

Review article

An interdisciplinary literature review of floating solar power plants

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ABSTRACT

Floating photovoltaic is predicted to be the most ubiquitous energy technology in the future, with global installations projected to reach 10 GW by 2030, potentially generating 13.5 TWh of clean electricity annually. The extrapolation of solar power plants from land-based to water-based requires interdisciplinary expertise from fields such as energy systems, hydrodynamics, structures, environments, and electrical engineering. To bridge the disciplines, the present review analyses existing floating solar related publications comprehensively. Initially, a comprehensive literature scan of over 900 publications is presented, selectively leading to approximately 400 papers included. Subsequently, three review sectors are presented: design, modelling, and environmental effects. These cover various structural components, system-air-water interactions, their modelling approaches, power output prediction, and potential impacts on the surrounding environment including vegetation and animals. Key findings suggest the potential for enhancing energy efficiency through water-based cooling techniques, innovative modularised designs to support upscaling, positive environmental impacts including artificial habitats, and the utilisation of advanced marine structure designs such as a breakwater to protect the solar systems from ocean wave loads. In addition, the levelised cost of electricity of various floating solar studies are presented, including both theoretical and practical projects. The levelised cost of electricity has been decreasing, to a level of 0.05–0.07 USD/kWh, making FPV increasingly competitive as a clean and affordable energy choice. Overall, this review aims to facilitate interdisciplinary research and projects on the booming floating photovoltaic industry.

Contents

1.	Introduction	2
2.	Literature scan and analysis	4
3.	Design	5
3.1.	Structural design	5
3.1.1.	Floating support	5
3.1.2.	Hybrid design of FPV and other energy systems	7
3.2.	Auxiliary	7
3.2.1.	Cooling systems	7
3.2.2.	Cleaning system	8
3.3.	Materials	8
3.3.1.	Bifacial/submerged FPV floating photovoltaic systems	9
4.	Modelling	9
4.1.	Wind loads	9
4.2.	Hydrodynamic loads	11
4.2.1.	Wave loads	11
4.2.2.	Current loads	13
4.3.	Combined loads	13
4.4.	Fluid–structure interaction	13
4.5.	Heat transfer	14

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4.6.	Power prediction	14
5.	Environmental effects	15
5.1.	Effects of FPV systems on the environment	15
5.1.1.	Evaporation	15
5.1.2.	Water quality and algae blooms	15
5.2.	Effects of the environment on FPV systems	17
6.	Summary and recommendations for future work	18
7.	Conclusions	19
	CRedit authorship contribution statement	19
	Declaration of competing interest	19
	Acknowledgements	19
	Appendix A.	19
	Appendix B.	21
	Appendix. Data availability	21
	References	21

1. Introduction

The global energy portfolio is transforming, driven by climate actions with a growing demand for zero-emission generations. Solar energy, particularly photovoltaic (PV) technology, plays a vital role in this trajectory, with rapidly increasing installed capacity and decreasing costs (as shown in Fig. 1). As countries set ambitious renewable energy targets, PV installations have become ubiquitous in urban and rural settings. However, the expansion of land-based PV systems has highlighted a critical challenge – competition for land usage. As plans for PV deployment reach the ambitious target of over 14,000 GW by 2050, a critical question emerges: where can we deploy these solar power plants that require extensive surface coverage [2]. Contemporary FPV installations approximately cover 165 Acres per GW (based on 150 W/m²), conflicting with human activities, infrastructure, transportation, and agriculture use [3–5].

To address this challenge, floating photovoltaic (FPV) systems have emerged as an innovative solution to expand the solar capacity without occupying more lands. FPV has been successfully implemented on calm water worldwide, e.g. on natural lakes [6–10] and water reservoirs [11–20]. Recently, a growing interest in deploying FPV on seas has arisen due to the abundant space, i.e., [21–23]. In general, the future blueprint of global PV development will have a significant share for FPV, and this has been attracting numerous stakeholders in both industry and academia.

Compared to its land-based counterparts, the advantages of FPV systems are:

- Cooling and dust-reducing effects: floating systems installed on bodies of water can take advantage of natural cooling to operate at lower temperatures. This can increase power generation efficiency [24] and can help gain additional energy by up to 10%–12% [25].
- Reduction in water evaporation: the coverage of FPV on the water surface conserves water by lowering the temperature of the water and reducing the size of the water area exposed to air. As stated in [26], this is particularly beneficial in arid climates such as Central Australia or the Sahel region, where more than 80% of the water evaporation of the covered surface can be saved.
- Shading effect: the placement of FPV systems can reduce the amount of sunlight that penetrates through the water. This shading effect can effectively reduce undesired algae growth and the likelihood of developing toxic species [27]. The algae growth depends on climate conditions and on the percentage of the covered surface. When the water surface coverage is between 40%–60%, it could cause a notable decrease in algae blooms [28].
- Installation: inland FPV plants can be installed easily as water body is often flat and hardly has obstacles. Water-based engineering work requires much less ground planning than land, and it can also avoid shading from surrounding buildings and geographic features [29].

- Hybrid renewable energy systems: PV plants can be integrated with other water-based renewable energy systems to share infrastructure costs and enhance power output. Various hybrid technologies are reviewed in [30,31], such as FPV combined with offshore wind turbines, wave energy converters, and hydropower plants.

Despite the significant benefits of FPV, stakeholders have raised reasonable concerns regarding FPV operation in oceanic environments, particularly related to design and environmental impacts. The deployment of FPV in such environments introduces challenges that require interdisciplinary expertise from fields such as fluid mechanics, structure engineering and hydrodynamics. However, most existing research on FPV systems has been conducted from a solar engineering perspective, leaving significant gaps in the understanding of the hydromechanical and environmental dynamics of FPV systems in oceanic settings.

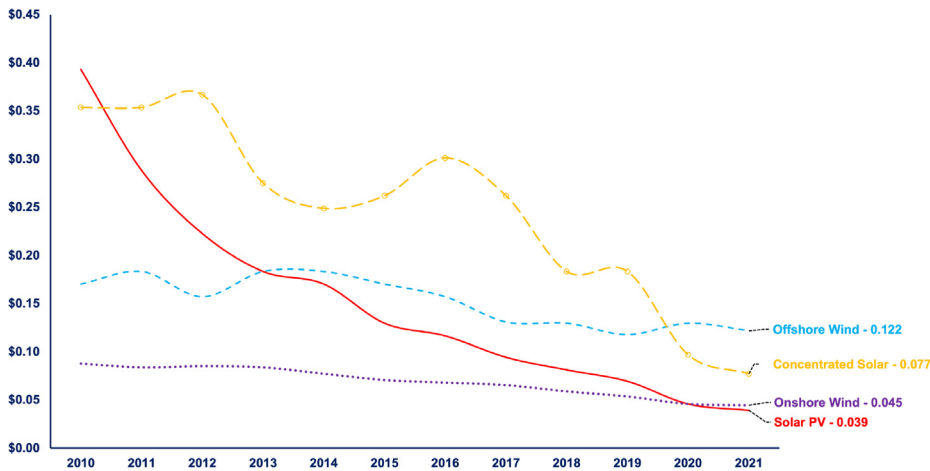
While numerous valuable review and journal paper have covered various aspects of FPV systems, including site selection [32–36], installation [37,38], structures [3,22,29,39–59], case studies [60–83,83–91], electrical systems [92–96], sun-tracking [97], environmental effects [98–113,113–115], cleaning [116,117], water-cooling [118–122], hybrid renewable energy systems [30,31], economical aspects [24,123–143], ocean engineering [21–23,144–165], storage systems [166–169], hybrid renewable devices [30,31,84,91,170–201] and future perspectives [21,202–207].

The key innovation of this review lies in its comprehensive, interdisciplinary approach to examining FPV systems. It is one of the first reviews to synthesise knowledge across multiple domains, including hydrodynamics, structural analysis, power prediction, and environmental impacts. This review uniquely combines the analysis of technical engineering challenges with environmental considerations. By applying expertise from near/offshore structures to this emerging technology, the paper adopts a multi-physics perspective, examining the complex interplay between hydrodynamic forces, structural responses, heat transfer mechanisms, and power generation efficiency. Another key contribution is that the review synthesises research on both the environmental impacts of FPV systems and the effects of environmental factors on FPV performance. This dual focus provides valuable insights into the reciprocal relationship between FPV technology and its surrounding ecosystem. By consolidating current knowledge, evaluating modelling techniques, and highlighting areas for further investigation, this review establishes a robust framework for future research in floating solar technology.

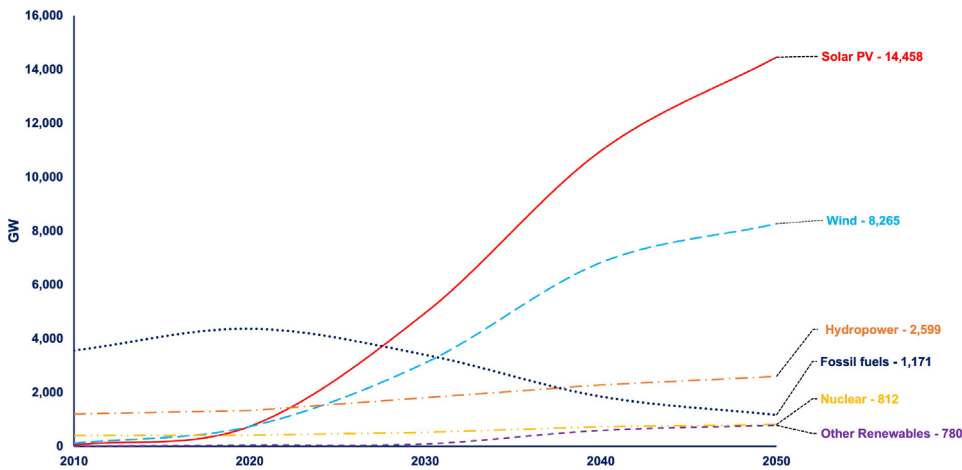
In this context, the present paper scrutinises the FPV literature, divided into three main aspects: design, modelling and environmental impacts. This review demonstrates (a) how FPV design has been evolving to support PV panels and sustain in wind, current, and wave conditions, (b) how computational and experimental modelling techniques have been used to evaluate and optimise the designs, (c) the interactions between FPV and the water environment — how positive environmental impacts are assessed and utilised, and how negative

Nomenclature	
Abbreviation	Meaning
PV	Photovoltaic
FPV	Floating Photovoltaic
LCOE	Levelised Cost of Energy
CAPEX	Capital Expenses
OE	Ocean Engineering
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
FE	Finite Element
HDPE	High-Density Polyethylene
BEM	Boundary Element Method
DNV	Det Norske Veritas
FSI	Fluid–Structure Interaction
LPOFPV	Polymer Offshore Floating Photovoltaics
EBVK	Euler–Bernoulli–von Karma
FRP	Fibre-Reinforced Polymer
MEPCM	Microencapsulated Phase Change Material
PCM	Phase Change Material
SAM	System Advisor Model
EVM	Evaporation Model
RAO	Response Amplitude Operator
Symbol	Meaning
m^2	Square Metre
km^2	Square Kilometre
MW	Megawatt
km/h	Kilometre per Hour
W	Watt
GW	Gigawatt
MWp	Megawatt-peak
mph	Miles per Hour
TWh	Terawatt-hours
y	year
s	Second
λ	Wave Length
L_{float}	Floater Length
F_{Wave}	Wave Force
ρ	Water Density
g	Gravitational Acceleration
H	Wave Height
L	Structure Length
A	Project Area of Panels
C_D	Drag Coefficient
V	Wind Speed
β	Incident Wind Angle
C_S	Shielding Factor
P_m	Module Power
P_{peak}	Module's Peak Power
$G_T, G_{SI}, G_{T,NOCT}$	Intensity of Total Irradiance on the Module Surface
T_m	Cell Temperature
T_{NOCT}	Nominal Operating Cell Temperature
$T_{a,NOCT}$	Ambient Nominal Operating Cell Temperature
η_m	Module Efficiency
A_p	Effective Area
η_P	PV System's Efficiency
$\tau\alpha$	Coefficient of Transmittance Absorptance
η_{cable}	Efficiency of the Cable
$\eta_{inverter}$	Efficiency of the Inverter
$\eta_{transformer}$	Efficiency of the Transformer
I_S	Incoming Irradiance

U_c	Current Speed
T	Wave Period
β_w	Wave direction
P_{out}	Power Output



(a) Cost of renewable technologies, \$/kWh [1]



(b) World power capacity by sources [2]

Fig. 1. Comparison of costs and installation capacity of energy technologies [1,2].

environmental impacts are identified and managed. Finally, this review discusses research gaps and provides suggestions for future research.

2. Literature scan and analysis

The first step of this review is to investigate FPV research articles, reviews, and proceedings available in the scientific literature. The literature scan was performed using the Web of Science, searching for “floating solar”, or “floating photovoltaic”, or “floating PV”, or “FPV”

in any paper’s title and abstract. Around 900 papers were found as of October 2024. Their distribution by publication year is shown in Fig. 2. The increasing articles confirm that FPV is an emerging research trend with majority the of publications appearing from 2020 onward. From the research category, it is evident that a substantial number of papers are case studies and techno-economic analyses; many of these papers may not be established based on an available technical solution, e.g. assuming FPV could be placed in a specific region and evaluating the potential impacts. Although engineering-based papers

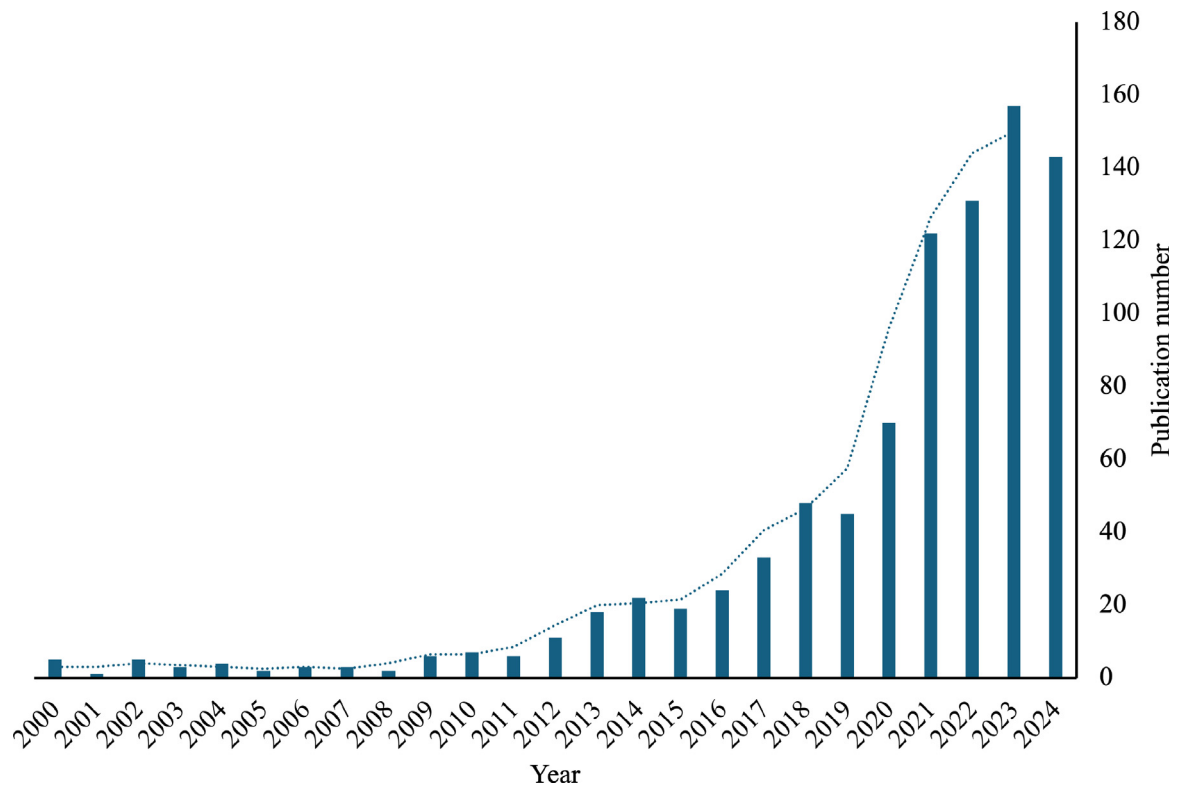


Fig. 2. Publication number of FPV research by year (data accessed on 01 October 2024 from Web of Science).

discuss the technical viability and are the prerequisite of large-scale FPV deployment, these papers are a minority; this indicates that the actual engineering aspects of FPV are currently understudied. As such, there is a need to review FPV's contemporary status and identify future research directions. There are also certain papers focusing on solar cell technology itself but not necessarily specific to FPV; this part of the papers will not be discussed in the present review as they are out of the scope. As an error analysis, since it is impractical to discuss over 900 papers in this review, the authors selected around 400 to be included in this review, focusing on technical papers that are underdeveloped. Here, a bias can exist. Additionally, grey literature (e.g. reports) is not indexed in the Web of Science and therefore is omitted in this review.

3. Design

The design for FPV structures has not yet been standardised. This means that there is currently no universally accepted set of guidelines or specifications for designing FPV structures. However, Det Norske Veritas–Germanischer Lloyd (DNV GL), a global classification society, has recently provided some valuable insights and recommendations in their publication titled “Design Considerations for FPV Structures” [208]. Three key requirements that should be taken into consideration when designing FPV structures are highlighted below.

- **Reliability:** since FPV systems are installed in water bodies, the material of the floating structure should withstand marine corrosion and humidity. Their structure must sustain environmental loads, such as wind, wave and current. Potential biological growth should be taken into consideration when assessing the structural reliability under environmental loading. Additionally, an effective Operations and Maintenance (O&M) strategy,

e.g. cleaning, is essential for the long-term performance and cost-effectiveness of an FPV system [92].

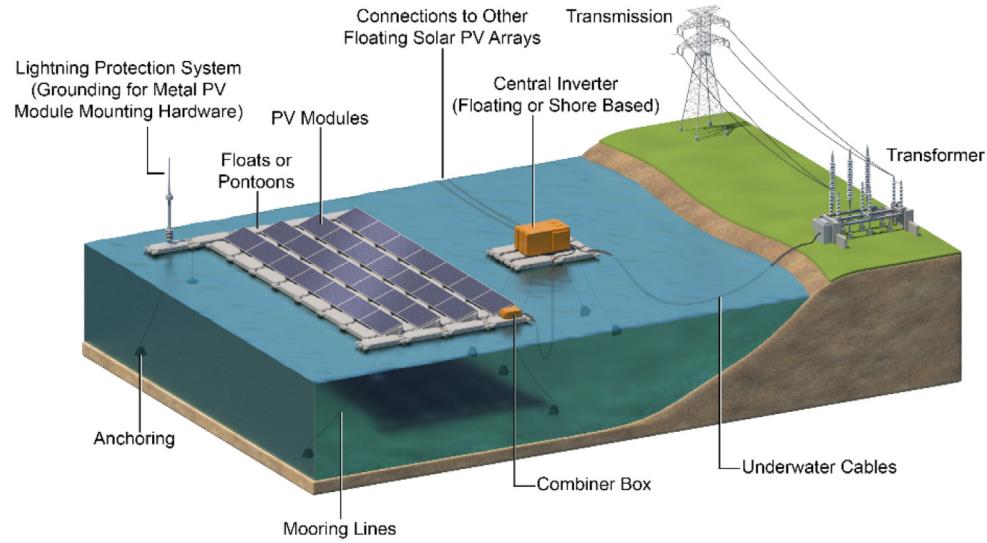
- **Scalability:** an FPV plant should be scalable to meet various power requirements of different sites, making the deployment and relocation of the systems straightforward and cost-effective [209].
- **Sustainability:** FPV systems should be designed considering its environmental impacts, minimising negative effects on the local ecosystem, water quality, and aquatic life. It is important to carefully assess the potential environmental effects such as shading, changes in water temperature, and alteration of water circulation patterns. Additionally, the design should consider using eco-friendly materials, recycling end-of-life components, and following relevant environmental regulations and guidelines [4].

3.1. Structural design

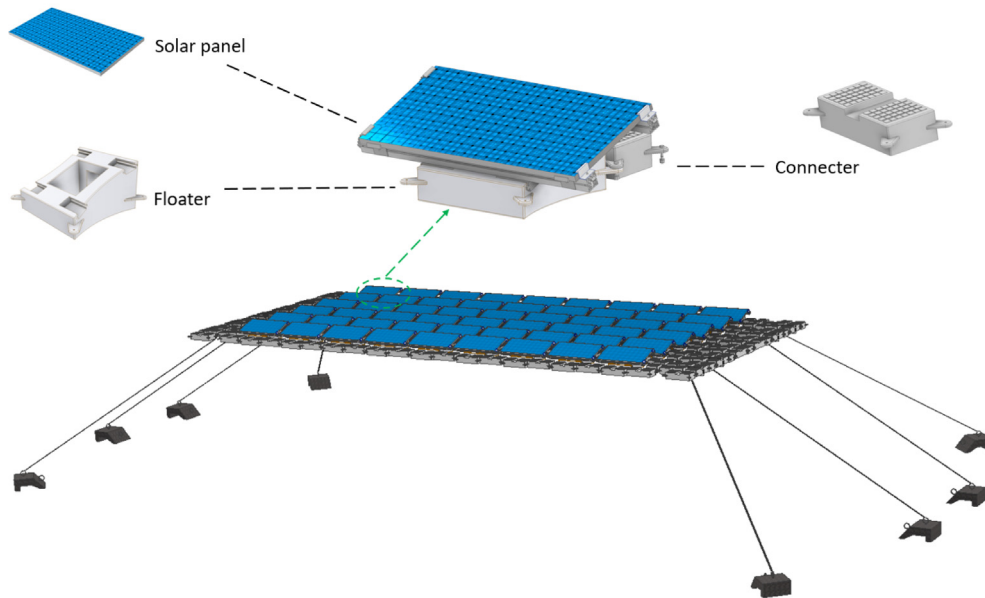
The base structure of FPV typically relies on a floating platform, to provide buoyancy that supports PV panels installed above, alongside an anchoring and mooring system to keep the platform in the desired position [210], as shown in Fig. 3. The platform size is determined based on the power requirement of the site. Similar to land-based PV power plants, FPV can use a central inverter or multiple string inverters for alternating-current conversion and power transmission through cables and connectors [202]. A comprehensive review of various innovations in the structural aspects of FPV systems over the last two decades is presented below.

3.1.1. Floating support

The floating support provides essential buoyancy and restoring forces, making it crucial to design with consideration for deployment



(a) Overview of the application [30].



(b) Structural components of an FPV platform

Fig. 3. Schematic of a typical floating solar farm with key elements.

environments and conditions [162]. The classification of FPV structural arrangements is distinguished into three main categories: *modular*, *integrated* and *superficial* [145,146,211–213]. Since the amount of PV panels used in a power plant is completely flexible, a *modular* design may be adopted, where each PV panel may have its corresponding floating unit power, and the whole power plant consists of individual FPV units connected, as shown in Fig. 4(a). The *integrated* design applied large-dimension rafts made of high-density polyethylene (HDPE) pipes in combination with metal bars to complete the structure, as shown in Fig. 4(b). The above two designs use floaters to lift the solar panels above the sea surface. By contrast, Fig. 4(c) shows the *superficial* design where a membrane is placed on the ocean surface and solar panels are deployed on top; meanwhile, a doughnut shape of the barrier may be applied on the edge of the membrane to enhance the

hydrodynamic performance. Due to the mechanical distinction among these three designs, their ocean engineering (OE) performance can be significantly different, particularly during the structural interaction with waves. A modular FPV power plant presents multiple rigid bodies connected through joints, an integrated FPV power plant behaviours like a large rigid body, while a superficial FPV power plant tends to present a hydroelastic behaviour where the membrane contours with the variation of the water surface.

Kaymak et al. [216,217] conducted an assessment of structural failure on steel-frame type FPV power plants installed on Büyükçekmece Lake in Istanbul, with three scales of 9 kWp, 30 kWp, 90 kWp. The fatigue study lasted for 20 months, during which the research examined the floaters, frames, and their connections for difficulties and critical faults. The study revealed that the integrated design can lead to high



(a) Modular floating support [212]



(b) Integrated floating support [212]



(c) Superficial floating support [214]

Fig. 4. Primary categories of buoyancy providers for PV [214,215].

bending loads and subsequent structural failure due to hydroelastic effects.

To mitigate the hydroelastic impact on the system, an alternative design approach is to modularise the entire FPV system. This design employs multiple connections, either rigid or soft, allowing the power plant to move along the wave propagation so as to withstand rough waves without experiencing local stress peaks [218]. This not only increases the system's longevity but also enhances its performance in harsh weather conditions, making it ideal for large-scale use [22].

Several publications can be found on the development of modular types of FPV. For instance, Kim et al. [219] presented a unit structure framework of modular FPV that was linked by stainless C-type hinges. The hinge designs were observed to have a positive impact on minimising local shear stress and their effects of reducing the induced bending moments. Specifically, the research recommended using fibre-reinforced polymer (FRP) members for floaters, which offer superior performance, corrosion resistance, and cost-effectiveness compared to traditional materials. In addition to this, Dai et al. [220] proposed a modular FPV frame design that is corrugated with ribs and troughs to mitigate possible accidental slipping and carry more imposed load than a flat surface. The FEA analysis is further conducted to examine the local high-shear stress components. Kjeldstad et al. [221] evaluated the performance, reliability, and operational characteristics of the modular design FPV with rotary hinge connections.

Another type of floater is based on the membrane type of FPV. It is strategically positioned in close proximity to the free surface and is designed to move harmoniously with the waves. This unique feature offers several advantages, including the reduction of wave and wind effects on the system [222,223]. The flexibility and suitability of such membrane in wave motions have been thoroughly assessed and reviewed by Mayville et al. [224] and highlighted the potential of flexible design to withstand even more severe sea conditions. In the economical aspect, it could significantly reduce overall costs compared to other options such as raft-based FPV and land-based racking PV. More details are discussed in Section 4.4 below.

3.1.2. Hybrid design of FPV and other energy systems

FPV systems have shown great potential as a sustainable source of renewable energy. However, there are still several challenges to be addressed to ensure the economic and efficient use of these systems [178]. One promising solution is the hybrid design of FPV systems with other marine energy resources. This approach can reduce deployment, maintenance, and decommissioning costs by combining devices in an integrated framework or co-locating distinct technologies in an ecosystem layout [225,226]. Solomin et al. [31] reviewed various novel combinations between FPV systems with other renewable resources, such as offshore wind turbines and hydrogen production, as shown in Fig. 5. Claus and López [227] reviewed the installation guidelines and synergies of marine FPV plants that combine wind turbines and offshore structures.

There are also several publications available on the integration of FPV with other technologies. For instance, Temiz and Javani [228] proposed a hybrid system that combines FPV with hydrogen production in Mumcular Dam located in the Aegean Region of Turkey. The system uses excess solar energy to produce hydrogen, which can be stored and used as fuel for transportation or other applications. Cazzaniga et al. [229] integrated compressed air energy storage with floating FPV. The system uses excess solar energy to compress air, which is then stored and used to generate electricity when solar energy is not available. Choi et al. [230] combined FPV with a thermal power plant ash pond. The system uses the cooling water from thermal power plants to improve the efficiency of FPV systems and reduce the water temperature of ash ponds. In addition, Ramos et al. [231] evaluated the innovative solution for the Renewable Energy Network (Hy4REN) based on well-studied elements to produce the best final solution. The Hy4REN system is a hybrid energy system that combines FPV, wind energy, and energy storage to provide a reliable and sustainable power supply.

3.2. Auxiliary

3.2.1. Cooling systems

FPV systems can naturally benefit from the cooling effects of the surrounding environment, resulting in improved energy conversion performance and longer module lifespan. Golroodbari and van Sark [233] predicted from simulation results that the annual average output

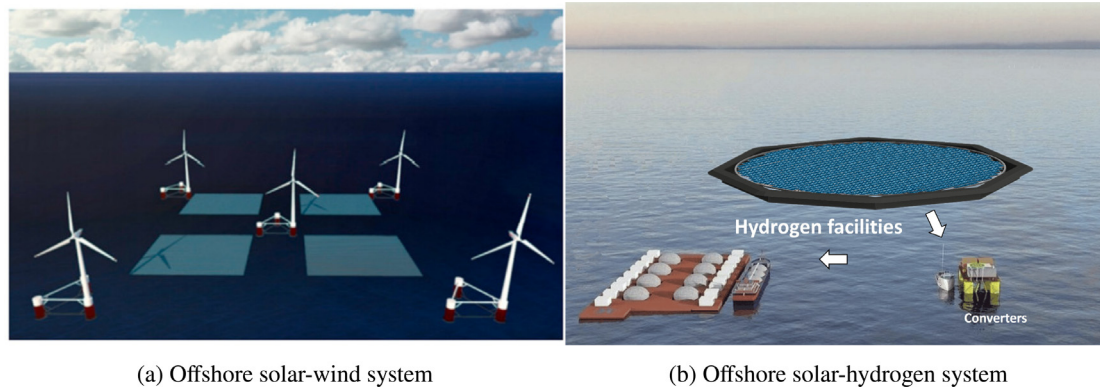


Fig. 5. Examples FPV-related hybrid energy systems [31].

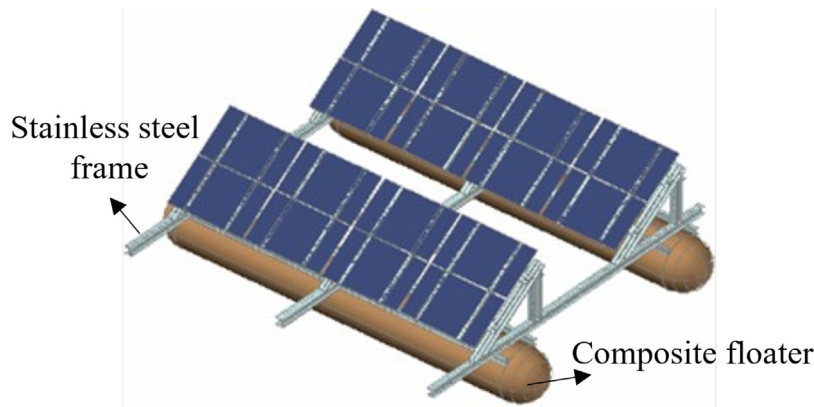


Fig. 6. Example of combined composite and metal materials for FPV structure [232].

energy of a floating solar farm can increase by approximately 12%–18% compared to an on-shore PV farm due to the PV cooling effects. Therefore, to control the PV panel temperature within the optimal working ranges, cooling techniques are important for PV facilities to resist the effects of heat rising due to sun radiation. Some cooling techniques initially investigated for onshore PV plants [234] have shown promising results and can provide inspiration for floating applications.

Since FPV is installed on water, advanced water-based cooling techniques have been proposed. Micheli [235]. The water-based cooling technique includes the water spray application over panel surfaces. Experimental studies were conducted by [236,237] and a series of economic feasibility analyses were carried out by de Oliveira Busson et al. [238] and Micheli [235]. In another study, Sheikh et al. [239] introduced a lightweight and minimally invasive cooling system design with forced water cooling to reduce temperatures and increase system efficiency. A water circulation system was added underneath the PV panels, where water pumps up from the water underneath the system, takes out the heat, and sends it back. Kjeldstad et al. [240] assessed the effect of water cooling on a floating membrane-type FPV system with horizontally mounted PV modules allowing for thermal contact between modules and the water. Recently, Tina et al. [241] conducted an economic analysis of FPV and land PV, taking into consideration the improvement of the energy efficiency of FPV due to the cooling effects. Recent research [242,243] analysed the efficiency enhancement of various cooling techniques for FPV systems.

3.2.2. Cleaning system

Soiling is a common issue in the operation of PV systems. It refers to the accumulation of various particles on the surface of PV panels, such as dust and bird droppings. This accumulation can hinder the absorption of sunlight and lead to a decrease in the performance of PV systems [202]. Dust accumulation can cause a decline in the power generation of PV panels by up to 15% per day [244], thus it is important to clean the solar panels as needed. FPV provides the convenience of the adoption of water-based cleaning approaches, which is deemed effective and cost-effective as reviewed by [116]. Techniques based on applying water to wash PV cells also have additional benefits, such as lowering the operating temperature [227]. However, if the water stays on the panel surfaces, it can cause solar spectrum modification [245] and a change in the reflected light [246], so a tilting angle of the panels may be considered to avoid this. There is also a direction of adding an automated mechanical device to clean the panels, but this may be the most costly [116].

3.3. Materials

The majority of research has focused on using composite materials for floaters due to their outstanding strength and buoyancy. Composite floaters may be combined with metal that provides a structural framework [147,247], as shown in Fig. 6. Lee et al. [232] used Pultruded Fibre-Reinforced Polymer (PFRP) in their structural design to

Table 1
Aerodynamic boundary conditions for FPV analysis.

Reference	Location Inland/Nearshore/Offshore	Wind speed [m/s]	Tilt angle °	Wind direction °	With wave yes/no	$C_l(-)/C_d$ $\beta = 0^\circ$
Yang et al. [261]	Inland (intertidal zone)	6.0~25.0	10	All	Yes	0.75~1.5/not available
Choi et al. [262]	Inland	12	15	0~180	No	Not available/0.1~0.6
Choi et al. [263]	Inland	13.4	10	0~180	No	0.05~0.6/0.15~0.6
Su et al. [264]	Offshore	20	20/40	0~180	No	0.9/not available
Lee et al. [265]	Nearshore	45	15	0~180	No	0.51~0.74/0.67~0.83
Elminshawy et al. [266]	Inland	0~4.2	30	0~180	No	Not available/not available
Choi et al. [267]	Nearshore	35~75	14	0~180	No	0.5~2.5/0.1~0.65
Honaryar et al. [268]	Nearshore	30~40	10	0	No	Not available/not available

prevent corrosion, with computational simulations to ensure structural integrity. Han et al. [248] investigated the use of composite primary beams with a ply of glass fibre fabric, increasing the system's ultimate compressive and bending capacity compared to UPVC plastic tubes, with experimental studies conducted to evaluate its fatigue. Kim et al. [249] incorporated a structure made of high-durability steel in their frame design for a 500-kW-class FPV system. The results showed that the tensile, compressive, flexural, and shear stresses of the applied member structure were within the allowable domestic design stress values. Hayibo et al. [250] conducted a test on a crystalline silicon-based photovoltaic (PV) module backed with foam, resulting in lower operating temperatures and a 3.5% higher energy output per unit of power than conventional pontoon-based FPV. In addition, FPV floaters are consistently exposed to the water-based environment, and the regulations and standards for their long-term durability are insufficient; Liu et al. [251] proposed an accelerated ageing method and fast corrosion methods to address this issue.

3.3.1. Bifacial/submerged FPV floating photovoltaic systems

Bifacial floating photovoltaic (BFPV) technology is an innovative and cutting-edge system that combines the benefits of both bifacial photovoltaic (BPV) technology and FPV systems [252,253]. Bifacial photovoltaic panels are different from traditional monofacial photovoltaic panels in that they can generate electricity from both sides of the panel, which enhances their energy output. A field test study for bifacial PV for inland water areas has been conducted, as reported by Ziar et al. [254]. Researchers have conducted comparative studies between monofacial and bifacial FPV modules for floating power plants, as reported by Widayat et al. [255] and Tina et al. [256]. Additionally, Bhang et al. [257] designed large-scale bifacial FPVs with maximum power density, while Jahangir et al. [258] presented a critical analysis of different bifacial solar farm configurations using theoretical modelling and experimental testing. The study examined several factors that can impact the performance of bifacial solar panels, including the angle of incidence of sunlight, the albedo (reflectivity) of the ground surface, and the height of the panels above the ground. Recent research focused on their combination effects (energy [259], economic and environmental) of bifacial FPV systems with multiple optimisation techniques [260] to identify the optimal panel heights, water depths, and azimuth angles.

Another special FPV type is the Partially Submerged FPV system (PSFPV) can improve performance, energy output, efficiency, and lifespan of the modules compared to the conventional dry design [266]. In previous studies, Lanzafame et al. [246] have conducted simulations and experiments to investigate the energy performance of the single-crystalline submerged photovoltaic (PV) solar panel (SP2), which is dependent on the depth of the water. The main finding is that the PV efficiency is reduced by about 10% when 10% of the SP2 panel is submerged in water and by about 35% when the panel is fully submerged. The optimal water depth for the operation was in shallow water (0 cm to 50 cm) varying with panel materials. Tina et al. [269] and Clot et al. [270] continued studies on SP2 systems with regard

to efficiency increase under high irradiance and ambient temperature and evaluated the increment of efficiency through cooling effects. Elminshawy et al. [271] studied the optimal value for the submerged ratio of PSFPV based on experiments and field tests [246]. The research discovered that submerging the panel by 12% led to a 15.1% reduction in its operating temperature and enhanced the performance ratio of the PSFPV by up to 23%. Additionally, the Levelized Cost of Electricity (LCOE) was reduced by about 11%. The use of PSFPV systems, which incorporate attached fins as an additional passive cooling technique [272], offers superior performance in reducing PV module temperature. Inspiration for this technique can be found in [273]. The effect of attaching lapping fin height, number of fins, fin spacing, and solar irradiance on PV module performance was investigated by [274].

4. Modelling

The placement of FPV systems typically requires a broad and open water area, which exposes them to wind and wave regimes that can pose significant challenges. As illustrated in Fig. 7, FPV systems are commonly subjected to loads from wind, waves, currents, and the combination of these forces. These loads can cause various physical effects, including structural, heat transfer, and power generation, which have critical roles in the overall performance of the system. Therefore, it is crucial to develop accurate and reliable modelling approaches to effectively analyse and understand these aspects. This section provides a comprehensive review of the existent modelling approaches available for studying aerodynamics, hydrodynamics, and their combined effects on FPV systems.

4.1. Wind loads

In particular, wind loads are crucial for FPV systems, as wind flow can come from any direction and is difficult to predict. Despite having a relatively low profile, the panels' large surface area interacts with the air, creating lift forces that can add dangerous moments and overturn the system, making it essential to understand the effects of wind on these systems.

To study wind effects on FPV systems, pioneering research can be found for land-based PV applications, where numerous publications have looked into the influences of the wind conditions [276] on structural perspectives [277] and PV temperature distributions [278,279], to name a few. However, there is a lack of research on wind effects specific to FPV applications, which are unique due to their floating nature.

One of the recent FPV accidents was induced by Typhoon Faxai in September 2019 [280]. Japan's largest floating solar plant location at Yamakura Dam, with an effective installation surface of approximately 18,000 m² and a maximum output of 13.7 MW, was damaged by the 120 mph wind brought by Typhoon Faxai [3,267]. The strong wind caused the modular FPV to stack on top of each other, and the collisions between the structures resulted in failure and damage to the power system. This caused contact between loose and moored panels, and overheating of around 50 panels resulted in a fire. This unfortunate

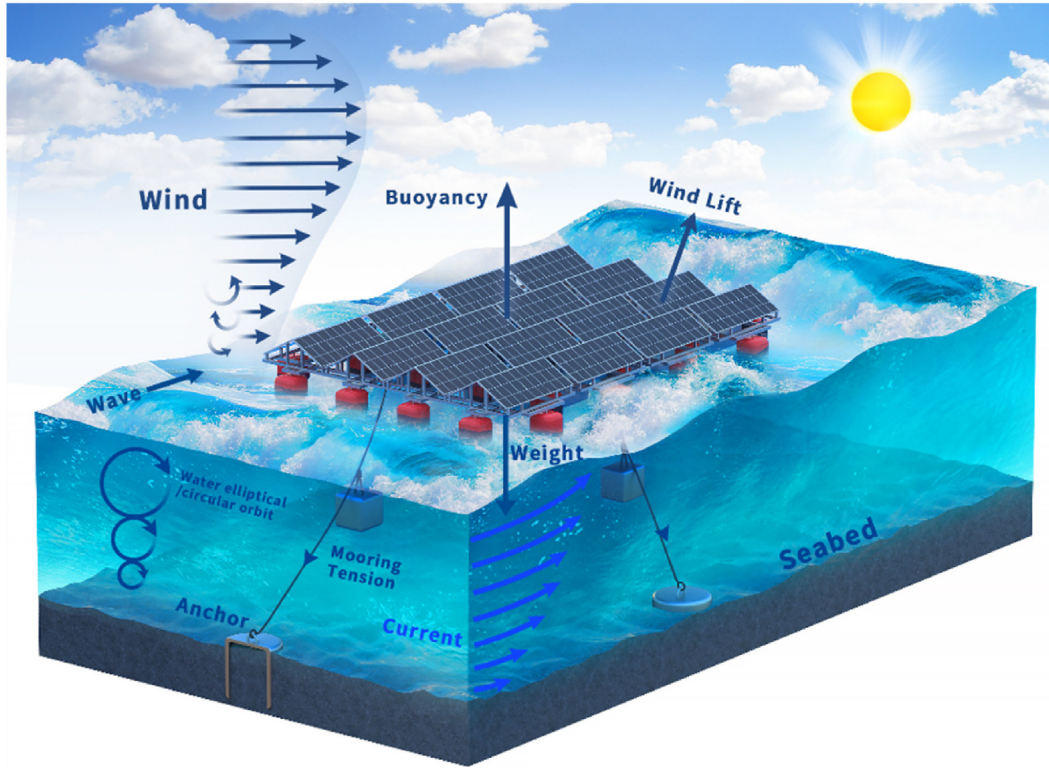


Fig. 7. Illustration of various environmental loadings on an FPV system [41].

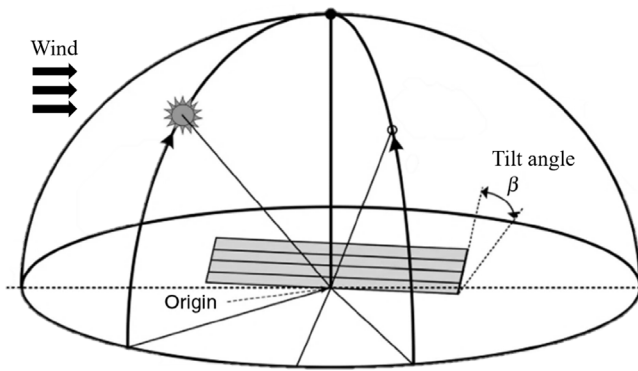


Fig. 8. Representation of wind direction and tilt angle of a solar panel [275].

event highlights the need for a better understanding of the wind-structure interaction studies to ensure the safety and stability of the FPV systems.

Table 1 summarises the wind load conditions, including the ranges of wind speeds (0–40 m/s), wind directions (0–180°), PV tilt angle β (10–40°) and the lift and drag coefficients C_l/C_d . The tilt angle is illustrated in Fig. 8. The table also includes the deployment sites from inland to offshore, highlighting the need to customise the analysis of loads and system dynamics to specific conditions.

Wind loads are typically measured in the streamwise and vertical directions, which correspond to the drag and lift forces, respectively. The drag force can be predicted by the equation $F_y = 0.5C_D\rho V^2A$, where C_D represents the drag coefficient, A is the projected area of panels in the wind direction and it is proportional to the square of wind force. Several windy environments may induce large drag forces of the system, which result in significant structural drift, an increase in mooring tensions and overlapping between connections objects [261, 281]. On the other hand, the lift force needs more attention in floating systems because its action affects the balance of buoyancy and gravity, which may result in the structure's overturn and submersion. It can be predicted using the following equations [267]: $F_z = 0.5C_L\rho V^2A$. Several studies have analysed the influence of each parameter based on these equations, including wind speed, wind direction, and tilt angle on the wind loads of the structure [261, 264, 268, 282, 283]. Recent research from Velaz-Acera et al. [284] determined ideal tilt angles based on intelligent optimisation (Genetic Algorithm), resulting in LCOE improvements of 2.1% to 8.4% compared to conventional ground-based methods.

Honaryar et al. [268] presented numerical simulations on a single FPV floater with varying wind speeds using a viscous flow solver. The results indicated that wind loads were dependent on wind speeds. However, as wind speeds increase, waves are induced, and the structure's angular motion is significantly affected by both aero and hydrodynamics. Therefore, to investigate extreme typhoon conditions where wind speeds approaching 30–40 m/s, numerical simulations should generate wind-induced waves accurately. This is a challenging task since such waves require long-term processing, and their shape may not be the same as wind waves in nature, leading to large errors in the simulations.

Considering varying combinations of panel tilt angle and angle of incidence wind, Su et al. [264] conducted numerical simulations on

the wind load effects on a full-scale floating solar panel, taking wave effects into consideration. The critical wind loads are observed at lower angles of incidence for the wind ($\beta = 15\text{--}60^\circ$) when the angle of tilt for the panel is $>30^\circ$. It was found from the surface pressure pattern that flow separation occurs near the front edge, as well as the formation of side-edge and windward vortices. In all cases, the load distribution on the surface panel showed that the highest stress was located at the upper edge of the solar panel. However, it should be noted that such numerical models are unable to consider the mechanical loads on the structural frame. By studying the optimal tilt angle, the peak normal force on panel surfaces can be reduced by about 20%–50% [282].

Wind loads on an individual FPV platform and FPV array can vary significantly [227]. Due to the shielding effects from the front panel to the following panels, the wind loads can be re-formulated using the DNVGL-RP-C205 guidelines [148,285]: $F_w = 1/2 C_D C_S \rho A V^2$, where C_S is the shielding factor. The shielding factor quantifies the proportion of sunlight blocked or diffused before it reaches the solar panels. As such, numerical and experimental studies were conducted by Yang et al. [261] on an individual FPV platform consisting of four rows of panels installed with a tilt angle of 10 degrees. The pressure distribution plot revealed that the largest forces were observed at the windward row, which was approximately twice as large as the other rows. Furthermore, flow separations were created with the circulation airflow generated upstream of the solar panel array to form a negative pressure area, which can impact the stability of the system. A similar finding was achieved by the numerical simulation from Choi et al. [267] on the wind loads on a solar panel array. The drag and lift coefficients of the solar panel array gradually decreased along the wind direction because of the sheltering effect of the first row of solar panels. Furthermore, the drag and lift forces on the solar panels increased with the turbulent kinetic energy, especially for the first row of solar panels. The vortex formed at the side edges, and the chaotic flows may cause structure instabilities. Therefore, it is crucial to consider the wind load conditions during the design phase for FPV arrays to ensure that it is structurally reliable and can withstand harsh environmental conditions. Although the spacing of solar panels has been found to have no significant effect on wind loads [283], none of the existing research looks in-depth into multi-array FPV designs. Therefore, this conclusion may be limited to a small scope.

It is worth noting that wind loads can also have significant economic implications for the design of FPV systems. Choi et al. [263] examined wind load on FPV arrays through experimental and economic analyses. The study specifically measured pressure distributions on each panel surface and derived drag and lift coefficients at various wind inlet directions. The research recommended that a higher-strength structural design should be applied to the surrounding edges of the FPV platform, while the inner part can be made of less rigid material. This approach can help to reduce manufacturing costs, as well as to increase the potential for higher output power. Replacing the material of the centre of the solar panel array with less expensive materials resulted in a 7% reduction in manufacturing costs for a single solar panel and a potential increase of up to 19% for a 2.5 MW system.

In Choi et al. [262], the research conducted a safety analysis using a one-way coupling Computational Fluid Dynamics (CFD) & Finite Element Analysis (FEA) simulation to study the motion and loads of a modular FPV system exposed to severe environmental conditions. The effects of the inlet angle of wind loads were analysed in detail. First, wind loads were estimated using the CFD method. It was found that wind loads on the first and last rows of solar panels showed higher values due to the sheltering effects. Afterwards, FEA was conducted using boundary conditions obtained from the CFD and hydraulic dynamics results. The FEA results showed that the junction at the frame between the floating body and the PV panel was subjected to the highest stress in the single-unit FPV system.

Lee et al. [265] conducted an analysis of the wind–wave coupling effects on two different types of FPV frameworks utilising CFD methods [154]. The two types of framework investigated were the frame

type and pontoon type. The study showed that the structures' response to waves, especially pitch motion, can result in blocking effects on the wind on one side of the framework. In contrast, blocking the backside of the PV panel further reduces fluid-dynamic force by removing flow impingement on the panel.

Conversely, the movement of air brought by the wind can remove some of the heat from the FPV structure. As the temperature has a direct impact on PV efficiency [245], FPV may benefit from the wind as a passive coolant to increase system efficiency. According to a series of experiments conducted by Elminshawy [266], including wind directions and speeds, the average output power of semi-submerged FPV was observed to increase by about 20% due to the cooling effect provided by the blowing wind (0–15 km/h). It is important to note that the increased power efficiency is partly due to the water coolant, and the results are valid only for this type of FPV.

4.2. Hydrodynamic loads

One of the striking differences between land-based and floating PV installations in terms of loading conditions is the additional hydrodynamic loads on the system. The hydrodynamic loads can be distinguished between wave and current loads, while, in situ, often a combination of those loads prevails. However, FPV installations, if not built from entirely new materials, such as flexible membranes, are usually fashioned from modular, lightweight, interconnected structures. Thus, while, some of the findings from classical coastal, naval, and offshore engineering for complex floating structures (e.g. [295]) may provide valuable insights into the hydrodynamic behaviour of FPV systems [145], specific analysis is required and knowledge for FPV systems needs to be expanded

4.2.1. Wave loads

Hydrodynamic wave loading is studied in a number of publications, considering varying combinations of wave heights and periods. Depending on the location of their deployment, FPV systems may be exposed to significantly different load conditions. Table 2 summarises the wave load conditions, considered in the literature. The considered range of wave heights (0.04–17.08) and wave periods (0.2–16) across the literature, together with the ranging deployment sites (small inland lakes to offshore [296]) highlights the importance of tailoring the analysis of loads and system dynamics to the prevailing conditions.

Ikhennicheu et al. [290] present a comprehensive study, considering three different deployment sites with varying system sizes: small inland lake (2.5 MWp), large inland lake (7.5 MWp), offshore site (2.5 MWp). The specific wave conditions can be extracted from Table 2. It should be noted that wind loads are also considered for all case studies and current loads are included for the offshore site. Based on an industry-standard quasi-static analytical analysis, the research finds the loads on the FVP system to be the smallest for the small lake deployment. Despite the significantly larger size of the large inland lake installation, the largest loads are found for the offshore installation. For this case, it is also highlighted that wave loads dominate the overall loading of the system, while for the lake installations, wind loads are significant. Such larger loads in the offshore compared to the inland environment are confirmed by Claus and Lopez [145]. From their findings on the different load conditions for varying installation size, Ikhennicheu et al. [290] finally conclude that the “ratio of loads over installed power will become more favourable for the offshore case” once such installations get larger.

Considering varying wave conditions, many studies highlighted the influence of the ratio between wavelength and floating-unit dimensions [147,286,288,289,297,298]. In a fundamental study on resonance effects enclosed shallow water basins with slender floating elastic bodies, such as FPV systems, Papathanasiou et al. [297] highlighted that the eigenstate of the basin can be significantly influenced by the

Table 2

Hydraulic boundary conditions for FPV analysis. All wave heights, wave periods, and current speeds are given at full scale. If no scaling is provided, quantities are marked with an asterisk. Symbols in this table: H wave height, H_s significant wave height, T wave period, T_p : peak wave period, U_c current velocity.

Reference	Location	Wave height	Wave period	Current speed	WCI
	Inland/Nearshore/Offshore	H/H_s [m]	T/T_p [s]	U_c [m s^{-1}]	Yes/no
Lee et al. [286]	Nearshore	1.09~1.35	4~7	Not available	No
Lee et al. [287]	Nearshore	0.20~1.30	3.22	Not available	No
Lee et al. [288]	Nearshore	0.04~0.12*	0.90~1.24*	Not available	No
Al-Yacoubi et al. [289]	Offshore	3~9.5	9~22	Not available	No
	Inland (small lake)	0.26	1.1	Not available	No
Ikhennicheu et al. [290]	Inland (large lake)	0.90	2.2	Not available	No
	Offshore	2.0	6.0	1	Yes
Ikhennicheu et al. [149]	Inland	0.9	2.2	Not available	No
Dai et al. [291]	Inland	4~6	0.2	Not available	No
Friel et al. [292]	Nearshore	2~8	0.5~1	Not available	No
Sree et al. [293]	Nearshore	0.2~2.5	0.5~5.5	Not available	No
Abbasnia et al. [147]	Offshore	0.252~0.284	1.76~4.24	Not available	No
Magkouris et al. [211]	Offshore	0.5~3	4~9	Not available	No
Ghigo et al. [146]	Offshore	0.375~1.125	3.625~5.375	Not available	No
Han et al. [248]	Not available	0.3~0.6	2~3	0.7~0.8	Yes
Kaymak et al. [216,217]	Inland	0.56~17.08	Not available	Not available	No
Li et al. [294]	Inland	1.5	18.9	0.32	No
Yang et al. [261]	Nearshore	0.8~3	2.8~16	Not available	No

presence of FPV systems, in particular when the plate span was approximately half the basin length. The research further indicated that the occurring resonance effects may have a significant influence on the structural integrity of the system. However, the study was performed for relatively shallow basins with thin hydroelastic structures, thus, findings were only applicable to a particular type of installation. More practically, Lee et al. [288] investigated the loading, mooring line tension, and Response Amplitude Operators (RAOs) of a modular 4×4 arrangement of raft-type, hinged floaters, designed for deployment in the nearshore environment. The research found a linear increase in the RAO for heave and pitch with increasing relative wave lengths (λ/L_{float}), where L_{float} is the overall length of the floating structure. The pitch RAO convergences for $\lambda/L_{\text{float}} > 2.4$. In terms of mooring loads, the study found peak loads for $\lambda/L_{\text{float}} = 2$.

The analysis of structural and/or mooring loads, as well as the RAO of FPV systems, is the main purpose of the different studies considering hydrodynamic wave loading [147,149,288,292,293]. To that end, various analysis tools and modelling approaches are exercised, ranging from analytical method [216,217,249,290,299] to high-fidelity computational simulation [248,286,289] and experimental tank testing [147, 261,288,293].

Analytical modelling techniques, such as the quasi-static model in [290] used for mooring design, showed the advantage of fast turnaround times, enabling excessive parametric studies. While wind and current loads are included in the analytical model via simple drag force calculations including empirical coefficients for drag and sheltering effects, wave loads are considered under the assumption of large bodies in deep water, thereby neglecting first-order wave loads. Following [300,301] with pre-defined reflection characteristics of the FPV installation [302], wave forces are expressed as $F_{\text{Wave}}(N) = 0.1 \cdot \rho g H^2 L \beta_w$, where ρ is the water density, g is the gravitational acceleration, H is the regular wave height, β_w is the wave direction, and L is the width of the FPV installation (exposed to the waves). Based on the acquired loads, an initial mooring design is proposed.

In [149], the research performed a more detailed analysis of the system dynamics of a float array, using the non-linear time-domain model OrcaFlex. While a 3×3 floating array serves as a baseline, three different modelling approaches are considered: (1) all floats are treated as single floats (no hydrodynamic interaction); (2) rigid ensemble, where all floats are treated as one rigid body; (3) multi-float arrangement, accounting for hydrodynamic interactions between floats. While the research finds that the assumption of a rigid ensemble largely under-estimates the system dynamics (expressed by means of

RAOs in heave and pitch), the consideration of the multi-body system without hydrodynamic interaction results in acceptable differences (slight over-estimation) compared to the multi-float arrangement while saving significant computational resources.

Other non-linear time domain modelling tools based on potential flow theory can be found in [292,303] for the analysis of the system dynamics of a single rigid tube type FPV system or in [146] for the definition of the environmental loads and system dynamic during the performance evaluation of an FPV system.

Computationally more efficient models based on linear potential flow theory solved by using the boundary element method (BEM), e.g., in [211,261,287,294]. For instance, Li et al. [294] employed the commercial BEM solver Ansys AQWA to gain the hydrodynamic loads on an FPV array, considering the array as a single rigid body. The hydrodynamic loads were then fed into the structural analysis in the remainder of the study, using a finite element (FE) model. Also considering a coupling between FE and BEM, Dai et al. [291] performed a limited study on the hydroelastic displacement of FPV floats and the corresponding von Mises stress. However, the research found that the occurring hydrodynamic loads are, in this case, insignificant compared to other loads acting on the system. Similar to Li et al. [294], Lee et al. [287] also employed Ansys AQWA and compared results of the acting hydrodynamic pressure on a 4×4 FPV array, considered as rigid body, to common analytical design methods. The research finds discrepancies between the methods of up to 20%, which are, amongst others, attributed to simplifications in the floater shape. Using an in-house BEM solver, Magkouris et al. [211] analyse the dynamics of a twin-hull floating structure for FPV installations in a two-dimensional fashion. With the results from BEM, the research performs a subsequent analysis of the power production of FPV under the influence of wave loading (see Section 4.6).

While linear (e.g. Ansys AQWA) and weakly non-linear (e.g. Orcaflex) hydrodynamic models suffer from well-known model limitations, high-fidelity models based on Computational Fluid Dynamics (CFD) can alleviate such limitations at the expense of high computational cost. For instance, Al-Yacoubi et al. [289] used Ansys' Fluent CFD solver for the validation of an analytical model. Comparing the hydrodynamic forces for different wave heights on a single float of an FPV installation revealed satisfying results between the modelling approaches with differences between 3%–4%. A slightly more detailed CFD analysis was presented by Han et al. [248], employing the STAR CCM+ CFD tool. For the analysis of hydrodynamic forces and system dynamics, the research considered combined loading from wind, wave,

and currents. More details are provided in Section 4.3. Lee et al. [286] used a coupled hydrodynamic and structural solver for their analysis of the stresses on the FPV system. While the information on the specific model setup were limited, the research found a small stress magnitude for longer waves with maximum effective stresses lower than the allowable stress. Wang et al. [136] investigated how draft depth, water velocity, and the number of floating bodies affect the resistance characteristics of FPV, using a $k-\epsilon$ turbulence model and experimental data to analyse flow field characteristics and their impact on drag.

Finally, a number of studies can be found presenting both numerical and experimental results [147,261,288,293]. While the numerical hydrodynamic modelling approach differs (Ansys Aqwa [261], in-house BEM [147], high-fidelity CFD [288,293]), experimental data is used for validation of the numerical model in all studies. The experimental studies, however, differ quite significantly in the setup and investigated structure. Sree et al. [293], for instance, considered the FPV system as a perforated flexible sheet, spanning the entire width of the wave flume. During the experiments, surface elevation and sheet deflection data were recorded using ultrasonic gauges. All tests were conducted at a 1:30 scale. The research noted complications in the correct scaling of the material properties, i.e. Young's modulus, of one order of magnitude. However, comparing numerical and experimental results, the research found a reasonable agreement between the data.

Considering a 4×4 float array including a taut spread mooring system and uniaxial hinges, Lee et al. [288] performed experiments in a towing tank. During the experiments, data of float motion, mooring tension, and free surface elevation were recorded. Information on the scale of the model were omitted. The experimental data were employed to validate a STAR CCM+ CFD model. In particular, the RAOs in heave and pitch, as well as the tension forces were compared for the different loading conditions. The research found "similar trend[s]" in their experimental and numerical results, regarding the numerical model as validated. Recent research from Li et al. [304] investigated the multi-body interaction effects in a four-module hexagon-type FPV using a composite hydrodynamic method, comparing multi-body and single-body models under combined wave and wind conditions, revealing that multi-body interactions lead to more significant motion responses but decreased mooring tension oscillations and maximum values, with varying effects across different modules and environmental conditions. Yang et al. [261] performed an experimental test campaign for a single module of an FPV system in a wind-wave-current flume. For the tests, combined wind-wave loading was considered where irregular waves for operational and extreme conditions, as well as free decay tests, were performed. The module was equipped with a motion tracking system, load cells for mooring line tension and a gyroscope. Furthermore, wave gauges were placed within the flume. To minimise the well-known discrepancy between Froude- and Reynolds-scaling, the research selected a relatively large model scale of 1:4. The experimental data was only used for a relatively basic comparison of the Eigenfrequency of the system, as well as the surge, heave, and pitch motion. While the research found reasonable agreement between the numerical (Ansys AQWA) and experimental data for the pitch motion, the surge and heave degree of freedom showed deviations of factor 2 and 10, respectively. The research argued that differences occur due to the neglected viscous effects in the numerical model. The missing implementation of the wind loads in the numerical model which were included in the experimental setup was not further discussed. Finally, Abbasnia et al. [147] performed experimental tests on the support structure of an FPV system by means of a single and a twin cylinder in the wave flume under a two-dimensional assumption. The experiments were again considered for numerical model validation of a novel BEM-based in-house code. The structures resembled 1:4.5 scaled models of systems currently under commercial development. As for [261,288], a motion capture system, mooring line load cells, and wave gauges were used throughout the tests. Only regular waves are tested in the study. While the focus of [147] clearly lay on the numerical model development,

the analysis and comparison of the experimental data was limited. However, quantification of the agreement between the experimental and numerical models was provided for the heave and pitch motion, as well as the forces, resulting in maximum root-mean-square errors of 6.2%, occurring for the longest wave.

4.2.2. Current loads

Only a few studies in the literature considered current loading in their analysis of environmental loads of FPV systems (see Table 2). Li et al. [294] performed structural analysis using the FE code Abaqus, where current (and wind) loads were considered through a simple drag force formulation using drag coefficients for literature. It should be noted that different structural characteristics of the FPV system for different current directions were taken into account. Choi et al. [299] also implemented current loads via a drag force formulation with a drag coefficient of $C_d = 1.5$; however only considering a single current direction.

4.3. Combined loads

Finally, combined load conditions of wave and current loads were considered in the literature. As mentioned in Section 4.2.1, Han et al. [248] considered combined loading from wind, wave, and currents for their analysis of hydrodynamic forces and system dynamics. While the combination of environmental load conditions was mentioned in the description of the model setup, only wave loads were considered during the analysis of the results. Since the research considered two different load conditions with non-constant values for the current and wind speed, as well as the wave period and wave height (see Table 2), an analysis of the influence of the individual loads was near impossible.

In their analytical approach, Ikhennecheu et al. [290] superimposed environmental loads based on analytical formulations for wind, current, and wave loads. In particular, current loads were only considered for the offshore case study and omitted for the analysis of lake deployments. The current (and wind) loads were followed a drag force formulation considering sheltering and drag through different coefficients. The specific coefficients followed the DNV guideline DNVGL-RP-C205, suggesting a drag coefficient of 2.2 and different sheltering coefficients for different float rows ranging from 1.0–0.2 for rows 1 and ≥ 4 , respectively. Ultimately, the research found that current loads play a "small but non-negligible role (<15%)".

4.4. Fluid–structure interaction

With the rapid advancement of computer hardware, aero/hydrodynamic methods can now be coupled with structural solvers to create a more sophisticated fluid–structure interaction model (FSI) that can investigate the deformation characteristics of flexible floating photovoltaics (FPV) under environmental excitations. This numerical framework is well-suited for thin-film flexible modules [227].

Xu et al. [222] analytically investigated the hydroelasticity of a large-scale polymer offshore floating photovoltaics (LPOFPV) based on a concept of nonlinear fluid–structure interaction, where the floating structure was represented based on a nonlinear Euler–Bernoulli–von Karman (EBVK) beam theory. Notably, thin-film FPV used minimal materials and were flexible, and their hydrodynamic properties experienced less structural loading. Li et al. [294] conducted a one-way FSI approach to investigate the mass distribution effects of an FPV with four sub-plants. The hydrodynamic analysis was undertaken using Ansys/AQWA. The pressure and acceleration response operator amplitudes were transferred to finite element analysis (FEA) for structural analysis. A similar approach was applied by Li et al. [294] to study the performance of composite material for FPV floaters to experience structural local loads. However, these studies did not consider the added mass effects that a two-way FSI simulation can account for. Instead, Han et al. [248] conducted a two-way FSI simulation to

investigate the effects of Fibre-Reinforced Polymer (FRP) composite structures on the FPV system. The commercial CFD package, STAR-CCM+, was used to model the environmental flow field, incorporating wind, waves, and flows. The structure deformation was accounted for using beam elements with rigid connections. However, there was no detailed description provided on how the beam was modelled in their models.

In investigating the local structural behaviours of a compact system, Dai et al. [291] coupled potential flow theory and FEA method to model fluid and structure interaction. The research found that the edge and corner floating modules experience larger hydrodynamic responses compared to the inner modules. Local stress peaks were only observed near the two end bays in the longitudinal direction under head and beam seas. The inner floater modules were also observed to experience large torsional forces in oblique waves. The use of advanced numerical models such as the coupled viscous flow solver with FEA simulation [293] can help to provide more accurate predictions of how these systems will behave under different environmental conditions, as it takes into account the effects of turbulence and other viscous forces that may be present.

Meanwhile, Papathanasiou et al. [297] studied the hydroelastic response of floating slender bodies with large spans in enclosed shallow water basins with variable bathymetries. Enclosed basins have unique wave phenomena due to their limited size and geometric complexity, altering the resonant behaviours of the floating structures. Parametric studies were conducted including basin size, water depth, and the geometry and material properties of the elastic body. Recent research [305,306] presented a novel Reduced-Order-Discrete-Module method for analysing hydroelastic responses of flexible FPV structures, discretising the structure into modules to simplify the interactive simulations [307]. These studies take into consideration spatial inhomogeneity in wind/wave fields, advancing accurate loading analyses of FPV systems.

Floating photovoltaic

4.5. Heat transfer

The deployment of FPV makes the natural cooling effects on the solar panel [308]. The mechanism of such cooling effects is significant to understand and belongs to a type of multi-physical modelling [309, 310]. The numerical simulations were used to determine if the PV module could effectively store solar radiation energy at the PV panel and release it to the underneath water [311,312].

Multi-phase heat transfer is studied by [313], who presented a MEPCM (microencapsulated phase change material)-PV module that floated on the water surface. The PCM material can effectively store or release latent heat through phase changes, making it suitable for protecting aqua farms under the FPV during the winter season. A conjugate heat transfer model was derived theoretically and conducted in numerical simulations to study the temperature changes due to the composite material and flow-cooling effects [314]. Nysted et al. [315] investigated panel temperatures and heat loss coefficients (U-values) of a FPV system in Sri Lanka using module temperature measurements and CFD modelling. The research determined that wind direction, system configuration, and sensor placement significantly influence U-values and temperature distribution, thereby future experiments are required.

Sheikh et al. [239] conducted a numerical simulation using COMSOL Multiphysics software to investigate the efficiency of a water-cooling system on a general thermal PV system model. The simulation included the transmission of fluid flow in the pipe and the conjugate heat transfer module in both the solid and fluid volumes. The composite layers of the PV panels are considered with different solar absorption rates by introducing cell fill factors. Ramanan et al. [316] conduct CFD simulations to analyse how various parameters like wind, temperature, height, and tilt angle affect the cooling performance of floating solar PV systems compared to conventional ground-mounted systems, finding that floating PV performs best at lower heights and tilt angles, with a minimum 5 °C temperature difference between wind and water needed for enhanced cooling.

4.6. Power prediction

The overarching goal of FPV installation, clearly, is the generation of electricity. To assess the system's efficiency (under, e.g., site-specific environmental load conditions) and, ultimately, its economic viability, modelling and prediction of the power production of FPV is required [317]. Even though power production is the primary objective of FPV installations, the modelling thereof is largely underexplored. The relevant studies are discussed in the following.

In their case study for Lake Nasser, Egypt, Abdelgaied et al. [318] found an annual energy yield of 467.99 TWh for a 50% of the lake. The research provided the underlying equations for the module power, as well as the output power including a number of relevant efficiencies. The module power follows:

$$P_m = P_{\text{peak}} \left(\frac{G_T}{G_{ST}} \right) [1 - \alpha_T (T_m - T_{ST})], \quad \text{with} \quad (1)$$

$$T_m = T_a + \left(\frac{G_T}{G_{T,\text{NOCT}}} \right) \left(\frac{9.5}{5.7 + 3.8u} \right) (T_{\text{NOCT}} - T_{a,\text{NOCT}}) \left[1 - \frac{\eta_m}{\tau_a} \right]. \quad (2)$$

The output AC power is then

$$P_{\text{output,AC}} = P_m \eta_{\text{cable}} \eta_{\text{inverter}} \eta_{\text{transformer}} \quad (3)$$

In Eqs. (1)–(3), P_{peak} denotes module's peak power. G_T , G_{ST} , and $G_{T,\text{NOCT}}$ are the intensity of total irradiance on the module surface, the intensity of total irradiance under standardised conditions, and the intensity of total irradiance under the nominal operating cell temperature, respectively. α_T denotes the temperature coefficient, T_m is the cell temperature, and T_{ST} is the temperature in standardised conditions. T_{NOCT} and $T_{a,\text{NOCT}}$ are the nominal operating cell temperature and the ambient nominal operating cell temperature, respectively. η_m and τ_a are the module efficiency and the coefficient of transmittance absorptance, respectively. u denotes the wind speed. η_{cable} , η_{inverter} , and $\eta_{\text{transformer}}$ are the efficiencies of the cable, the inverter, and the transformer, respectively.

Also considering Lake Nasser as a study site, Abd-Elhamid et al. [319] use a simpler model based on the area and energy density, finding relatively high values of the energy yield (2850 TWh y^{-1} to 11 380 TWh y^{-1}), which can be reasoned by the negligence of losses and very large coverage (up to 100%).

Hayibo et al. [250] also use a rather simple model, where the output power follows

$$P_{\text{out}} = I_S \cdot A_p \cdot \eta_p, \quad (4)$$

with I_S being the incoming irradiance, A_p the effective area, and η_p the PV system's efficiency, which includes the electrical efficiency of the module as a function of the operating temperature, the shading losses, the soiling and hotspot losses, as well as the mismatch losses. For the operating temperature, the research provided further functional dependencies, considering, amongst others, the panel efficiency, and temperature coefficients. Ultimately, for the study site at Lake Mead, USA, the research found energy yields of 25.9 TWh y^{-1} to 127.93 TWh y^{-1} , depending on the coverage (10%–50%).

Not only including the power production, but also considering the LCOE, Agrawal et al. [320] estimates the LCOE for an FPV installation at the Rajghat Dam, India, at around 0.036\$/kWh, including values of capital and operational expenditure (CAPEX/OPEX) of 0.50–0.73 \$/Wp (CAPEX) and 0.072\$/Wp (OPEX). Data for this estimation are taken from the literature and from dedicated stakeholder interviews. For the power production estimation, the research resorted to the PVsyst software [321]. Under consideration of topographic limitations, environmental constraints (e.g., solar irradiance), and panel characteristics, the research finds 6513 MWp at 25% coverage at the study site.

While the above-mentioned studies consider “standalone” FPV systems, the combination of FPV systems with hydropower is discussed

in the literature in terms of power production [322]. For instance, Pouran et al. [323] consider seven different reservoirs in Vietnam and perform a performance assessment for FPV in combination with existing hydropower. For their modelling, the research uses the System Advisor Model (SAM), developed by NREL, which is a free techno-economic software model for, e.g., land-based PV [324]. For a combined coverage of 1% of the considered reservoirs, the research finds an annual energy yield of 1 TWh. To adapt the SAM model to FPV, the research assumes a 10% higher efficiency for FPV compared to land-based installations. Input data for the SAM consists of location data, module and inverter characteristics, system design, shading and layout considerations, energy losses, and grid limits set-up.

Also employing SAM, Lopes et al. [325] perform an analysis of combined FPV and hydropower for a case study in Brazil. The research finds an energy yield between 2.3 TWh y^{-1} to 12 TWh y^{-1} for the FPV system, depending on the selected scenario, i.e. coverage of the reservoir. A more general discussion on the benefits of combined FPV and hydropower regarding the utilisation of existing transmission infrastructure, reduced curtailment, and smoothing of power generation can be found in [326].

From an ocean engineering standpoint, it should be noted that all the above studies neglect the influence of hydrodynamic (or more general environmental) loading. In the reviewed literature, only Magkouris et al. [211] are found to combine the analysis of the hydrodynamic response (based on a 2D BEM model) with the power production. The latter is parametrised through the angle of incidence of solar irradiation, which is a function of the dynamics of the system. The research finds that the resulting fluctuations of the angle of incidence can lead to a degradation of the FPV performance, as a direct function of the severity of the exposed sea state.

5. Environmental effects

FPV is constantly in contact with the water body, marine vegetation, and marine species, as depicted in Fig. 9. With the rapid expansion of FPV, there have been many concerns regarding FPV's environmental impacts, which are reviewed in this section. Also, there is an interactive process between FPV and the environment, thus environmental impacts on FPV projects are also significant. As such this section first examines the effects of FPV on the environment and then looks at the effect of the environment on FPV systems [327,328] (see Section 5.2).

5.1. Effects of FPV systems on the environment

In an early review, Gasparatos et al. [329] indicated a variety of environmental impacts from FPV at all phases of a project (planning, construction, and operation and decommissioning), ranging from glare over contaminant spill to geomorphological and geohydraulic effects. Hooper et al. [4] supported these concerns in their short review on the environmental impacts and benefits of marine FPV, highlighted negative environmental effects, ranging from anchoring and cable impacts on the sediment (and associated re-suspension), shading, and spread of alien species, all the way to electromagnetic field effects. Pouran et al. [27] appended this list by, e.g., restricted oxygen and gas exchanges, chemical pollution, or release of microplastics. Hooper et al. [4] further noted that the specific effects were significantly influenced by the system design, as well as the geographic, meteorological, and hydrological characteristics at the installation site.

More specifically, two main focus areas of effects of FPV on the environment can be identified in the reviewed literature: (1) Evaporation loss reduction; (2) Water quality and algae blooms. Detailed reviews of the modelling and analysis of these effects are given in the following sub-sections.

5.1.1. Evaporation

It is widely acknowledged that the installation of FPV, in particular on inland water bodies in arid regions, can significantly reduce the evaporation loss of water [250,318–320,322,325,330–338]. In the literature, the analysis of the evaporation loss and its reduction due to FPV installation has been studied based on purely theoretical analysis, physical modelling with simplified test setups, field studies [Ref] and combinations thereof. Table 3 lists the various studies including information on the case study site (if applicable), the evaporation model (or modelling strategy), as well as the identified water savings (based on the considered FPV coverage).

Bontempo Scavo et al. [332] provided a useful overview of the evaporation models (EVM), namely Penman Monteith and modifications thereof, Valiantzas, Rohwer, McGuinness and Bordne, or Hargreaves. The different models require different input parameters, such as water surface temperature, air temperature, relative humidity, wind speed, or vapour pressure. As can be seen in Table 3, the most used evaporation model for the analysis of FPV systems is the Penman Monteith with modifications.

In a comparison of various evaporation models including a novel evaporation model in free and partially covered water basins, Bontempo Scavo et al. [332] found good agreement with general deviations of <5% between the models and physical reference measurements, with a single model showing deviations of up to ~11%. Regarding their novel EVM, the research stated the benefit of using only “a few usually known environmental variables, i.e., solar radiation, humidity, air temperature, water temperature, and wind velocity”, while maintaining accuracy. Indeed, the availability and source of input data was discussed in the available literature. This data may either stem from literature, databases (e.g., NOAA-National Data Buoy Center [250] or Google Earth [331]), as well as field surveys (e.g., data buoys [250] or weather stations [15,331]). As pointed out by Lopes et al. [325], the lack of input data (e.g. due to a lack of weather stations) may be directly linked to potential uncertainties of the employed models.

The model by Bontempo Scavo et al. [332] was later used by Agrawal et al. [320] for their analysis of the evaporation loss reduction for the case study on the Rajghat Dam, India. In fact, as also evident in Table 3, many studies performed detailed case studies of the evaporation loss reduction across the globe, for example in India [320], Iran [331], USA [250], Singapore [15], Brazil [325], Egypt [318,319], and Jordan [333,336], and Europe [339]. For all the case studies, generally, a significant benefit of FPV installations for evaporation loss reduction is found. Coupled with techno-socioeconomic analysis, some studies even provided a monetary assessment of the evaporation loss reduction. For instance, Lopes et al. [325] perform an analysis on the avoided cost due to the reduction of evaporation loss for the case study of the Apodi/Mossoro basin, Brazil, finding avoided cost between $246\text{k}–281\text{k} \y^{-1} . Regarding the techno-socio-economic analysis, it should be mentioned that the analysis of evaporation loss is closely linked to the increasing efficiency of PV panels due to cooling effects, thus effects of the environment on FPV systems (see Sections 5.2 and 4.6).

Next to the mostly mathematically based modelling of specific case studies, studies were found in the literature using rather simple experimental surrogate models of FPV systems, e.g., Zhang et al. [335], Majumder et al. [334], Al-Widyan et al. [336] and Abdelal [330]. For instance, Zhang et al. [335] investigated the evaporation loss using a novel semitransparent polymer PV cell in a small test stand. Al-Widyan et al. [336] collected experimental data on evaporation over a test period of 30 days, highlighting a water saving of 31.2% with a 30% coverage, compared to an uncovered container.

5.1.2. Water quality and algae blooms

As for the evaporation analysis, water quality and algae bloom was investigated using both experimental [330,337,344–347] and mathematical modelling approaches [15,28,348,349], as well as their combinations thereof [350–352]. Table 4 lists the available literature clustered by modelling approach, including information on the specific

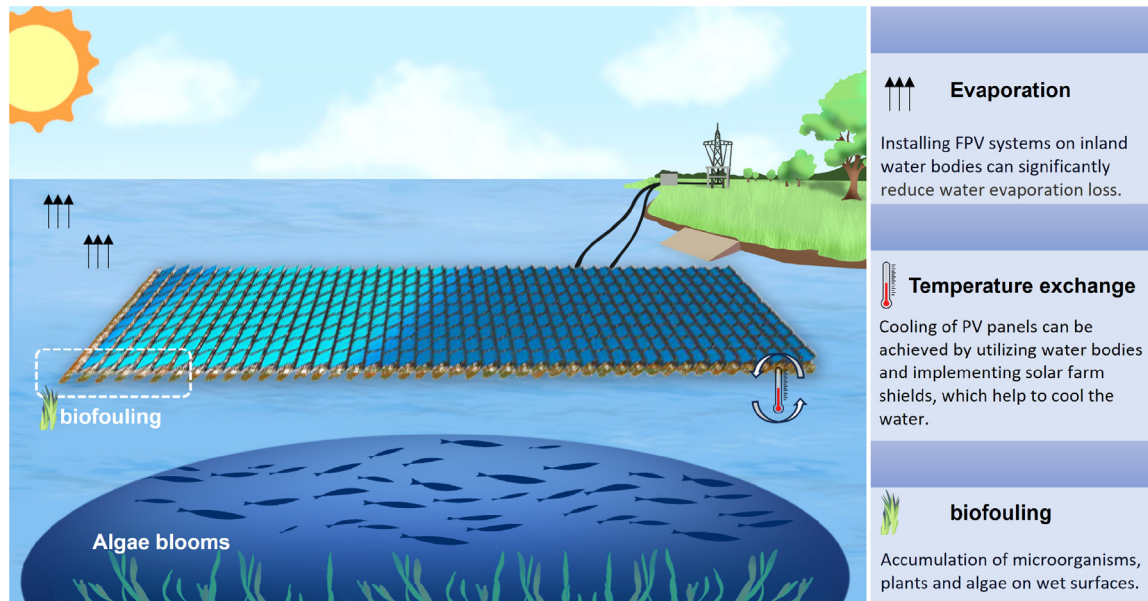


Fig. 9. Illustration of FPV interactions with the environment.

Table 3

Studies concerning the modelling of evaporation loss in the pertinent literature.

Reference	Case study	Coverage	Evaporation model	Water saving ^d
Soltani et al. [331]	Yazd, Iran	90%	Penman–Monteith with ANN	70% (a level with 90% coverage)
Bontempo Scavo et al. [332]	Biviere Lake, Italy ^a	30% & 50%	Penman Monteith and modifications thereof, Valiantzas, Rohwer, McGuinness and Bordne, Hargreaves, and linear regression models	18~49% & 30~64% ^b
Agrawal et al. [320]	Rajghat Dam, India	25%	Bontempo Scavo et al. [332]	0.91 m ³ per kWh
Farrar et al. [333]	Mafraq, Jordan	Small & large footprint ^c	Bontempo Scavo et al. [332]	42 & 8%
Ghasempour et al. [322]	Khuzestan, Iran	2.45%	Fereshtehpour et al. [340]	1.97%
Abdelgaied et al. [318]	Lake Nasser, Egypt	20~50%	Penman–Monteith	27~62%
Abd-Elhamid et al. [319]	Lake Nasser, Egypt	25~100%	Bulk aerodynamic method, based on Harbeck equation	2100~8400 million m ³ y ⁻¹
Hayibo et al. [250]	Lake Mead, USA	10~50%	Penman–Monteith	127 to 633 million m ³ y ⁻¹
Lopes et al. [325]	Apodi/Mossoro basin, Brazil	5~70%	Assouline et al. [341]	3.4~55.2%
Abdelal [330]	No specific location	100%	Penman–Monteith [342] & Experimental	60%
Majumder et al. [334]	No specific location	17%	Experimental	30%
Zhang et al. [335]	No specific location	100%	Experimental	23%
Al-Widyan et al. [336]	No specific location	30% & 50%	Experimental	31.2% & 54.5%
Nisar et al. [343]	No specific location	Partially & fully	Experimental	17% & 28%

^a For validation only.

^b Range depends on the system design (suspended, surface covering, etc.).

^c Exact figures for the coverage are omitted.

^d Data is provided here as given in the respective reference. A direct comparison of the percentage values is challenging due to varying reference values.

model, if applicable the case study site, as well as the specific quantities investigated in the study.

As stated by Haas et al. [28] and Exley et al. [349], mathematical models were useful tools for prognostic and extreme event analysis, providing a “less time- and resource-demanding alternative” to experimental analysis. From Table 4, the ELCOM-CAEDYM [353] and the MyLake model [354] can be highlighted as frequently used models. While ELCOM-CAEDYM is a 3D hydrodynamic model based on unsteady Reynolds-averaged Navier–Stokes equations with a Boussinesq approach, including modelling of chemical processes for the analysis of, e.g., total chlorophyll-a content, MyLake was a 1D model using a

partitioning approach for horizontal layer volumes from interpolated lake bathymetric data. Based on 24-h time steps, MyLake took into account diffusive mixing processes, local heat fluxes, as well as convective mixing, wind-induced mixing, and the effect of river inflow. Detailed information on ELCOM-CAEDYM and MyLake was provided in [15,28,348,349].

Yang et al. [15] used ELCOM-CAEDYM for the analysis of a generic installation of a 50 MW FPV system with 30% coverage at the Poyan Reservoir, Singapore. Analysing Chlorophyll-a, total organic carbon, dissolved oxygen concentrations, Nitrogen, Phosphorus, temperature, and stability (Richardson number), the research, first, found good

Table 4

Studies concerning the modelling of evaporation loss decrease in the pertinent literature.

Reference	Modelling approach	Model	Case study	Quantities
Haas et al. [28]	Mathematical	ELCOM-CAEDYM [353]	Rapel reservoir, Chile	Total chlorophyll-a
Exley et al. [348]	Mathematical	MyLake v1.2 [354]	South basin of Windermere, UK	Wind speed, temperature, mixing depth, stratification
Exley et al. [349]	Mathematical	MyLake v1.2 [354]	QEII reservoir, UK	Wind speed, temperature, Phytoplankton biomass and species composition
Wang et al. [337]	Experimental	Field data	Chupei/Lukang/Cigu, Taiwan	pH, water temperature, dissolved oxygen, oxidation–reduction potential, biochemical oxygen demand, orthophosphate-P, suspended solids, total ammonia nitrogen, total phosphate-P, total photosynthetic pigments, aquaculture yield
Abdelal [330]	Experimental	Pilot test setup with two tanks	–	Nitrate, ortho-phosphate, chlorophyll-a, meteorological data
Kumar et al. [345]	Experimental	Generic containers stored in dark	–	Nitrate, biomass
Wang et al. [346]	Experimental	Field study	Subsidence pond, Xieyi coal mine, China	Carcinogenic risks via heavy metal content
Mathijssen et al. [347]	Experimental	Leaching experiments for the PE tubing, PE caps and sealant material of the caps	Kralingen storage reservoir, Netherlands	Heavy metals, poly- and monocyclic aromatic hydrocarbons, volatile halogenated hydrocarbons, monocyclic (halogenated) nitrogen compounds, phenols and halogenated phenols
de Lima et al. [344]	Experimental	Field study	Bomhofsplas lake, Netherlands	Underwater images, temperature, electrical conductivity, dissolved oxygen, pressure, wind speed, precipitation intensity, global radiation, cloud cover, and relative humidity
Yang et al. [350]	Both	Field study and heat balance model	Singapore	Shortwave radiation, longwave radiation, air and near-surface water temperature
Yang et al. [15]	Both	ELCOM-CAEDYM [353] & Field data	Poyan Reservoir, Singapore	Chlorophyll-a, total organic carbon, dissolved oxygen concentrations, Nitrogen, Phosphorus, temperature, stability (Richardson number)
Château et al. [352]	Both	Monte-Carlo & Field data	N/A	Water temperature, phytoplankton, Nitrogen, phosphorus, detritus, dissolved oxygen, artificial fodder, fish population
Ali et al. [351]	Both	Opaque box & mathematical decay model	–	Biomass, nicotinamide adenine dinucleotide hydrogen phosphate

agreement between acquired field data and modelled results and, second, highlighted an increase in water column stability and reduced wind mixing, leading to a reduction of dissolved oxygen concentrations, as well as an enhanced nutrient accumulation near the reservoir bottom, as key effects of FPV coverage. Haas et al. [28] used ELCOM-CAEDYM for the analysis of the algae growth (approximated by the chlorophyll-a content) for the Rapel reservoir, Chile. While the research found little effect of the FPV installation on the algae growth for coverage <40%, coverage of 40%–60% prevented algae blooms, due to the increased light blockage. In their analysis, the research furthermore combined the analysis of algae growth with the economic analysis of a hydropower plant, used for FPV installation.

The MyLake model was used by Exley et al. [348] for the analysis of wind speed, temperature, mixing depth, and stratification under the influence of different FPV coverage, ranging from 0 to 100% in the south basin of Windermere, UK. As one of their key results, the research highlighted a non-linear behaviour of the lake parameters, which can be concisely summarised by a reduced temperature, a shortened stratification, and shallower mixing depths for increasing coverage. In a follow-up study [349], the research performed an analysis for the QEII reservoir, UK, to analyse the phytoplankton biomass and species composition using MyLake. In this study, the results suggested that cooler water temperatures in combination with the altered light conditions slow down phytoplankton growth.

Considering experimental modelling, de Lima et al. [344] motivated an extensive field measurement campaign with the fact that, in the research's opinion, studies in the literature rely at large on modelling without proper validation. To provide measurements for such model

validation, the research used a variety of measuring devices (data loggers, remotely operating vehicles, weather stations, etc.) to monitor marine growth, temperature, electrical conductivity, dissolved oxygen, pressure, wind speed, precipitation intensity, global radiation, cloud cover, and relative humidity at the Bomhofsplas lake, Zwolle, Netherlands. A 27.4 MW_p FPV system with 30% coverage was installed at the test site. Data was recorded with varying sampling frequencies (depending on the measuring device) over a period of 10 months, divided into two periods from February–June and July–December 2020. Detailed information on the measuring devices and the recorded data, including the sampling frequency, were provided in the paper. Comparing their data taken underneath and in the vicinity to the FPV system with data from a reference site in the lake, the research found main differences in the dissolved oxygen concentration under the FPV system; however, concluded that the FPV system does not result in “major differences in water quality”.

5.2. Effects of the environment on FPV systems

While the previous section concerned the effects of FPV systems on the environment, this section reviews studies concerning the effects of the environment on FPV systems. In the literature, next to, e.g., geographical characteristics [355], environmental effects are mostly reduced to the improved efficiency of FPV systems due to evaporation cooling effects [266,334,343,356–358]; thereby, are tightly linked to the power production analysis (see Section 4.6).

Jeong et al. [356] used regression analysis and neural networks for their analysis of environmental factors (panel temperature, air–water temperature, and wind speed) affecting the power generation of

FPV, where results confirmed a correlation between water evaporation effects and low panel temperature, hence high panel efficiency. The research quantified the increased output of FPV systems, compared to land-based systems, with 3%. For a similar study on the increased FPV efficiency, Sukarso and Kim [357] used field data from West Java, Indonesia, and remote sensing. However, the research only found a 0.61% efficiency increase for the FPV system, compared to a ground-mounted reference.

Amiot et al. [359] used a 1D thermal modelling approach together with field data to correlate wind patterns on the water surface and air temperature modified by evaporation cooling with the FPV performance. From their results, the research found that, compared to a ground-mounted system, FPV systems were more influenced by wind patterns, due to the potentially lower roughness of the water surface. Interestingly, the research also found that for their case study for a “low-size waterbody”, water thermal radiations had an opposite effect on the panel temperature than the wind patterns, i.e. heating the module. Noting the limited size of the considered waterbody, the research noted that thermal optimisation of the FPV system should be performed rigorously.

Uniquely, de Lima et al. [344] considered biofouling on FPV systems in their extensive field measurement campaign. While noting that biofouling was observed a few months after installation of the system, no further assessment of the effects of biofouling, e.g., on the system dynamics, was considered by the research.

6. Summary and recommendations for future work

From a design perspective, the modular design of FPV (Fig. 4(a)) presents superior scalability, and the connections between different PV units can mitigate significant environmental loads. By contrast, waves would induce critical bending stress in the integrated design, if the design becomes sufficiently large (Fig. 4(b)). For the superficial design (Fig. 4(c)), although such designs offer the advantage of simple and flexible structures, they are envisioned that the buoyancy provided by the doughnut barrier may not be enough when the required power (hence the surface coverage) is extensive. With the ongoing global demand that large-scale FPV projects are lacking, the modular design appears to allow the quickest expansion, and it is easy to manufacture and install as the modular feature can free up the need for case-by-case designs.

Although there are some innovative designs for FPV, such as submerged and bifacial, these innovations have not been put into commercialisation. It appears that the industry is satisfied with the current designs that lift mature rooftop silicon solar panels by floating support. It is identified that cleaning the solar panels may remain an issue, as manual labour is still required around the world for cleaning deployed FPV systems. Considering the expense of robotics, incorporating a water-spray cleaning system could be the way forward.

Contemporarily, OE simulation approaches for naval architecture, offshore platforms, and fixed/floating wind turbines have focused on the dynamic response of a single structure [360], which can be used to simulate an integrated FPV platform (Fig. 4(b)). For the superficial case (Fig. 4(c)), there are also available OE simulation approaches which have been used for the hydroelastic performance of Very Large Floating Structures (VLFSs), such as floating airport and sea ice [361, 362]. However, the modelling approaches for modular FPV appear to have significant research gaps. Modular FPV can consist of hundreds or thousands of floating structures connected together. This type of multi-body dynamics has barely been modelled using a high-fidelity approach [144], and the direct extension of contemporary modelling approaches to numerous structures would be impractical due to a prohibitive computational cost required for mesh refinement around each floating structure. On the other hand, using low-fidelity theoretical models would exclude some significant features such as wave energy dissipation during propagation [363], overtopping [364–368],

and structural complexity [225,369,370]. The present review suggests one way forward might be performing FPV array simulations with a small array first, and gradually increasing the array to derive an empirical relationship [371–374]. Considering the multi-body dynamics of hundreds or thousands of structures linked together, it may be indeed sufficient to identify the most fragile parts and reduce the computational costs based on symmetry and extendability. In line with this, the FPV deployment locations and design of mooring lines for FPV should be further studied and optimised.

Heat transfer and power output problems of FPV have been widely studied. However, it appears that the investigated cooling effect considers an FPV system being placed on calm water; when the water is flowing and/or with waves, it is envisioned that a different cooling effect will be identified. The present review recommends combining heat transfer equations into a hydrodynamic solver to investigate this problem.

The environmental research of FPV has suggested positive effects, such as reducing evaporation and water temperature, which then help to increase the growth of fish. The associated effects on aquatic plants seem to be insignificant, while this could vary when more criteria have been set. There has been no clear negative effect identified so far. Whilst the coverage of FPV systems could significantly reduce the growth of plankton, it is not necessarily negative in some cases. Reversely, looking at the effects of the environment on FPV, biofouling could increase the self-weight and affect the global responses of FPV systems, while this has been barely studied. The corrosion of materials used for FPV is also understudied.

Going offshore, an obvious challenge for FPV is wave action/loads. Calm water-based FPV is not designed to handle wave power, thus those FPV structures may not be able to survive. Another negative impact of waves on FPV is to induce motions, where the rotation of solar panels riding waves will cause a mismatch to sunlight, thus an energy loss [375]. Also, waves can cause an overtopping and bring salt to deposit on the solar panel's surface, which also reduces its efficiency evidently [376]. Therefore, it may be essential to minimise wave interaction with FPV systems. One feasible approach is to implement a breakwater that is widely used for coastal protection [377–379]. Fig. 10 presents a concept proposed by Cranfield University UK. Integrating a breakwater into the edge of an FPV power plant can break incoming waves, with promising laboratory results provided as an initial feasibility study [380]. The breakwater can cause waves to lose continuity and only radiate a short distance downstream. A buffering zone can be used to cover the radiation distance and eliminate the wave, thus the solar panels will have minimal interactions with waves and can remain intact as well as avoid rotational motions or salt disposition. It is worth noting that the main additional component is the breakwater barriers, thus the additional cost does not increase proportionally with the surface coverage. Namely, the larger the surface area of the solar farm, the cheaper the average energy cost will be. However, the economic and technical performance of FPV systems varies significantly across different installations and regions. A technical design guidance on this will be valuable.

As detailed in Appendix A, data from 2013 to 2023 show that global FPV power densities generally range from 0.4 to 1.2 kW/m², with some advanced configurations achieving higher density of 2.25–3.0 kW/m² in Asian installations. LCOE values for these systems span from 0.05 to 0.15 per kWh, with CAPEX ranging between 0.7 and 2.0 per watt. Applying a modest power density of 0.5 kW/m² (detailed in Appendix A) and assuming utilisation of only 1% of available water bodies [381]: the United States signifies 125 GW capacity potential, yielding 275 TWh annually [96]. The European Union follows substantial potential with 100 GW capacity, generating approximately 175 TWh annually at a 20% capacity factor [25]. Globally, considering approximately 1,500,000 km² of artificial water surfaces, the conservative technical potential would reach 750 GW capacity and 1450 TWh/year generation [382].

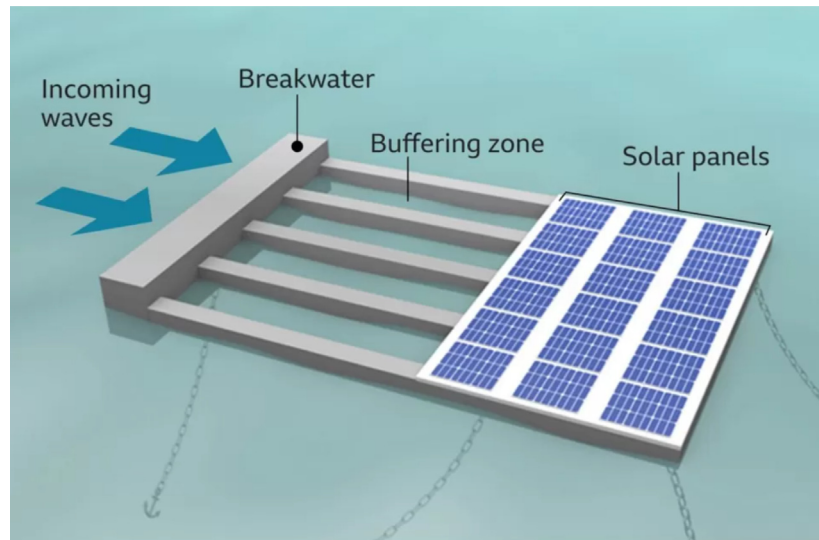


Fig. 10. Illustration of the integration of a floating breakwater with FPV [151].

Technological advancements have led to improvements in these metrics, with recent projects demonstrating more favourable LCOE and CAPEX figures. For example, the Queen Elizabeth II Reservoir in the UK and the Three Gorges project in China illustrate how regional and technological progress can significantly impact economic performance, achieving competitive power densities and reduced LCOE. The observations from the economic model also highlight the need to consider system capacity and energy production when evaluating the feasibility and economic viability of FPV systems.

The recommendations and future work are summarised in [Appendix B](#), which highlights key areas for advancement in FPV technology, emphasising the need for multidisciplinary collaboration and integrated approaches to renewable energy development. The identified research gaps provide a focused roadmap for future FPV research and development.

7. Conclusions

Due to its superior flexibility and affordability, PV is predicted to be the most popular energy source in the future. Whilst the energy output of a PV system is proportional to its surface coverage area, finding available space for future deployment points the finger towards water bodies, and in particular, the abundant coastal and offshore space.

In this context, the present paper reviewed a large volume of literature linked to FPV systems. The design, modelling and environmental effects of existing FPV research are discussed in detail. It has been identified that these research share certain similarities with OE research, but significant research gaps remain. What is lacking in the design is to mitigate wave loads on the vulnerable PV structure, such as adapting breakwater technologies for attenuating the potential destructive power of waves. The review on modelling highlights an urgent need to simulate the dynamics of numerous floating bodies in waves, i.e. modular FPV systems, and this is different from existing OE simulation approaches. There is also a significant gap to designing and optimising the mooring system. FPV systems have somewhat

shown positive impacts on the environment, but the environment can induce biofouling and corrosion on FPV, which is barely studied nor mitigated. Overall, the present review provided useful insights into the development of FPV, facilitating this application's ongoing expansion on waters.

CRediT authorship contribution statement

Yujia Wei: Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Visualisation. **Danial Khojasteh:** Writing – original draft, Writing – review & editing, Formal analysis, Investigation. **Christian Windt:** Writing – original draft, Writing – review & editing, Formal analysis, Investigation. **Luofeng Huang:** Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Funding acquisition, Project Management, Conceptualisation, Visualisation.

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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Appendix A

Power density, LCOE and CAPEX

See [Table A.1](#).

Table A.1
Power density, LCOE and CAPEX

FPV power plants summary	(Peak/Installed Capacity per Unit Area) (kW/m ²)	LCOE (USD/kWh)	CAPEX (USD/W)	Lake or Ocean (–)
Global (2013–2023)	0.4–1.2	0.05–3.12	0.7–2.74	Mixed
Global (2016–2022) [382]	–	0.04–0.085	–	Mixed
Global (2010–2019) [152]	–	0.15–0.59	–	Mixed
Queen Elizabeth II Reservoir, UK (6.3 MW) [383,384]	1.5	0.05–0.07	1.22	Lake
Sheeplands, UK (0.2 MW) [385]	0.5–1	1.14	1.02–1.52	Lake
Lazard, USA [153]	0.5–2.75	0.045–0.056	–	Mixed
Three Gorges (150 MW), China [385]	0.8–1.7	0.99	0.7–1.0	Lake
- (10 MW), China [386]	–	0.047	–	Lake
Anhui Xinyi (20 MW), China [385]	0.7–1.5	1.48	0.8–1.1	Lake
Taiwan [387]	3	–	–	Ocean
China [387]	2.25–2.73	–	–	Lake
Anhui Sungrow (40 MW), China [385]	1–1.7	1.13	0.8–1.2	Lake
Kayamkulam (171 MW), India [13]	0.49–0.71	0.084	0.38	Lake
-(10 MW), India [388]	–	0.026	0.647–0.677	Lake
Andhra Pradesh, (2 MW), India [385]	0.83	0.092	1.0	Lake
-(5 MW), India [389]	–	0.041	–	Lake
-(105 MW), India [390]	–	0.11	–	Lake
-, Malaysia [391]	–	0.052	0.495	Lake
Shiroishi Saga [385]	0.83	3.12	2.329	Lake
Mita Kannabe (13.7 MW), Japan [385]	0.6–0.8	0.97	1.5–2.0	Lake
-, Thailand [392]	–	0.0187–0.0241	0.52	Lake
-(211.94 MW), Turkey [228]	–	0.6121	1.19	Lake
-, Egypt [271]	–	0.067–0.075	–	Lake
-(0.174), Egypt [393]	–	0.015	–	Lake
-, Pakistan [394]	–	0.0564	0.348	Lake
-, Brazil [395]	–	0.032	0.938	Lake
-, (10 MW), Brazil [396]	–	0.039–0.081	–	Lake
-, (15.5 MW), South Africa [397]	–	0.714	1.1	Lake
FPV-GIS [398]	–	0.03	1.3	Mixed
Hy4REN (140.6 MW) [231]	–	0.12	–	Lake
Theoretical study (1 MW), Indonesia [357]	–	0.0337	–	Lake
Economic model, Pvsyste [123]	1.2	0.03–0.11	0.77	Mixed
Economic model (201 MW) [399]	–	0.08	–	Lake
Economic model (15 MW) [400]	–	0.047	–	Lake
Economic model (253 kW) [401]	–	–	2.743	Lake
Theoretical study (1 MW), Indonesia [158]	–	0.1	–	Ocean

Appendix B

Recommendations and Future Work

See Table B.1.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

References

- [1] IRENA. How falling costs make renewables a cost-effective investment. Technical Report, 2020.
- [2] IEA. World energy outlook 2022. Technical Report, 2022.
- [3] Sahu Alok, Yadav Neha, Sudhakar K. Floating photovoltaic power plant: A review. *Renew Sustain Energy Rev* 2016;66:815–24.
- [4] Hooper Tara, Armstrong Alona, Vlaswinkel Brigitte. Environmental impacts and benefits of marine floating solar. *Sol Energy* 2021;219:11–4.
- [5] Cuce Erdem, Cuce Pinar Mert, Saboor Shaik, Ghosh Aritra, Sheikhejad Yahya. Floating PVs in terms of power generation, environmental aspects, market potential, and challenges. *Sustainability* 2022;14(5):2626.
- [6] Song Jinyoung, Choi Yosoon. Analysis of the potential for use of floating photovoltaic systems on mine pit lakes: Case study at the Ssangyong open-pit limestone mine in Korea. *Energies* 2016;9(2):102.
- [7] Đurković Vladan, Đurišić Željko. Analysis of the potential for use of floating PV power plant on the Skadar Lake for electricity supply of aluminium plant in Montenegro. *Energies* 2017;10(10):1505.
- [8] Bax Vincent, van de Lageweg Wietse I, Hoozemans Rik, van den Berg Bas. Floating photovoltaic pilot project at the Oostvoornse lake: Assessment of the water quality effects of three different system designs. *Energy Rep* 2023;9:1415–25.
- [9] Hayibo Koami Soulemane, Pearce Joshua M. Foam-based floatovoltaics: A potential solution to disappearing terminal natural lakes. *Renew Energy* 2022;188:859–72.
- [10] Andini Syarifina, Suwartha Nyoman, Setiawan Eko Adhi, Ma'arif Samsul. Analysis of biological, chemical, and physical parameters to evaluate the effect of floating solar PV in Mahoni Lake, Depok, Indonesia: mesocosm experiment study. *J Ecol Eng* 2022;23(4).
- [11] Kim Sun-Hee, Yoon Soon-Jong, Choi Wonchang, Choi Ki-Bong. Application of floating photovoltaic energy generation systems in South Korea. *Sustainability* 2016;8(12):1333.
- [12] Mamatha G, Kulkarni PS. Assessment of floating solar photovoltaic potential in India's existing hydropower reservoirs. *Energy Sustain Dev* 2022;69:64–76.
- [13] Sanchez Rocio Gonzalez, Kougias Ioannis, Moner-Girona Magda, Fahl Fernando, Jäger-Waldau Arnulf. Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa. *Renew Energy* 2021;169:687–99.
- [14] Perez Marc, Perez Richard, Ferguson Craig R, Schlemmer James. Deploying effectively dispatchable PV on reservoirs: Comparing floating PV to other renewable technologies. *Sol Energy* 2018;174:837–47.
- [15] Yang Peipei, Chua Lloyd HC, Irvine Kim N, Nguyen Manh Tuan, Low E-Wen. Impacts of a floating photovoltaic system on temperature and water quality in a shallow tropical reservoir. *Limnology* 2022;23(3):441–54.
- [16] Redón-Santafé Miguel, Ferrer-Gisbert Pablo-S, Sánchez-Romero Francisco-Javier, Torregrosa Soler Juan Bautista, Ferran Gozálvez José Javier, Ferrer Gisbert Carlos Manuel. Implementation of a photovoltaic floating cover for irrigation reservoirs. *J Clean Prod* 2014;66:568–70.
- [17] Nagananthini R, Nagavinothini R. Investigation on floating photovoltaic covering system in rural Indian reservoir to minimize evaporation loss. *Int J Sustain Energy* 2021;40(8):781–805.
- [18] Sacramento Elissandro Monteiro do, Carvalho Paulo CM, de Araújo Jose Carlos, Riffel Douglas Bressan, Corrêa Ronne Michel da Cruz, Pinheiro Neto José Sigfredo. Scenarios for use of floating photovoltaic plants in Brazilian reservoirs. *IET Renew Power Gener* 2015;9(8):1019–24.
- [19] Santafé Miguel Redón, Soler Juan Bautista Torregrosa, Romero Francisco-Javier Sánchez, Gisbert Pablo S Ferrer, Gozávez José Javier Ferrán, Gisbert Carlos M Ferrer. Theoretical and experimental analysis of a floating photovoltaic cover for water irrigation reservoirs. *Energy* 2014;67:246–55.
- [20] Yang Yifeng, Huang Luofeng. Waves and structural strain induced by a uniform current flow underneath a semi-infinite floating solar coverage. *Phys Rev Fluids* 2024;9(9):094804.
- [21] Vo Thi Thu Em, Ko Hyeyoung, Huh Junho, Park Namje. Overview of possibilities of solar floating photovoltaic systems in the offshore industry. *Energies* 2021;14(21):6988.
- [22] Wang Jun, Lund Peter D. Review of recent offshore photovoltaics development. *Energies* 2022;15(20):7462.
- [23] Wei Yujia, Ou Binjian, Wang Junxian, Yang Liang, Luo Zhenhua, Jain Sagar, Hetharia Wolter, Riyadi Soegeng, Utama IKAP, Huang Luofeng. Simulation of a floating solar farm in waves with a novel sun-tracking system. In: *IOP conference series: materials science and engineering*, vol. 1288, IOP Publishing; 2023, 012041.
- [24] Gorjian Shiva, Sharon H, Ebadi Hossein, Kant Karunesh, Scavo Fausto Bon-tempo, Tina Giuseppe Marco. Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems. *J Clean Prod* 2021;278:124285.
- [25] Cazzaniga R, Cicu M, Rosa-Clot M, Rosa-Clot P, Tina GM, Ventura C. Floating photovoltaic plants: Performance analysis and design solutions. *Renew Sustain Energy Rev* 2018;81:1730–41.
- [26] Rosa-Clot Marco, Tina Giuseppe Marco, Nizetic Sandro. Floating photovoltaic plants and wastewater basins: an Australian project. *Energy Procedia* 2017;134:664–74.
- [27] Pouran Hamid M, Lopes Mariana Padilha Campos, Nogueira Tainan, Branco David Alves Castelo, Sheng Yong. Environmental and technical impacts of floating photovoltaic plants as an emerging clean energy technology. *Iscience* 2022;25(11).
- [28] Haas J, Khalighi J, De La Fuente A, Gerbersdorf SU, Nowak W, Chen Po-Jung. Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. *Energy Convers Manage* 2020;206:112414.
- [29] Cazzaniga Raniero, Rosa-Clot Marco. The booming of floating PV. *Sol Energy* 2021;219:3–10.
- [30] Lee Nathan, Grunwald Ursula, Rosenlieb Evan, Mirlitz Heather, Aznar Alexandra, Spencer Robert, Cox Sadie. Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential. *Renew Energy* 2020;162:1415–27.
- [31] Solomin Evgeny, Sirotkin Evgeny, Cuce Erdem, Selvanathan Shanmuga Priya, Kumarasamy Sudhakar. Hybrid floating solar plant designs: a review. *Energies* 2021;14(10):2751.
- [32] Ali Fida, Shahidi Amir Etemad, Stewart Rodney A, Sanjari Mohammad J, Hayward Jennifer A, Nicholson Robert. Co-located offshore wind and floating solar farms: A systematic quantitative literature review of site selection criteria. *Renew Energy Focus* 2024;100611.
- [33] Karipoğlu Fatih, Koca Kemal, İlbahar Esra. Convenient site selection of a floating PV power plant in Türkiye by using GIS-fuzzy analytical hierarchy process. *Environ Sci Pollut Res* 2024;31(15):23193–210.
- [34] Haspolat Emre, Cicek Doga Derman, Gokmener Serkan, Melek Abiddin Berhan, Devci Muhammet, Oguz Elif. Site selection of floating photovoltaic systems on hydropower reservoirs using fuzzy sine trigonometric decision-making model: Turkey as a case study. *Renew Sustain Energy Rev* 2024;206:114830.
- [35] Melek Abiddin Berhan, Gokmener Serkan, Haspolat Emre, Çiçek Doğa Derman, Devci Muhammet, Oğuz Elif, Khorasanchi Mahdi. Fuzzy Einstein-based decision-making model for the evaluation of site selection criteria of floating photovoltaic system. *Ocean Eng* 2024;301:117521.
- [36] Islam Md Imamul, Al Mansur Ahmed, Jadin Mohd Shawal, Saaduzzaman DM, Naiem-Ur-Rahman Md. Potential data for feasibility assessment and deployment of a 6.7 MW floating solar PV plant in Hatirjheel Lake, Dhaka, Bangladesh. *Data Brief* 2024;110586.
- [37] Trapani Kim, Redón Santafé Miguel. A review of floating photovoltaic installations: 2007–2013. *Prog Photovolt, Res Appl* 2015;23(4):524–32.
- [38] Sikora Mateusz, Kochanowski Dominik. Potentials of green hydrogen production in P2G systems based on FPV installations deployed on pit lakes in former mining sites by 2050 in Poland. *Energies* 2024;17(18):4660.
- [39] Essak Laura, Ghosh Aritra. Floating photovoltaics: A review. *Clean Technol* 2022;4(3):752–69.
- [40] Zhang Min, Schreier Sebastian. Review of wave interaction with continuous flexible floating structures. *Ocean Eng* 2022;264:112404.
- [41] Shi Wei, Yan Chaojun, Ren Zhengru, Yuan Zhiming, Liu Yingyi, Zheng Siming, Li Xin, Han Xu. Review on the development of marine floating photovoltaic systems. *Ocean Eng* 2023;286:115560.
- [42] Koondhar Mohsin Ali, Albasha Lutfi, Mahariq Ibrahim, Graba Bisma Bechir, Touti Ezzeddine. Reviewing floating photovoltaic (FPV) technology for solar energy generation. *Energy Strategy Rev* 2024;54:101449.
- [43] Wang Bin, Li Yan, Huang Lei, Yao Ye, Qin Yao. Dynamic analysis of a novel star-type floating photovoltaic system with flexible connectors. *Ocean Eng* 2024;304:117854.
- [44] Saeed Ahmed, Rehman Shafiqur, Al-Sulaiman Fahad A. Study of a grid-connected floating photovoltaic power plant of 1.0 MW installed capacity in Saudi Arabia. *Heliyon* 2024;10(16).
- [45] Tveit Sigbjørn, Reyes Aase, Erduran Emrah. A continuum approach to multiaxial high-cycle fatigue modeling for ductile metallic materials. *Results Eng* 2024;22:102171.
- [46] Kyrnaki Nikoleta, Nivelle Philippe, Bouguerra Sara, Paesa Marta Casasola, De Jong Richard, Delbeke Oscar, Spannan Lars, van der Heide Arvid, Kaaya Ismail, Moschner Jens, et al. Investigation of static and dynamic mechanical loads on light-weight PV modules for offshore floating applications. *Eng Struct* 2024;319:118760.

Table B.1
Recommendations and Future Work

Main	Sub	Topics
Design	Structural design	<ul style="list-style-type: none"> – Conduct life span experimental studies on existing FPV system, testing the fatigue and operational durability. – Develop innovative, modular designs that can easily scale from small to large installations. – Investigate advanced materials and structures to enhance durability in marine environments. – Optimise designs for extreme weather conditions.
	Floating support	<ul style="list-style-type: none"> – Research novel buoyancy systems that can adapt to changing water levels and tidal conditions. – Develop effective anchoring and docking systems suitable for near-shore installations. – Investigate dynamic positioning systems for FPV platforms.
	Hybrid design of FPV and other energy systems	<ul style="list-style-type: none"> – Feasibility analysis of integrating the FPV with offshore wind turbines to maximise space utilisation and energy production. – Develop hybrid systems combining FPV with wave or tidal energy converters. – Investigate the potential of FPV-powered hydrogen production facilities. – Explore synergies between FPV and marine biomass production for Sun-fish industry. – Investigate the potential of hybrid renewable land.
	Auxiliary	<ul style="list-style-type: none"> – Develop cost-effective cleaning systems. – Innovate cooling systems that better utilise surrounding water. – Design cost-effective monitoring and maintenance operations.
Modelling	Computational model	<ul style="list-style-type: none"> – Advanced computational model to investigate the effects of wind-induced vibrations on long-term structural integrity and panel efficiency. – Reduced order model or mix-fidelity model that captures wind, wave, current, and structure interaction in an effective manner. – Advanced numerical model for extreme events like tsunamis or storm surges. – Optimisation model is desired to find the optimal structural shapes, and array designs for large-scale FPV. – Develop models to predict long-term effects for wave structure interactions considering fatigue or damaged conditions. – Explore machine learning and deep learning techniques for real-time load prediction and system optimisation under varying conditions. – Develop efficient FSI models capable of simulating large-scale FPV arrays with reasonable computational cost. – Explore the use of reduced-order modelling techniques for rapid FSI simulations in design optimisation. – Create models to predict long-term thermal cycling effects on panel degradation and structural materials. – Explore the potential of using waste heat for auxiliary applications, such as desalination or biomass production.
	Power prediction	<ul style="list-style-type: none"> – Investigate the impacts of panel shading, soiling, and degradation on long-term power production. – Create machine learning models for real-time power forecasting based on environmental and operational data. – Explore probabilistic power prediction models to better quantify uncertainties in energy production estimates.
Environment effects		<ul style="list-style-type: none"> – Conduct long-term studies on the impact of FPV installations on local biodiversity. – Study the effects of large-scale FPV deployments on air and water temperature patterns. – Explore the potential of FPV systems to reduce harmful algal blooms and improve overall ecosystem health. – Develop advanced models to predict the long-term impacts of reduced evaporation on local water cycles and weather patterns. – Investigate the deployment of FPV on the effects of reduced light penetration on aquatic ecosystems. – Develop models to predict and optimise FPV coverage for improving water quality in polluted or eutrophic water bodies.
Costs and political consideration		<ul style="list-style-type: none"> – The economic perspectives of the FPV system are briefly mentioned but not deeply explored. The analysis may not be directly applicable to all global contexts, especially in regions with significantly different environmental conditions and economic factors. – The site performance of FPV systems can vary widely based on local conditions such as water body characteristics, climatic conditions, and technological integration. These variabilities are difficult to standardise in a broad review.
Ocean engineering		<ul style="list-style-type: none"> – Accurate modelling of a large number of FPV modules' multibody dynamics in waves. – Design of breakwaters to protect FPV; Integration of FPV with wind and wave energy devices. – fatigue mitigation and corrosion resistance of FPV components in waves and marine environments. – Effective sensors for monitoring in seas and further supporting the developments of energy management software and digital twins. – Systematic and optimal mooring design considering the vast surface expansion of FPV power plants on the ocean.

- Eng 2024;308:118298.
- [48] Ma Chao, Wu Runze, Liu Zhao, Li Xinyang. Performance assessment of different photovoltaic module technologies in floating photovoltaic power plants under waters environment. *Renew Energy* 2024;222:119890.
 - [49] Kim Gihwan, Park Moonsu. Design loads for floating solar photovoltaic system: Guide to design using DNV and ASCE standards. *Struct Eng Mech* 2024;89(2):171–9.
 - [50] Lee Kangsu, Sim Kichan. An experimental study on the motion-structure coupled characteristics of multi-linked floating unit offshore structure with two different connection conditions. *Int J Nav Archit Ocean Eng* 2024;16:100614.
 - [51] Zhang Min, Yang Darui, Du Junfeng, Xu Kun, Yuan Wenyong. Aerodynamic effects of an offshore floating photovoltaic platform undergoing pitch and heave motions. *Ocean Eng* 2024;310:118753.
 - [52] Yakubu Rahimat O, Quansah David A, Mensah Lena D, Ahiataku-Togobo Wisdom, Acheampong Peter, Adaramola Muiyiwa S. Comparison of ground-based and floating solar photovoltaic systems performance based on monofacial and bifacial modules in Ghana. *Energy Nexus* 2023;12:100245.
 - [53] Hayibo Koami Soulemane. Quantifying the value of foam-based flexible floating solar photovoltaic systems (Master's thesis), Michigan Technological University; 2021.
 - [54] Itiki Rodney, Di Santo Silvio Giuseppe, Itiki Cinthia, Manjrekar Madhav, Chowdhury Badrul Hasan. A comprehensive review and proposed architecture for offshore power system. *Int J Electr Power Energy Syst* 2019;111:79–92.
 - [55] Vivar Marta, Sharon H, Fuentes Manuel. Photovoltaic system adoption in water related technologies—A review. *Renew Sustain Energy Rev* 2024;189:114004.
 - [56] Yusop Zulkifli Mohd, Ibrahim Siti Atirah, Daud Muhamad Zalani, Suyono Hadi. Evaluating the horizon of renewable power: A comprehensive review of floating photovoltaic systems' performance and technologies. *J Adv Res Appl Sci Eng Technol* 2024;67–88.
 - [57] Sulaiman Mohd Herwan, Jadin Mohd Shawal, Mustaffa Zuriani, Azlan Mohd Nurulakla Mohd, Daniyal Hamdan. Short-Term forecasting of floating photovoltaic power generation using machine learning models. *Clean Energy Syst* 2024;9:100137.
 - [58] Alcañiz Alba, Agarwal Shagun, Tiwald Philipp, Isabella Olindo, Ziar Hesani, Colomés Oriol. Structural analysis and power losses in floating solar platform in offshore environment. Available at SSRN 4892393.
 - [59] Florin Barbu, Eugen Rusu, Cătălin Făitar. A review of the harvesting methods for offshore renewable energy—advances and challenges. *J Mar Technol Environ* 2024;2.
 - [60] Di Lorenzo Gianfranco, Stracqualursi Erika, Vescio Giovanni, Araneo Rodolfo. State of the art of renewable sources potentialities in the middle east: A case study in the Kingdom of Saudi Arabia. *Energies* 2024;17(8):1816.
 - [61] Elminshawy Nabil AS, Ahmed Asmaa, Osama Amr, Kabeel AE, Elbak-sawi Osama. The potential of optimized floating photovoltaic system for energy production in the Northern Lakes of Egypt. *Eng Anal Bound Elem* 2024;161:226–46.
 - [62] Cosgun Atıl Emre, Demir Hasan. Investigating the effect of albedo in simulation-based floating photovoltaic system: 1 MW bifacial floating photovoltaic system design. *Energies* 2024;17(4):959.
 - [63] Grimson Marc, Almeida Rafael, Shi Qinru, Bai Yiwei, Angarita Héctor, Pacheco Felipe Siqueira, Schmitt Rafael, Flecker Alexander, Gomes Carla P. Scaling up pareto optimization for tree structures with affine transformations: Evaluating hybrid floating solar-hydropower systems in the amazon. In: *Proceedings of the AAAI conference on artificial intelligence*. Vol. 38, 2024, p. 22067–75.
 - [64] Arnold Wyatt, Giuliani Matteo, Castelletti Andrea. Floating photovoltaics may reduce the risk of hydro-dominated energy development in Africa. *Nat Energy* 2024;1–10.
 - [65] Passos Rubens, Seneda José Antonio, Ortiz Nilce. Mathematical simulation and technical feasibility of floating solar systems installation in hydroelectric power reservoirs in Brazil. *J Sustain Dev Energy Water Environ Syst* 2024;12(1):1–14.
 - [66] Liu Zhao, Ma Chao, Yang Yilin, Li Xinyang, Gou Haixing, Folkard Andrew M. Water temperature and energy balance of floating photovoltaic construction water area—field study and modelling. *J Environ Manag* 2024;365:121494.
 - [67] Aboshosha Ashraf, Hamad Hisham A. Computer Aided Design and Simulation based development of floating solar resort. *Energy* 2024;294:130862.
 - [68] Ilgen Konstantin, Schindler Dirk, Armbruster Alfons, Ladwig Robert, Eppinger Ruiz de Zarate Irene, Lange Jens. Evaporation reduction and energy generation potential using floating photovoltaic power plants on the Aswan High Dam Reservoir. *Hydrol Sci J* 2024;1–12.
 - [69] Moqolo Rorisang Christopher. Design and analysis for a feasibility study of a floating solar PV power system for Metolong Dam (Master's thesis), National University of Lesotho; 2022.
 - [70] Faruqi MdFatin Ishraq, Jawad Atik, et al. Techno-economic assessment of power generation potential from floating solar photovoltaic systems in Bangladesh. *Heliyon* 2023;9(6).
 - [71] Zubair Muhammad, Bilal Awan Ahmed, Ghuffar Sajid, Butt Arslan Dawood, Farhan Muhammad. Analysis and selection criteria of lakes and dams of Pakistan for floating photovoltaic capabilities. *J Sol Energy Eng* 2020;142(3):031001.
 - [72] Liu Haohui, Krishna Vijay, Lun Leung Jason, Reindl Thomas, Zhao Lu. Field experience and performance analysis of floating PV technologies in the tropics. *Prog Photovolt, Res Appl* 2018;26(12):957–67.
 - [73] Islam Md Imamul, Maruf Md Hasan, Al Mansur Ahmed, Ashique Ratil H, ul Haq Mohammad Asif, Shihavuddin ASM, Jadin Mohd Shawal. Feasibility analysis of floating photovoltaic power plant in Bangladesh: A case study in Hatirjheel Lake, Dhaka. *Sustain Energy Technol Assess* 2023;55:102994.
 - [74] Jawad Atik, Hasan Md Sajid, Faruqi MdFatin Ishraq, et al. Small-scale floating photovoltaic systems in university campus: A pathway to achieving SDG 7 goals in Bangladesh. *Energy Convers Manage* 2023;297:117722.
 - [75] Piancó Felipe, Moraes Leo, dos Prazeres Igor, Lima Antônio Guilherme Garcia, Bessa João Gabriel, Micheli Leonardo, Fernández Eduardo, Almonacid Florencia. Hydroelectric operation for hybridization with a floating photovoltaic plant: A case of study. *Renew Energy* 2022;201:85–95.
 - [76] Bajc Tamara, Kostadinović Danka. Potential of usage of the floating photovoltaic systems on natural and artificial lakes in the Republic of Serbia. *J Clean Prod* 2023;422:138598.
 - [77] Iqbal Tariq, Asgher Muhammad Nadeem. Dynamic modelling and analysis of a hybrid power system of floating solar PV system for an offshore aquaculture site in Newfoundland. 2023.
 - [78] Workneh Tewodros G, Taye Biniyam Z, Nebey Abraham H. Design and performance analysis of 125 mw floating photovoltaic power plant in Ethiopia: Metema Vs Lake Tana. In: *Advances of science and technology: 9th EAI international conference, ICST 2021, hybrid event, Bahir Dar, Ethiopia, August 27–29, 2021, proceedings, part i*. Springer; 2022, p. 184–95.
 - [79] Tarigan Elieser. Potential of floating photovoltaic system at Tanjung Dam Mojokerto, Indonesia. In: *2023 international conference on smart-green technology in electrical and information systems. ICSGTEIS, IEEE; 2023, p. 13–7*.
 - [80] Ramadan Ahmad Awad, Hashem Gamal GS, Tahir Ahmed. Technical feasibility study of a grid-tied 85 MW floating solar PV power plant in Benghazi—Libya. In: *2022 13th international renewable energy congress. IREC, IEEE; 2022, p. 1–6*.
 - [81] Tahir Ahmed, Hashem Gamal GS, Ramadan Ahmad Awad. Technical Feasibility Study of a Grid-Tied 85 MW Floating Solar PV Power Plant in Benghazi—Libya.
 - [82] Chen Xin, Zhou Wenjia. Performance evaluation of aquavoltaics in China: Retrospect and prospect. *Renew Sustain Energy Rev* 2023;173:113109.
 - [83] Lauvandy Alexander Fernando, Raihananda Faiz Akbar, Estefan Michael Julian, Damanik Wawan Septiawan, Mu'min Gea Fardias, Juangsa Firman Bagja, Sambegoro Poetro. Application of a low-cost floating solar still in Indonesia. *Energy Sustain Dev* 2024;79:101410.
 - [84] Trapani Kim, Millar Dean L. Proposing offshore photovoltaic (PV) technology to the energy mix of the Maltese islands. *Energy Convers Manage* 2013;67:18–26.
 - [85] Althuwaini Yaqoub E. Mitigation measures to address soiling effect in solar photovoltaic system performance in Kuwait. 2024.
 - [86] Bhimaraju Ambati, Mahesh Aeidapu, Nirbheram Joshi Sukhdev. Feasibility study of solar photovoltaic/grid-connected hybrid renewable energy system with pumped storage hydropower system using abandoned open cast coal mine: A case study in India. *J Energy Storage* 2023;72:108206.
 - [87] Wu Yunna, Li Lingwenying, Song Zixin, Lin Xiaoshan. Risk assessment on offshore photovoltaic power generation projects in China based on a fuzzy analysis framework. *J Clean Prod* 2019;215:46–62.
 - [88] Song Chenchen, Guo Zhiling, Liu Zhengguang, Hongyun Zhang, Liu Ran, Zhang Haoran. Application of photovoltaics on different types of land in China: Opportunities, status and challenges. *Renew Sustain Energy Rev* 2024;191:114146.
 - [89] Meit J, Amato JCS, Vlaswinkel B. Offshore solar in high seas—assessment of resource complementarity for a case in Malta. In: *7th offshore energy & storage symposium. OSES 2023, Vol. 2023, IET; 2023, p. 24–30*.
 - [90] Pamik Murat, Bayraktar Murat, Konur Olgun, Nuran Mustafa. A revelatory case study for the emergence of powerships: the floating power plant innovation for rural electrification. *Trans Marit Sci* 2022;11(01):54–66.
 - [91] Jiang Hou, Yao Ling, Zhou Chenghu. Assessment of offshore wind-solar energy potentials and spatial layout optimization in mainland China. *Ocean Eng* 2023;287:115914.
 - [92] Ranjbaran Parisa, Yousefi Hossein, Gharehpetian GB, Astarai Fatemeh Razi. A review on floating photovoltaic (FPV) power generation units. *Renew Sustain Energy Rev* 2019;110:332–47.
 - [93] Zhou Bowen, Hudabaiardi Diliyaer, Qiao Jian, Li Guangdi, Xiao Zhaoxia. Design and control strategy of an integrated floating photovoltaic energy storage system. *J Mar Sci Eng* 2024;12(6):912.
 - [94] Fu Jingjing, Shi Hangrui, Cai Miao, Xu Mengjian, Fu Yuxin, Zhang Jinhua, Guo Xuguang, Wang Fang, Zhu Yiming, Rogalski Antoni. Non-volatile and gate-controlled multistate photovoltaic response in WSe₂/h-BN/graphene semi-floating gate field-effect transistors. *Adv Opt Mater* 2024;2400638.
 - [95] Eskandari Aref, Nedaei Amir, Milimonfared Jafar, Aghaei Mohammadreza. A multilayer integrative approach for diagnosis, classification and severity detection of electrical faults in photovoltaic arrays. *Expert Syst Appl* 2024;252:124111.

- [96] Spencer Robert S, Macknick Jordan, Aznar Alexandra, Warren Adam, Reese Matthew O. Floating photovoltaic systems: assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States. *Environ Sci Technol* 2018;53(3):1680–9.
- [97] El Hammoumi Aboubakr, Chtita Smail, Motahhir Saad, El Ghzizal Abdelaziz. Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels. *Energy Rep* 2022;8:11992–2010.
- [98] Ma Chao, Wu Runze, Su Hui. Design of floating photovoltaic power plant and its environmental effects in different stages: A review. *J Renew Sustain Energy* 2021;13(6):062701.
- [99] Oliveira Paula Mazza Barbosa, Almeida Rafael Marques, Cardoso Simone Jaque-line. Effects of floating photovoltaics on aquatic organisms: a review. *Hydrobiologia* 2024;1–16.
- [100] Lamnatou Chr, Cristofari C, Chemisana D. Photovoltaic/wind hybrid systems: Smart technologies, materials and avoided environmental impacts considering the Spanish electricity mix. *Sustain Energy Technol Assess* 2024;70:103920.
- [101] Ouro Pablo, Fernandez Riya, Armstrong Alona, Brooks Barbara, Burton Ralph R, Folkard Andrew, Ilic Suzana, Parkes Ben, Schultz David M, Stallard Tim, et al. Environmental impacts from large-scale offshore renewable-energy deployment. *Environ Res Lett* 2024;19(6):063001.
- [102] Frehner Alena, Stucki Matthias, Itten René. Are alpine floatovoltaics the way forward? Life-cycle environmental impacts and energy payback time of the worlds' first high-altitude floating solar power plant. *Sustain Energy Technol Assess* 2024;68:103880.
- [103] Benjamins Steven, Williamson Benjamin, Billing Suzannah-Lynn, Yuan Zhiming, Collu Maurizio, Fox Clive, Hobbs Laura, Masden Elizabeth A, Cottier-Cook Elizabeth J, Wilson Ben. Potential environmental impacts of floating solar photovoltaic systems. *Renew Sustain Energy Rev* 2024;199:114463.
- [104] Wu Sheng, Jiang Nian, Zhang Shuai, Zhang Pingping, Zhao Peng, Liu Yang, Wang Yanhui. Discussion on the development of offshore floating photovoltaic plants, emphasizing marine environmental protection. *Front Mar Sci* 2024;11:1336783.
- [105] Elbaksawi Osama, Elminshawy Nabil AS, Diab Sodfa, Eltamaly Ali M, Mahmoud Amera, Elhadidy Hala. Innovative metaheuristic algorithm with comparative analysis of MPPT for 5.5 kW floating photovoltaic system. *Process Saf Environ Prot* 2024;185:1072–88.
- [106] Chen Ching-Feng, Chen SK. Carbon footprint inventory using life cycle energy analysis. *MRS Energy Sustain* 2024;11(1):107–22.
- [107] Choi Young-Kwan, Lee Young-Geun. A study on development of rotary structure for tracking-type floating photovoltaic system. *Int J Precis Eng Manuf* 2014;15:2453–60.
- [108] Kulat Muhammed Imran, Tosun Kursad, Karaveli Abdullah Bugrahan, Yucel Ismail, Akinoglu Bulent Gultekin. A sound potential against energy dependency and climate change challenges: Floating photovoltaics on water reservoirs of Turkey. *Renew Energy* 2023;206:694–709.
- [109] Cagle Alexander Earl. Land sparing, environmental, and hydrological impacts of floating solar photovoltaic energy installations. Davis: University of California; 2023.
- [110] Pringle Adam M, Handler RM, Pearce Joshua M. Aquavoltaics: Synergies for dual use of water area for solar photovoltaic electricity generation and aquaculture. *Renew Sustain Energy Rev* 2017;80:572–84.
- [111] Luqman Muhammad, Mahmood Farhat, Al-Ansari Tareq. Supporting sustainable global food security through a novel decentralised offshore floating greenhouse. *Energy Convers Manage* 2023;277:116577.
- [112] Huang Ziyi, Zhu Rui, You Linlin. Unravelling the effects of dynamic urban thermal environment on utility-scale floating photovoltaic electricity generation. *Sustainable Cities Soc* 2023;99:104964.
- [113] Rahman Abidur, Farrok Omar, Haque Md Mejbaul. Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. *Renew Sustain Energy Rev* 2022;161:112279.
- [114] Ma Chao, Liu Zhao. Water-surface photovoltaics: Performance, utilization, and interactions with water eco-environment. *Renew Sustain Energy Rev* 2022;167:112823.
- [115] Ni George, Zandavi Seyed Hadi, Javid Seyyed Morteza, Boriskina Svetlana V, Cooper Thomas A, Chen Gang. A salt-rejecting floating solar still for low-cost desalination. *Energy Environ Sci* 2018;11(6):1510–9.
- [116] Zahedi Rafi, Ranjbaran Parisa, Gharehpetian Gevork B, Mohammadi Fazel, Ahmadihangar Roya. Cleaning of floating photovoltaic systems: a critical review on approaches from technical and economic perspectives. *Energies* 2021;14(7):2018.
- [117] Gao Xifeng, Wang Ting, Liu Mengmeng, Lian Jijian, Yao Ye, Yu Lina, Li Yichu, Cui Yiming, Xue Runze. A framework to identify guano on photovoltaic modules in offshore floating photovoltaic power plants. *Sol Energy* 2024;274:112598.
- [118] Grubišić-Čabo Filip, Nizetić Sandro, Giuseppe Marco Tina. Photovoltaic panels: A review of the cooling techniques. *Trans FAMENA* 2016;40(S1-1):63–74.
- [119] Sato Daisuke, Yamada Noboru. Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method. *Renew Sustain Energy Rev* 2019;104:151–66.
- [120] Du Shixiong, Liang Changmei, Sun Huaiwei, Wang Kaixun, Wang Jing, Li Haicheng, Xue Jie, Chen Fulong, Tuo Ye, Disse Markus, et al. Evaluating the potential benefits of float solar photovoltaics through the water footprint recovery period. *J Clean Prod* 2024;446:141399.
- [121] Elminshawy Nabil AS, Osama Amr, Naeim Noha, Elbaksawi Osama, Tina Giuseppe Marco. Thermal regulation of partially floating photovoltaics for enhanced electricity production: A modeling and experimental analysis. *Sustain Energy Technol Assess* 2022;53:102582.
- [122] Sutanto Bayu, Indartono Yuli Setyo, Wijayanta Agung Tri, Iacovides Hector. Enhancing the performance of floating photovoltaic system by using thermosiphon cooling method: Numerical and experimental analyses. *Int J Therm Sci* 2022;180:107727.
- [123] Oliveira-Pinto Sara, Stokkermans Jasper. Assessment of the potential of different floating solar technologies—Overview and analysis of different case studies. *Energy Convers Manage* 2020;211:112747.
- [124] Veliathur Chinnasamy Srinivasan Chellappillai, Soori Prashant Kumar, Ghaith Fadi A. Techno-economic feasibility of the use of floating solar PV systems in oil platforms. *Sustainability* 2024;16(3):1039.
- [125] Djalab Aicha, Djalab Zohra, El Hammoumi Aboubakr, Tina Giuseppe Marco, Motahhir Saad, Laouid Abdelkader Azzeddine. A comprehensive review of floating photovoltaic systems: Tech advances, marine environmental influences on offshore PV systems, and economic feasibility analysis. *Sol Energy* 2024;277:112711.
- [126] Sunny Mahmood Reaz, Kabir Md Ahsan, Sarker MdShakawat Zaman, Aghaloo Kamaledin, Ali Tausif. Feasibility study of floating solar photovoltaic systems using techno-economic assessment and multi-criteria decision-making method: A case study of Bangladesh. *Energy* 2024;133202.
- [127] Muthia Rahma, Pramudya Anastasia Segari Putri, Maulana Mochamad Rafly, Purwanto Widodo Wahyu. Techno-economic analysis of green hydrogen production by a floating solar photovoltaic system for industrial decarbonization. *Clean Energy* 2024;8(4):1–14.
- [128] Chen Ching-Feng, Fan Chia-Ming. Are fossil fuels superior to floating photovoltaic on energy return?—an LCEA perspective. *Smart Grids Sustain Energy* 2024;9(2):30.
- [129] Elminshawy Nabil AS, Osama Amr, Gagliano Antonio, Oterkus Erkan, Tina Giuseppe Marco. A technical and economic evaluation of floating photovoltaic systems in the context of the water-energy nexus. *Energy* 2024;131904.
- [130] Alsunousi Mohammed, Kayabasi Erhan. Techno-economic assessment of a floating photovoltaic power plant assisted methanol production by hydrogenation of CO₂ captured from Zawiya oil refinery. *Int J Hydrog Energy* 2024;57:589–600.
- [131] Nagababu Garlapati, Bhatt Tirth N, Patil Parth, Puppala Harish. Technical and economic analysis of floating solar photovoltaic systems in coastal regions of India: a case study of Gujarat and Tamil Nadu. *J Therm Anal Calorim* 2024;1–8.
- [132] Martinez A, Iglesias A. Mapping of the levelised cost of energy from floating solar PV in coastal waters of the European Atlantic, North Sea and Baltic Sea. *Sol Energy* 2024;279:112809.
- [133] Pomodakis Evangelos E, Orfanoudakis Georgios I, Katsigiannis Yiannis, Karapidakis Emmanouel. Techno-economic feasibility analysis of an offshore wave power facility in the Aegean Sea, Greece. *Energies* 2024;17(18):4588.
- [134] Avasthi Atul, Garg Rachana, Mahajan Priya. Comparative analysis of bifacial and monofacial floating solar power plants: Performance evaluation and economic analysis. *Iran J Sci Technol Trans Mech Eng* 2024;1–19.
- [135] Dellora Jeffrey T, Palconit Eleonor V, Enano Nelson C. Risk assessment and policy recommendations for a floating solar photovoltaic (FSPV) system. *IEEE Access* 2024.
- [136] Wang Hao, Liu Xiaolei, Wang Kan. Research on floating body resistance characteristics of floating photovoltaic and analysis of influencing factors. *Front Mar Sci* 2024;11:1387564.
- [137] Thipwangmek Nattha, Suetrong Nopparuj, Taparugssanagorn Attaphongse, Tangparitkul Suparit, Promsuk Natthan. Enhancing short-term solar photovoltaic power forecasting using a hybrid deep learning approach. *IEEE Access* 2024.
- [138] Alhassan Mohammed Okoe, Opoku Richard, Uba Felix, Obeng George Y, Sekyere Charles KK, Nyanor Peter. Techno-economic and environmental estimation assessment of floating solar PV power generation on Akosombo dam reservoir in Ghana. *Energy Rep* 2023;10:2740–55.
- [139] Kumar Nallapaneni Manoj, Islam Sayemul, Podder Amit Kumer, Selim Ali, Bajaj Mohit, Kamel Salah. Lifecycle-based feasibility indicators for floating solar photovoltaic plants along with implementable energy enhancement strategies and framework-driven assessment approaches leading to advancements in the simulation tool. *Front Energy Res* 2023;11:1075384.
- [140] Pimentel Da Silva Gardenio Diogo, Branco David Alves Castelo. Is floating photovoltaic better than conventional photovoltaic? Assessing environmental impacts. *Impact Assess Proj Apprais* 2018;36(5):390–400.
- [141] Bolinger Mark, Weaver Samantha. Utility-scale solar 2013: An empirical analysis of project cost, performance, and pricing trends in the United States. 2014.
- [142] Gol Akram Elahi, Ščasny Milan. Techno-economic analysis of fixed versus sun-tracking solar panels. *Int J Renew Energy Dev-IJRED* 2023;12(3).

- [143] Zhang Yusheng, Ma Chao, Yang Yang, Pang Xiulan, Lian Jijian, Wang Xin. Capacity configuration and economic evaluation of a power system integrating hydropower, solar, and wind. *Energy* 2022;259:125012.
- [144] Huang Luofeng, Li Yuzhu, Benites-Munoz Daniela, Windt Christian Windt, Feichtner Anna, Tavakoli Sasan, Davidson Josh, Paredes Ruben, Quintuna Tadea, Ransley Edward, et al. A review on the modelling of wave-structure interactions based on OpenFOAM. 2022.
- [145] Claus R, López M. Key issues in the design of floating photovoltaic structures for the marine environment. *Renew Sustain Energy Rev* 2022;164:112502. <http://dx.doi.org/10.1016/j.rser.2022.112502>.
- [146] Ghigo Alberto, Faraggiana Emilio, Sirigu Massimo, Mattiazzo Giuliana, Bracco Giovanni. Design and analysis of a floating photovoltaic system for offshore installation: The case study of Lampedusa. *Energies* 2022;15(23):8804.
- [147] Abbasnia Arash, Karimirad Madjid, Friel Dallán, Whittaker Trevor. Fully non-linear dynamics of floating solar platform with twin hull by tubular floaters in ocean waves. *Ocean Eng* 2022;257:111320.
- [148] Ikhenicheu Maria, Danglede Benoát, Pascal Rémy, Arramounet Valentin, Trébaol Quentin, Gorintin Félix. Analytical method for loads determination on floating solar farms in three typical environments. *Sol Energy* 2021;219:34–41.
- [149] Ikhenicheu Maria, Blanc Arthur, Danglede Benoát, Gilleteaux Jean-Christophe. OrcaFlex modelling of a multi-body floating solar island subjected to waves. *Energies* 2022;15(23):9260.
- [150] Čatipović Ivan, Alujević Neven, Smoljan Darko, Mikulić Antonio. A review on marine applications of solar photovoltaic systems. In: 15th international symposium on practical design of ships and other floating structures PRADS 2022. 2022.
- [151] Woolacott Emma. Could floating solar farms survive out at sea? BBC 2023.
- [152] Temiz Mert, Dincer Ibrahim. Development and analysis of a solar-based offshore energy system for sustainable island communities. *Int J Energy Res* 2022;46(14):20357–68.
- [153] Oliveira-Pinto Sara, Stokkermans Jasper. Marine floating solar plants: An overview of potential, challenges and feasibility. In: Proceedings of the institution of civil engineers-maritime engineering. Vol. 173, Thomas Telford Ltd; 2020, p. 120–35.
- [154] Chowdhury Gofran, Haggag Mohamed, Poortmans Jef. How cool is floating PV? A state-of-the-art review of floating PV's potential gain and computational fluid dynamics modeling to find its root cause. *EPJ Photovolt* 2023;14:24.
- [155] Zheng Zhi, Jin Peng, Huang Qiang, Zhou Binzhen, Xiang Ruoxuan, Zhou Zhaomin, Huang Luofeng. Motion response and energy harvesting of multi-module floating photovoltaics in seas. *Ocean Eng* 2024;310:118760.
- [156] Wei Yujia, Zou Detai, Zhang Deqing, Zhang Chao, Ou Binjian, Riyadi Soegeng, Utama IKAP, Hetharia Wolter, Wood Tim, Huang Luofeng. Motion characteristics of a modularized floating solar farm in waves. *Phys Fluids* 2024;36(3).
- [157] Yang Yifeng, Ren Kang, Zhou Binzhen, Sun Shi Yan, Huang Luofeng. Wave interaction with multiple adjacent floating solar panels with arbitrary constraints. *Phys Fluids* 2024;36(3).
- [158] Esparza Ignacio, Olábarri Candela Ángela, Huang Luofeng, Yang Yifeng, Budiono Chayun, Riyadi Soegeng, Hetharia Wolter, Hantoro Ridho, Setyawan Dony, Utama IKAP, et al. Floating PV systems as an alternative power source: Case study on three representative Islands of Indonesia. *Sustainability* 2024;16(3):1345.
- [159] Jifaturrohman MI, Putranto T, Utama IKAP, Huang L. Effect of platform configurations and environmental conditions on the performance of floating solar photovoltaic structures. In: International marine design conference. 2024.
- [160] Jiang Zhiyu, Dai Jian, Saettone Simone, Tørå Glenn, He Zhao, Bashir Musa, Souto-Iglesias Antonio. Design and model test of a soft-connected lattice-structured floating solar photovoltaic concept for harsh offshore conditions. *Mar Struct* 2023;90:103426.
- [161] Zhang Chi, Dai Jian, Ang Kok Keng, Lim Han Vincent. Development of compliant modular floating photovoltaic farm for coastal conditions. *Renew Sustain Energy Rev* 2024;190:114084.
- [162] Jifaturrohman Mohammad Izzuddin, Utama IKetut Aria Pria, Putranto Teguh, Setyawan Dony, Huang Luofeng. A study into the correlation between single array-hull configurations and wave spectrum for floating solar photovoltaic systems. *Ocean Eng* 2024;312:119312.
- [163] Chen Di, Peng Qiuzhi, Lu Jiating, Huang Peiyi, Song Yufei, Peng Fengcan. Classification and segmentation of five photovoltaic types based on instance segmentation for generating more refined photovoltaic data. *Appl Energy* 2024;376:124296.
- [164] Dzamesi Samuel Kofi Ahiave, Ahiataku-Togobo Wisdom, Yakubu Sufyan, Acheampong Peter, Kwarteng Maxmilian, Samikannu Ravi, Azeave Ebenezer. Comparative performance evaluation of ground-mounted and floating solar PV systems. *Energy Sustain Dev* 2024;80:101421.
- [165] Cardoso Andressa, Jurado-Rodríguez David, López Alfonso, Ramos M Isabel, Jurado Juan Manuel. Automated detection and tracking of photovoltaic modules from 3D remote sensing data. *Appl Energy* 2024;367:123242.
- [166] Liu Luyao, Sun Qie, Li Hailong, Yin Hongyi, Ren Xiaohan, Wennersten Ronald. Corrigendum to “evaluating the benefits of integrating floating photovoltaic and pumped storage power system” [Energy Convers. Manag. 194 (2019) 173–185]. *Energy Convers Manage* 2024;312:118526.
- [167] Garrod Aydan, Hussain Shanza Neda, Ghosh Aritra, Nahata Saiyam, Wynne Caitlin, Paver Sebastian. An assessment of floating photovoltaic systems and energy storage methods: A comprehensive review. *Results Eng* 2024;101940.
- [168] Irshad Ahmad Shah, Ludin Gul Ahmad, Ludin Samiullah, Elkholy MH, Elias Said, Senjyu Tomonobu. Integration and performance analysis of optimal large-scale hybrid PV and pump hydro storage system based upon floating PV for practical application. *Energy Convers Manag* 2024;22:100599.
- [169] Turgut Hilal Sayhan Akci, Dincer Ibrahim. Development and assessment of a floating photovoltaic-based hydrogen production system integrated with storage options. *Process Saf Environ Prot* 2024;190:930–43.
- [170] Koca Kemal. Compensating energy demand of public transport and yielding green hydrogen with floating photovoltaic power plant. *Process Saf Environ Prot* 2024;186:1097–105.
- [171] Kazemi-Robati Ehsan, Silva Bernardo, Bessa Ricardo J. Stochastic optimization framework for hybridization of existing offshore wind farms with wave energy and floating photovoltaic systems. *J Clean Prod* 2024;454:142215.
- [172] Li Runzhao, Jin Xiaoming, Yang Ping, Feng Yimin, Liu Yun, Wang Shichao, Ou Xiaoliang, Zeng Pengxiao, Li Yaoneng. Large-scale offshore wind energy integration by wind-thermal bundled power system: A case study of Yangxi, China. *J Clean Prod* 2024;435:140601.
- [173] Venturini Paolo, Gagliardi Gabriele Guglielmo, Agati Giuliano, Cedola Luca, Migliarese Caputi Michele Vincenzo, Borello Domenico. Integration of floating photovoltaic panels with an Italian hydroelectric power plant. *Energies* 2024;17(4):851.
- [174] Al Saadi Kawthar, Ghosh Aritra. Investigating the integration of floating photovoltaics (FPV) technology with hydrogen (H₂) energy for electricity production for domestic application in Oman. *Int J Hydrog Energy* 2024;80:1151–63.
- [175] Tay Zhi Yung. Performance of integrated FB and WEC for offshore floating solar photovoltaic farm considering the effect of hydroelasticity. *Ocean Eng* 2024;312:119165.
- [176] Mamatha G, Kulkarni PS. Unlocking the floating solar photovoltaic potential on hydropower reservoirs: a case study of Srisailem dam, India. *Electr Eng* 2024;1–13.
- [177] Barbón Arsenio, Rodríguez-Fernández Claudia, Bayón Luis, Aparicio-Bermejo Javier. Evaluating the potential of floating photovoltaic plants in pumped hydropower reservoirs in Spain. *Electronics* 2024;13(5):832.
- [178] Chen Lingte, Yang Jin, Lou Chengwei. Floating wind-integrated PV system yield analysis considering AHSE dynamics & solar azimuth effects. *Energy Convers Manage* 2024;315:118799.
- [179] Gonzalez-Gonzalez J Jazmin, Arenas-López J Pablo, Badaoui Mohamed. Advancing towards zero emissions: Integrating floating photovoltaic systems in hydroelectric power plant reservoirs. *Results Eng* 2024;23:102742.
- [180] Jin Yubin, Zeng Zhenzhong, Chen Yuntian, Xu Rongrong, Ziegler Alan D, Chen Wenchuan, Ye Bin, Zhang Dongxiao. Geographically constrained resource potential of integrating floating photovoltaics in global existing offshore wind farms. *Adv Appl Energy* 2024;13:100163.
- [181] Almeida Rafael M, Chowdhury Areef-Ul-Hassan, Rodrigo Hansapani, Li Mingxu, Schmitt Rafael JP. Offsetting the greenhouse gas footprint of hydropower with floating solar photovoltaics. *Nat Sustain* 2024;1–5.
- [182] Madeško Mirsad, Helać Vahid, Fejzić Ajdin, Konjicija Samim, Akšamović Abdulah, Grebović Selma. Integrating floating photovoltaics with hydroelectricity. *Energies* 2024;17(11):2760.
- [183] Cui Yiming, Liu Mengmeng, Li Wei, Lian Jijian, Yao Ye, Gao Xifeng, Yu Lina, Wang Ting, Li Yichu, Yin Jilong. An exploratory framework to identify dust on photovoltaic panels in offshore floating solar power stations. *Energy* 2024;307:132559.
- [184] Singh Rohit Kumar, Srivastava Praveen Kumar, Tiwari Gopal Nath, Sinha Akhouri Sudhir Kumar. A sustainable floating dome biogas plants integrated with semi-transparent photovoltaic thermal collectors: construction, production and economic analysis. *J Clean Prod* 2024;143706.
- [185] Bhattacharya Sagnik, Sadhu Pradip Kumar, Goswami Anik. Energy estimation of FSPV-based microgrid for sustainable electricity generation and water conservation in hot semi-arid urban areas. *Microsyst Technol* 2024;1–13.
- [186] Zhou Shijie, Cao Sunliang. Co-ordinations of ocean energy supported energy sharing between zero-emission cross-harbour buildings in the Greater Bay Area. *Appl Energy* 2024;359:122718.
- [187] Weber Timothy, Blakers Andrew, Silalahi David Firnando, Catchpole Kylie, Nadolny Anna. Grids dominated by solar and pumped hydro in wind-constrained sunbelt countries. *Energy Convers Manage* 2024;308:118354.
- [188] Kakoulaki Georgia, Sanchez R Gonzalez, Amillo A Gracia, Szabó Sándor, De Felice Matteo, Farinosi Fabio, De Felice Luca, Bisselink Berny, Seliger Roman, Kougiannis Ioannis, et al. Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe. *Renew Sustain Energy Rev* 2023;171:112989.
- [189] Ferrer-Gisbert Carlos, Ferrán-González José J, Redón-Santafé Miguel, Ferrer-Gisbert Pablo, Sánchez-Romero Francisco J, Torregrosa-Soler Juan Bautista. A new photovoltaic floating cover system for water reservoirs. *Renew Energy* 2013;60:63–70.

- [190] Campana Pietro Elia, Wästhage Louise, Nookuea Worrada, Tan Yuting, Yan Jinyue. Optimization and assessment of floating and floating-tracking PV systems integrated in on-and off-grid hybrid energy systems. *Sol Energy* 2019;177:782–95.
- [191] Prasannalal Sheena Adithi. Feasibility Investigation of Floating PV in Hydro reservoirs: A case study on tropical and mediterranean climatic regions. 2021.
- [192] Zhou Yanlai, Chang Fi-John, Chang Li-Chiu, Lee Wei-De, Huang Angela, Xu Chong-Yu, Guo Shenglian. An advanced complementary scheme of floating photovoltaic and hydropower generation flourishing water-food-energy nexus synergies. *Appl Energy* 2020;275:115389.
- [193] Lin Zi, Liu Xiaolei. Sustainable development of decommissioned FPSO as a floating solar plant—Case study of the effects of tilt angle on energy efficiency. In: *Proceedings of the international conference on applied energy*, Västerås, Sweden. Vol. 15, 2019.
- [194] Bunn Derek W, Raghavendran Hari, Srinivasan P. Sustainable power purchase contracts for local industries from floating solar & pumped hydro integration. 2023, Available at SSRN 4755070.
- [195] Costoya X, DeCastro M, Carvalho D, Argüel-Pérez Beatriz, Gómez-Gesteira Moncho. Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: A case study on the western Iberian Peninsula. *Renew Sustain Energy Rev* 2022;157:112037.
- [196] Ouedraogo Dayagnewinde Victorien. Techno-economical optimization of green hydrogen production with renewable energy systems (Ph.D. thesis), WASCAL; 2023.
- [197] Catania Matteo, Bamoshmoosh Abdullah, Dipierro Vincenzo, Ficili Marco, Fusco Andrea, Gioffré Domenico, Parolin Federico, Pilotti Lorenzo, Vincenti Ferdinando, Zelaschi Andrea, et al. Improving the performance of a pumped hydro storage plant through integration with floating photovoltaic. In: *Energy proceedings*, volume 39. 2023, p. 1–7.
- [198] Bahadori Morteza, Ghassemi Hassan. Performance analysis of offshore monopile wind turbine co-located with floating photovoltaic systems in Shark Bay, Australia. In: *International conference on offshore mechanics and arctic engineering*. Vol. 85192, American Society of Mechanical Engineers; 2021, V009T09A005.
- [199] Asgher Muhammad Nadeem. Design and analysis of a hybrid power system for an offshore aquaculture site in Newfoundland, Canada (Ph.D. thesis), Memorial University of Newfoundland; 2024.
- [200] Arefian Amir, Hosseini Abardesh Reza. Ambient crosswind effect on the first integrated pilot of a floating solar chimney power plant: experimental and numerical approach. *J Therm Anal Calorim* 2021;1–19.
- [201] Reddy Vundrala Sumedha, Sreelekha Bhuvaneshwari, Tan Jovan, Chuanqi Zhang, Ramakrishna Seeram. Powering the transition to clean energy with floating photovoltaic systems. *J Sustain Energy* 2023;14(1).
- [202] Kumar Manish, Niyaz Humaid Mohammed, Gupta Rajesh. Challenges and opportunities towards the development of floating photovoltaic systems. *Sol Energy Mater Sol Cells* 2021;233:111408.
- [203] Ramanan CJ, Lim King Hann, Kurnia Jundika Candra, Roy Sukanta, Bora Bhaskor Jyoti, Medhi Bhaskar Jyoti. Towards sustainable power generation: Recent advancements in floating photovoltaic technologies. *Renew Sustain Energy Rev* 2024;194:114322.
- [204] Gümrükçüoğlu Yiğit Mahnaz, Akçadağ Bevin. Empowering sustainability: Floating solar photovoltaic systems in agriculture for reduced costs carbon emissions and evaporation. *Glob Chall* 2024;2300321.
- [205] Riley Sequoia, Bhuva Vatsal, Gamarra Carlos, Badoian-Kriticos Marina. Reducing energy burden and flood damage using energy-water nexus approach. *J Sustain Dev Energy Water Environ Syst (JSDEWES)* 2024;12(3).
- [206] Liu Luyao, Wang Qinxing, Lin Haiyang, Li Hailong, Sun Qie, et al. Power generation efficiency and prospects of floating photovoltaic systems. *Energy Procedia* 2017;105:1136–42.
- [207] Victoria Marta, Haegel Nancy, Peters Ian Marius, Sinton Ron, Jäger-Waldau Arnulf, del Canizo Carlos, Breyer Christian, Stocks Matthew, Blakers Andrew, Kaizuka Izumi, et al. Solar photovoltaics is ready to power a sustainable future. *Joule* 2021;5(5):1041–56.
- [208] Veritas Det Norske. Design, development and operation of floating solar photovoltaic systems. Technical report, Technical Report, 2021, Available online: <https://www.dnv.com/energy/standards>
- [209] Pimentel Da Silva Gardenio Diogo, Magrini Alessandra, Branco David Alves Castelo. A multicriteria proposal for large-scale solar photovoltaic impact assessment. *Impact Assess Proj Apprais* 2020;38(1):3–15.
- [210] Ko Jae Woo, Cha Hae Lim, Kim David Kwang-Soon, Lim Jong Rok, Kim Gyu Gwang, Bhang Byeong Gwan, Won Chang Sub, Jung Han Sang, Kang Dong Hyung, Ahn Hyung Keun. Safety analysis of grounding resistance with depth of water for floating PVs. *Energies* 2017;10(9):1304.
- [211] Magkouris Alexandros, Belibassakis Kostas, Rusu Eugen. Hydrodynamic analysis of twin-hull structures supporting floating PV systems in offshore and coastal regions. *Energies* 2021;14(18):5979.
- [212] Cazzaniga Raniero. Floating PV structures. In: *Floating PV plants*. Elsevier; 2020, p. 33–45.
- [213] El Hammoui Aboubakr, Chalh Abdelilah, Allouhi Amine, Motahhir Saad, El Ghizal Abdelaziz, Derouich Aziz. Design and construction of a test bench to investigate the potential of floating PV systems. *J Clean Prod* 2021;278:123917.
- [214] PV Magazine. Ocean Sun and Inseanergy settle floating solar patent dispute. 2023, URL pv-magazine.com/2023/03/14/ocean-sun-inseanergy-settle-floating-solar-patent-dispute/.
- [215] Liu Gang, Guo Jiamin, Peng Huanghua, Ping Huan, Ma Qiang. Review of recent offshore floating photovoltaic systems. *J Mar Sci Eng* 2024;12(11):1942.
- [216] Kaymak Mustafa Kemal, Şahin Ahmet Duran. The first design and application of floating photovoltaic (FPV) energy generation systems in Turkey with structural and electrical performance. *Int J Precis Eng Manuf-Green Technol* 2021;1–13.
- [217] Kaymak Mustafa Kemal, Şahin Ahmet Duran. Problems encountered with floating photovoltaic systems under real conditions: A new FPV concept and novel solutions. *Sustain Energy Technol Assess* 2021;47:101504.
- [218] Zhang Deqing, Yuan Zhi-Ming, Du Junfeng, Li Huajun. Hydrodynamic modelling of large arrays of modularized floating structures with independent oscillations. *Appl Ocean Res* 2022;129:103371.
- [219] Kim Sun-Hee, Yoon Soon-Jong, Choi Wonchang. Design and construction of 1 MW class floating PV generation structural system using FRP members. *Energies* 2017;10(8):1142.
- [220] Dai Jian, Zhang Chi, Lim Han Vincent, Ang Kok Keng, Qian Xudong, Wong Johnny Liang Heng, Tan Sze Tiong, Wang Chien Looi. Design and construction of floating modular photovoltaic system for water reservoirs. *Energy* 2020;191:116549.
- [221] Kjeldstad Torunn, Nysted Vilde S, Kumar Manish, Oliveira-Pinto Sara, Otnes Gaute, Lindholm Dag, Selj Josefine. The performance and amphibious operation potential of a new floating photovoltaic technology. *Sol Energy* 2022;239:242–51.
- [222] Xu Pengpeng, Wellens Peter R. Theoretical analysis of nonlinear fluid-structure interaction between large-scale polymer offshore floating photovoltaics and waves. *Ocean Eng* 2022;249:110829.
- [223] Xu Pengpeng, Wellens Peter R. Fully nonlinear hydroelastic modeling and analytic solution of large-scale floating photovoltaics in waves. *J Fluids Struct* 2022;109:103446.
- [224] Mayville Pierce, Patil Neha Vijay, Pearce Joshua M. Distributed manufacturing of after market flexible floating photovoltaic modules. *Sustain Energy Technol Assess* 2020;42:100830.
- [225] Khojasteh Danial, Shamsipour Abbas, Huang Luofeng, Tavakoli Sasan, Haghani Milad, Flocard Francois, Farzadkhoo Maryam, Iglesias Gregorio, Hemer Mark, Lewis Matthew, et al. A large-scale review of wave and tidal energy research over the last 20 years. *Ocean Eng* 2023;282:114995.
- [226] Nyoni Kumbuso Joshua, Maronga Anesu, Tuohy Paul Gerard, Shane Agabu. Hydro-connected floating PV renewable energy system and onshore wind potential in Zambia. *Energies* 2021;14(17):5330.
- [227] Claus R, López M. Key issues in the design of floating photovoltaic structures for the marine environment. *Renew Sustain Energy Rev* 2022;112502.
- [228] Temiz Mert, Javani Nader. Design and analysis of a combined floating photovoltaic system for electricity and hydrogen production. *Int J Hydrog Energy* 2020;45(5):3457–69.
- [229] Cazzaniga R, Cicu M, Rosa-Clot M, Rosa-Clot P, Tina GM, Ventura C. Compressed air energy storage integrated with floating photovoltaic plant. *J Energy Storage* 2017;13:48–57.
- [230] Choi Jung-Youl, Hwang Seong-Tae, Kim Sun-Hee. Evaluation of a 3.5-MW floating photovoltaic power generation system on a thermal power plant ash pond. *Sustainability* 2020;12(6):2298.
- [231] Ramos Helena M, Vargas Brandon, Saldanha João Roquette. New integrated energy solution idealization: Hybrid for renewable energy network (Hy4REN). *Energies* 2022;15(11):3921.
- [232] Lee Young-Geun, Joo Hyung-Joong, Yoon Soon-Jong. Design and installation of floating type photovoltaic energy generation system using FRP members. *Sol Energy* 2014;108:13–27.
- [233] Golroodbari S Zahra, van Sark Wilfried. Simulation of performance differences between offshore and land-based photovoltaic systems. *Prog Photovolt, Res Appl* 2020;28(9):873–86.
- [234] Sargunanathan S, Elango A, Mohideen S Tharves. Performance enhancement of solar photovoltaic cells using effective cooling methods: A review. *Renew Sustain Energy Rev* 2016;64:382–93.
- [235] Micheli Leonardo. The temperature of floating photovoltaics: Case studies, models and recent findings. *Sol Energy* 2022;242:234–45.
- [236] Nžetić Sandro, Čoko Duje, Yadav A, Grubišić-Čabo Filip. Water spray cooling technique applied on a photovoltaic panel: The performance response. *Energy Convers Manage* 2016;108:287–96.
- [237] Choi Young Kwan, Choi Won Seok, Lee Jae Hyeon. Empirical research on the efficiency of floating PV systems. *Sci Adv Mater* 2016;8(3):681–5.
- [238] de Oliveira Busson Bruna, de Oliveira Santos Leticia, de Carvalho Paulo Cesar Marques, de Oliveira Carvalho Filho Clodoaldo. Experimental assessment and modeling of a floating photovoltaic module with heat bridges. *IEEE Lat Am Trans* 2021;19(12):2079–86.
- [239] Sheikh YA, Butt AD, Paracha KN, Awan AB, Bhatti AR, Zubair M. An improved cooling system design to enhance energy efficiency of floating photovoltaic systems. *J Renew Sustain Energy* 2020;12(5):053502.
- [240] Kjeldstad Torunn, Lindholm Dag, Marstein Erik, Selj Josefine. Cooling of floating photovoltaics and the importance of water temperature. *Sol Energy* 2021;218:544–51.

- [241] Tina Giuseppe Marco, Scavo Fausto Bontempo, Micheli Leonardo, Rosa-Clot Marco. Economic comparison of floating photovoltaic systems with tracking systems and active cooling in a Mediterranean water basin. *Energy Sustain Dev* 2023;76:101283.
- [242] Wu How-Ping, Tseng Ching-Yi, Jen Chuan-Chung, Chiang Yuan-Ching, Chen Sih-Li. Analysis of the potential for enhancing the efficiency of a floating photovoltaic (FPV) system. *J Mar Sci Technol* 2024;32(2):7.
- [243] Amiot Baptiste, Pabiau Hervé, Le Berre Rémi, Giroux-Julien Stéphanie. An innovative method for measuring the convective cooling of photovoltaic modules. *Sol Energy* 2024;274:112531.
- [244] Deb Dipankar, Brahmabhatt Nisarg L. Review of yield increase of solar panels through soiling prevention, and a proposed water-free automated cleaning solution. *Renew Sustain Energy Rev* 2018;82:3306–13.
- [245] Rosa-Clot Marco, Rosa-Clot Paolo, Tina GM, Scandura PF. Submerged photovoltaic solar panel: SP2. *Renew Energy* 2010;35(8):1862–5.
- [246] Lanzafame Rosario, Nachtmann Silvia, Rosa-Clot Marco, Rosa-Clot Paolo, Scandura Pier Francesco, Taddei Stefano, Tina Giuseppe M. Field experience with performances evaluation of a single-crystalline photovoltaic panel in an underwater environment. *IEEE Trans Ind Electron* 2009;57(7):2492–8.
- [247] Trapani Kim, Millar Dean L. The thin film flexible floating PV (T3F-PV) array: The concept and development of the prototype. *Renew Energy* 2014;71:43–50.
- [248] Han Juan, Wan Chuqi, Fang Hai, Bai Yu. Development of self-floating fibre reinforced polymer composite structures for photovoltaic energy harvesting. *Compos Struct* 2020;253:112788.
- [249] Kim Sun-Hee, Baek Seung-Cheol, Choi Ki-Bong, Park Sung-Jin. Design and installation of 500-kW floating photovoltaic structures using high-durability steel. *Energies* 2020;13(19):4996.
- [250] Hayibo Koami Soulemane, Mayville Pierce, Kailey Ravneet Kaur, Pearce Joshua M. Water conservation potential of self-funded foam-based flexible surface-mounted floatovoltaics. *Energies* 2020;13(23):6285.
- [251] Liu Chun-Kuo, Kong Zhong-Ri, Kao Ming-Je, Wu Teng-Chun. A novel accelerated aging test for floats in a floating photovoltaic system. *Coatings* 2021;11(11):1283.
- [252] Yakubu Rahimat O, Mensah Lena D, Quansah David A, Adaramola Muiyiwa S. A systematic literature review of the bifacial photovoltaic module and its applications. *J Eng* 2024;2024(8):e12421.
- [253] Mahim Tanvir M, Rahim AHMA, Rahman M Mosaddequr. Review of mono-and bifacial photovoltaic technologies: A comparative study. *IEEE J Photovolt* 2024.
- [254] Ziar Hesan, Prudon Bjorn, Lin Fen-Yu, Roeffen Bart, Heijkoop Dennis, Stark Tim, Teurlinx Sven, de Senerpont Domis Lisette, Goma Elias Garcia, Extebarria Julien Garro, et al. Innovative floating bifacial photovoltaic solutions for inland water areas. *Prog Photovolt, Res Appl* 2021;29(7):725–43.
- [255] Widayat AA, Ma'arif S, Syahindra KD, Fauzi AF, Setiawan E Adhi. Comparison and optimization of floating bifacial and monofacial solar PV system in a tropical region. In: 2020 9th international conference on power science and engineering. ICPSE, IEEE; 2020, p. 66–70.
- [256] Tina Giuseppe Marco, Scavo Fausto Bontempo, Merlo Leonardo, Bizzarri Fabrizio. Comparative analysis of monofacial and bifacial photovoltaic modules for floating power plants. *Appl Energy* 2021;281:116084.
- [257] Bhang Byeong Gwan, Hyun Jin Hee, Ahn Seong-Hyeon, Choi Jin Ho, Kim Gyu-Gwang, Ahn Hyung-Keun. Optimal design of bifacial floating photovoltaic system with different installation azimuths. *IEEE Access* 2022;11:1456–66.
- [258] Jahangir Jabir Bin, Al-Mahmud Md, Shakir MdShahadat Sarker, Haque Anisul, Alam Muhammad A, Khan M Ryyan. A critical analysis of bifacial solar farm configurations: Theory and experiments. *IEEE Access* 2022;10:47726–40.
- [259] Pandian Ganesan Rathinavel, Balachandran Gurukarthik Babu, David Prince Winston, K Sangeetha. Performance analysis of floating bifacial stand-alone photovoltaic module in tropical freshwater systems of Southern Asia: an experimental study. *Sci Rep* 2024;14(1):20352.
- [260] Rathinavel Pandian Ganesan, Balachandran Gurukarthik Babu, David Prince Winston, Thangaraj Hariharasudhan. Optimization strategies for bifacial floating photovoltaic systems on different water bodies: A 10E performance evaluation. *Proc Inst Mech Eng E* 2024;09544089241281111.
- [261] Yang Ray-Yeng, Yu Sheng-Hung. A study on a floating solar energy system applied in an intertidal zone. *Energies* 2021;14(22):7789.
- [262] Choi Seok Min, Park Chang-Dae, Cho Sung-Hoon, Lim Byung-Ju. Effects of various inlet angle of wind and wave loads on floating photovoltaic system considering stress distributions. *J Clean Prod* 2023;135876.
- [263] Choi Seok Min, Park Chang-Dae, Cho Sung-Hoon, Lim Byung-Ju. Effects of wind loads on the solar panel array of a floating photovoltaic system—Experimental study and economic analysis. *Energy* 2022;256:124649.
- [264] Su Kao-Chun, Chung Ping-Han, Yang Ray-Yeng. Numerical simulation of wind loads on an offshore PV panel: the effect of wave angle. *J Mech* 2020;37:53–62.
- [265] Lee Gyu-Han, Choi Ji-Woong, Kim JaeUn, Seo Ji-Hyun, Ha Hojin. Numerical simulations of wind loading on the floating photovoltaic systems. *J Vis* 2021;24:471–84.
- [266] Elminshawy Nabil AS, Osama Amr, El-Damhogi DG, Oterkus Erkan, Mohamed AMI. Simulation and experimental performance analysis of partially floating PV system in windy conditions. *Sol Energy* 2021;230:1106–21.
- [267] Choi Seok Min, Lee Ga Ram, Park Chang Dae, Cho Sung Hoon, Lim Byung Ju. Wind load on the solar panel array of a floating photovoltaic system under extreme hurricane conditions. *Sustain Energy Technol Assess* 2021;48:101616.
- [268] Honary Amir, Karimirad Madjid, Abbasnia Arash, Whittaker Trevor. Wind parameters effects on floating solar array design—case study: Japan's largest floating solar array. In: International conference on offshore mechanics and arctic engineering. Vol. 85932, American Society of Mechanical Engineers; 2022, V008T09A008.
- [269] Tina GM, Rosa-Clot M, Rosa-Clot P, Scandura PF. Optical and thermal behavior of submerged photovoltaic solar panel: SP2. *Energy* 2012;39(1):17–26.
- [270] Clot Marco Rosa, Rosa-Clot Paolo, Tina Giuseppe Marco. Submerged PV solar panel for swimming pools: SP3. *Energy Procedia* 2017;134:567–76.
- [271] Elminshawy Nabil AS, Mohamed AMI, Osama Amr, Amin Islam, Bas-sam Ameen M, Oterkus Erkan. Performance and potential of a novel floating photovoltaic system in Egyptian winter climate on calm water surface. *Int J Hydrog Energy* 2022;47(25):12798–814.
- [272] Elminshawy Nabil AS, El-Damhogi DG, Ibrahim IA, Elminshawy Ahmed, Osama Amr. Assessment of floating photovoltaic productivity with fins-assisted passive cooling. *Appl Energy* 2022;325:119810.
- [273] Chandrasekar M, Senthilkumar T. Passive thermal regulation of flat PV modules by coupling the mechanisms of evaporative and fin cooling. *Heat Mass Transf* 2016;52:1381–91.
- [274] Elbreki AM, Sopian K, Fazlizan A, Ibrahim A. An innovative technique of passive cooling PV module using lapping fins and planner reflector. *Case Stud Therm Eng* 2020;19:100607.
- [275] Yunus Khan TM, Soudagar Manzoore Elahi M, Kanchan Mithun, Afzal Asif, Banapurmath Nagaraj R, Akram Naveed, Mane Suresh D, Shahapurkar Kiran. Optimum location and influence of tilt angle on performance of solar PV panels. *J Therm Anal Calorim* 2020;141:511–32.
- [276] Reina Giovanni Paolo, De Stefano Giuliano. Computational evaluation of wind loads on sun-tracking ground-mounted photovoltaic panel arrays. *J Wind Eng Ind Aerodyn* 2017;170:283–93.
- [277] Nivelle Philippe, Tsanakas John A, Poortmans Jef, Daenen Michaël. Stress and strain within photovoltaic modules using the finite element method: A critical review. *Renew Sustain Energy Rev* 2021;145:111022.
- [278] Armstrong S, Hurley WG. A thermal model for photovoltaic panels under varying atmospheric conditions. *Appl Therm Eng* 2010;30(11–12):1488–95.
- [279] Jaszczur Marek, Teneta Janusz, Hassan Qusay, Majewska Ewelina, Hanus Robert. An experimental and numerical investigation of photovoltaic module temperature under varying environmental conditions. *Heat Transf Eng* 2021;42(3–4):354–67.
- [280] Bellini E. Japan's largest floating PV plant catches fire after Typhoon Faxai impact. *PV Mag* 2019.
- [281] Tang Yichang, Chen Xi, Huang Guozhen, Chen Mingsheng, Zhang Kai, Jiang Yanlin, Li Tingqiu, Tao Tao, Yang Yi. Dynamic analysis of multi-module floating photovoltaic platforms with composite mooring system by considering tidal variation and platform configuration. *Ocean Eng* 2024;312:119243.
- [282] Browne Matthew TL, Taylor Zachary J, Li Sihan, Gamble Scott. A wind load design method for ground-mounted multi-row solar arrays based on a compilation of wind tunnel experiments. *J Wind Eng Ind Aerodyn* 2020;205:104294.
- [283] Wood Graeme S, Denoon Roy O, Kwok Kenny CS. Wind loads on industrial solar panel arrays and supporting roof structure. *Wind Struct* 2001;4(6):481–94.
- [284] Velaz-Acera Néstor, Hernández-Herráez Gustavo, López-Rebollo Jorge, González-Ayala Julián, Yáñez-Villareal David J, Lagüela Susana. An innovative approach to assessing and optimizing floating solar panels. *Energy Convers Manage* 2024;321:119028.
- [285] Veritas Det Norske. Recommended practice DNV-RP-C205: environmental conditions and environmental loads. Norway: DNV; 2010.
- [286] Lee Y-G, Joo H-J, Yoon S-J. Design and installation of floating type photovoltaic energy generation system using FRP members. *Sol Energy* 2014;108:13–27. <http://dx.doi.org/10.1016/j.solener.2014.06.033>.
- [287] Lee Gyu-Han, Choi Ji-Woong, Seo Ji-Hyun, Ha Hojin. Comparative study of effect of wind and wave load on floating PV: Computational simulation and design method. *J Korean Soc Manuf Process Eng* 2019;18(11):9–17. <http://dx.doi.org/10.14775/ksmpe.2019.18.11.009>.
- [288] Lee Jun-Hee, Paik Kwang-Jun, Lee Soon-Hyun, Hwangbo Jun, Ha Tae-Hyu. Experimental and numerical study on the characteristics of motion and load for a floating solar power farm under regular waves. *J Mar Sci Eng* 2022;10(5):565. <http://dx.doi.org/10.3390/jmse10050565>.
- [289] Al-Yacoubi AM, Halim Emiruddin Redza Bin Abdul, Liew MS. Hydrodynamic analysis of floating offshore solar farms subjected to regular waves. In: Advances in manufacturing engineering: Selected articles from ICMPE 2019. Springer; 2020, p. 375–90.
- [290] Ikhenichou Maria, Danglade Benoat, Pascal Rémy, Arramounet Valentin, Trébaol Quentin, Gorintin Félix. Analytical method for loads determination on floating solar farms in three typical environments. *Sol Energy* 2021;219:34–41. <http://dx.doi.org/10.1016/j.solener.2020.11.078>.
- [291] Dai Jian, Zhang Chi, Lim Han Vincent, Ang Kok Keng, Qian Xudong, Wong Johnny Liang Heng, Tan Sze Tiong, Wang Chien Looi. Design and construction of floating modular photovoltaic system for water reservoirs. *Energy* 2020;191:116549. <http://dx.doi.org/10.1016/j.energy.2019.116549>.

- [292] Friel D, Karimirad M, Whittaker T, Doran J. Hydrodynamic investigation of design parameters for a cylindrical type floating solar system. In: *Developments in renewable energies offshore*. CRC Press; 2020. <http://dx.doi.org/10.1201/9781003134572>.
- [293] Sree Dharma KK, Law Adrian Wing-Keung, Pang Dawn Sok Cheng, Tan Sze Tiong, Wang Chien Looi, Kew Jernice Huiling, Seow Wei Kiong, Lim Vincent Han. Fluid-structural analysis of modular floating solar farms under wave motion. *Sol Energy* 2022;233:161–81.
- [294] Li Chun Bao, Choung Joonmo. Structural effects of mass distributions in a floating photovoltaic power plant. *J Mar Sci Eng* 2022;10(11):1738.
- [295] Journée J, Massie W. *Offshore hydromechanics*. TU Delft; 2001.
- [296] Xu Pu, Zhang Zirui, Li Siliang, Song Qiming, Liu Wei. Numerical investigation into the dynamic responses of floating photovoltaic platform and mooring line structures under freak waves. *J Mar Sci Eng* 2024;12(1):96.
- [297] Papathanasiou TK, Belibassakis KA. Resonances of enclosed shallow water basins with slender floating elastic bodies. *J Fluids Struct* 2018;82:538–58.
- [298] van der Zanden Joep, Bunnik Tim, Cortés Ainhoa, Delhaye Virgile, Kege-lart Guillaume, Pehlke Thomas, Panjwani Balram. Wave basin tests of a multi-body floating PV system sheltered by a floating breakwater. *Energies* 2024;17(9):2059.
- [299] Choi Young-Kwan, Lee Jae-Hyeong. Structural safety assessment of ocean-floating photovoltaic structure model. *Isr J Chem* 2015;55(10):1081–90.
- [300] Longuet-Higgins Michael Selwyn. The mean forces exerted by waves on floating or submerged bodies with applications to sand bars and wave power machines. *Proc R Soc A* 1977;352(1671):463–80.
- [301] Maruo Hajime. The drift of a body floating on waves. *J Ship Res* 1960;4:1–10.
- [302] Linton CM. The finite dock problem. *Z Angew Math Phys ZAMP* 2001;52:640–56.
- [303] Zhang Yifan, Zhang Xiantao, Chen Yongqiang, Tian Xinliang, Li Xin. A frequency-domain hydroelastic analysis of a membrane-based offshore floating photovoltaic platform in regular waves. *J Fluids Struct* 2024;127:104125.
- [304] Li Yan, Li Guoyan, Cui Yiwen, Deng Wanru, Wang Bin, Li Haoran, Feng Yiting, Meng Hang. The influence of multi-body interaction on the hydrodynamic performance of a hexagon-type floating photovoltaic. *Ocean Eng* 2024;312:119302.
- [305] Shi Yongkang, Wei Yanji, Chen Zuogang. Development of Reduced-Order-Discrete-Module method for hydroelastic analysis of floating flexible structures. *J Fluids Struct* 2024;130:104188.
- [306] Ren Xiudi, Chen Yongqiang, Zhang Yu, Zhang Xiantao, Shen Kanmin, Cui Lin, Lu Mengyao. A discrete-module-beam hydroelasticity method with finite element theory in analyzing VLFS in different engineering scenarios. *Ocean Eng* 2024;307:118121.
- [307] Wei Yujia, Tezdogan Tahsin. A fluid-structure interaction model on the hydroelastic analysis of a container ship using PRECICE. In: *International conference on offshore mechanics and arctic engineering*. Vol. 85925, American Society of Mechanical Engineers; 2022, V007T08A035.
- [308] Charles Lawrence Kamuyu Waitithiru, Lim Jong Rok, Won Chang Sub, Ahn Hyung Keun. Prediction model of photovoltaic module temperature for power performance of floating PVs. *Energies* 2018;11(2):447.
- [309] Nicola Monica, Berwind Matthew. Improving module temperature prediction models for floating photovoltaic systems: Analytical insights from operational data. *Energies* (19961073) 2024;17(17).
- [310] Dörenkämper Maarten, Villa Simona, Kroon Jan, de Jong Minne M. The impact of system sizing and water temperature on the thermal characteristics of floating photovoltaic systems. *Energies* 2024;17(9):2027.
- [311] Lindholm Dag, Kjeldstad Torunn, Selj Josefine, Marstein Erik Stensrud, Fjær Hallvard Gustav. Heat loss coefficients computed for floating PV modules. *Prog Photovolt, Res Appl* 2021;29(12):1262–73.
- [312] Dörenkämper Maarten, de Jong Minne M, Kroon Jan, Nysted Vilde Stueland, Selj Josefine, Kjeldstad Torunn. Modeled and measured operating temperatures of floating PV modules: A comparison. *Energies* 2023;16(20):7153.
- [313] Ho CJ, Chou Wei-Len, Lai Chi-Ming. Application of a water-saturated MEPCM-PV for reducing winter chilling damage on aqua farms. *Sol Energy* 2014;108:135–45.
- [314] Ho CJ, Chou Wei-Len, Lai Chi-Ming. Thermal and electrical performance of a water-saturated floating PV integrated with a water-saturated MEPCM layer. *Energy Convers Manage* 2015;89:862–72.
- [315] Nysted Vilde Stueland, Lindholm Dag, Selj Josefine, Kjeldstad Torunn. Floating photovoltaics: modelled and experimental operating temperatures and the impact of wind speed and direction. *EPJ Photovolt* 2024;15:23.
- [316] Ramanan CJ, Lim King Hann, Kurnia Jundika Candra, Roy Sukanta, Bora Bhaskor Jyoti, Medhi Bhaskar Jyoti. Design study on the parameters influencing the performance of floating solar PV. *Renew Energy* 2024;223:120064.
- [317] Hasan ASM Mominul, Kesapabutr Prin, Möller Bernd. Bangladesh's pathways to net-zero transition: Reassessing country's solar PV potential with high-resolution GIS data. *Energy Sustain Dev* 2024;81:101511.
- [318] Abdelgaied Mohamed, Kabeel Abd Elnaby, Zelenáková Martina, Abd-Elhamid Hany F. Floating photovoltaic plants as an effective option to reduce water evaporation in water-stressed regions and produce electricity: A case study of Lake Nasser, Egypt. *Water* 2023;15(4):635.
- [319] Abd-Elhamid Hany F, Ahmed Ashraf, Zelenáková Martina, Vranayová Zuzana, Fathy Ismail. Reservoir management by reducing evaporation using floating photovoltaic system: A case study of Lake Nasser, Egypt. *Water* 2021;13(6):769.
- [320] Agrawal Karmendra Kumar, Jha Shibani Khanra, Mittal Ravi Kant, Vashishtha Sanjay. Assessment of floating solar PV (FSPV) potential and water conservation: Case study on Rajghat Dam in Uttar Pradesh, India. *Energy Sustain Dev* 2022;66:287–95.
- [321] PVsyst SA. *PVsyst Photovoltaic software*. 2023. <https://www.pvsyst.com/>, Last accessed 03/10/2023.
- [322] Ghasempour Roghayeh, Motlagh Saheb Ghanbari, Montazeri Mohammad, Shirmohammadi Reza. Deployment a hybrid renewable energy system for enhancing power generation and reducing water evaporation of a dam. *Energy Rep* 2022;8:10272–89.
- [323] Pouran Hamid, Lopes Mariana Padilha Campos, Ziar Hesam, Branco David Alves Castelo, Sheng Yong. Evaluating floating photovoltaics (FPVs) potential in providing clean energy and supporting agricultural growth in Vietnam. *Renew Sustain Energy Rev* 2022;169:112925.
- [324] NREL. *System advisory model*. 2023. <https://sam.nrel.gov/>, Last accessed 03/10/2023.
- [325] Lopes Mariana Padilha Campos, de Andrade Neto Sudá, Branco David Alves Castelo, de Freitas Marcos Aurélio Vasconcelos, da Silva Fidelis Neilton. Water-energy nexus: Floating photovoltaic systems promoting water security and energy generation in the semiarid region of Brazil. *J Clean Prod* 2020;273:122010.
- [326] Gadzanku Sika, Mirlitz Heather, Lee Nathan, Daw Jennifer, Warren Adam. Benefits and critical knowledge gaps in determining the role of floating photovoltaics in the energy-water-food nexus. *Sustainability* 2021;13(8):4317.
- [327] Ingo Tarelayefa Igedibor, Gyoh Louis, Sheng Yong, Kaymak Mustafa Kemal, Şahin Ahmet Duran, Pouran Hamid M. Accelerating the low-carbon energy transition in sub-Saharan Africa through floating photovoltaic solar farms. *Atmosphere* 2024;15(6):653.
- [328] Nagababu Garlapati, Patil Parth, Bhatt Tirth N, Srinivas Bhasuru Abhinaya, Puppala Harish. Floating solar panels: a sustainable solution to meet energy demands and combat climate change in offshore regions. *J Therm Anal Calorim* 2024;1–8.
- [329] Gasparatos Alexandros, Doll Christopher NH, Esteban Miguel, Ahmed Abubakari, Olang Tabitha A. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renew Sustain Energy Rev* 2017;70:161–84.
- [330] Abdelal Qasem. Floating PV; an assessment of water quality and evaporation reduction in semi-arid regions. *Int J Low-Carbon Technol* 2021;16(3):732–9.
- [331] Soltani Seyyed Rashid Khalifeh, Mostafaeipour Ali, Almutairi Khalid, Dehshiri Seyyed Jalaladdin Hosseini, Dehshiri Seyyed Shahabaddin Hosseini, Techato Kuaanan. Predicting effect of floating photovoltaic power plant on water loss through surface evaporation for wastewater pond using artificial intelligence: A case study. *Sustain Energy Technol Assess* 2022;50:101849.
- [332] Bontempo Scavo Fausto, Tina Giuseppe Marco, Gagliano Antonio, Nizetic Sandro. An assessment study of evaporation rate models on a water basin with floating photovoltaic plants. *Int J Energy Res* 2021;45(1):167–88.
- [333] Farrar Lewis W, Bahaj AbuBakr S, James Patrick, Anwar Arif, Amdar Nafn. Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study Jordan. *Energy Convers Manage* 2022;260:115598.
- [334] Majumder Arnab, Innamorati Roberto, Frattolillo Andrea, Kumar Amit, Gatto Gianluca. Performance analysis of a floating photovoltaic system and estimation of the evaporation losses reduction. *Energies* 2021;14(24):8336.
- [335] Zhang Nan, Jiang Tong, Guo Cui, Qiao Lifang, Ji Qing, Yin Luqi, Yu Liangmin, Murto Petri, Xu Xiaofeng. High-performance semitransparent polymer solar cells floating on water: Rational analysis of power generation, water evaporation and algal growth. *Nano Energy* 2020;77:105111.
- [336] Al-Widyan Mohammad, Khasawneh Mohammad, Abu-Dalo Muna. Potential of floating photovoltaic technology and their effects on energy output, water quality and supply in Jordan. *Energies* 2021;14(24):8417.
- [337] Wang Teng-Wei, Chang Ping-Hung, Huang Ying-Sheng, Lin Tain-Sheng, Yang Shuenn-Der, Yeh Shinn-Lih, Tung Che-Huang, Kuo Shih-Rong, Lai Hong-Thih, Chen Che-Chun. Effects of floating photovoltaic systems on water quality of aquaculture ponds. *Aquacult Res* 2022;53(4):1304–15.
- [338] Kaplanis Socrates, Kaplani Eleni, Kaldellis John K. PV temperature prediction incorporating the effect of humidity and cooling due to seawater flow and evaporation on modules simulating floating PV conditions. *Energies* 2023;16(12):4756.
- [339] Quaranta Emanuele, Aggidis George, Boes Robert M, Comoglio Claudio, De Michele Carlo, Patro Epari Ritesh, Georgievskia Evgeniia, Harby Atle, Kougias Ioannis, Muntean Sebastian, et al. Assessing the energy potential of modernizing the European hydropower fleet. *Energy Convers Manage* 2021;246:114655.
- [340] Fereshtehpour Mohammad, Sabbaghian Reza Javidi, Farrokhi Ali, Jovein Ehsan Bahrami, Sarindizaj Elham Ebrahimi. Evaluation of factors governing the use of floating solar system: A study on Iran's important water infrastructures. *Renew Energy* 2021;171:1171–87.

- [341] Assouline S, Narkis K, Or Dani. Evaporation suppression from water reservoirs: Efficiency considerations of partial covers. *Water Resour Res* 2011;47(7).
- [342] Valiantzas John D. Simplified versions for the Penman evaporation equation using routine weather data. *J Hydrol* 2006;331(3–4):690–702.
- [343] Nisar H, Janjua A Kashif, Hafeez H. Thermal and electrical performance of solar floating PV system compared to on-ground PV system—An experimental investigation. *Sol Energy* 2022;241:231–47.
- [344] de Lima Rui L Pedroso, Paxinou Katerina, C. Boogaard Floris, Akkerman Olof, Lin Fen-Yu. In-situ water quality observations under a large-scale floating solar farm using sensors and underwater drones. *Sustainability* 2021;13(11):6421.
- [345] Kumar Amit, Ng Daphne HP, Bairolia Sakcham, Cao Bin. The dark side of microbial processes: Accumulation of nitrate during storage of surface water in the dark and the underlying mechanism. *Microbiol Spectr* 2022;10(1):e02232–21.
- [346] Wang Xingming, Zhao Yingying, Chu Zhaoxia, Yu Xiaokun, Fan Tingyu, Li Gang, Zhang Jiamei, Xu Xiaoping, Zhen Quan, Cheng Xiaojing, et al. Influence of solar photovoltaic system on the concentration and environmental risks of heavy metals in subsidence pond water from coal mining area: A case study from Huainan subsidence pond. *Water* 2022;14(14):2257.
- [347] Mathijssen D, Hofs B, Spierenburg-Sack E, van Asperen R, van der Wal B, Vreeburg J, Ketelaars H. Potential impact of floating solar panels on water quality in reservoirs; pathogens and leaching. *Water Pract Technol* 2020;15(3):807–11.
- [348] Exley Giles, Armstrong Alona, Page Trevor, Jones Ian D. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. *Sol Energy* 2021;219:24–33.
- [349] Exley Giles, Page Trevor, Thackeray Stephen J, Folkard Andrew M, Couture Raoul-Marie, Hernandez Rebecca R, Cagle Alexander E, Salk Kateri R, Clous Lucie, Whittaker Peet, et al. Floating solar panels on reservoirs impact phytoplankton populations: A modelling experiment. *J Environ Manag* 2022;324:116410.
- [350] Yang Peipei, Chua Lloyd HC, Irvine KN, Imberger Jorg. Radiation and energy budget dynamics associated with a floating photovoltaic system. *Water Res* 2021;206:117745.
- [351] Ali Basit, Fatima Kaniz, Mahnoor. Mathematical model validation of floating PV parks impact on the growth of green algae using experimental chamber. *Energy Sources Part A: Recovery Util Environ Eff* 2023;45(1):804–16.
- [352] Château Pierre-Alexandre, Wunderlich Rainer F, Wang Teng-Wei, Lai Hong-Thih, Chen Che-Chun, Chang Fi-John. Mathematical modeling suggests high potential for the deployment of floating photovoltaic on fish ponds. *Sci Total Environ* 2019;687:654–66.
- [353] Hodges B, Dallimore C. Estuary, lake and coastal ocean model: ELCOM v2. 2 science manual. Western Australia: Contract Research Group, Centre for Water Research, University of Western Australia; 2010.
- [354] Saloranta Tuomo M, Andersen Tom. MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecol Model* 2007;207(1):45–60.
- [355] Cagle Alexander E, Armstrong Alona, Exley Giles, Grodsky Steven M, Macknick Jordan, Sherwin John, Hernandez Rebecca R. The land sparing, water surface use efficiency, and water surface transformation of floating photovoltaic solar energy installations. *Sustainability* 2020;12(19):8154.
- [356] Jeong Han Sang, Choi Jaeho, Lee Ho Hyun, Jo Hyun Sik. A study on the power generation prediction model considering environmental characteristics of Floating Photovoltaic System. *Appl Sci* 2020;10(13):4526.
- [357] Sukarso Adimas Pradiyanto, Kim Kyung Nam. Cooling effect on the floating solar PV: Performance and economic analysis on the case of west Java province in Indonesia. *Energies* 2020;13(9):2126.
- [358] Dörenkämper Maarten, Wahed Arifeen, Kumar Abhishek, de Jong Minne, Kroon Jan, Reindl Thomas. The cooling effect of floating PV in two different climate zones: A comparison of field test data from the Netherlands and Singapore. *Sol Energy* 2021;219:15–23.
- [359] Amiot Baptiste, Le Berre Rémi, Giroux-Julien Stéphanie. Evaluation of thermal boundary conditions in floating photovoltaic systems. *Prog Photovolt, Res Appl* 2023;31(3):251–68.
- [360] Liu Yuanchuan, Xiao Qing, Incecik Atilla, Peyrard Christophe, Wan Decheng. Establishing a fully coupled CFD analysis tool for floating offshore wind turbines. *Renew Energy* 2017;112:280–301.
- [361] Huang Luofeng, Ren Kang, Li Minghao, Tuković Željko, Cardiff Philip, Thomas Giles. Fluid-structure interaction of a large ice sheet in waves. *Ocean Eng* 2019;182:102–11.
- [362] Wei Yujia, Yu Shuangrui, Jin Peng, Huang Luofeng, Elsherbiny Khaled, Tezdogan Tahsin. Coupled analysis between catenary mooring and VLFS with structural hydroelasticity in waves. *Mar Struct* 2024;93:103516. <http://dx.doi.org/10.1016/j.marstruc.2023.103516>, URL <https://www.sciencedirect.com/science/article/pii/S0951833923001491>.
- [363] Nelli Filippo, Bennetts Luke G, Skene David M, Toffoli Alessandro. Water wave transmission and energy dissipation by a floating plate in the presence of overwash. *J Fluid Mech* 2020;889:A19.
- [364] Khojasteh Danial, Tavakoli Sasan, Dashtimanesh Abbas, Dolatshah Azam, Huang Luofeng, Glamore William, Sadat-Noori Mahmood, Iglesias Gregorio. Numerical analysis of shipping water impacting a step structure. *Ocean Eng* 2020;209:107517.
- [365] Fontes Jassiel VH, Martínez-Flores Alejandro, Hernández Irving D, Mendoza Edgar, Silva Rodolfo. Flow kinematics in the generation of different types of green water events with incident wave trains. *Ocean Eng* 2022;258:111519.
- [366] Hernández-Fontes JV, Torres L, Mendoza E, Escudero M. Identification of the advection-diffusion equation for predicting green water propagation. *Ocean Eng* 2020;214:107658.
- [367] Hernández-Fontes Jassiel V, Vitola Marcelo A, Esperança Paulo TT, Sphaier Sergio H, Silva Rodolfo. Patterns and vertical loads in water shipping in systematic wet dam-break experiments. *Ocean Eng* 2020;197:106891.
- [368] Hernández-Fontes Jassiel V, Esperança Paulo TT, Silva Rodolfo, Mendoza Edgar, Sphaier Sergio H. Violent water-structure interaction: Overtopping features and vertical loads on a fixed structure due to broken incident flows. *Mar Struct* 2020;74:102816.
- [369] Wei Yujia, Incecik Atilla, Tezdogan Tahsin. A hydroelasticity analysis of a damaged ship based on a two-way coupled CFD-DMB method. *Ocean Eng* 2023;274:114075.
- [370] Huang Luofeng, Tavakoli Sasan, Li Minghao, Dolatshah Azam, Pena Blanca, Ding Boyin, Dashtimanesh Abbas. CFD analyses on the water entry process of a freefall lifeboat. *Ocean Eng* 2021;232:109115.
- [371] Zheng Siming, Meylan Michael H, Zhu Guixun, Greaves Deborah, Iglesias Gregorio. Hydroelastic interaction between water waves and an array of circular floating porous elastic plates. *J Fluid Mech* 2020;900:A20.
- [372] Zheng Siming, Porter Richard, Greaves Deborah. Wave scattering by an array of metamaterial cylinders. *J Fluid Mech* 2020;903:A50.
- [373] Michele Simone, Zheng Siming, Buriani Federica, Borthwick Alistair GL, Greaves Deborah M. Floating hydroelastic circular plate in regular and irregular waves. *Eur J Mech B Fluids* 2023;99:148–62.
- [374] Huang Luofeng, Li Zhiyuan, Ryan Christopher, Ringsberg Jonas W, Pena Blanca, Li Minghao, Ding Li, Thomas Giles. Ship resistance when operating in floating ice floes: Derivation, validation, and application of an empirical equation. *Mar Struct* 2021;79:103057.
- [375] Huang Luofeng, Yang Yifeng, Khojasteh Danial, Ou Binjian, Luo Zhenhua. Floating solar power loss due to motions induced by ocean waves: An experimental study. *Ocean Eng* 2024;312:118988.
- [376] Setiawan Firdaus, Dewi Tresna, Yusi Syahirman. Sea salt deposition effect on output and efficiency losses of the photovoltaic system; a case study in Palembang, Indonesia. In: *Journal of physics: conference series*, vol. 1167, IOP Publishing; 2019, 012028.
- [377] Huang Luofeng, Li Yuzhu. Design of the submerged horizontal plate breakwater using a fully coupled hydroelastic approach. *Comput-Aided Civ Infrastruct Eng* 2022;37(7):915–32.
- [378] Dai Jian, Wang Chien Ming, Utsunomiya Tomoaki, Duan Wenhui. Review of recent research and developments on floating breakwaters. *Ocean Eng* 2018;158:132–51.
- [379] Zhou Binzhen, Zheng Zhi, Jin Peng, Wang Lei, Zang Jun. Wave attenuation and focusing performance of parallel twin parabolic arc floating breakwaters. *Energy* 2022;260:125164.
- [380] Yang Yifeng, Mi Chenhao, Ou Binjian, Wong Anson, Duffy John Gordon, Wood Tim, et al. A comparative experimental study on the hydrodynamic performance of two floating solar structures with a breakwater in waves. *Solar Energy* 2024;284:113029.
- [381] Solar Energy Research Institute of Singapore. Where sun meets water: Floating solar market report. Energy Sector Management Assistance Program; 2018, Available online: <https://openknowledge.worldbank.org/handle/10986/31880>.
- [382] Vidović Vladimir, Krajačić Goran, Matak Nikola, Stunjek Goran, Mimica Marko. Review of the potentials for implementation of floating solar panels on lakes and water reservoirs. *Renew Sustain Energy Rev* 2023;178:113237.
- [383] Mesbahi Mina. Top 100 floating solar projects. 2019, URL <https://www.solarplaza.com/resource/11968/top-100-floating-solar-projects/>. [Accessed 26 July 2024].
- [384] EcoWatch. 5 floating solar farms helping power the world. 2016, URL <https://www.ecowatch.com/5-floating-solar-farms-helping-power-the-world-1891141371.html>. [Accessed 26 July 2024].
- [385] World Bank Group. Where sun meets water: floating solar market report. World Bank; 2019.
- [386] Ji Qianfeng, Liang Ruifeng, Yang Shiwei, Tang Qi, Wang Yuanming, Li Kefeng, Zhang Zhongwei. Potential assessment of floating photovoltaic solar power in China and its environmental effect. *Clean Technol Environ Policy* 2023;25(7):2263–85.
- [387] Li Ming, Luo Haojie, Zhou Shijie, Kumar Gokula Manikandan Senthil, Guo Xinman, Law Tin Chung, Cao Sunliang. State-of-the-art review of the flexibility and feasibility of emerging offshore and coastal ocean energy technologies in East and Southeast Asia. *Renew Sustain Energy Rev* 2022;162:112404.
- [388] Charles Rajesh Kumar J, Majid MA. Floating solar photovoltaic plants in India—a rapid transition to a green energy market and sustainable future. *Energy Environ* 2023;34(2):304–58.
- [389] Goswami Anik, Sadhu Pradip Kumar. Degradation analysis and the impacts on feasibility study of floating solar photovoltaic systems. *Sustain Energy Grids Netw* 2021;26:100425.

- [390] Nuvvula Ramakrishna, Devaraj Elangovan, Srinivasa Kishore Teegala. A comprehensive assessment of large-scale battery integrated hybrid renewable energy system to improve sustainability of a smart city. *Energy Sources Part A: Recovery Util Environ Eff* 2021;1–22.
- [391] Islam Md Imamul, Jadin Mohd Shawal, Mansur Ahmed Al, Kamari Nor Azwan Mohamed, Jamal Taskin, Hossain Lipu Molla Shahadat, Azlan Mohd Nurulakla Mohd, Sarker Mahidur R, Shihavuddin ASM. Techno-economic and carbon emission assessment of a large-scale floating solar Pv system for sustainable energy generation in support of Malaysia's renewable energy roadmap. *Energies* 2023;16(10):4034.
- [392] Jamroen Chaowanan. Optimal techno-economic sizing of a standalone floating photovoltaic/battery energy storage system to power an aquaculture aeration and monitoring system. *Sustain Energy Technol Assess* 2022;50:101862.
- [393] Elminshawy Nabil AS, Osama Amr, Elbaksawi Osama, Arıcı Müslüm, Naeim Noha. Energetic, environmental and economic (3E) analysis of a CSA algorithm optimized floatovoltaic system integrated with heat sink: Modeling with experimental validation. *Eng Anal Bound Elem* 2024;159:384–401.
- [394] Zahid Herman, Altamimi Abdullah, Kazmi Syed Ali Abbas, Khan Zafar A, Almutairi Abdulaziz. Floating solar photovoltaic as virtual battery for reservoir based hydroelectric dams: A solar-hydro nexus for technological transition. *Energy Rep* 2022;8:610–21.
- [395] da Costa Luana Carolina Alves, da Silva Gardenio Diogo Pimentel. Save water and energy: A techno-economic analysis of a floating solar photovoltaic system to power a water integration project in the Brazilian semiarid. *Int J Energy Res* 2021;45(12):17924–41.
- [396] Silva Domisley Dutra, Cardoso Elaine Maria, Basquerotto Cláudio, Pereira João Antonio, Turra Antonio Eduardo, Feldhaus Jhonny. Outlook on the Brazilian scenario of floating photovoltaic solar energy. *Energy Rep* 2023;10:4429–35.
- [397] Nkambule Mpho Sam, Hasan Ali N, Shongwe Thokozani. Performance and techno-economic analysis of optimal hybrid renewable energy systems for the mining industry in South Africa. *Sustainability* 2023;15(24):16766.
- [398] Prinsloo FC, Schmitz Peter, Lombard Andrea. System dynamics characterisation and synthesis of floating photovoltaics in terms of energy, environmental and economic parameters with WELF nexus sustainability features. *Sustain Energy Technol Assess* 2023;55:102901.
- [399] Nazir Cawas Phiroze. Coastal power plant: a hybrid solar-hydro renewable energy technology. *Clean Energy* 2018;2(2):102–11.
- [400] Goswami Anik, Sadhu Pradip Kumar. Adoption of floating solar photovoltaics on waste water management system: a unique nexus of water-energy utilization, low-cost clean energy generation and water conservation. *Clean Technol Environ Policy* 2021;1–26.
- [401] Kichou Sofiane, Skandalos Nikolaos, Wolf Petr. Floating photovoltaics performance simulation approach. *Heliyon* 2022;8(12).



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