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A comprehensive review of floating renewable energy technologies

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ABSTRACT

The growing global demand for clean and reliable power has accelerated the transition from conventional fossil fuels to renewable energy sources. Among emerging solutions, floating renewable energy (FRE) systems have attracted significant attention for their ability to harness solar, wind, and hydropower resources on water surfaces while minimizing land-use conflicts. Despite rapid progress in individual technologies, a unified assessment covering their technical maturity, performance, and environmental impact remains limited. This study provides a comprehensive comparative review of the main FRE technologies floating photovoltaic (FPV), floating offshore wind turbines (FOWT), and floating hydropower, tidal, and wave energy systems. The analysis is based on a critical synthesis of recent research and industrial data, evaluating each technology in terms of efficiency, energy yield, levelized cost of energy (LCOE), technology readiness level (TRL), and operational challenges. The results show that FPV currently represents the most mature and cost-effective option, benefiting from high scalability and minimal environmental disturbance. FOWTs demonstrate strong potential for large-scale deployment but require further optimization in mooring stability and maintenance strategies. Marine-based systems such as tidal and wave energy remain at an early stage, constrained by technological and economic limitations. Overall, the findings highlight that hybrid FRE configurations combining solar, wind, and hydropower components offer the most promising pathway toward stable, high-efficiency, and sustainable offshore power generation. Continued research on advanced materials, system integration, and environmental resilience is essential to enhance the long-term viability of floating renewable systems in future energy transitions.

1. Introduction

In an effort to decrease the use of fossil fuels and the resulting greenhouse gas emissions, global power generation capacity is progressively shifting toward renewable energy sources [1,2].Globally, renewable energy sources have been expanding rapidly in recent years [3,4]. Due to its widespread availability and sustainability, solar energy is regarded as one of the most promising renewable energy alternatives [4,5]. Solar energy is freely and abundantly available throughout the world [6].The new technology known as floating photovoltaic (FPV) has emerged by combining current photovoltaic technologies with flotation systems [5,7]. Over the past decade, there have been significant advancements in the installed capacity of the technology, which was first implemented to counteract land use limitations utilization andreduce

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reliance on traditional energy sources in the agricultural sector [8,9]. According to a World Bank Group report, the installed capacity worldwide is projected to reach 1.1*GWp* by the end of 2018 [10].Although solar PV has historically been deployed on water-deployed and ground- or rooftop-mounted structures, floating solar photovoltaic (FSPV) often referred to as floatovoltaic system have become popular in recent years [11,12]. With an anticipated annual average growth rate of 22 %, the global cumulative FPV capacity more than tripled among the top 70 FPV systems between 2018 and 2019 [13,14].

Since 2007, work on the development and installation of FPV power plants has been underway. In Aichi, Japan, one of the first FPV projects was set up for research purposes, with a capacity of 20*kW* [15].Trapani, K. and M. RedónSantafé [16] examined the FPV projects installed between 2007 to 2013, including a larger-scale plant in California (2008) with a capacity of 175*kW* and a 24*kW* FPV prototype placed in Spain to reduce evaporation. Numerous organizations, including government agencies, are working on projects to increase the number of FPV power plants in Korea. Cazzaniga, R. et al. [17] examined the raft system and FPV systems mounted on water surfaces. Additionally, various designs for floating solar systems have been proposed to improve system efficiency. Specifically, systems with features like tracking, cooling, and concentration have been examined; the findings have shown that tracking and cooling significantly influence on system efficiency. Charles Rajesh Kumar, J. and M. Majid [18] reported that India had a total FSPV capacity of 2.7MW. However, more than 1.7GW of FSPV capacity projects are are currently in various stages of development. By 2022, annual capacity expansion is expected to rise from the 2018 prediction of 1.314GWp to 4.6GWp. Expressions of interest have been invited for the construction of floating solar power plants with a capacity of 10GW in 2017 − 18 and 150GW in 2018 − 19 by Solar Energy Corporation of India Limited. India aims to achieve its renewable energy (RE) target of 175GW to reach 227GW by 2030.

As a case study [19], focuses on the FPV pilot project at the Oostvoornse lake in the Netherlands. For widespread recreational and tourism use, the Oostvoornse Lake presents a unique opportunity to investigate how local stakeholders and recreationists in the lake's immediate vicinity see the installation of FPV. To assess the electrical performance, mechanical stability, and environmental impact of three distinct FPV systems over approximately one year pilot project was formed in the summer of 2020 [7]. The According to the European Commission's Energy Report, photovoltaic (PV) stations, onshore wind turbines, hydroelectric power plants, and offshore wind turbines will collectively generate about 85% of the world's electricity between now and 2050, making up roughly 50% of global energy [20]. Furthermore, these resources will continue to advance in response to the growing demand for energy [21]. For example, by the end of 2021, the overall capacity of renewable energy is projected to grow by −11% to about 3146*GW*. About 90% of all renewable energy sources are derived from solar and wind turbine electricity.

As shown in Fig. 1, global renewable-energy deployment has increased markedly over the past decade, led by sustained expansion in solar photovoltaic and onshore wind technologies. In recent years, offshore wind capacity has grown more rapidly, supported by declining installation costs, improved turbine designs, and strong national energy policies in coastal regions such as East Asia and Northern Europe. This steady progress reflects a broader transition toward diversified and interconnected renewable-energy systems that utilize both land-based and marine resources. These trends provide the foundation and motivation for the present study, which explores the potential of floating renewable-energy platforms as an integrated approach to sustainable power generation.

1.1. *Latest advancements in floating technologies*

Due to increasingly extreme weather events and widespread flooding, policymakers are beginning to acknowledge that global warming poses a serious threat to life as we know it [8,21]. The window of opportunity to take serious action to stop global warming is rapidly closing [22]. The development of floating offshore wind turbines (FOWT) has intensified in recent years, driven by the urgency and demand for clean renewable energy, and new designs and developments are anticipated to continue [23,24]. However, offshore engineers have faced significant challenges due to the hostile ocean environment and the intricacy of designing and installing FOWT [25].

1.2. *Latest applications in floating technologies*

Rosa-Clot and Cazzaniga claim that the awareness and development of FPV could continue to grow, with FPV systems perhaps accounting for as much as 1.9%(710*TWh*) of all universal power output by 2030 [1]. Both the hybridized FPVS and the stand-alone PV systems depicted in Fig. 2 use panels that are placed on water rather than a rooftop [1]. In addition to generating electricity from renewable sources, FPV is a desirable option because of its anticipated co-benefits beyond the

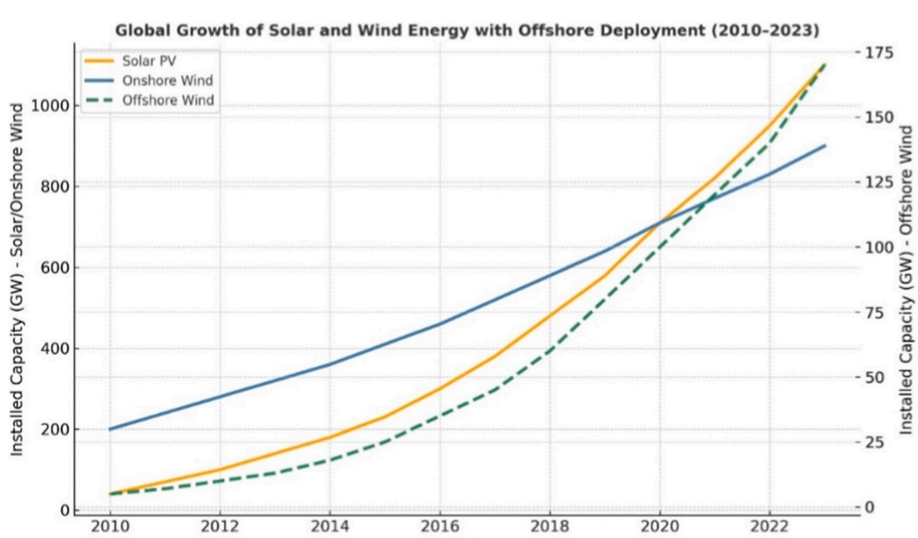


Fig. 1. Global installed capacity of solar PV, onshore wind, and offshore wind (2010–2023). Offshore wind shows rapid post-2018 growth, reflecting rising global investment and technology advancement.

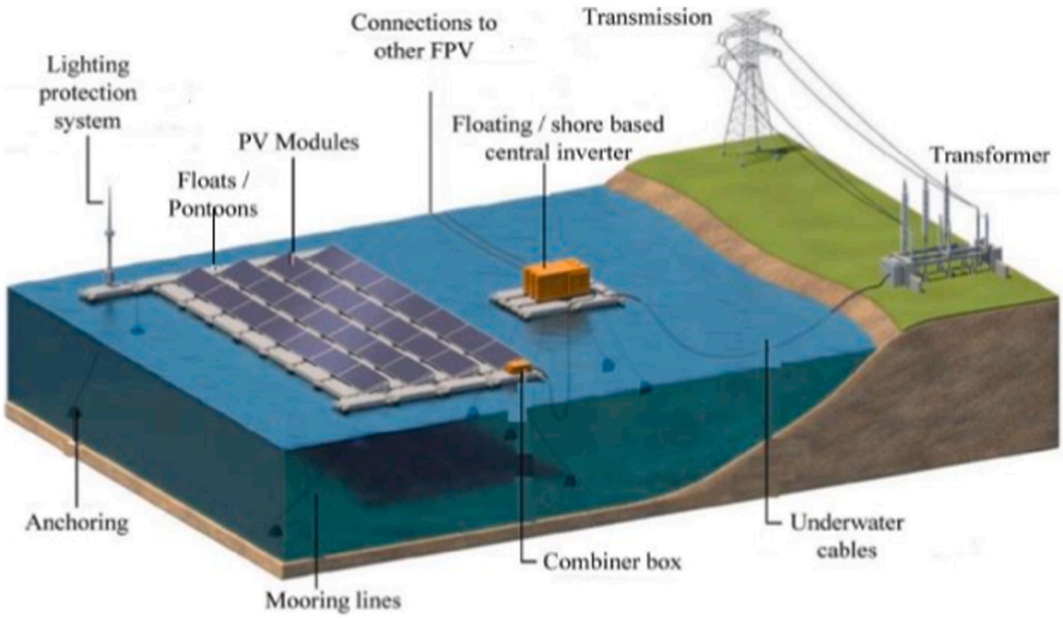


Fig. 2. FPV system [1,26].

production of RE. Anchoring and mooring systems are used to keep the floats in the desired orientation and prevent those from moving. HDPE is known for its high tensile strength, resistance to corrosion, and ability to withstand ultraviolet (UV) rays [27]. PVs were previously installed on utility scales, on the ground, or on building facades and rooftops. However, water bodies also offer significant potential for PV applications, such as FPV power stations [28].

1.3. Challenges in floating technologies

Despite the aforementioned advantages, solar PV technology faces two major obstacles that significantly restrict its widespread adoption [29]. The first obstacle is land use since a $1GWp$ solar PV system requires roughly $15km^2$ of land. Since the PV market is unable to compete with other RES to low incentive rates, the second difficulty is low incentives. To overcome the aforementioned disadvantage in practice, alternative solutions are taken into consideration for solar PVs [30]. One such option that might be regarded as a novel approach for utilizing solar energy is FPV. In nations where land for the installation of land-based photovoltaics (LBPVs) is expensive or rare, FPVs have a greater competitive advantage [31,32]. For FPV systems to be considered as a substitute for land-based PVs, suitable water bodies must be available for installation [33]. The installation cost of FPVs is estimated to be higher than that of conventional PV systems, 100000$/MW, despite the fact that their energy production performance is superior to that of LBPV [34]. Therefore, it is noted that the primary disadvantage of FPV systems is their high cost [35]. According to the Fraunhofer Institute's research on solar energy systems, Germany has approximately 56 GW potential for FPV installation [36].

Furthermore, floating technologies face the following challenges.

- The creation of marine-grade systems and the maximization of existing designs: It is a challenging task to incorporate more robust components that can tolerate the high corrosiveness of salt water as well as forces caused by waves and wind.
- Improving investor confidence or “bankability” by introducing and adhering to a practical set of design and operating standards.
- Evolving the technologies to become cost-competitive with their land-based equivalents to further support cumulative growth [10].

1.4. Research gap

Although FRE systems such as FPV, FOWT, and FHS have gained increasing global attention, the current body of research remains fragmented and technology-specific. Most existing studies focus on individual systems without establishing a unified framework that compares their performance, cost-effectiveness, and environmental implications. Previous reviews have primarily addressed isolated aspects of FRE technologies, such as structural design, mooring configurations, or efficiency improvements, but **lack a comprehensive evaluation** integrating **technical, environmental, and economic perspectives.** Similarly, hybrid floating systems that combine solar, wind, and hydro resources have been only superficially discussed in the literature, leaving significant uncertainty about their feasibility, cost optimization, and long-term durability. Furthermore, there is limited comparative data linking **Technology Readiness Levels (TRLs), Levelized Cost of Energy (LCOE),** and **Operational and Maintenance (O&M)** challenges across different FRE technologies. This **gap prevents policymakers** and engineers from identifying optimal configurations for scalable deployment. Hence, there is a need for a **systematic and analytical review** that consolidates fragmented information, compares key performance indicators across FRE technologies, and evaluates hybrid integration potential. Addressing this research gap forms the foundation of the present study.

1.5. Motivation

The growing global demand for sustainable and low-carbon energy has accelerated research into innovative renewable energy solutions. The extensive land requirements of traditional solar, wind, and hydropower installations often create competition with agriculture, urban expansion, and natural habitats. In many densely populated and water-rich regions, this limitation has become a critical barrier to the large-scale deployment of renewable technologies. The FRE systems comprising FPV, FOWT, and floating hydro-wave-tidal platforms have emerged as a promising solution to these challenges. By utilizing the vast, underused surface areas of lakes, reservoirs, and oceans, FRE technologies provide a sustainable alternative that avoids terrestrial land conflicts while harnessing stronger and more consistent offshore resources. Moreover, the natural cooling effect of water enhances solar module performance, while offshore wind and tidal systems exploit high-energy marine environments for continuous power generation.

Despite their potential, several barriers remain. Current FRE installations face high initial capital costs, limited standardization of mooring and anchoring designs, and concerns regarding durability and ecological impact in marine environments. These issues hinder their transition from pilot projects to commercial maturity. Therefore, a comprehensive assessment of existing technologies, comparative performance, cost competitiveness, and environmental implications is essential to support further innovation and large-scale deployment. The motivation of this study arises from the need to consolidate fragmented research on FRE systems and to provide an integrated understanding of their technical evolution, operational challenges, and economic feasibility. By addressing these aspects, this review aims to guide policymakers, engineers, and researchers toward optimizing hybrid floating systems capable of supporting the global shift toward net-zero energy production. To enhance analytical depth, this review employs a comparative evaluation framework that integrates technical, economic, and environmental indicators. The framework is based on (i) Technology Readiness Level (TRL) for maturity assessment, (ii) Levelized Cost of Energy (LCOE) for economic performance, (iii) Capacity Factor and Efficiency for operational evaluation, and (iv) Environmental Impact Indicators for sustainability assessment. Each technology is critically examined using these parameters to derive cross-comparative conclusions.

1.6. Problem Statement

Floating renewable energy (FRE) technologies are becoming increasingly popular as a sustainable substitute for traditional land-based energy systems as they generate renewable energy by being deployed on water bodies without taking up important land area. These technologies include offshore wind turbines (OWT), floating wave and tidal energy systems, and floating solar photovoltaic (FPV) FPV. Recent developments in FRE have focused on increasing efficiency, integrating advanced technical solutions, and strengthening integration with current electrical networks. Despite their potential, these technologies have several obstacles, including relatively high installation costs, intricate maintenance needs, and environmental issues, namely the disruption of marine habitats. Although continuous research in materials, mooring systems, and hybrid energy solutions is driving the advancement of floating renewable technologies, these obstacles must be overcome before they can be widely adopted. Additionally, by lowering water evaporation, decreasing land use conflicts, and creating chances for collaboration with aquaculture and hydropower, these systems provide a number of environmental advantages. Reliability and energy efficiency could be improved by hybrid floating renewable energy (HFRE) platforms that integrate solar, wind, and wave energy. Notwithstanding their potential, these technologies require advancements in manufacturing techniques, design, and regulatory incentives in order to become more commercially viable. The purpose of this article is to analyze the current state of floating renewable energy technologies (RET) today, their effects on the environment, and their potential for further advancement. It also highlights the necessity of greater research to make them more affordable, resilient, and sustainable so that they may play a part in the worldwide shift to sustainable energy.

1.7. Objectives

The objectives of this review are to provide an in-depth analysis of emerging FRE technologies, such as wave and tidal energy systems, FPV, and OWTs. Particular attention is given to the latest technological developments, including innovations in design, materials, energy efficiency improvements, and strategies for grid integration. The review also highlights the main challenges these technologies face, such as high installation and capital costs, complex maintenance requirements, and potential environmental impacts on marine ecosystems. In addition, the potential of HFRE systems integrating wave, wind, and solar technologies to enhance overall efficiency and reliability is assessed. Finally, the study explores how advances in manufacturing, supportive financial incentives, and appropriate regulatory frameworks could foster the scalability and commercial viability of floating renewable energy platforms.

1.8. Novelty and contribution of the study

Although several studies have discussed individual aspects of FRE technologies such as FPV, FOWT, and floating hydropower systems (FHS), a unified, multi-dimensional analysis of these technologies remains limited. Existing reviews tend to focus narrowly on either technical configurations, economic performance, or environmental implications, often neglecting the interconnection between these domains. The novelty of this work lies in its comprehensive and integrative analytical framework that evaluates FRE systems across technical, economic, environmental, and policy dimensions. Unlike prior compilations, this study emphasizes cross-technology comparisons and hybrid integration potential among FPV, FOWT, and hydropower platforms. It provides a systematic evaluation of their technology readiness levels (TRL), levelized cost of energy (LCOE), dynamic stability, and eco-structural sustainability under marine and freshwater conditions. Moreover, this paper introduces a hybrid floating renewable energy (HFRE) perspective highlighting how combining solar, wind, and hydropower systems can enhance generation reliability, reduce intermittency, and optimize infrastructure use. Through the inclusion of policy, techno-economic, and environmental insights, this study contributes a novel interdisciplinary synthesis aimed at supporting future large-scale deployment and regulatory standardization of FRE technologies.

By providing a thorough and critical examination of FRE systems' present development, technological maturity, and integration potential within current energy infrastructures, this study adds to the expanding body of knowledge on FRE systems. Recent developments in OWT, wave and tidal energy technologies, and FPV are consolidated, and the growing significance of HFRE platforms which combine many energy sources is also highlighted. By weighing the benefits of FRE systems, including land conservation, water resource benefits, and compatibility with other marine uses, against their drawbacks, including as operational, ecological, and economic difficulties, the study offers a balanced viewpoint. Crucially, the study integrates technological, environmental, and economic perspectives to pinpoint critical areas that require additional innovation and policy backing. The study provides insightful advice for scientists, engineers, and legislators aiming to develop and expand the use of sustainable marine-based energy sources through this comprehensive evaluation.

Although several studies have discussed individual floating renewable technologies, most remain limited to descriptive summaries of FPV or offshore wind systems without comparative integration across all FRE categories. The present study contributes novel insights by establishing a comparative analytical framework that evaluates each technology in terms of technological readiness, cost-effectiveness, operational reliability, and environmental sustainability. Furthermore, it identifies synergistic hybrid configurations among FPV, FOWT, and hydropower systems an area that has received limited attention in previous literature.

1.8.1. Organization of the paper

Paper contains nine sections: Section one comprises Introduction and FPV System, while Section two discusses the FPV System. Deeper Critical Comparison Analysis of Floating Renewable Energy Technologies with other Technologies included in sections three. Section four focuses on Offshore Wind Energy Revolutionized by FWT, whereas Sections five and six cover Floating Hydropower Systems (FHS) and Floating Renewable Energy Systems (FRES), respectively. Section seven contains Techno-Economic Cost Assessment of Floating Solar Energy Systems, Battery based Energy Storage Solutions Integrated with FPV and OWT, Levelized Cost of Energy based Cost Estimation Models, Data Sources, Risk and Reliability Modeling is covered. While optimization framework for hybrid floating renewable energy, and conclusion and discussion are presented in sections eight and nine.

2. Floating photovoltaic system

The FPV power generation system is a new concept that has not been commercially implemented, with only a limited number of demonstration projects carried out globally [37,38].

In numerous regions around the globe, there is an adequate number of PV power generation devices globe. There is insufficient land, particularly in Japan, Singapore, South Korea, the Philippines, and numerous other islands. Countries such as Japan, the United States, South Korea, Australia, Brazil, and India have begun to request FPV [39]. This demand could grow and spread globally. FPV solar systems can be installed on water bodies, including oceans, lakes, ponds, reservoirs, irrigation ponds, wastewater treatment facilities, dams, and canals. The amount of electricity generated depends on the solar cell technology and on environmental factors such as solar irradiance, temperature, and shading. The leftover solar radiation is converted into heat, resulting in a rise in PV temperature [40,41].The output power of a solar cell varies with temperature changes. The ease of use of Photovoltaic Module (PVM) is temperature-dependent. Therefore, when a solar PV system is installed on a water surface, the cooling effect of the water lowers the module temperature, which is not fully reflected by measurements of the ambient air temperature alone [42]. Fig. 3 illustrates the configuration of a solar power plant installed on floating structures, highlighting the fundamental design and operational concept of FPV systems. In this arrangement, photovoltaic modules are mounted on buoyant platforms or modular rafts that rest on the water surface; while anchoring and mooring systems ensure stability against wind and wave motion. The proximity of the panels to the water enables effective natural cooling, which lowers the module temperature and enhances energy conversion efficiency compared to conventional land-based installations. This setup also minimizes land-use conflicts and reduces water evaporation from reservoirs by providing surface shading. Overall, the figure demonstrates how floating solar plants combine renewable energy generation with efficient use of aquatic environments, offering a sustainable solution for regions with limited land availability and high energy demand [43].

Floating photovoltaic (FPV) systems are an emerging technology that enables the installation of PV modules on water bodies such as reservoirs, lakes, and ponds [42].This approach provides a viable alternative to land-based PV plants, especially in regions where land availability is limited or valuable for other uses. In addition to generating electricity, FPV installations can reduce water evaporation by shading the reservoir surface [44]. For example, studies in Australia have reported that open

Fig. 3. Solar power plants on floating structures [43].

reservoirs can lose up to 40 % of their water through evaporation, and FPV coverage can significantly mitigate this loss [45]. The performance of FPV systems is primarily determined by the power conversion efficiency of the PV modules the ability to convert incident solar radiation into electrical energy under real operating conditions which directly influences overall energy production [44].

The electrical efficiency of a photovoltaic (PV) module can be expressed as:

$$\eta_{el} = \frac{P_{max}}{G \times A_{PV}} \times 100\% \quad (1)$$

Where.

- η_{el} = Electrical efficiency of the PV module (%)
- P_{max} = Maximum power output of the PV module (W)
- G = Solar irradiance incident on the PV surface (W/m^2)
- A_{PV} = Active surface area of the PV module (m^2)

In this study, P_{max} is determined under Standard Test Conditions (STC), which corresponds to a solar irradiance of 1000 W/m^2, a cell temperature of 25 °C, and an air mass (AM) of 1.5. It is important to note that the actual performance of PV modules varies with irradiance level, ambient temperature, and operating conditions. Therefore, while the above equation provides a reference efficiency under STC, real-world efficiency is typically adjusted using temperature correction factors and performance ratio (PR) parameters to account for environmental variations.

2.1. Benefits of FPV

FPV systems offer multiple benefits, including improved energy yield and efficiency due to the natural cooling effect of water surfaces [46]. An additional advantage is their contribution to water conservation, as the shading effect reduces evaporation losses from reservoirs and other water bodies studies have reported reductions of up to 28 % [47,48]. Beyond these performance and environmental benefits, FPV also enables significant expansion of solar capacity without competing for valuable land resources. Looking ahead, the vast coverage potential of oceans highlights a new frontier for FPV deployment. However, the marine environment poses unique challenges, such as turbulence and strong currents, which demand robust structural solutions. Current research and development efforts, particularly in China and the United Kingdom, are focused on designing FPV systems capable of withstanding these extreme ocean conditions [49].

2.2. FPV applications

A typical FPV system is defined as solar PV arrays installed on the water basin surfaces, such as hydropower plants, freshwater and man-made reservoirs, mining ponds, water treatment facilities, near the coast of seas or oceans, as illustrated in Fig. 4 [28]. Nonetheless, the primary system elements are nearly identical and include cables, mooring systems, floats or pontoons, PV modules, and an inverter [50,51].

For scientific reasons, the first FPV system was set up in Japan in 2007. Subsequently, FPV systems were thought to be constructed for commercial use, and their initial implementations using water reservoirs were noted in the USA [52,53]. According to reports, the first FPV system in the USA had an installed capacity of 175kW. According to recent World Bank estimates, there is a noticeable push for FPV system installation worldwide, particularly in the Far East (China, Japan, and the Republic of Korea), the United States, the United Kingdom, the Netherlands, Norway, Portugal, Spain, Singapore, Turkey, and Vietnam. Using two distinct metrics, such as cumulative and yearly installed capacity (which reached up to 1.3GW and 786MW, respectively), Fig. 5

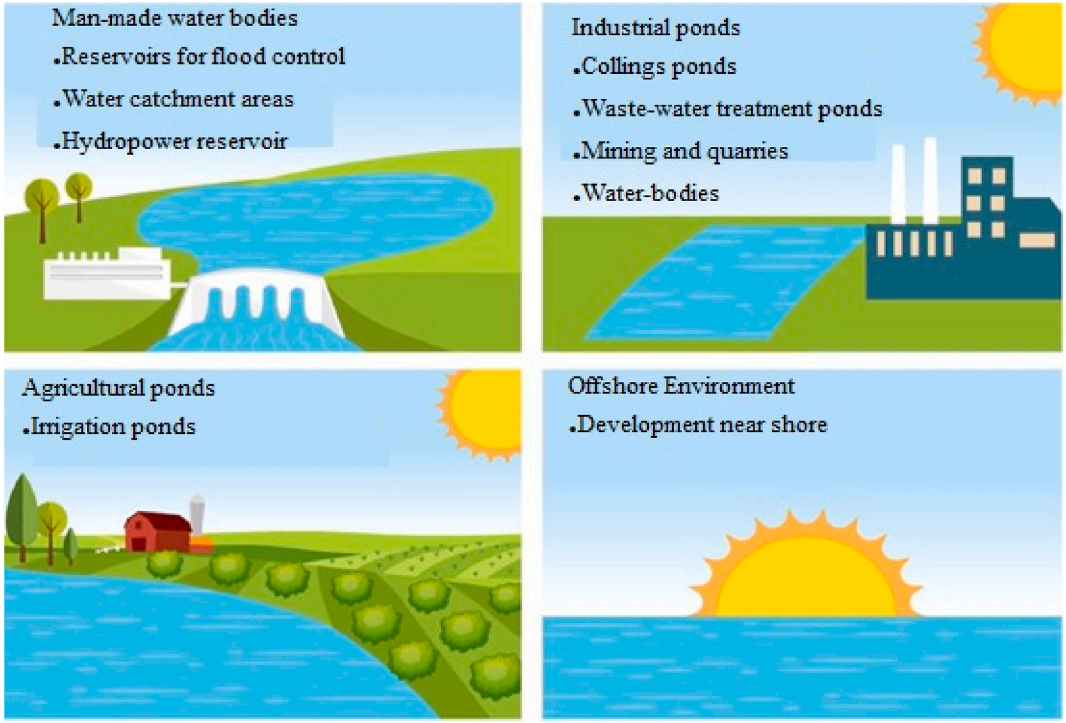


Fig. 4. Diagrammatic representations of uses for FPV [28].

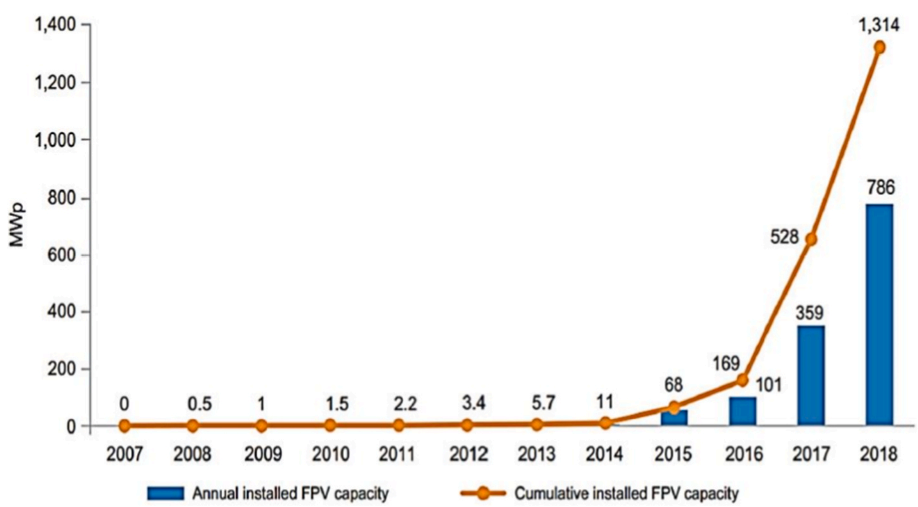


Fig. 5. Globally utilized capacity of FPV technology [28].

shows the growth in FPV installation [28].

2.3. *Floating PV systems installed over fresh water plants*

The deployment of PV panels on freshwater and marine surfaces has been expanding rapidly. At present, most FPV power plants are located on inland water bodies such as lakes, dam reservoirs, irrigation ponds, and former mining lakes. By contrast, large-scale FPV deployment in seawater remains limited due to challenges such as high wind exposure and the corrosive effects of saltwater on system components [54]. To address these issues, flexible thin-film modules capable of floating on wave surfaces have been proposed as a potential solution [55]. An alternative approach is the development of submerged PV systems, where panels are installed below the water surface. This configuration helps maintain lower and more stable operating temperatures, reduces the need for frequent cleaning, and can simplify inverter structures [56]. Fig. 6 illustrates an example of such a submerged PV system [15]. Reported results indicate that, under summer conditions, submerged PV panels can achieve approximately 20 % higher efficiency compared to conventional air-exposed modules [6].

2.3.1. *Saltwater's corrosive characteristics*

Installing renewable energy systems in maritime areas presents a substantial problem because saltwater is a naturally occurring corrosive element. Below is a summary of the main concerns [57].

Water that contains salt is more aggressive in encouraging oxidation and material breakdown, and it also has a high conductivity. For example, iron and steel can rust quickly, and if protective coatings or treatments are not applied, the lifespan of metals exposed to seawater is greatly shortened [58].Dissolved salts, especially sodium chloride

Fig. 6. Photovoltaic system underwater [15].

(NaCl), found in saltwater can hasten metal electrochemical corrosion. When exposed to the electrolytes in seawater, metal parts (such as the turbine's framework, blades, and electrical components) may deteriorate more quickly [59].

Aluminum, stainless steel, and carbon steel are among the metallic components used in the majority of renewable energy systems, including offshore wind turbines and tidal turbines. These metals are vulnerable to pitting, corrosion, and structural collapse in the absence of adequate protection [60].

2.3.2. Higher power output in marine water

Renewable energy sources like OWT and tidal energy can produce more electricity in marine areas than in freshwater ones [61].

Tidal turbines, for instance, capture energy from the flow of water in and out of bays, estuaries, or along coastlines; because seawater is denser than freshwater, tidal turbines in the ocean can produce more energy than their freshwater counterparts would under the same conditions. The power that a turbine can extract from the moving water is directly proportional to the density of the water, meaning that more dense water means more energy per unit of flow [62].The density of seawater is around $1.025 kg/m^3$, which is higher than that of freshwater, which is approximately 1.0 kg/m^3. Seawater has more mass per unit volume due to its higher density. This higher density causes more energy to be transferred from the flowing water to the turbine when energy is generated using tidal or underwater turbines [63].

Tidal currents are a dependable energy source for power generation since they are more predictable and have the potential to be quite strong. Freshwater systems, such as rivers, on the other hand, can have fluctuating flow rates, making them more difficult to rely on for ongoing energy production. More consistent and dependable energy generation is available in marine environments, especially those with significant tidal motions [64].

2.3.3. Rate of degradation per year

The amount of wear and tear that environmental variable, particularly the corrosive effects of seawater, cause on equipment over the course of a year is known as the annual degradation rate. Here's a closer look at this difficulty [65].

A turbine placed in a maritime environment, for example, would only survive 15 to 20 years, whereas a freshwater turbine might endure more than 25 years. Beyond metal components, electronics that are likewise subjected to the severe sea environment, such sensors and controllers, may also deteriorate [66].Components in marine renewable energy plants deteriorate more quickly than those in freshwater systems because saltwater is corrosive. As a result, parts must be serviced or replaced more frequently, raising overall operating expenses [67].

Protective coatings are a popular method for preventing metal surfaces from coming into direct contact with seawater. The longevity of underwater constructions can also be increased by using cathodic protection devices [68].Engineers utilize cutting-edge materials developed for maritime settings, such titanium, stainless steel alloys, or composite materials, to lessen the effects of corrosion. Although these materials are more resilient to harm from saltwater, the initial investment is increased because they are frequently more costly than standard materials [69].

2.3.4. Challenges with maintenance

Saltwater's corrosive properties make more frequent maintenance checks and inspections necessary. Higher maintenance expenses and more equipment downtime are the results of this. Remotely operated vehicles (ROVs), specialist vessels, or divers may be needed for these assessments for offshore assets, which raises the expense and complexity of logistics [70].

2.3.5. Trade-off between energy production and maintenance costs

Because seawater has a higher density than freshwater, marine renewable plants can produce higher power outputs, but the tradeoff is higher maintenance costs and shorter equipment lifespans due to corrosion, which over time can result in a higher total cost of energy production than for freshwater or land-based systems. Therefore, the advantages of higher energy output must be weighed against the continuous costs of equipment replacement and corrosion management [71].

2.4. Life-time and degradation rate based comparing of floating with different RET

To evaluate long-term performance and sustainability, it is essential to take into account the operating lifetime and degradation rates of various FRE sources. Depending on mechanical wear, maintenance needs, and exposure to the environment, different floating energy systems such as FPV, offshore wind, wave energy, and tidal energy have different lifespans and degradation characteristics. With an annual degradation rate of $0.3 - 0.7\%$, FPV systems normally have a $25 - 30$ year operational lifespan. Though they have extra difficulties such moisture exposure, biofouling, and seawater corrosion, these systems are comparable to land-based solar PV [72]. They are a promising option for large-scale renewable energy generation on water bodies because of their very low rate of degradation. Their longevity can be further increased with proper care and the usage of cutting-edge materials [73]. With a deterioration rate of $0.2 - 0.5\%$ annually, OWT typically have a slightly shorter lifespan of $20 - 25$ years. They are subjected to severe marine conditions, such as high winds, corrosion from saltwater and severe weather, all of which exacerbate mechanical wear and material fatigue [60]. But improvements in coatings, maintenance techniques, and turbine design help lessen these impacts and increase operational effectiveness. With an operational lifespan of 15 to 20 years, wave energy systems have one of the highest rates of degradation, ranging from $0.5 - 1\%$ annually [74]. These devices function in extremely dynamic marine conditions where substantial mechanical stress is imposed by constant wave action. Their lifespan is also shortened by corrosion, biofouling, and structural fatigue [60]. Better anchoring methods and materials could increase durability as wave energy technology advances. Tidal energy systems typically last $20 - 30$ years, with deterioration rate of $0.2 - 0.6\%$ annually, making them just as long as or even longer than offshore wind turbines [75]. Compared to wave energy sources, tidal turbines experience less mechanical stress due to predictable tidal movements. They still have problems, though, like silt buildup, marine growth, and wear from saltwater, all of which need to be maintained on a regular basis to remain effective. Table 1 summarizes the key operational parameters and associated maintenance challenges of floating photovoltaic (FPV) systems. With an expected service life of 25–30 years and an annual degradation rate between 0.3 % and 0.7 %, FPV installations exhibit stable long-term performance compared to

Table 1
Operational lifespan, degradation characteristics, and key maintenance challenges of floating photovoltaic (FPV) systems.

Technology	Yearly based Operational Lifetime	Per year-based Degradation Rate	O&M Complexity	Key Challenges	Ref
Wave Energy	15 – 20	0.5 – 1%	Moderate to High	Weather dependence, mechanical fatigue, and the requirement for specialized vessels.	[76]
Tidal Energy	20 – 30	0.2 – 0.6%	High	Marine wear, accessibility issues, and inadequate maintenance procedures.	[77]
Offshore Wind	20 – 25	0.2 – 0.5%	Low	Algal proliferation, deterioration, and restricted access in expansive arrays.	[78]
FPV	25 – 30	0.3 – 0.7%	Low	Despite their long lifespan and low degradation, FPV systems face challenges related to material durability, anchoring stability, electrical safety, and limited regulatory and recycling frameworks, which affect long-term reliability and large-scale deployment.	[17]

land-based systems. However, material durability, anchoring reliability, and electrical safety remain critical issues due to continuous exposure to water, humidity, and UV radiation. Although the overall operation and maintenance (O&M) complexity is low, routine inspections of mooring lines, floats, and cabling are essential to prevent performance losses and structural degradation. These parameters collectively define the reliability, lifecycle cost, and sustainability of FPV technology in large-scale renewable deployments [79].

3. Comparative Analysis of floating renewable energy technologies

The Technology Readiness Level (TRL) scale and the actual deployment status are used in Table 2 to evaluate each technology's maturity. With a TRL of 8–9, FPV has the highest score, suggesting widespread deployment and commercial maturity, especially in Asia and Europe [80]. Its ability to take advantage of the current PV production infrastructure is partly responsible for its quick adoption. Although promising, FOWT technologies are still in the TRL 7–8 range. Hywind Scotland and Floatgen in France are two examples of early commercial initiatives that are currently operational. Prior to widespread rollouts, these systems need more thorough validation. The majority of projects are restricted to pilot arrays, and wave energy is still in the early demonstration phase (TRL 4–6). The table emphasizes the necessity for ongoing R&D support and field testing for wave energy, as well as the maturity difference between FPV and the other two technologies. Table 2 provides a comparative overview of the main FRE technologies in terms of their technological maturity, performance efficiency, and economic viability. Among the listed options, FPV systems exhibit the highest technology readiness level (TRL 8–9) and the LCOE, making them the most commercially viable for near-term deployment. The FOWT offer higher capacity factors but remain limited by high installation and maintenance costs. Marine-based systems such as tidal, wave, and ocean thermal energy conversion (OTEC) technologies demonstrate strong resource potential but are still in early development phases, with relatively high LCOE values. Overall, the comparison emphasizes that while FPV currently leads in cost efficiency and operational simplicity, other FRE technologies present significant long-term potential for complementary, large-scale offshore integration.

Table 3 assesses each technology's social acceptability and environmental impact. Although FPV has minor environmental hazards, such as the potential to disturb aquatic habitats and shade the water's surface, it is widely accepted, especially when used on man-made water bodies like dams and reservoirs. Because of its offshore position, which prevents land-use conflicts, FOWT is generally well-accepted despite having a low to moderate environmental impact, primarily in terms of noise and habitat interaction. Although the impact of wave energy is still mostly unknown, it is anticipated to be low, with little surface disturbance and no emissions; yet, because it is still in its infancy, social acceptance and public awareness are still low. The environmental benefits of all three technologies over fossil fuels are reaffirmed in this Table 3; however, stakeholder involvement and ecological monitoring are necessary for successful implementation, especially for FPV and wave systems.

3.1. *Mooring systems in renewable energy-based floating technologies*

The performance, safety, and survival of floating platforms depend heavily on mooring systems as the deployment of renewable energy moves farther offshore to capture wind, wave, and solar resources across vast sea surfaces [81]. These systems have a direct impact on energy conversion efficiency and operational longevity in addition to ensuring station-keeping and structural stability. Incorporating thorough load analysis and stress testing into mooring system design is crucial because floating renewable platforms like FPV arrays, OWT, and hybrid floating systems are exposed to extremely dynamic and harsh marine

Table 3
Effects on the environment and society.

Social Acceptance	Environmental Impact	Technology
High in offshore environments; steers clear of land-use conflicts.	Minimal to moderate (e.g., impact with marine ecosystem, noise).	FOWT
High, but low awareness.	Minimal (based on a small number of installations).	Wave Energy
High in general, particularly for inland bodies of water.	Moderate (e.g., disturbance of aquatic environment, water shading).	FPV

Table 2
Comparative performance and economic indicators of floating renewable energy (FRE) technologies.

Technology	Technology Readiness Level (TRL)	Typical Capacity Factor (%)	Average Resource Availability	LCOE (USD/MWh)	Key Strengths
FPV	8–9 (Commercially mature)	15–22	High (most regions with stable irradiance and water availability)	40–80	Low O&M cost, cooling effect enhances efficiency, rapid installation
FOWT	7–8 (Pre-commercial to early commercial)	35–50	High in coastal and deep-sea regions	80–140	Access to stronger offshore winds, scalable capacity
Floating Hydrokinetic/ Tidal Systems	5–7 (Demonstration)	30–45	Site-specific (strong tidal flow areas)	120–250	Predictable energy output, low visual impact
OTEC	4–6 (Pilot scale)	10–12	High in tropical deep waters	200–300	Constant baseload energy, minimal intermittency
Floating Wave Energy Converters (WEC)	4–6 (Pilot to early demonstration)	25–40	Moderate (depends on wave height and frequency)	180–280	Abundant resource potential in oceanic zones

environments [82]. The complex and frequently non-linear multidirectional environmental pressures produced by wind, waves, currents, and tidal forces must be taken into consideration in a detailed load study. The coupled reaction of the mooring lines and floating platform should be modeled using time-domain simulations spanning six degrees of freedom (heave, surge, sway, pitch, roll, and yaw) [83]. Depending on their configuration (catenary, taut-leg, or hybrid), the mooring lines undergo snatch loads, tension changes, and different geometric stiffness. Platform motions are influenced by these pressures, which in turn have an impact on solar panel or wind turbine alignment and power generation system efficiency. Excessive pitch or surge, for instance, might cause wind rotor misalignment or lower solar panel output, both of which lower energy yield [84].

The ability of mooring systems to sustain peak loads without yielding or failing must be verified against Ultimate Limit State (ULS) requirements in order to guarantee structural integrity under extreme sea states, such as cyclones or long-period swell conditions [85]. For floating renewable platforms that run continuously for decades, fatigue limit state (FLS) analysis is essential because cyclic loads from wind and waves can cause mooring components to gradually deteriorate [86]. To analyze the risk of drift-off or capsize and to evaluate the system's response under fault conditions, it is also necessary to simulate Accidental Limit State (ALS) scenarios, such as partial line failure or anchor slippage. To capture the distribution of stress in crucial components such as chain links, fairleads, and anchor foundations, sophisticated simulation technologies such as Finite Element Analysis (FEA) and coupled dynamic modeling (e.g., utilizing OrcaFlex, AQWA, or ANSYS AQD) are necessary [87]. Additionally, these models include useful outputs like anchor holding capacity, platform excursion limits, and maximum line tensions, which help determine design safety margins and guarantee adherence to global standards like ISO 19901-7, DNV-RP-C205, and API RP 2SK. If wave-induced resonance and mooring slack are not adequately damped or pre-tensioned, they can nevertheless produce hazardous dynamic amplification in floating solar arrays, where mooring lines are usually under less tension than in OWTs [88].

3.1.1. Dynamic stability under extreme weather conditions FPV and FWT

This section discusses the dynamic stability challenges faced by both FWT and FPV systems during extreme weather events such as typhoons and severe storms. These conditions subject floating renewable energy platforms to combined aerodynamic, hydrodynamic, and structural stresses that can affect their reliability and performance.

In deeper waters when fixed-bottom foundations are not feasible, FWTs are installed. They are directly exposed to harsh offshore conditions when they sleep on floating platforms that are tethered to the ocean floor [89].

3.1.1.1. Challenges of dynamic stability during storms.

1. Aerodynamic Overloads

Typhoon winds have the potential to surpass the ~25 m/s turbine cut-out speeds. Turbines are set to shut down above this point, but storm gusts continue to affect the blades [90]. Wind loads cause strong lift and torque forces, which can cause flutter, blade bending, or even root fracture [91].

2. System Instability for Mooring

When the floating base moves dramatically during a storm, mooring lines experience significant tension swings [92]. Snap loads put lines at danger of rupture or anchor failure when they suddenly tighten after becoming slack [93]. Asymmetric wave and wind stress can further destabilize mooring geometry in directed storms (such as cyclonic rotation) [94].

3. Coupled Motion in Multiple Directions

Six degrees of freedom (6-DOF) are experienced by the floating foundation: pitch, roll, yaw, heave, sway, and surge [95]. The platform's inherent frequencies may be resonated with wave periods and wind fluctuations during a storm, producing enhanced oscillations [96]. This resonance can cause tower vibration, blade-tower strikes, or yaw drift, compromising generator alignment and power quality [97].

FPV systems consist of solar panels affixed to floating structures, which are frequently placed in lakes, reservoirs, or coastal waters. Although they are usually set up in calmer surroundings, there is a growing trend of deploying them offshore, which subjects them to winds of typhoon strength, high wave activity, and surges in current [98].

3.1.1.2. Major hydrodynamic and aerodynamic challenges.

1. Wind Pressure and Drag

Wind speeds from typhoons (exceeding 50 m/s) result in aerodynamic uplift on the surfaces of panels and lateral drag throughout the array [99]. The risk of panel detachment or frame torsion is increased when panels that are not flush with the water such as those that are slanted or angled experience higher wind-induced moment forces [100].

2. Hydrodynamic and Current Forces

Strong horizontal currents brought on by storm surges increase drag on the platform base and mooring lines [101]. If dynamically corrected, this can result in partial submersion, mooring misalignment, or platform drift [102].

3. Wave Induced Motions

Wave heights during storms can reach several meters, with intervals of 10–20 s [103]. These waves cause the FPV platform to rotate (pitch and roll) and oscillate vertically (heave) [104].

3.1.2. Mitigation strategies for FPV and FWT

Table 4 present a variety of focused mitigation techniques have been created for both FPV and FWT platforms to improve the dynamic stability of floating renewable energy systems during severe weather events like typhoons and storms. While FWTs use storm-resistant blades, adjustable ballast systems, and optimized hull designs to limit motion and wind loading, FPV systems use flexible modular floats and wave barriers to absorb wave energy and reduce mechanical stress. In terms of mooring, perimeter anchoring and redundant elastic mooring lines are advantageous for FPV platforms since they help preserve positional stability during periods of high wave activity [105]. On the other hand, FWT systems use predictive load management technology and hybrid mooring arrangements, including tension leg platforms (TLPs), to adjust

Table 4
Mitigation strategies.

FPV	FWT	Classification	Reference
Modular floats that are flexible and wave barriers.	Optimized hull, movable ballast, and storm-resistant blades.	Design of Structures	[105]
Peripheral anchoring and redundant elastic moorings.	Descriptive load management, TLPs, and hybrid mooring.	Systems for Mooring	
Motion sensors and weather-based warning systems.	Real-time monitoring of structural health and pitch/yaw control.	Management and Observation	
Moving, disassembling, and submerging.	Emergency mooring release, rotor locking, and auto shutdown.	Operational Actions	

to changing ocean conditions. Control and monitoring systems are also essential. FPVs adapt to changing loads using real-time motion sensors and weather-triggered alarms, while FWTs use sophisticated blade pitch and yaw control and ongoing structural health monitoring [106]. In terms of operation, FPV arrays may be moved, dismantled, or submerged to prevent storm damage, whereas FWTs have rotor locking systems, automated shutdown processes, and emergency mooring release mechanisms for high-severity situations. When combined, these tactics create a multi-layered defense system that greatly improves floating renewable infrastructure's performance reliability and survival in harsh marine settings [107].

4. Offshore Wind Energy Revolutionized by FWT

An innovation in the field of renewable energy, FWT offer a special way to capture wind energy in deeper areas where conventional fixed-bottom turbines are impractical. FWT are becoming a key technology to assist satisfy the world's energy needs as it seeks to diversify its RE sources and lower carbon emissions [108].

4.1. WT affixed to floating structures

Compared to onshore wind turbines, offshore wind turbines have several advantages. While offshore turbines are generally larger and can deliver higher capacity factors, the LCOE of offshore wind remains higher than that of onshore wind in most markets due to substantially greater capital expenditures, installation and grid-connection costs, higher O&M and more expensive financing; recent reviews and LCOE analyses are cited to support this point. Additional potential advantages of offshore wind include reduced land-use conflicts compared to onshore projects and access to stronger and more consistent wind resources available at sea; however, these benefits are highly site-specific and must be weighed against higher costs and technical challenges [109]. As seen in Fig. 7, offshore wind turbines generally follow a similar structural configuration, consisting of the rotor, nacelle, tower, and foundation [110].

The majority of commercial OWT are horizontal-axis, three-bladed upwind devices, with torque-generating blades attached to the hub, a crucial nacelle component, as part of the above sea level components. The generator, gearbox and main shaft are all housed in the nacelle. From the nacelle, power lines descend via the tower to the supporting structure, which has an exterior deck that allows operators to access both the tower and the nacelle [111]. The way OWT are structurally sustained is the primary distinction between them and onshore wind turbines. OWT can be divided into two general categories: floating and fixed-support. As the names imply, FOWT have floating support structures that are attached to the seabed by mooring cables, and fixed-support offshore wind turbines have foundations that are fastened to the seabed [112].

The hybrid off-shore wind-solar power plant that China SPIC completed is the only confirmed hybrid off-shore wind-solar power plant. It has a peak capacity of 0.5 MW and is moored to an offshore turbine via a shared submarine cable; plans are in place to upgrade the pilot project to 20 MW next year [113]. RWE and a company named Solar Duck have a joint venture for an offshore pilot of 0.5 MWp in the North Belgian Sea in 2023 [114]. As these are the first two pilot schemes and this technology has been relatively untested, case studies of a hybrid FPV and wind power plant have been examined. To maximize energy production per unit area of the sea, solar arrays should be placed in the large spaces between the turbines; however, combining the two technologies may result in lower environmental conditions due to park effects, since placing structures in the water can significantly alter the local marine climate [115], and turbines must be spaced far apart to avoid interference from their wake effects. Fig. 8 shows the proposed locations for the solar panels [116].

4.2. Advantages of FWT

FWT represent a major technological advancement in offshore renewable energy, offering numerous advantages over traditional fixed-bottom wind turbines [117]. One of their most significant benefits is the ability to operate in deep waters, unlike fixed-bottom systems that are limited to shallow continental shelf regions. This capability opens vast new areas for wind energy development, particularly in locations where wind speeds are stronger and more consistent, thereby enhancing overall energy potential [118].FWT also lessen the environmental

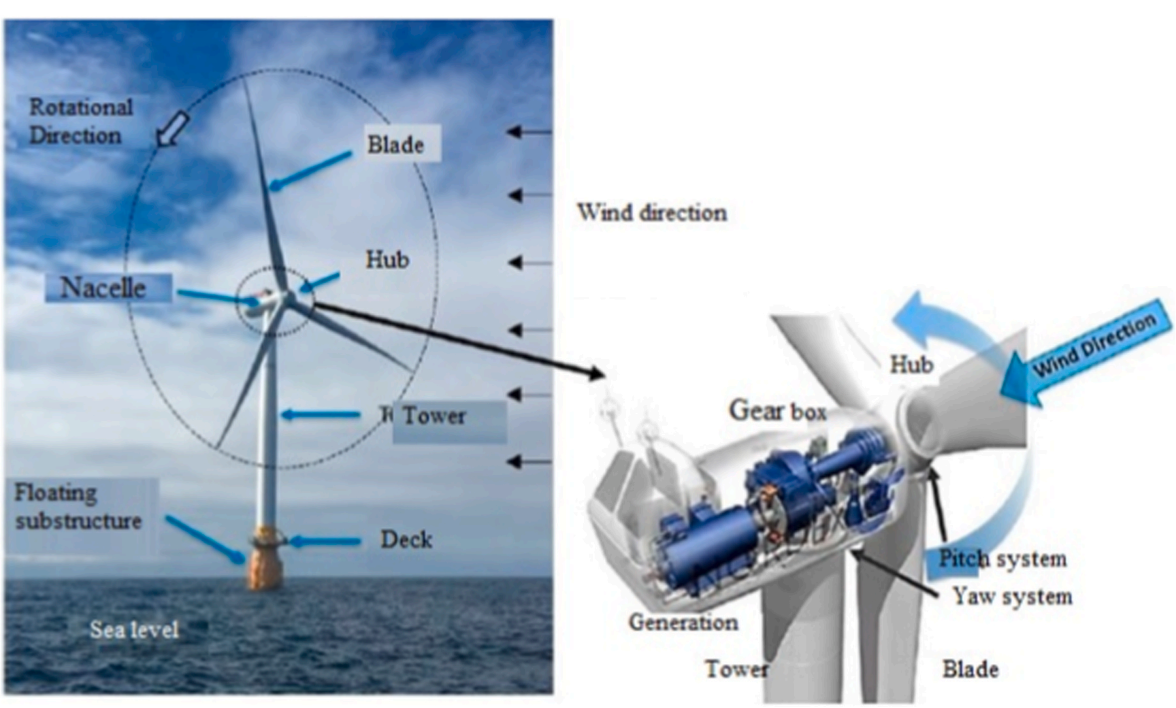


Fig. 7. A typical OWT [110].

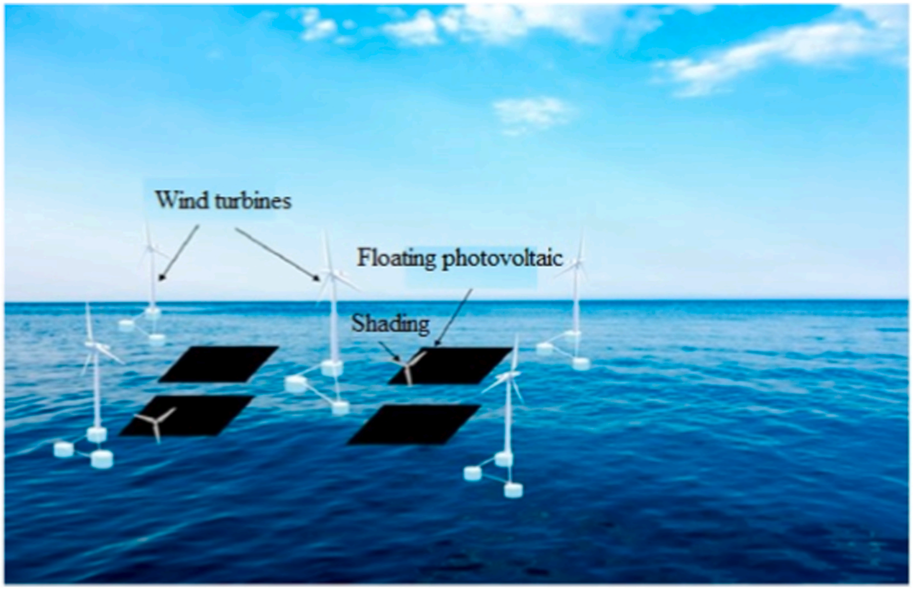


Fig. 8. An illustration of the possible configuration for an offshore wind farm coupled with floating photovoltaics [116].

impact on marine ecosystems because they do not require heavy seabed drilling or construction, reducing ecological disturbance compared with conventional offshore installations [61].Another advantage of floating wind technology is the ability to position turbines far from the coastline. This offshore placement minimizes visual intrusion for coastal communities and helps avoid issues typically associated with land-based wind farms, such as land-use conflicts and property rights concerns [119]. Because floating turbines can be positioned in locations where winds are stronger and more reliable, this makes it possible to increase energy generation. As a result, power generation is more efficient than with conventional turbines in shallow waters [120].In areas distant from the shore, where it would be hard or too costly to construct conventional turbines, FWT may offer a more economically viable installation option [121].FWT can be positioned further out to sea, which helps them avoid conflicts with other ocean-based activities such as fishing and shipping. This aids in alleviating the strain between the renewable energy sector and other industry sectors that utilize the ocean [122].FWT can be installed modularly, allowing for scaling up or down based on the project's requirements. It is possible to add new installations without requiring major infrastructure modifications [123].Floating wind farms can be deployed in extensive configurations across large ocean expanses, producing substantial electricity while leaving valuable land free and not disrupting current industries [124].Because these turbines can be situated at a distance from the shore, they are less prone to affecting coastal travel or the attractive value of coastal regions. In coastal communities, the noise and visual disturbance caused by wind turbines can be a significant concern [125].FWT can generate green hydrogen through electrolysis, providing a means to store energy offshore and transport it to markets without relying on extensive grid infrastructure [126].

4.3. Disadvantages of FWT with latest projects and developments

FWT offer significant potential for expanding renewable energy production, particularly in deep-water environments where fixed-bottom turbines are not feasible. Despite their advantages, several challenges continue to limit their widespread deployment. One major drawback is the high cost associated with their design, construction, and installation. Floating platforms require advanced engineering, specialized materials, and complex deployment procedures, all of which contribute to considerably higher project costs compared with conventional offshore wind turbines (OWT) **[**89**] .**Moreover, because FWT are located in deep and often harsh marine environments, maintaining them is both difficult and expensive. Routine inspections and repairs demand specialized vessels and equipment, and adverse weather conditions can further hinder maintenance operations, leading to increased operational expenses [127]**.**Connecting floating wind farms to onshore electricity grids also presents significant technical and financial challenges. Subsea cables are needed to transport the electricity produced offshore, but these cables are vulnerable to damage from marine activities, anchoring, and natural seabed movements, resulting in higher transmission costs and potential disruptions **[**128**].**Although FWT are considered more environmentally friendly than fossil fuel-based energy sources, their installation and operation can still pose ecological risks. The presence of floating structures may disturb marine habitats and pose threats to local wildlife, including marine mammals and seabirds **[**128**].** Another limitation is that FWT technology remains relatively new and continues to evolve. As a result, uncertainties persist regarding long-term structural stability, operational efficiency, and the durability of these systems under extreme ocean conditions **[**130**].**Furthermore, floating turbines are more exposed to severe weather events, such as storms, strong waves, and turbulent seas. These conditions can affect platform stability and overall performance, potentially causing damage or reducing energy output during critical weather episodes **[**131**].**

The installed capacity of FOWT is currently 121MW, but it is expected to rise to 18.9GW by 2030 and 264GW by 2050 [131]. Fig. 9 displays the historical (dark blue) and projected (light blue) global capacity of floating wind, along with the breakdown of current and projected capacity by nation [132].

Research comparing two reference wind farm projects one fixed and one floating—was carried out. For 25 years, 1006.1MW turbines were in operation at each project. In the North Atlantic (USA), the fixed wind farm was situated at 34 meters below the surface 50 kilometers from the coast, and in the Pacific (USA), the floating wind farm was situated at 739 meters below the surface 36 kilometers from the shore utilizing a semi-sub platform. The floating project's LCOE was 132$/MWh (about 121€/MWh), whereas the fixed project was 85 $/MWh (approximately 78 €/MWh). The floating project's substructure accounted for 29.5% of the overall CAPEX expenditure, while the fixed project's substructure accounted for 13.5%. Additionally, it was demonstrated that 30% of the whole LCOE cost will go toward operation and maintenance (and 34.3% for fixed) [133].In Ref. [134] reported on a heat mapping research that

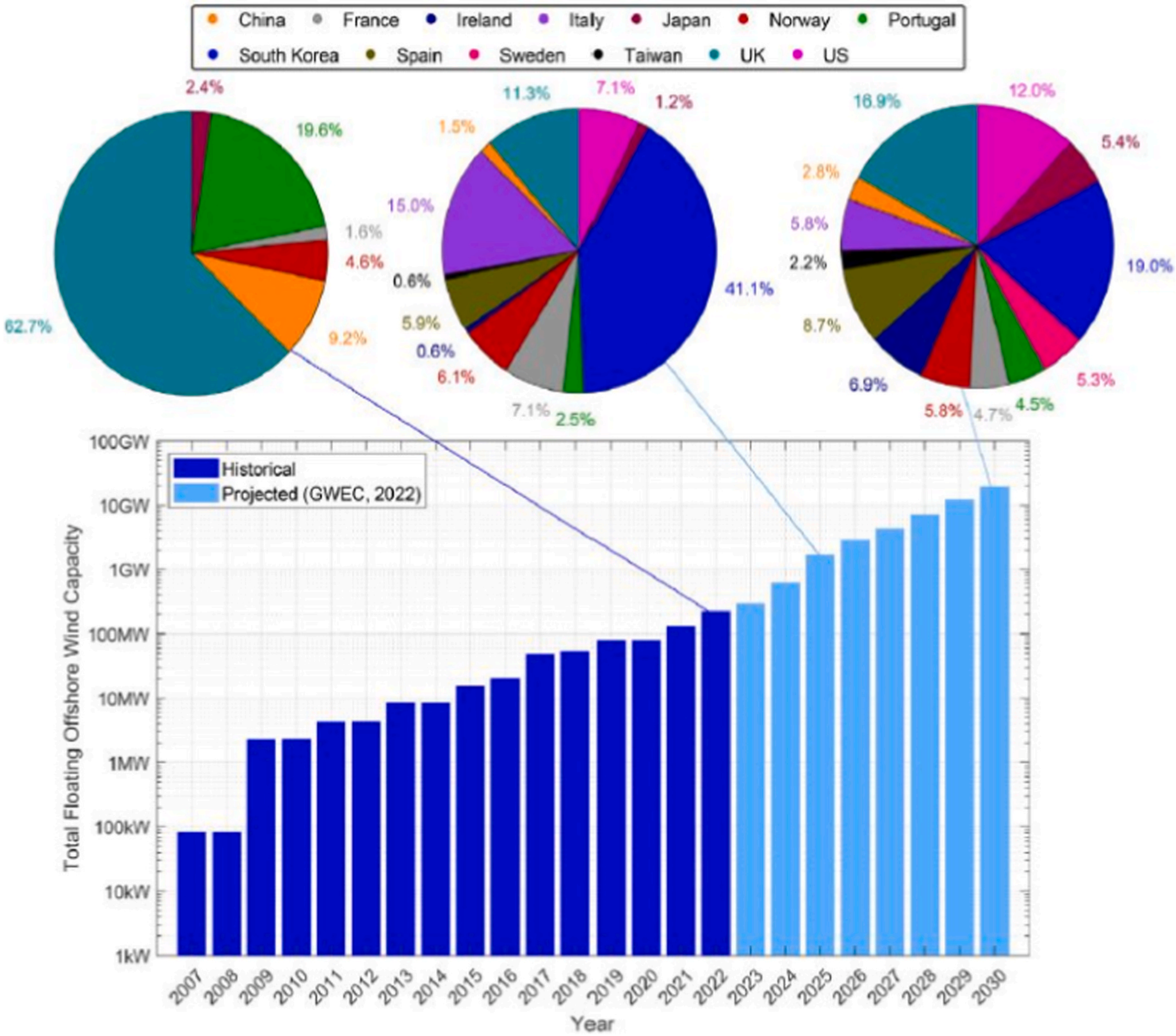
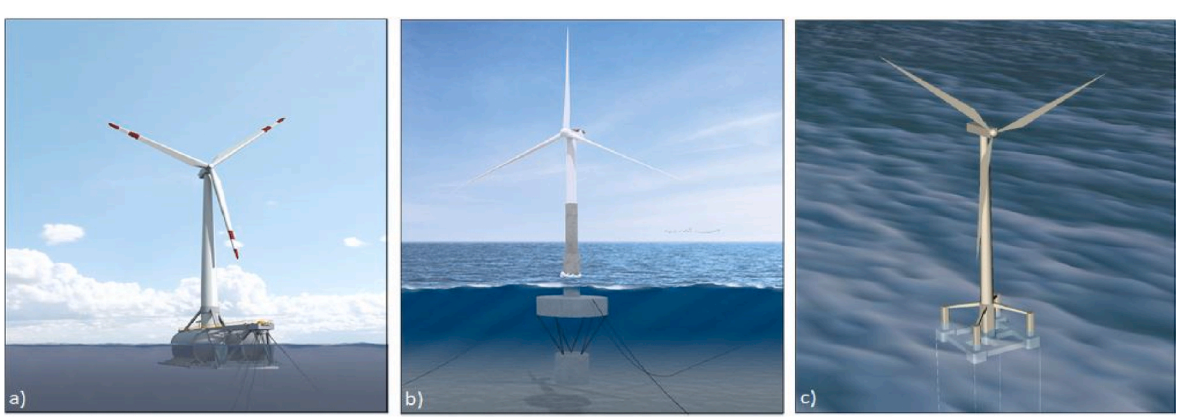


Fig. 9. Global floating offshore wind capacity, depicted by historical (dark blue) and projected (light blue) percentages of installed capacity as of 2022 and projected capacity per nation in 2025 and 2030 (top). GWEC predicted capacity [132].

was conducted to evaluate FOWTs' competitiveness in specific markets. Based on a 2030 timeframe, the techno-economic offshore wind performance model computes lifetime power generation and overall project cost while taking into consideration the turbine and substructure technological advancements. According to the model, California (USA) will have an LCOE of 64 – 161€/MWh, Italy 84 – 153€/MWh, Ireland 52 – 75€/MWh, and the Philippines 95 – 170€/MWh. These ranges demonstrate how location including within a single nation affects wind resources, port accessibility, and ocean depth.

ARCWIND's floating ideas, Spar-Buoy (TELWIND) [135], Tension-Leg-Platform (CENTEC-TLP) [136], and Semi-Submersible (SATH) [137] are the substructures under study. The information for



(a) SATH® (SSP) b) TELWIND® (SB) c) CENTEC-TLP (TLP)

Fig. 10. The Arc wind project includes floating platforms [138].

the floating turbines is derived from preliminary data collected from project Arc wind partners as well as existing empirical data. To create unique solutions for every situation, a thorough cost study of every platform would take a significant amount of work. The cost of floating platforms is significantly influenced by technical factors related to location and turbine capacity installation conditions. A comparable reference scenario is thought to be obtained by the 5–10 MW generators. The complexity factor affecting the fabrication needs is used to estimate the costs of the transition piece and secondary steel components. As can be seen in Fig. 10, the substructure's cost decreases by 5–20 times when the same platforms are built of concrete [138].

5. Floating hydropower systems (FHS)

The installed capacity of hydroelectric electricity has increased at the fastest rate among all renewable energy sources in recent years. However, solar energy currently holds the distinction after achieving the fastest growth, with a 58% share recorded between 2017 and 2021 [46]. Research and development of FPV on ocean platforms ushers in a new era of solar energy with the creation of sturdy floating buildings, while 70% of the planet is submerged under water. It should be remembered, nevertheless, that oceans are not always calm, and FPV structures may face significant difficulties due to strong ocean currents, stability, storms and wave loads. Research and development initiatives to tackle this problem are therefore essential. China and the UK are currently at the forefront of structural analysis for FPV systems that can withstand harsh ocean conditions [49]. Similarly, by using just 1% of the surface area of 146 hydroelectric reservoirs in Europe, FPV has the potential to treble power generation [139]. According to another study, 42.31TWh of energy might be produced by covering just 2.3% of the surface area of hydropower reservoirs [140]. Additionally, installing FPV in the EU can prevent water evaporation by about 557000 liters. With a planned installed capacity of 500MW, Portugal is expected to host the largest FPV in the EU [141]. Additionally, new studies have highlighted FPV's potential for cleaner energy production in Romania; estimates suggest that a 540W FPV system in some areas might generate over 700kWh [142]. Similarly, FPV might produce an astounding 80TWh of energy per year in Spain if it were harnessed in 10% of its inland water bodies [143]. The creation of an independent power generation system that makes use of the water flow in rivers and canals is the idea behind floating waterwheel power generators, as explained in the document [144]. The system is made up of a floating structure with a water wheel that is propelled by the water's movement. Bridge street lights, agricultural water pumping, and village electrification are just a few of the uses for the power produced by the water wheel's revolution. The system's physical construction is made of non-corrosive, indestructible materials like fiberglass and mild steel [145]. To ensure continuous power generation, the water wheel is uniquely built with blades that rotate in the direction of the water flow. The system runs on its own without requiring external grid electricity. The power produced can either be used right away or saved for later use in batteries. As seen in Fig. 11, one of the primary benefits of waterwheel power generators over conventional hydropower turbines is their portability and flexibility [62].

Fig. 11. Waterwheel floating power generators [62].

5.1. Tidal energy

The movement of water brought on by the moon and sun's gravitational attraction is captured by tidal energy, which causes the tides to rise and fall. Power is produced by these systems using either tidal currents (water flowing in and out) or water level variations (the height differential between high and low tides) [146].According to the theoretical idea of "dynamic tidal power," big floating platforms are positioned in regions with high tidal flows. Both the tidal currents and the variations in water level (the height between high and low tides) would provide electricity for these platforms. This technology is still in the research stage and has not yet reached full development [147].In essence, tidal stream generators (TSGs) are underwater turbines that function in tidal currents and mimic wind turbines. The turbines rotate and produce electricity in response to the tide [148].

5.2. Wave energy

The energy derived from the wind-driven movement of the ocean's surface is known as wave energy. Depending on the wind's strength, length, and the area it blows across, waves can vary in size and severity. Devices that move with the waves are commonly found in floating hydropower systems that are intended to capture wave energy. These devices transform wave motion into electrical, mechanical, or hydraulic energy that can be utilized to produce power [149].These lengthy, segmented structures follow the direction of the waves and float on the surface. Various sections of the structure bend and flex as waves pass through them, absorbing energy from the longitudinal wave motion. After that, the energy is transformed into electrical power [150].These gadgets use the water's rise and fall inside a chamber to generate energy. The compressed air inside the chamber powers a turbine as waves force water into it. Power is produced when the water recedes because the air is displaced [151].These are constructions that resemble buoys and are fixed to the seafloor so they may move with the waves. Using hydraulic pumps or other mechanical systems, the buoy's motion with its anchor produces energy [152].

5.3. Advantages of FHS

By deploying FHS in deep-water and offshore places where conventional land-based hydropower might not be practical, more sites for the production of renewable energy can be made available [153].Floating systems are perfect for places with a high population density or limited land availability since they don't occupy important land space, unlike traditional hydropower, which needs enormous land expanses for dams, reservoirs, and infrastructure [154].Compared to conventional hydropower, FHS often have a smaller environmental impact. They protect natural habitats and ecosystems by not requiring big dams. They also refrain from upsetting nearby populations or wildlife that land-based energy projects may impact [155].Because these systems are flexible enough to be employed in a variety of water conditions, such as lakes, reservoirs, rivers, and oceans, there are greater chances for the production of clean energy globally [156].

Floating hydropower, like other hydropower systems, uses tidal, wave, or water current energy to produce electricity. In addition to supporting the shift to cleaner, more sustainable energy systems, this helps to lower greenhouse gas emissions [6].Large dams are necessary for traditional hydropower plants, which can have serious negative social, environmental, and financial effects. In contrast, FHS eliminate the need for expensive and frequently contentious dam construction projects by not requiring such infrastructure [157].Multiple floating units can be installed in a specific area to boost power generating capacity without needing significant changes to the surrounding environment. Depending on energy needs, FHS can be scaled up or down [155].

5.4. Challenges of FHS

Floating systems rely on stable water conditions; strong storms, large waves, or strong winds may cause damage to the platforms or decrease their effectiveness; it can be challenging to ensure the dependability of these systems in regions with severe weather; platforms need to be built to withstand severe conditions, which can increase the complexity and cost of construction [158].It may require a significant amount of capital to create floating hydropower installations. The initial expenditures might be substantially greater than those of conventional or land-based hydropower projects due to the requirement for specialized materials, underwater infrastructure, anchoring systems, and floating platforms. Further raising expenses is the possibility that installation in deep sea or offshore environments will call for sophisticated machinery and technologies [159].While FHS generally have less of an impact on the environment than conventional hydropower, there are still certain issues with them [160].Local ecosystems may be impacted by turbine noise, variations in water flow, and possible disturbances to marine life. Careful monitoring is necessary, and the long-term environmental impact is currently being investigated [61].The severe maritime and aquatic conditions that FHS are subjected to might cause corrosion and wear and tear [161].Constant exposure to waves, strong currents, and saltwater can shorten the lifespan of parts like electrical systems, turbines, and anchors, necessitating more regular maintenance and replacement, which can raise expenses [162].It can be difficult to transfer power generated on the floating platform to the electrical grid or land. It is necessary to install subsea cables, which can be expensive and susceptible to damage from storms, fishing, or marine life [163].

5.5. Floating waterwheel scale-up challenges and power output density compared to small hydropower plants

5.5.1. Scale-up challenges

When floating waterwheel systems are scaled up, a number of operational and technical challenges arise that need to be carefully considered throughout the design and implementation process. Materials and structural integrity are among the main issues. The river current and the additional weight of the larger structure itself both exert considerably stronger hydrodynamic forces on the waterwheel as its size grows [164].To resist bending, corrosion, and possible breakage, larger systems require stronger and more durable building materials. Though they also increase complexity in terms of cost, manufacturability, and weight distribution, advanced composites and coated metals are frequently seen as workable options [165]. Scaled-up devices may experience mechanical wear in the absence of proper structural engineering, especially in high-flow situations, which could ultimately result in an early system failure [166].Equally crucial are the issues involved with mooring and anchoring. It becomes more challenging to maintain stability at a given site in a dynamic river environment as waterwheel systems get larger. Tilting, undesired rotation, and even drifting can result from inadequate or improper anchoring, all of which reduce durability and efficiency [167]. Passive anchoring solutions might not be sufficient for large-scale deployments; instead, more sophisticated techniques like active positioning systems or sophisticated anchoring technologies made to manage fluctuating hydrodynamic loads are needed. Addressing these problems is vital to ensuring that up scaled floating waterwheel systems can run reliably and efficiently over lengthy periods [105].

Hydrodynamic efficiency further complicates the scaling process. Since river flow conditions are rarely uniform across the channel width, broader waterwheels encounter uneven flow distributions along their surface [168]. This can cause certain sections of the wheel to rotate more quickly than others, leading to uneven wear and reduced energy output [169]. To mitigate such effects, designers must carefully select installation sites and may need to integrate flow-straightening devices to ensure a more stable and uniform inflow across the wheel [170].Finally, access and maintenance become more challenging for larger waterwheels. Units deployed midstream or under adverse weather conditions are difficult to inspect, clean, or repair [171]. Because regular maintenance is essential for reliable long-term operation, insufficient accessibility may lead to operational downtime or even safety hazards [172]. Addressing these issues requires the development of modular system designs or docking mechanisms that allow easier maintenance and minimize service interruptions in large-scale applications [173].

5.5.2. Comparison of power output densities

The performance of floating waterwheels can be further evaluated by comparing their power output density with that of conventional small hydropower (SHP) systems. Power output density is defined as the power generated per unit area of the energy-capturing surface, expressed in watts per square meter (W/m^2) [174]. This metric serves as an important indicator of the efficiency with which a system converts the kinetic energy of river flow into useable electricity [175].SHP systems are typically located in regions with high water flow volumes and significant hydraulic head [176]. By employing enclosed turbines that capture large amounts of energy from fast-moving or falling water, SHPs can achieve power densities ranging from 300 to 1000 W/m^2 [177]. In contrast, floating waterwheels typically produce between 50 and 150 W/m^2 [178]. This lower performance is expected because they operate in rivers with little or no head and are directly exposed to natural, uncontrolled flow conditions, unlike SHPs that benefit from engineered tunnels and optimized flow channels [179].Despite their lower power density, floating waterwheels provide several advantages. They can be deployed in shallow or slow-flowing rivers where SHPs are impractical [180], they generally cause minimal ecological disruption [181], and they are comparatively inexpensive and quick to install [1]. These benefits make them attractive for decentralized and off-grid applications, especially in locations where SHPs or centralized electricity infrastructure are not feasible [62].

5.5.3. Ocean thermal energy converter (OTEC)

Utilizing the natural temperature differential between warm surface saltwater and cool deep seawater, ocean thermal energy conversion (OTEC) is a renewable energy technique that produces electricity [182]. A working fluid with a low boiling point, like ammonia, is usually evaporated using warm saltwater that is between 25 and 30 °C. The vapor that is produced powers a turbine that is attached to a generator [183]. The cycle is then completed when the vapor is condensed back into liquid form by cold saltwater that is extracted from depths of 700–1000 m. In tropical and subtropical areas, where there is a significant enough temperature differential to maintain high efficiency, this process can run continuously [184]. To reduce land use and offer direct access to deep ocean waters, OTEC systems a floating renewable energy technology are frequently built as offshore platforms. Long cold-water pipe installation costs can be decreased by placing these systems in areas where the continental shelf dips sharply thanks to floating platforms. OTEC is a desirable alternative for island nations and coastal areas with limited energy resources because of the possibility of co-generating freshwater through desalination, as well as integration with aquaculture and hydrogen production. Notwithstanding these benefits, implementing OTEC on a broad scale is fraught with difficulties [185]. Large cold-water intake pipes are expensive and technically challenging to build and maintain in deep-sea environments. Environmental factors also need to be carefully evaluated, such as the effects on marine ecosystems caused by the release of deep water that is rich in nutrients. Additionally, compared to more established floating technologies like offshore wind and floating photovoltaic systems, OTEC requires a larger capital commitment [186,187]. OTEC is still a viable option for expanding the range of floating renewable energy sources, particularly in equatorial areas with significant annual temperature variations [188].

6. Floating renewable energy systems (FRES) overview

Floating renewable energy systems encompass a range of technologies designed to harness natural resources in marine and freshwater environments [189]. Floating tidal devices capture the kinetic energy of moving water such as tidal flows and ocean currents to generate electricity, making them particularly valuable in deep locations where fixed infrastructure is difficult to install [190]. Floating solar platforms, which support photovoltaic panels on lakes, reservoirs, or coastal waters, provide an alternative in regions where land-based solar farms are costly or impractical, while also benefiting from the cooling effect of water that can enhance panel efficiency [191]. FWT represent another major FRES technology. Mounted on floating platforms and secured with mooring systems, these turbines operate efficiently in deep offshore waters that cannot accommodate fixed-bottom structures. As a result, floating wind technology is considered ideal for harnessing the vast wind potential available in deeper marine environments [192]. When multiple renewable technologies are combined within the same project, significant economic synergies can be achieved [193]. Hybrid deployments enhance the overall energy yield and can lead to higher economic returns by reducing operational costs and improving resource utilization [194]. The integration of diverse sources also increases energy reliability, as the intermittent nature of one resource can be offset by another. For instance, solar output may decline during stormy conditions when wind speeds are high, while wind power may decrease during calm, sunny periods when solar production peaks [61]. FRES also promote space efficiency, enabling developers to utilize the same water surface area for multiple renewable systems. This approach is particularly valuable in regions where land is scarce or expensive [195]. However, the deployment of multiple technologies within a shared environment introduces operational complexity. Coordinating maintenance activities, safety protocols, and monitoring systems requires careful management to address the unique needs of each technology [196]. Effective energy integration is another challenge, as combining variable sources such as wind, solar, and tidal energy demands advanced grid management and suitable energy storage solutions. These technologies are essential to maintain a stable and continuous power supply despite fluctuating environmental conditions [197]. Lastly, hybrid FRES implementations must consider their environmental impact. Installing multiple systems in the same marine or freshwater environment may affect aquatic ecosystems, water quality, and local biodiversity. Therefore, comprehensive environmental assessments are crucial to understand how each technology interacts with its surroundings and to mitigate any potential ecological risks [198].

6.1. FPV's co-location with HPP

FPV installations on Hydropower Plant (HPP) reservoirs offer several advantages beyond electricity generation. When FPV systems are deployed on water surfaces already used by hydropower facilities, the configuration is known as FPV–HPP co-location. In this arrangement, both technologies operate independently but complement one another in terms of resource utilization and overall system performance. One key benefit of FPV–HPP co-location is water conservation. Because FPV panels are mounted on floating structures, they partially block sunlight from reaching the water surface, which significantly reduces evaporation. This helps to retain more water within the reservoir, making additional stored water available for hydropower generation during periods of high demand or limited inflows [199]. Another advantage relates to increasing energy capacity. Traditionally, expanding hydropower output requires constructing new dams—an approach that can lead to environmental and social concerns. FPV systems provide an alternative means of boosting total energy generation by using the existing reservoir surface, thereby avoiding the need for extensive new infrastructure, although their own environmental impacts must still be carefully assessed [200]. FPV–HPP co-location also enhances infrastructure efficiency. Since HPPs are already connected to the electrical grid, FPV installations can utilize the same transmission system, reduce grid connection costs and improve the overall use of existing capacity. Shared access roads, monitoring facilities, and maintenance pathways further simplify installation and operational activities for both systems, resulting in lower overall project costs and more effective asset utilization [201]. In addition to these technical and economic advantages, FPV systems can also yield environmental benefits. By shading parts of the reservoir, FPV arrays can inhibit the growth of algae, thereby improve water quality and contribute to healthier ecological conditions within the reservoir environment [202].

7. Techno-economic cost assessment of floating solar energy systems

7.1. Battery based energy storage solutions integrated with FPV and OWT

Particularly in coastal and offshore areas, energy production via OWT and FPV systems provide a promising route toward sustainable power generation [81]. Both methods, however, are susceptible to natural fluctuation; wind energy is dependent on wind patterns and speed, while solar production varies with weather and irradiance [203]. Advanced energy storage systems must be included to reduce these intermittencies and provide a steady and dependable power supply. Lithium-ion, sodium-sulfur, or flow batteries are examples of battery energy storage systems (BESS) that can be intelligently combined with FPV and OWT platforms to store excess energy during times of high generation and release it during times of low generation or demand peaks [204]. Long-duration storage potential for hybrid systems is also provided by new storage technologies, such as offshore electrolysis-based hydrogen generation. Incorporating such storage improves energy dispatch ability, facilitates islanded operation in remote locations, and permits more efficient use of renewable resources in addition to improving grid stability and frequency management [205]. Thus, the operational flexibility, financial feasibility, and resilience of floating renewable energy infrastructures are greatly enhanced by the integration of energy storage with FPV and OWT systems [81].

7.2. Levelized cost of energy based cost estimation models

Cost estimation models, especially the Levelized Cost of Energy (LCOE), are essential for techno-economic analysis because they enable assessments of the financial viability of floating renewable energy systems [206]. LCOE determines the cost per unit (typically $/MWh or $/kWh) of electricity produced by a particular technology throughout its operational lifespan. LCOE is calculated by dividing the total costs by the total energy generated throughout the system's lifetime [207].It is essential for assessing how cost-effective floating wind, solar, or wave energy technologies are compared to other energy sources [208]. LCOE considers multiple costs, including capital expenditures (CAPEX) for constructing the infrastructure, operational expenditures (OPEX) for operating and maintaining the system, and financing costs that may involve loan interest and returns anticipated by investors. A technology with a low LCOE is likely to be cost-competitive and economically viable [209].

Financial Models: These models serve to compute the payback period, return on investment (ROI), and net present value (NPV). To accommodate uncertainties, the cash flows can be modeled through discounted cash flow (DCF) models and Monte Carlo simulations [210].

OPEX: Comprises upkeep expenses, insurance coverage, operational personnel, and energy transmission facilities [211].

CAPEX: Involves the expenses for the infrastructure, installation, turbines, and platform [212].

LCOE: The most widespread measure for evaluating the economic viability of RES is this one [213]. It is provided by:

$$LCOE = \frac{\sum_{t=0}^{T} (C_t + O_t)}{\sum_{t=0}^{T} E_t} \tag{5}$$

Where:

C_t = capital expenditure (CAPEX) at time t
O_t = operational expenditure (OPEX) at time t
E_t = energy produced at time t

7.3. Data sources

Any robust techno-economic assessment of floating renewable energy systems requires drawing upon a broad range of accurate and reliable data rather than a limited set of sources [214,215]. Meteorological and oceanographic information, including wind speeds, wave heights, solar irradiance, and water temperature, is typically obtained from weather stations, buoy networks, satellite observations, and global reanalysis datasets [216]. Site-specific geographic and environmental data, such as bathymetry, current profiles, and marine spatial planning, are essential for assessing technical feasibility and environmental impacts [217]. Cost and market information, covering both capital and operational expenditures, is usually sourced from vendor quotations, industry reports, and market surveys [218]. Technological specifications and performance data are often provided by manufacturers, pilot projects, and research institutions, including information on turbine efficiency, platform durability, and reliability [219]. In addition, regulatory and policy frameworks such as permitting requirements, subsidies, and environmental standards together with financial and economic data, including electricity market prices, financing structures, and discount rates, strongly influence the viability of floating energy projects. Integrating these diverse data categories ensures that techno-economic analyses are comprehensive and credible, while avoiding over-simplification or reliance on narrowly selected references. [220].

Cost and financial data form a critical component of evaluating floating renewable energy systems, and government policies play a significant role in shaping these financial models. Incentives such as subsidies, tax credits, and feed-in tariffs offered by various countries are essential inputs for analyzing economic feasibility and developing accurate financial projections for renewable energy projects [221].In addition to policy information, detailed OPEX and CAPEX data are required to estimate overall project costs. These data are commonly obtained from industry analyses, government publications, market research firms such as Bloomberg New Energy Finance and IRENA, as well as historical cost records from previously implemented projects [222]. Resource data for renewable energy systems are equally important and are typically derived from specialized environmental databases. For wave and tidal systems, parameters such as wave height, direction, and period are collected from oceanographic models and repositories including the Copernicus Marine Service and NOAA. Tidal information is often sourced from gauge networks like XTide and hydrographic surveys, which provide precise tidal measurements for coastal regions [223].Solar energy assessments rely on datasets such as the Photovoltaic Geographical Information System (PVGIS) and NASA's Surface Meteorology and Solar Energy (SSE), which offer detailed information on global horizontal irradiance (GHI) and direct normal irradiance (DNI) across different locations [224].Wind resource evaluation uses data on wind speed, direction, and turbulence obtained from meteorological stations and satellite observations, with high-resolution wind maps available from tools like NASA's POWER system and global wind atlases [225].

Operational and performance data are also vital for modeling floating renewable energy technologies. Information on component reliability, maintenance schedules, and associated costs is often compiled from industry reports and operational records from similar renewable energy installations [226].Real-time operational data, particularly for floating systems, are typically gathered from pilot projects and demonstration sites. Offshore wind farms such as Hywind in Norway and Wind Float in Portugal provide valuable performance insights that help improve system design and predict long-term behavior [227].Finally, accurate offshore site data are necessary for assessing platform stability and anchoring requirements. Soil and seabed characteristics play an essential role in designing mooring systems capable of supporting floating technologies over long operational lifetimes [228]. Bathymetric information, which describes seabed depth and underwater terrain, is also critical for determining site suitability and modeling platform performance. These datasets can be obtained from sources such as NOAA's bathymetric surveys and the European Marine Observation and Data Network (EMODnet) [229].

7.4. Risk and reliability modeling

Risk and reliability modeling is crucial for understanding the uncertainties and potential challenges that floating renewable energy systems might face over time. These models focus on estimating the likelihood of system failures, maintenance needs, and unexpected downtime [162]. One common approach is to use failure rate models, which analyze the probability of failure of key components, such as turbines, floating platforms, and mooring systems. These models help predict the potential cost of repairs, downtime, and the impact on energy production [230]. Another useful tool is Monte Carlo simulation, which assesses the uncertainty in input variables by running multiple simulations to predict different potential outcomes. This approach helps understand the range of possible financial results and risks [231]. Additionally, Markov chains can be used to model the transition between different operational states and estimate how much time a system will spend in each state, which helps in evaluating system reliability and downtime costs [232]. By accounting for risk factors, these models provide insights into the resilience and long-term viability of FRE systems [233].

8. Optimization Framework for Hybrid Floating Renewable Energy

A strong optimization framework is needed to demonstrate the viability and improve the efficiency of hybrid floating renewable energy systems, such as combinations of OWT, WEC, and FPV [234]. The three fundamental goals of this framework optimizing energy production efficiency, maximizing system reliability, and reducing operating and maintenance costs are frequently at odds with one another [235]. The ratio of the total useable power produced by the hybrid system to the greatest amount of energy that may theoretically be collected from the environment is known as the energy output efficiency, or η_{Total} [236]. This can be stated mathematically as:

$$\eta_{Total} = \frac{E_{output}}{E_{available}} \tag{17}$$

Where.

E_{output} is the combined energy output from solar, wind, and wave components

$E_{available}$ is the total potential energy from environmental resources at the deployment site

Smart energy management techniques, low conversion losses, and ideal placement are necessary to achieve high efficiency [237].

Dependability of the system Another important goal is R_{sys}, which is the likelihood that the system will function flawlessly for a specific amount of time. The failure probability function can be utilized to model it [238]:

$$R_{sys} = 1 - P_{failure}(t) \tag{18}$$

Where.

$P_{failure}$ is the probability of failure over time t

High dependability minimizes operational disruptions and guarantees steady energy delivery. Mean Time Between Failures (MTBF) analysis, structural resilience in harsh marine environments, and redundancy in vital subsystems like mooring, energy converters, and power electronics are frequently included in reliability studies [239].

$$C_{OM} = C_{\text{inspection}} + C_{repair} + C_{\text{downtime}} + C_{logistics} \tag{19}$$

The significance of modular design, remote monitoring, and predictive maintenance in reducing costs throughout the system's life cycle is emphasized by this equation, which accounts for both predictable and unpredictable cost components [240].

Additionally, the optimization needs to adhere to a number of practical limitations. The floating platform must maintain structural stability and safety while subjected to combined wind, wave, and current stresses, making sure that motion (such as pitch, roll, and heave) stays within allowable bounds. The energy supply must continuously or at intervals backed by storage fulfill demand needs. Seabed disturbance, marine noise, and spatial zoning are among the environmental requirements that must be adhered to. Platforms must be positioned in locations with the best availability of solar, wind, and wave resources, at appropriate depths, and away from navigational routes [89].The system incorporates a number of design aspects that affect its performance in order to investigate ideal configurations. These include the tilt angle of solar panels, the height and length of the turbine blades, the mooring line design, the distribution of platforms (e.g., centralized vs. modular), and the capacity ratio of each energy subsystem (e.g., 40 % solar, 40 % wind, 20 % wave). The size and kind of energy storage devices, as well as the control schemes employed for load management and grid integration, are additional factors. During the optimization process, these factors are changed to determine the best combination for a particular site [241].

The multi-objective problem is solved by means of sophisticated optimization algorithms. Large, nonlinear design spaces are ideal for the exploration of genetic algorithms (GAs), which are especially useful when calculating derivatives is challenging [242]. Multi-objective Pareto optimization techniques, such NSGA-II (Non-dominated Sorting Genetic Algorithm II), provide a Pareto front of non-dominated solutions and find trade-offs between competing objectives [243]. To minimize processing effort, surrogate modeling approaches such as Radial Basis Functions (RBFs) and Artificial Neural Networks (ANNs) approximate simulation outcomes [244]. Monte Carlo simulations are also helpful for adding uncertainty to component failures or environmental inputs, which increases the final design's robustness [245].

Lastly, high-fidelity simulation tools and data inputs assist the optimization framework. Computational Fluid Dynamics (CFD) simulates hydrodynamic interactions, while Finite Element Analysis (FEA) examines the structural behavior of floating platforms under dynamic marine loads [246]. To represent actual conditions, real-time environmental data is included, including solar irradiance, wind speeds, wave height/frequency, and seawater properties. SCADA systems provide model validation and offer operational feedback. To ensure the best possible location in terms of resource availability, environmental sensitivity, and logistical viability, Geographic Information Systems (GIS) are also used for site assessment. When combined, these data streams and simulations allow for accurate modeling, validation, and decision-making inside the optimization loop [247].

Integrated hybrid offshore renewable systems often rely on the design of multipurpose floating platforms capable of hosting several energy components simultaneously. Instead of deploying separate structures for solar, wind, and wave technologies, a unified platform can accommodate all systems within a single floating framework [248].This approach offers several advantages: it reduces deployment and infrastructure costs [249],minimizes spatial requirements in marine environments [250],and centralizes operational activities, thereby improving maintenance efficiency [251]. However, developing such a platform requires careful consideration of buoyancy, structural balance, and dynamic stability to ensure safe operation under harsh ocean conditions. Another important design factor is the natural complementarity of renewable resources. Solar, wind, and wave energy typically reach their peak outputs at different times of the day and under varying weather conditions. Solar intensity is highest during midday [252], while wind resources especially offshore often strengthen during the evening and nighttime [253].Wave energy, in contrast, tends to remain relatively stable even after storm events, providing a more continuous source of power [254].By integrating these resource streams, hybrid systems can produce electricity more consistently throughout daily and seasonal cycles, reducing reliance on energy storage and backup generation.

The stability and survivability of floating hybrid platforms depend heavily on the design of their mooring systems. Mooring mechanisms anchor the platform to the seabed, and decentralized or flexible configurations allow the structure to adapt to changing sea states. Such systems reduce concentrated stress during storms and increase overall safety and durability [255].For example, tension-leg mooring systems offer lateral flexibility while maintaining vertical stability. Incorporating real-time load sensors enables continuous monitoring of mooring tension, helping to prevent fatigue-related failures by responding to excessive stress. Efficient storage and energy management systems are also essential for hybrid offshore energy platforms. These systems coordinate the interplay between grid dispatch, energy generation, and storage operations [256].Stored energy is used strategically to compensate for periods of low generation [257],while loads are prioritized based on supply availability and demand requirements. Combining batteries which offer longer-duration storage with super capacitors, which provide rapid power delivery, ensures stable, reliable, and smooth electricity output even during fluctuations in resource availability.

9. Conclusion and Discussion

A promising move toward sustainable energy generation is represented by FRE technologies, such as OWT, FPV, and floating wave and tidal energy systems. These technologies have the special benefit of using water bodies to generate renewable energy, which helps to resolve land-use issues and preserve valuable land regions. As these systems develop further, their incorporation into existing electrical grids, efficiency gains, and continuous technological improvements show great promise for a worldwide energy shift. Nevertheless, a number of obstacles still exist in spite of the potential of FRE technology. The substantial upfront capital expense of installing these systems is one of the main issues. The cost is increased by the infrastructure needed to implement floating devices, such as strong anchoring systems, cutting-edge materials, and specialized installation procedures. Operational costs are further increased by the difficulty of maintenance in challenging marine settings. To lower costs and improve the financial feasibility of these technologies, ongoing research and development is essential in fields including material innovation, maintenance automation, and hybrid energy solutions. Concerns are raised about floating systems from an environmental standpoint, even though they typically have benefits like less land use and less water evaporation than conventional terrestrial-based systems. For example, the installation and use of floating energy systems may cause disturbances to marine ecosystems, particularly with regard to underwater noise, changes in water flow, and the loss of aquatic species' habitat. Although careful site selection and design may reduce these effects, thorough environmental studies must be carried out to make sure that the advantages outweigh any possible ecological concerns. The novelty of this review lies in establishing a structured comparative framework that integrates technical, economic, and environmental parameters across multiple FRE technologies. By synthesizing cross-disciplinary data into a unified assessment, the study identifies hybrid floating platforms as the most viable direction for future offshore renewable development. This analytical approach provides both a benchmark for future research and a foundation for technology optimization and policy formulation.

Furthermore, HFRE platforms which integrate wave, wind, and solar energy are gaining popularity. By utilizing various renewable sources at once, these hybrid systems have the potential to increase energy efficiency and reliability while mitigating the intermittency problems that frequently beset standalone energy systems. The capacity of hybrid systems to deliver a more reliable and regular energy source is anticipated to be a major factor in their adoption as they advance, especially in distant or offshore locations. It is anticipated that as the market for floating renewable energy continues to grow, these systems will become more cost-competitive with traditional land-based energy systems, which will help to expand the use of renewable energy. Cost analyses indicate that although the initial investment is still high, continuous improvements in design, manufacturing methods, and scale economies are steadily lowering the costs of FRE systems. Additionally, government incentives and policy support, such as subsidies, tax breaks, and feed-in tariffs, play a significant role in improving the economic feasibility of these technologies.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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