouse effect.
- 3) PV plants can be integrated or coupled with offshore-hydro and offshore-wind farms, which help increase the combined plant capacity factor.
- 4) Reduction in energy pricing
- 5) Reduction in commissioning and decommissioning prices, since offshore floating PV plants are quite compact compared to land-based PV technology.
- 6) Mitigating water evaporation losses that might occur from the water surface with no floating PV.
- 7) Economic cooling and solar tracking facility
- 8) Environmental benefits are also associated with floating PV technology (Cazzaniga and Rosa-clot, 2021).
- 9) Such systems reduce land usage and enhance electricity generation efficiency compared to land-dependent systems due to effective thermal cooling (Exley et al., 2021).
- 10) Commissioning hydroelectric power generating structures in conjunction with the floating type of PV systems could improve the reliability, and energy efficiency could be optimized. It also alleviates social as well as environmental impacts compared to standalone plants (Exley et al., 2021).
- 11) According to Kjeldstad et al. (2021), the PV structure in contact with water exhibits 5 to 7% enhanced performance compared to air contact structures. The overall heat transfer coefficient in the case of offshore PV in the immediate vicinity of water is estimated to be approximately 70-80 W/m²K. The modules are supposed to mount on the floating film/membrane, establishing thermal contact between the module/panel and the water level. Regarding the thermal management of floating PV systems, the water temperature is also an important parameter. The obstruction caused by the winds blowing over the panels may increase the panel temperatures, which ultimately hampers the performance.
- 12) Floating PV systems erected over water platforms help generate more electrical power than ground- and roof-mounted PV systems. Using this technology, water evaporation loss as well as algae growth could be mitigated, which saves freshwater reservoirs for agricultural produce. The material (highly dense polyethylene) used for FPV structures could be recycled as many times as possible, and it resists UV rays and corrosion. The installations of FPV systems could be executed on reservoirs, seas, dam reservoirs and lakes. These FPV plants reduce CO₂ production and are 16% more

efficient than offshore plants. Reduction of photosynthesis and algae growth leads to better water quality. FPV technology is less prone to dust as well as other pollutant depositions. It saves land for tourism, mining, agriculture and other uses.

Minimum tilt angles for floating PV panels are generally preferred so that a larger surface area can be utilized. It also causes less shading in the case of lesser tilt angles; drifting as well as wind uplifting would be less at reduced tilt angles; and less wind forces reduce the complexity involved in structure building as far as structural stress design is concerned (Gorijan et al., 2021).

Along with all these benefits, FPV technology has some impacts on the environment.

2.1.3. Environmental Impacts

The deployment of offshore floating or marine structures may disturb the marine atmosphere. The lower temperature natural cooling of PV panels may increase the performance of the systems. Additionally, it must bear harsh salty climatic conditions (Hooper et al., 2021).

Regarding the thermal management of this technology, the heat loss from the submerged cables is affected by the growth of algae and other oceanic organisms. Surface fouling (biofouling), corrosion, and colonization over PV panels (Hooper et al., 2021).

Additionally, anchoring, cabling, resuspension of sediments, radiation shading, lack of solar penetration in the ocean depth, and the effects of electronic fields disturb and harm the oceanic flora and aquatic life/organisms.

The deployment of PV structures obstructs the offshore wind velocity and solar radiation reaching the water depths. It perturbs water body processing and functioning (Exley et al., 2021).

2.1.4. Drawbacks:

Below, we list drawbacks associated with ground-mounted PV units, rooftop PV units, canal top PV units, and FPV units on the ocean. Drawbacks associated with ground-mounted PV units include:

- There remains hardly any space for PV plant erection on account of the fast growth of urbanization.
- Solidified structures provide strengths to protect from natural calamities.

Drawbacks associated with Roof top PV units include:

- PV installations on roofs must address many obstacles, such as chimneys, trees, air ducts and satellite antennas.
- The needed designed capacity of the PV system could not be fit over a roof of limited size.
- The limitation of south-facing roofs mitigates the generation capacity.

Drawbacks associated with canal top PV units are the following. The structures mounted on canals are complex in nature. It needs an impracticably long structure. Power loss takes place due to shadows of trees that surround canals for the stability of the ground and to reduce erosion. Covering channels prevent birds as well as marshes. This causes it to be difficult and costly to discharge a small amount of power over longer distances. It also causes security troubles on account of poor fencing over longer distances.

Drawbacks associated with FPV units on the ocean include the following:

- It needs protection from high tides, oceanic waves, storms, and heavy cyclones.
- Consistent exposure to salty ambience reduces the life of metal structures.
- Reduction of sunlight infiltration prevents growth of algae greenery as well as animals in the water.
- The negative temperature values on account of temperature and moisture reduce the electrical conversion efficiency.
- PV panels need to be regularly cleaned from clay deposition.
- It affects fishing as well as other transportation tasks.

2.2. Wind power technology

2.2.1. Overview

To harness wind energy from oceanic winds, the following two types of wind turbines are generally used.

- 1) Retractable blade type wind turbines (Chen et al., 2016). It can handle a wider range of wind velocities. It can also help yield an enhanced wind power coefficient by diameter as well as adjustable velocity features.
- 2) Hemispherical oscillators. For extracting energy efficiently from oscillating offshore waves, hemispherical oscillators are generally used (Chen et al., 2016).

Classifications of offshore wind turbines can be made according to the type of foundation: (1) floating kind offshore wind turbines and (2) bottom fixed offshore wind turbines. The bottom fixed offshore wind turbines comprise monopile, gravity-based and jacket types, as depicted in Figure 1 (Jiang, 2021).

The offshore wind turbines can be of floating type, which can be classified as (i) mooring with spar platform type, mooring with semisubmersible platform type and tension leg-platform type with tendon anchor type, as depicted in Figure 2.

Offshore wind turbines could also be classified according to their restoring mechanisms as hybrid, windfloat, Dutch-trifloater, Asway, Floatgen, flow and Gicon-TLP types.

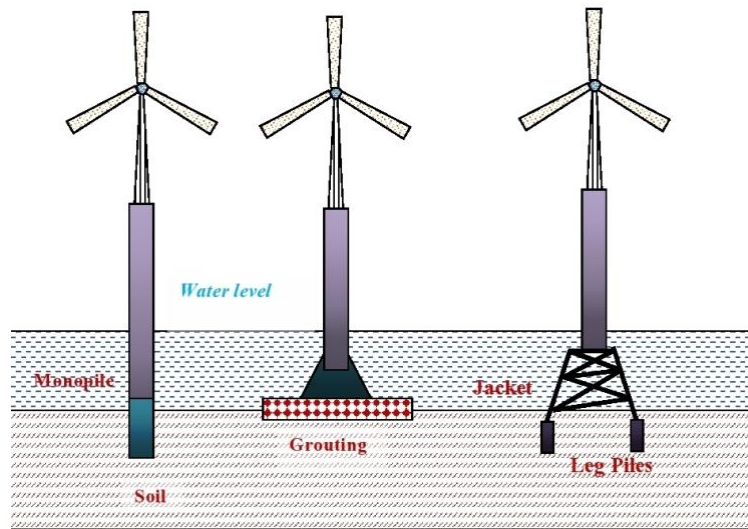


Figure 1 Monopile, gravity base and jacket type wind turbine foundations.

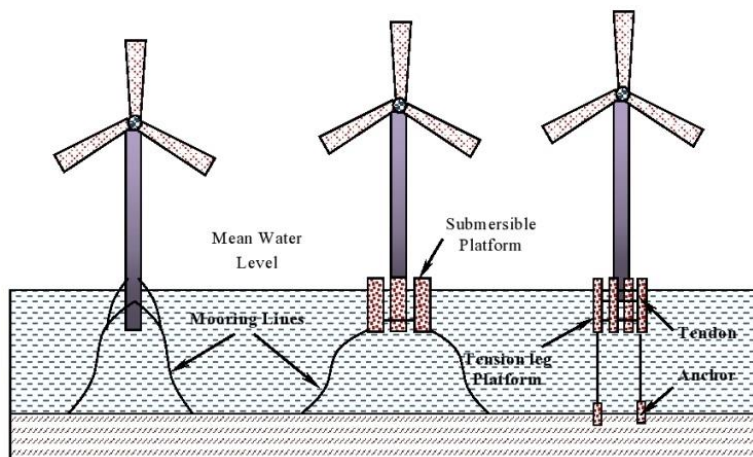


Figure 2 Floating type wind turbine structures.

2.2.2. Integrated wind and offshore waves

Here, plentiful available wind and oceanic wave energy sources are stimulated by solar energy. Floating platforms for wind turbines include (Chen et al., 2016).

- 1) Spar floater,
- 2) Tension leg platform,
- 3) Semisubmersible platform

Conventional wind turbine generators are generally directly driven (quite expensive) and gear train driven. Currently, hydraulically coupled wind turbine generators are used. Such modifications help reduce the weight of the wind turbine structures. It also reduces the installation as well as maintenance expenses. The mechanical power generated by the rotors by extracting energy from the wind as well as offshore waves is converted into hydraulic power. After storing hydraulic energy in the accumulators, it is transformed into electric energy with the assistance of generators or hydraulic motors. The accumulators also help stabilize the oil pressure.

The arrangement of equipment in the case of hydraulically coupled wind and offshore wave power systems is shown in Figure 3. The energy from such integrated power installations can be used for domestic electricity residing near offshore driving mining structures to produce hydrogen, water desalination, etc.

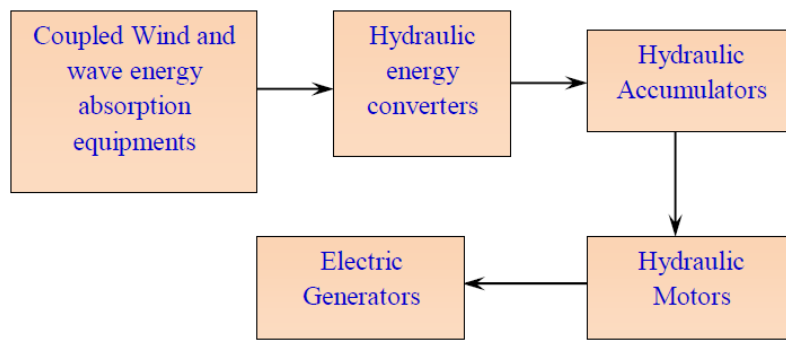


Figure 3 Block diagram of hydraulically coupled offshore wind and wave power unit (Chen et al., 2016).

2.2.3. Offshore wave energy conversion

Wave power is a promising option for renewable power production due to the higher power intensity of oceanic waves relative to the other renewable energy options. These energy generators generally work according to three basic principles: (1) Oscillating offshore column type, (2) Wave-activated oscillating body type structures having a single degree of freedom, and (3) Overtopping conversion type.

The oscillating offshore column type turbine is shown in Figure 4(a). The air compressed due to level fluctuations drives the turbine rotors. The wave-activated oscillating body-type wave energy converters are shown in Figure 4(b). The overtopping type conversion device is shown in Figure 4(c). The energy generated in this case is due to offshore waves overtopping the structures. The returning water then drives the turbines.

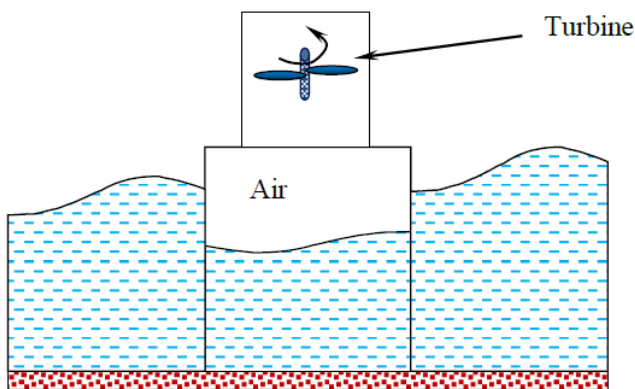


Figure 4(a) Oscillating offshore column type turbine.

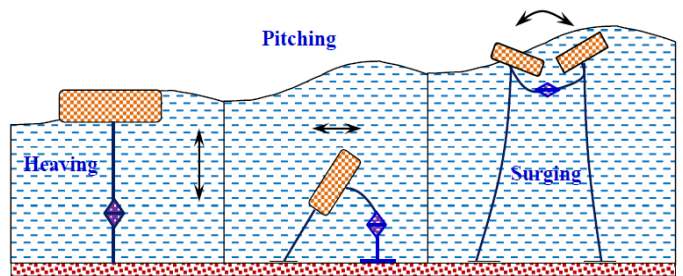


Figure 4(b) Oscillating body type wave energy converters.

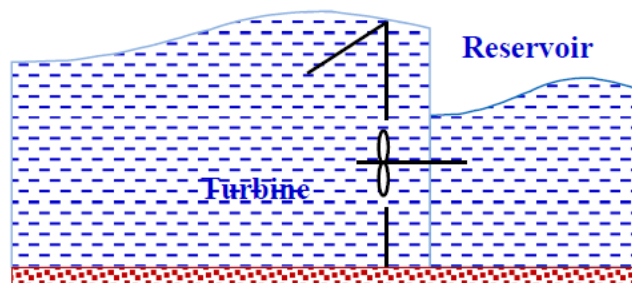


Figure 4(c) Overtopping type rotor.

The coupled wind- and wave-driven generators, acting as one unit, are generally erected on the same offshore stage. The energy potential is estimated to be approximately 8000 to 80000 TWh per year from offshore waves (Leijon and Bostrom, 2018). The mooring system generally applied for wave energy converters is of hybrid type with elastic synthetic ropes (Xu et al., 2019).



2.2.4. Benefits

Below, we list the benefits associated with wave energy.

- 1) The overwhelming feature of offshore waves as a renewable resource is that the energy or power intensity is higher than that in the case of other renewable energy options, e.g., wind and solar power. Intensity values of approximately 2 to 3 kW/m² in the case of wave energy, 0.4 to 0.6 kW/m² with wind and 0.1 to 0.2 kW/m² with solar options have been reported (Nguyen et al., 2020).
- 2) Solar and wind as renewable energy options can produce up to 30% power, while rotors working on wave power can produce up to 90% power (Nguyen et al., 2020).
- 3) To mitigate the cost caused by offshore structure installation, integration with other renewable energy options is suggested. Integration also improves the reliability since additional structures meant for other renewable sources give strength to the wave energy platforms that may bear the strong wave impacts (Nguyen et al., 2020).
- 4) The integration of power systems allows efficient offshore space utilization.
- 5) Improves the hydrodynamic stability of floating platforms since wave energy converters absorb offshore or sea waves.
- 6) It helps provide electricity supply for tasks or operations to be performed on the platforms
- 7) Oceanic waves have the highest power/energy density (Xu et al., 2019).
- 8) Energy loss is almost negligible in the case of oceanic wave travel.
- 9) It is an environmentally friendly resource for power production.

Wave energy structures can be coupled with floating-type wind rotors/turbines, bottom-founded offshore or floating breakwaters, conventional floating-type platforms and ship platforms. Additional floating platforms comprise floating runways, mobile type offshore bases, floating piers, floating bridges, floating ports, floating breakwaters, etc.

2.2.4. Drawbacks

The electricity produced from oceanic waves is estimated to be quite expensive relative to other renewable energy options. This is due to the high costs of foundation, installation, maintenance and consistent operation. Oceanic wave energy converters could continue power production approximately 90% of the time, whereas the energy demand for 20-30% of the time could be met using solar and wind energy options (Mitra and Pawar, 2019).

3. Technical and economic feasibility of the integrated systems

The technical and economic feasibility of the integrated systems are presented herewith in integrated systems such as i) floating PV cum wind power, ii) floating offshore wave energy, and iii) independent wind farm installations.

Golroodbari et al. (2019) computed the best possible combination of offshore wind power and PV capacity for various scenarios. According to them, the best possible floating photovoltaic capacity decreases for increasing costs per wind power. The gain of encouraging subsidies might lead to increased optimum photovoltaic capacities. For such computation, the authors have considered scenarios such as energy price, number of simultaneous hours of operation of both power units, capacity of cabling, degradation of systems and an initial investment. The efficiency of solar PV panels is affected by the shading effect of wind turbines and the degradation of PV material over its lifetime. It is reduced by 0.5% over the year lifetime. In the case of integrated solar cum wind power systems, the power output by solar PV is curtailed by 0-100%, not meeting the requirements of the grid. Executing the economic analysis of such integrated plants, the very prior step is to calculate the cost of energy produced, which is dependent on the market price, grid connection cost, and cost of renewable energy. Finally, lifetime benefits in terms of revenue have also been estimated. According to them, the combination of floating PVs with wind yards is technically and economically beneficial. Adding solar power to transport electrical energy from wind farms increases the usage of offshore electrical cables. The revenue obtained from integrated PV cum wind power farms generally shows dependency on two parameters: minor power delivery by solar PV to the grid and the initial cost of the floating PV system.

An economic feasibility in the case of wave energy converters built on offshore farms was presented by Santos et al. (2020). According to them, the wave energy converters exhibit attractive outcomes in terms of levelized costs of energy, net present value, and rate of revenue returns. The process of estimation involves consideration of factors such as wind parameters for shape and the scale, height and period of oceanic waves, distances from nearby structures and depth of the ocean. Additionally, integrating floating PV and wind farms with wave energy converters (WECs) would reduce investment costs and offer great opportunities for future offshore power generation.

Pakenham et al. (2019) developed financial models for estimating energy output and various costs. The variables used for estimating energy output per year comprise the rated capacity of wind farms, capacity factor and rate of degradation per year. The new installation cost estimation comprises the cost of system per wattage installed, total installed cost, insurance, initial cost of maintenance, increase in maintenance cost per year, other operations costs and repowering costs. The initial installation cost estimation involves the discount rate for present value calculations, interest rate for loan, initial down

payment and decommissioning cost. According to them, technological developments such as an increase in sensors and data capture/storage will help operators of wind farms handle wind turbine issues arising in the future. Current mistakes or economic failures of present generation turbines help enlighten future generation wind farms.

Like other sectors of energy, the renewable sector also has some attackers that might be disadvantageous to the integration of power generation modes. Apart from other risks and shutdowns that are usually involved in integrated power systems at initial stages, such integration will prove beneficial in the future.

4. Hybrid systems

Hybrid power systems comprise floating PV systems combined with hydro, pumping hydro, wave energy converters, solar-tree type, wind turbines offshore, conventional fuel-based units and hydrogen-fueled units (Solomin et al., 2021). The places suggested for such hybrid installations encompass climate suitable for the same, lakes, canals, dams, reservoirs, ponds, etc. It is well known that power generation by means of renewable source-based systems, e.g., floating PV, wind or waves, is intermittent. Therefore, to reduce the effect of variations in these power sources, such as solar and wind, the combination of these renewable source units would be a promising solution. Therefore, to meet the residual energy requirements, the difference between complete demand and power generation by means of renewable sources should be met using fossil-based (gas, oil, coal), renewable (concentrating type solar, biomass, hydro, etc.) sources. or nuclear kind backup production. Therefore, such kinds of integrated power systems are dependent on both weather conditions and on both types of technologies, e.g., renewable or fossil fuel. Zappa and Broek (2018) optimized the spatial distribution of integrated power system capacities with the help of weather data to minimize the residual demand and investigated the various factors on which it depends. The life of integrated PV cum wind turbine-based power units is approximately 25 to 30 years. In the case of wind cum floating PV integrating systems, the residual demand could be reduced by an increased share of wind (i.e., 60% to 90%). The increase in energy storage capability would also help reduce the residual demands. It needs the extension of infrastructure for power distribution and transmission. Integrated PV and wind systems could meet 82% of the demand for electricity. The optimized share in power generation is 74% wind power and 26% solar photovoltaic, which results in 8% additional energy generation from renewable sources. Therefore, it is concluded that floating wind power units have the capability to meet the surplus power demands and convey additional benefits to integrated power systems. Access may therefore be granted to offshore sites with peak wind power capacity factors and credits. The orientations of PV panels considerably influence electricity generation and vary with the location on the Earth. It is suggested to erect PV with different orientations to produce more and in a continuous manner (Zappa and Broek, 2018).

Recent contributions (Eurek et al., 2016) have stated that the wind unit capacity factors show dependency on the overall wind capacity erected on the entire globe. According to the researchers, the deployment of wind units on a large scale would considerably lower the wind velocities beyond the local scale. Offshore, the global wind power potential is reported to be approximately 315 PWhr. Tiernan and Sharman (2016) discussed power production by means of integrated wind and wave waves. They found promising potential in evolving hybrid wave cum offshore wind energy generators, with the possibility of incurring more project installation costs and wind turbine risks. The integrated wave wind power systems comprise a wider range of wave energy converter devices. The oscillating water body type is the most commonly used. Such integrated systems are erected on buoyancy steady platforms. Such integrations sharing common platforms would help reduce offshore structural loading, enhance power generation and improvise levelised energy costs. It streamlines grid connectivity and enables smooth maintenance compared to conventional separate power generation systems. Wave energy generators can be placed close together, whereas wind generators require larger spacing. During lower wind intensities, wave energy generators help smoothen the energy fluctuations. Wave energy converters producing approximately 1 MW (presently 100 to 500 kW) contribute significantly to offshore wind power generators with a capacity of 5 to 10 MW and balance each other. Such integrated systems curb platform movement by dampening wave motion and fulfill local nearby energy needs. It helps reduce the fatigue loading of the platforms by approximately 23%. Such integrations help reduce the surge motion by 16%, pitch motion by 21%, and fatigue stress by approximately 6%. It has been reported that through research inventions and probable innovations, wave energy converters can be clubbed with offshore floating wind energy generators for optimized energy generation at minimal structural loadings.

According to Lopez et al. (2020) compared to the distinctive offshore wind energy yard, a hybrid kind of solar-wind farm is seen to increase the power production and capacity per unit offshore area by multiplying factors of seven and ten, respectively. It is also stated that the energy output is comparatively smooth in nature. According to them, the parameter that quantifies power generation smoothing is found to exceed 63%.

While comparing offshore floating technologies, Lopez et al. (2020) reported that floating PV promotes effective cooling of solar panels that result in 10% more production, and cleaning of panels using available water gives 3-6% enhanced power output. It also helps reduce the growth of algae by shading effects. The authors reported that floating PV systems are less expensive than wind-based floating power units. Integrating floating power units enhances power generation and reduces operation and maintenance costs accordingly. The wind energy density is promising away from offshore, which helps improve the performance of hybrid systems. Combined floating solar and wind power units produce more than offshore wind

power units. Such combinations reduce power variations throughout the day. The only drawback is that the shading caused by wind rotor cum towers may reduce the output of PV units. The power generation density in the case of hybrid solar cum wind farms may reach 57.5 MW/km². The variation in the energy output of such hybrid systems could be reduced by approximately 68% compared to the wind power unit standalone (Solomin et al., 2021). Therefore, by reducing the variation in power generation, the quality and quantity of power production are increased. Clean energy used in power production reduced the pollution in environment (Tirpude et al., 2022).

5. Final considerations

In the present paper, we discuss integrated multitype offshore renewable energy-producing technologies. Such integrated as well as coupled structures could reduce expenditures associated with installation, maintenance, operation and grid connections. However, we emphasize that energy-producing technology of one kind may have destructive and constructive interferences on power production. Holistic and systematic assessment of the technical aspects of evolving and erecting floating-type multipurpose and multitype power-producing structures is the key to realizing their potential. Integrating various offshore energy-producing devices could help meet energy needs more efficiently. The offshore power-producing technologies discussed are still evolving. Challenges/issues associated with this technology include:

- Nonexistence of technical guidelines
- Nonexistence of oceanic body data (water area, surface level fluctuations, local temperature variations, etc.)
- Structural material safety as well as reliability.
- Unavailability of local suppliers of its components
- Oceanic ownership issues
- Floating body transportation
- Operational- and maintenance-related issues
- Affordability of power generation units installed over oceans (It incurs costs 20-40% more than those erected on ground).

Overall, integrating floating-type photovoltaic technology with other renewable resources would improve both economics and power demand-supply dynamics.

Ethical considerations

Not applicable

Conflict of Interest

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

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