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Floating solar sustainability on land and ocean: A strategic assessment using SWOT-TWOS-PESTLE analysis

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Abstract. Floating Solar Projects (FSP) offer a revolutionary approach to harnessing solar energy, with the potential to address land-use constraints and tap into the expansive resources both on land and ocean surfaces. This paper conducts a comparative analysis of land-based and ocean-based Floating Solar Photo Voltaic (FSPV) deployments using SWOT (Strengths, Weaknesses, Opportunities, and Threats), TOWS (a strategic approach based on SWOT), and PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analysis. We identify the unique strengths and weaknesses of each approach, such as land-based FSP's easier implementation versus ocean-based FSP's potential for large-scale generation. The TOWS matrix further develops strategic options for leveraging these differences, while the PESTLE analysis assesses the political, economic, social, technological, legal, and environmental factors that will shape the success of each deployment. Additionally, the analysis highlights the abundance of opportunities for FSPV systems, particularly in terms of policy and economic support, contributions to Sustainable Development Goals (SDGs), and technological advancements. This comprehensive assessment provides critical insights for stakeholders aiming to implement FSPV strategically, driving the transition toward a sustainable energy future.

Keywords: Floating solar, SWOT analysis, TOWS matrix, PESTLE analysis, Land-use constraints, Sustainable energy.

1 Introduction

The ever-growing demand for clean energy has inspired innovation in renewable energy sources. Solar energy, with its abundance and scalability, has emerged as a frontrunner [1, 2]. However, conventional land-based solar farms face challenges such as limited land availability, competition for land use, and potential social conflicts [3]. This has paved the way for the exploration of novel approaches, and floating solar has emerged as a promising solution. Floating Solar Projects (FSP) systems utilize man-made reservoirs, lakes, and even oceans to deploy solar panels on floating platforms [4]. This innovative approach offers the potential to significantly expand solar capacity without compromising valuable land resources [2]. Floating solar technology holds immense promise for the future of renewable energy [5]. By harnessing the vast potential of water bodies, Floating Solar PhotoVoltaic (FSPV) systems can overcome the limitations of land-based solar farms [5]. The concept of floating solar is relatively new, with the first commercial installation emerging in 2007 at the Far Niente Winery in California [1]. However, research and

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development efforts have intensified in recent years, driven by the increasing demand for clean energy and the limitations of land-based solar farms [6]. Several studies have explored the technical and economic feasibility of floating solar [7]. A report by the *National Renewable Energy Laboratory* (NREL) in the United States highlights the potential of FSPV systems to increase solar energy generation without requiring additional land [8]. This report also identifies cost reductions as a critical factor for broader adoption. Similarly, research by the University of Central Florida emphasizes the economic benefits of FSPV systems, including reduced land acquisition costs and potentially higher energy production due to the cooling effect of water bodies [7]. Beyond economic advantages, FSPV systems offer several environmental benefits [9]. Research suggests that floating solar panels can suppress algal blooms by reducing sunlight penetration into the water [10]. Additionally, studies have shown that FSPV systems can help conserve water by reducing evaporation rates in reservoirs and lakes [11]. However, challenges remain for the widespread adoption of FSPV systems [12]. A key concern is the development of robust anchoring and mooring systems capable of withstanding harsh weather conditions on open water bodies [13]. Additionally, the environmental impact of FSPV systems on aquatic ecosystems requires further investigation. Studies are ongoing to assess potential effects on fish populations and water quality [14].

1.1 Literature review/state of art

The current state of the art reveals rapid growth in the FSPV sector, particularly in Asia. Countries like China, Japan, and South Korea boast several large-scale FSPV installations [15, 16]. These developments indicate the increasing viability and attractiveness of FSPV systems [16]. While technical advancements are ongoing, a critical aspect is the development of regulations and standards for FSPV systems. Regulatory frameworks are essential for ensuring the safe and sustainable deployment of this technology across different geographical and environmental environment [17]. Table 1 provides a comparative analysis of stagnant water bodies and ocean-based projects including their potential benefits and drawbacks.

The concept of FSPV was first explored in Japan in 2007, with the *Institute of Advanced Industrial Science and Technology* (AIST) developing a 20-kW prototype [25]. Commercialization began in 2008 when a 175-kW system was installed over an irrigation pond in California, driven by the increasing costs of land acquisition for large-scale GPV projects [26]. Over the past decade, FSPV installations have seen substantial growth globally. By 2017, the global installed FSPV capacity had reached approximately 134,308 kW [27]. This trend has continued with landmark projects such as the 192 MWp FSPV system deployed in West Java, Indonesia, in 2023. This installation is the largest FSPV system on a reservoir to date, operating under challenging conditions with a water depth of 100 m and significant water level fluctuations [28]. By harnessing solar power on water bodies, these countries are making significant strides towards achieving the United Nations' Sustainable Development Goals (SDGs) of affordable and clean energy.

1.2 Research gap

Existing research has largely concentrated on the technical feasibility and economic viability of floating solar projects. Numerous studies have examined the performance of floating solar panels under different environmental conditions, and some have evaluated the economic competitiveness of FSPs compared to traditional ground-mounted systems. However, comprehensive comparative analyses of land-based and ocean-based FSPs, considering a broader range of factors beyond just technical and economic considerations, remain relatively unexplored. Despite the promising advancements in floating solar technology, there remains a critical knowledge gap regarding the comparative advantages and challenges between land and ocean-based installations, necessitating an in-depth investigation to inform strategic decision-making in renewable energy development. Unlike previous studies that primarily focus on the technical and economic aspects of FSP.

1.3 Research question and objective

To provide a comprehensive assessment of floating solar technology (FSP), this research examines the following key question: How can a combined SWOT (Strengths, Weaknesses, Opportunities, and Threats), TOWS (a strategic approach based on SWOT), and PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analysis framework be used to evaluate the potential and challenges of deploying floating solar systems on both land and ocean surfaces to contribute to a sustainable energy future? This article aims to comprehensively analyze the potential and challenges of floating solar on land and ocean surfaces. A SWOT analysis identifies the key internal and external factors influencing the development and adoption of FSPV systems. A PESTLE analysis has also been used to examine the broader political, economic, social, technological, legal, and environmental factors shaping the future of floating solar systems.

(a) To assess floating solar technology's strengths, weaknesses, opportunities, and threats using SWOT analysis.
(b) To develop TOWS matrix strategic options for maximizing the potential and overcoming the challenges associated with FSPV systems.
(c) To perform a PESTLE analysis to assess the political, economic, social, technological, legal, and environmental factors influencing the future of floating solar.
(d) To provide valuable insights for stakeholders interested in developing and deploying FSPV systems to achieve SDGs Goal.

1.4 Main scientific contribution and novelty statement

This research employs a strategic framework incorporating SWOT, TOWS, and PESTLE analyses to identify the unique strengths, weaknesses, opportunities, and threats associated with each deployment type. By examining these factors in conjunction with each other, this study provides an understanding of the complex studies between

Table 1. Comparison of floating solar installations on stagnant water bodies and ocean-based floating solar.

Study	Location	Parameters studied	Key findings	Advantages	Disadvantages	Reference
Potential from Specific Water Bodies (USA)	USA, Inland Water Bodies	Potential energy generation	27% of water bodies hold 10% potential for national power generation	High potential for power generation	Requires large coverage area	[18]
Floating Solar PV on Lake Nasser (Egypt)	Lake Nasser, Egypt	Stability, efficiency, water conservation	Analyses wind/wave impact, evaluates water savings, high energy generation potential	High potential for power generation, Reduces water evaporation		[4]
Wave Stability of Floating PV (Europe)	Water Bodies, European	Wave impact on stability	Studies wave impact using simulations		Limited to technical analysis	[19]
Photovoltaic Potential in Spain	Inland Waterbodies, Spain	Photovoltaic potential	10% coverage meets 31% of energy demand and reduces emissions	High potential for power generation	Requires large coverage area	[20]
Photovoltaic Potential in Brazil	Waterbodies, Brazil	Photovoltaic potential, wind speed, air temperature, economic analysis	1% coverage generates 12.5% of electricity	High potential for power generation	Requires large coverage area	[21]
Climate Impact on Efficiency (Netherlands & Singapore)	Netherlands & Singapore	Climate impact on efficiency	Floating PV 3–6% more efficient, higher efficiency in tropics	Improved efficiency		[22]
Societal/Legal Obstacles of FSPV (Thailand)	FSPV installations in Thailand	Societal and legal obstacles	FSPV plants have lower cost and shorter payback period	Economically viable		[9]
Small-Scale FSPV Installations (Malaysia)	FSPV in Malaysia	Small-scale installations	16 FSPV systems with 50 MW total capacity identified		Limited study on small scale installations	[5]
Techno-Economic & Environmental Comparison (Iran)	Iran	Techno-economic & environmental comparison	Floating PV superior to land-based systems, reduces water evaporation	High potential for power generation, Reduces water evaporation		[23]
Offshore Floating PV Systems (India)	India	In-depth climate analysis, performance evaluation, cost analysis, carbon emission reduction	In-depth analysis for offshore floating PV systems		Limited to technical analysis	[24]

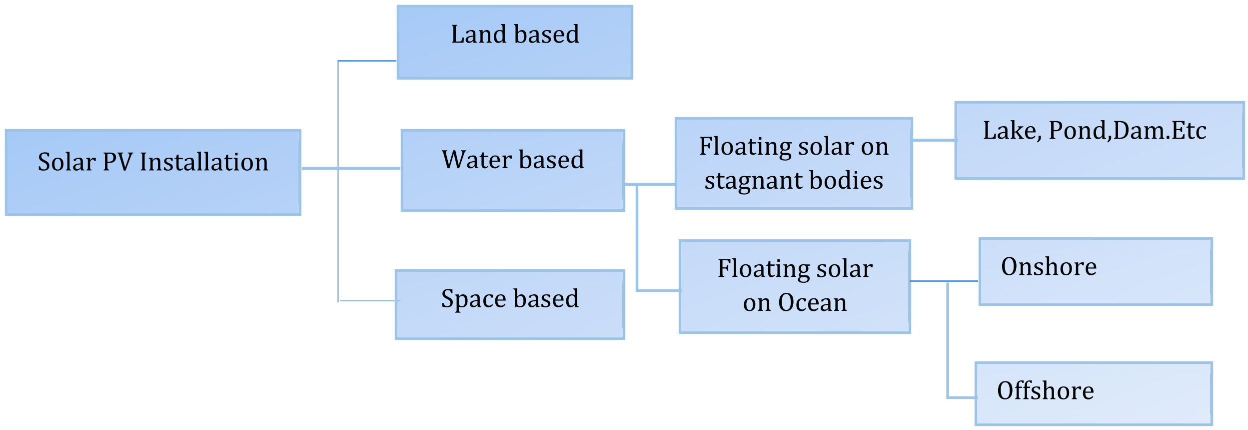


Fig. 1. Classification of solar PV installation.

technological, environmental, economic, and policy dimensions influencing FSP's success. This research empowers policymakers, investors, and industry stakeholders to make informed strategic decisions for advancing the FSPV towards sustainable energy futures.

1.5 Organisation of manuscript

The foundation of floating solar technology, along with its potential benefits, is introduced in Section 1, setting the stage for a comprehensive exploration of this innovative energy solution. Section 2 expands the discussion by offering a global overview of existing floating solar installations, highlighting key projects and trends worldwide. The research methodology and flowchart are detailed in Section 3, outlining the approach used to evaluate floating solar potential. In Section 4, various analytical frameworks SWOT, TOWS, and PESTLE are employed to assess the viability of floating solar systems in both inland and ocean environments. Section 5 connects the analysis to the SDGs, providing a deeper examination of the strengths, weaknesses, opportunities, and challenges that floating solar technology presents in both inland and ocean environments. Finally, Section 6 offers recommendations for the future development and implementation of floating solar technology, along with concluding insights on its potential impact on global energy systems.

2 Concept of floating solar on land and ocean

Renewable energy sources such as hydropower, wind, wave, and solar play a crucial role in sustainable energy solutions [29]. Solar energy, in particular, is harnessed through various methods, including ground-based, nearshore, and floating solar farms [25]. Over the last two decades, solar electricity generated by PhotoVoltaic systems (PVs) has seen significant growth, expanding its applications across diverse sectors. A comprehensive classification of PV system installations is illustrated in Figure 1.

2.1 Floating solar on stagnant water bodies

Floating solar panels are installed on frames that float on the surface of bodies of water, such as lakes, reservoirs, or other man-made ponds (Tab. 2). Figures 2a and 2b illustrate the feature and concept of floating solar on land [26].

2.2 Floating solar on ocean

Similarly, land-based systems, ocean FSPV utilizes robust platforms designed to withstand harsher wave conditions. These platforms can be anchored to the seabed and house large solar arrays. Figures 3a and 3b illustrate the feature and concept of floating solar on the ocean (Tab. 3).

These are just a few examples, and the landscape of floating solar projects is constantly evolving. As the technology matures and costs decrease, we can expect to see even larger and more innovative offshore FSPs deployed worldwide, contributing significantly to a sustainable energy future.

2.3 Comparison of floating solar on land and ocean

The deployment of floating solar panels on land-based water bodies with those situated on the open ocean is discussed in this section. While both approaches share the core benefit of harnessing solar energy without affecting valuable land resources, there are significant differences to consider. Table 4 provides a detailed breakdown of these key factors, including location suitability, water conditions, platform design, and potential environmental impacts.

2.4 Analysis of various parameters for floating solar systems

In floating solar systems installed on both oceanic and inland water bodies, a range of design and orientation parameters critically, influence energy output, system stability, and overall efficiency. Key factors include environmental conditions, the selection of PV panel types, panel geometry and shape of floaters, connectors, cabling, and

Table 2. Global floating solar installations on stagnant water bodies.

Projects name	Description	Reference
Dezhou Dingzhuang Floating Solar Farm, China (320 MW)	Completed in 2020, the world's largest floating solar farm, located on a reservoir in Shandong Province, China, project generates 550,000 MWh electricity annually.	[27]
Tengeh Reservoir Floating Solar Farm, Singapore (60 MW):	Officially opened in 2021, this project on Singapore's Tengeh Reservoir showcases the potential of FSPs in urban environments. With 122,000 solar panels spread across 45 hectares, it contributes significantly to Singapore's goal of expanding its solar energy capacity.	[28]
Sirindhorn Dam Floating Solar Project, Thailand (58.5 MW):	Located on the Ubon Ratchathani province's Sirindhorn Dam, this project demonstrates the viability of FSPs in Southeast Asia with a coverage of 121 hectares. Completed in 2018, it generates clean energy and helps reduce water evaporation from the dam.	[30]

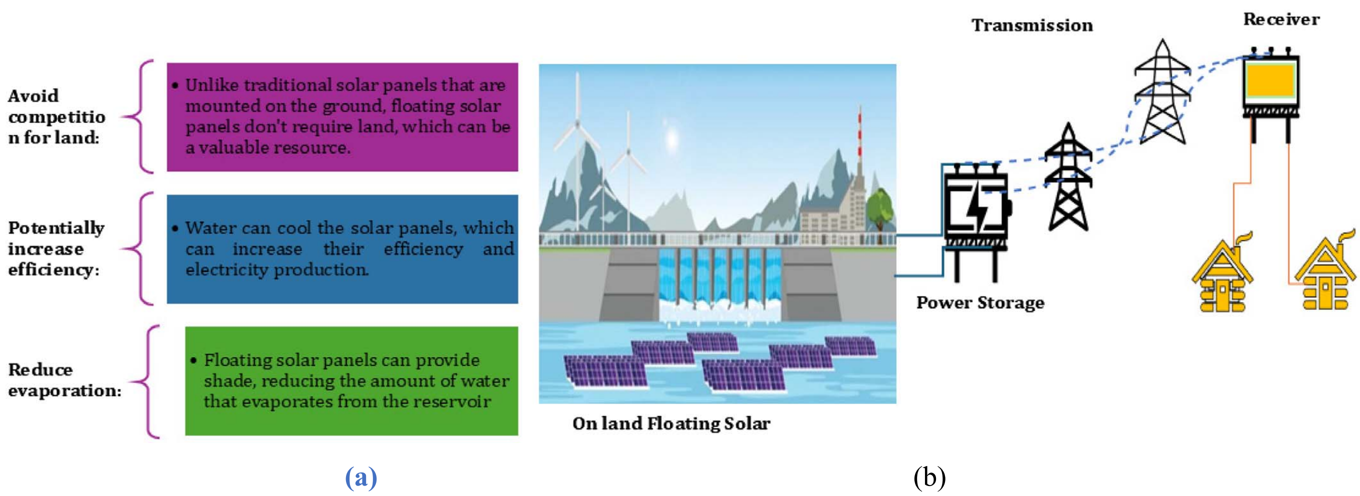


Fig. 2. Schematic illustration of a floating solar photovoltaic system. (a) Features of floating solar on land; (b) Visual representation of floating solar on Stagnant Bodies.

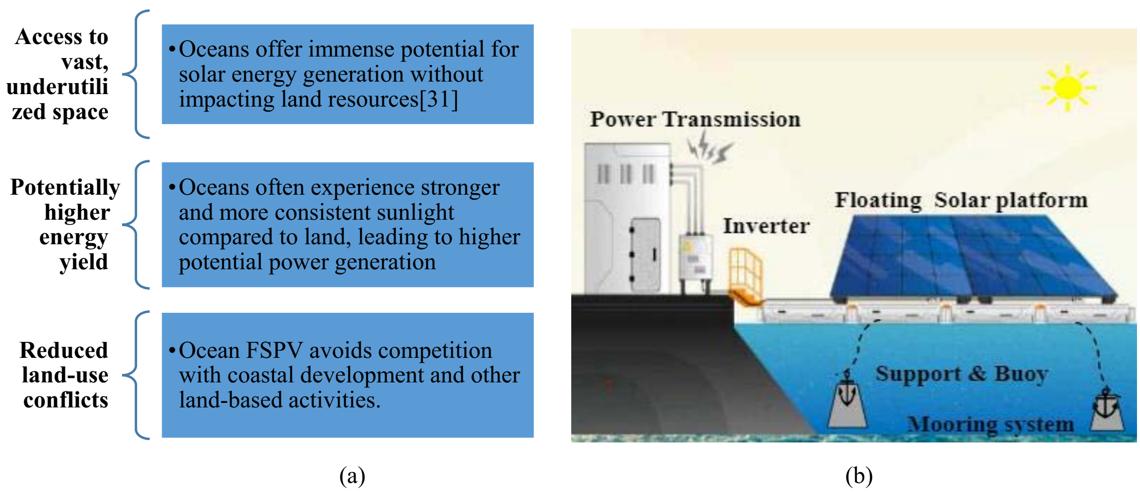


Fig. 3. FSPV system on the ocean. (a) Features of floating solar on ocean; (b) Visual representation of floating solar on ocean.

Table 3. Overview of global ocean-based floating solar projects.

Project name/country	Description	Reference
Maldives Floating Solar Project 2 MWp (Soneva Secret Resort, Maldives)	Collaborating with Canopy Power, Ocean Sun is implementing a floating solar system to reduce reliance on diesel generators. The project includes three 74-meter diameter solar rings and is expected to be completed in early 2025, significantly lowering the resort's carbon footprint while promoting sustainable tourism.	[31]
World's Largest Offshore Floating PV Project, China (1 GW)	Located on the Dongying Sea coast of Shandong, China, this pilot project was completed in 2024. Located on 1,223-hectare, 2934 PV platforms with dimensions 60 m in length and 35 meters in width. 66-kilovolt offshore cable paired with onshore cable for long-distance transmission.	[32]
Offshore floating solar plant, Taiwan (440 MW)	Completed in 2024, 347 hectares of surface area can supply energy to approximately 74,000 households in Taiwan. This project highlights the growing trend of utilizing ocean water surfaces for solar energy generation, particularly in regions with scarce land.	[33]

Table 4. Characteristics and considerations for floating solar installations on stagnant bodies and oceans.

Characteristic	Floating solar-stagnant water bodies	Ocean-based floating solar
Location	Man-made reservoirs, lakes, ponds	Near-shore regions of oceans
Water Conditions	Calm and sheltered	Harsher wave conditions, potential for strong currents
Platform Design	Simpler design focused on buoyancy and hydrostatic load (water pressure)	Robust design to withstand waves, currents, and potential for mooring to seabed
Anchoring System	Simpler anchoring systems using cables and weights	Complex anchoring systems using mooring lines and anchors designed for seabed conditions
Construction	Easier construction due to calmer water conditions	More challenging construction due to wave and current considerations
Environmental Impact	Lower potential impact on aquatic ecosystems due to calmer waters	Potential for more significant impact on marine life and ecosystems, requiring careful study
Energy Production	Potentially higher energy production due to the water-cooling effect	Potentially even higher energy yield due to stronger and more consistent sunlight (depending on location)
Land-Use Conflict	No land-use conflict	No land-use conflict
Scalability	Limited scalability due to the finite size of inland water bodies	High scalability due to vast ocean surface area
Regulations	Established regulations for inland water bodies	Emerging regulations for ocean-based applications

specific PV panel design considerations that directly affect power generation.

2.4.1 Site environmental conditions

The ideal site conditions for FSPV systems are determined by various environmental factors, such as water depth, temperature, water quality, solar radiation, and wind and wave speeds (see Fig. 4). These conditions critically impact the efficiency and performance of FSPV installations, which aim to capture solar energy effectively while mitigating temperature-induced losses [34].

a) Water depth and wind, wave motion

FSPV systems demonstrate ideal performance when used in water depths, which is sufficient to support stable anchoring with minimum wave interference. A recommended minimum depth of 1.5 m enhances stability by reducing the impact of surface wave motion, thus maintaining system integrity [35, 36]. FSPV designs must account for wave-induced stresses for coastal applications to preserve structural resilience and operational efficiency. Wind conditions also play a critical role in FSPV structural integrity, with optimal wind speeds required to mitigate risks associated with high wind loads and to ensure system strength [36].

b) Solar radiation and temperature

Global Horizontal Irradiance (GHI) is a key determinant in FSPV system performance, as higher GHI levels directly correlate with increased energy production and make sites more favourable for FSPV deployment [37]. Cooler water temperatures facilitate heat dissipation from solar panels,

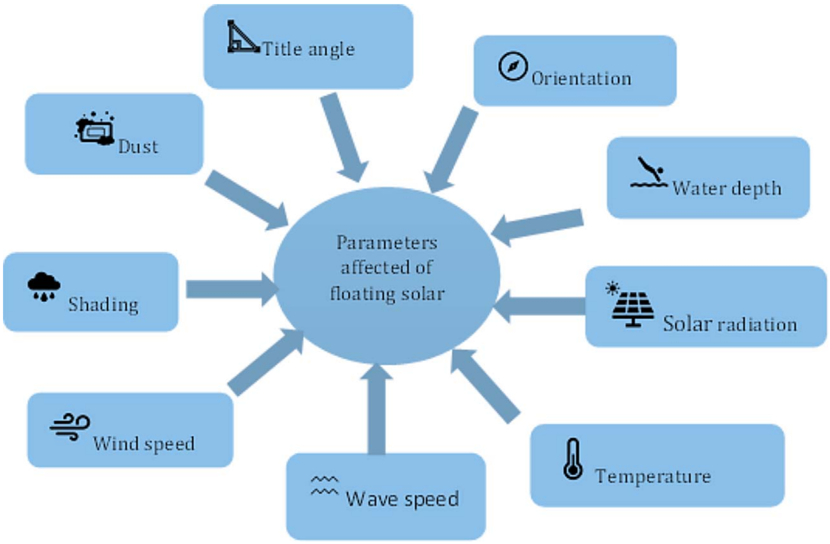


Fig. 4. Key environmental parameters affecting Floating solar PV system performance.

enhancing their efficiency [38]. Ideally, a temperature differential of at least 5 °C between the wind and water optimizes this heat transfer. However, FSPV systems can induce slight localized increases in water temperature – typically around 0.3 °C – beneath the panels. This temperature shift may affect dissolved oxygen levels and local aquatic ecosystems, necessitating careful monitoring to mitigate potential ecological impacts. Operating temperatures significantly impact solar panel efficiency; for example, stable conditions support an operational efficiency of approximately 15.5% under specific climate conditions [39]. Lower ambient temperatures help reduce panel temperatures, thereby improving energy yield. Compared to ground-mounted systems, FSPV installations may see an efficiency gain due to cooler conditions, with panel performance enhanced by 4–7 °C [39].

c) Water quality

Water quality is a critical factor affecting FSPV system performance, with high turbidity and frequent temperature fluctuations potentially degrading panel efficiency and lifespan [40]. In coastal environments, elevated salinity poses additional challenges, as it can lead to material corrosion, underscoring the importance of selecting materials resistant to saline conditions to ensure system durability and reliability [41]. Studies have documented varying impacts on water quality indicators under FSPV installations, with notable decreases in chlorophyll and dissolved oxygen concentrations, alongside increases in total nitrogen and phosphorus levels [42]. Conversely, research in specific contexts, such as agricultural ponds, indicates that FSPV systems may improve nitrate and chlorophyll concentrations [43]. Offshore FSPV installations have complex effects on water quality, influencing temperature, oxygen levels, and nutrient dynamics. While FSPV can provide benefits, including cooling effects and reduced evaporation, risks such as diminished dissolved oxygen levels and altered nutrient cycles are also observed [44]. Continuous research is essential to better understand these impacts, guiding the optimal design and placement of FSPV systems to support environmental sustainability.

2.4.2 Solar PV panel

a) Types of PV panels and materials

Photovoltaic (PV) systems, composed of semiconducting materials, convert photon energy from sunlight into electricity. When photons reach these materials, they initiate the movement of electrons, producing Direct Current (DC) electricity. Common commercial PV materials include multi-crystalline silicon, mono-crystalline silicon, amorphous silicon, and thin-film technologies such as Cadmium Telluride (CdTe) and Copper Indium Diselenide (CIS) (see Fig. 5) [45]. Silicon (Si)-based technologies, regarded as highly developed, are classified into crystalline silicon, amorphous silicon, and thin films, with crystalline silicon further subdivided into single crystalline, multi-crystalline, and ribbon cast multi-crystalline forms [46, 47]. A significant advantage of PV systems is their direct, instantaneous conversion of solar energy to electricity without requiring complex mechanical components or integration [48, 49].

Crystalline silicon thin films are particularly promising for solar cells due to silicon's availability, established semiconductor properties, and high conversion efficiencies approaching 25% [45]. However, achieving this efficiency necessitates high-quality silicon wafers and sophisticated processing techniques. To balance efficiency and cost, extensive research is underway on various thin-film technologies [50, 51]. Large-area polycrystalline silicon (pc-Si) wafers can be fabricated with enhanced light absorption using reactive-ion etching, a plasma processing method that increases light absorption by approximately 40%. Texturing of pc-Si, which maximizes its efficiency, has led to the production of textured pc-Si solar cells with efficiencies up to 19.8% [52]. Surface bulk hydrogenation and nitride passivation have also shown positive results. However, cost differences between crystalline silicon (c-Si) and polycrystalline silicon (pc-Si) cells remain minimal, with commercial

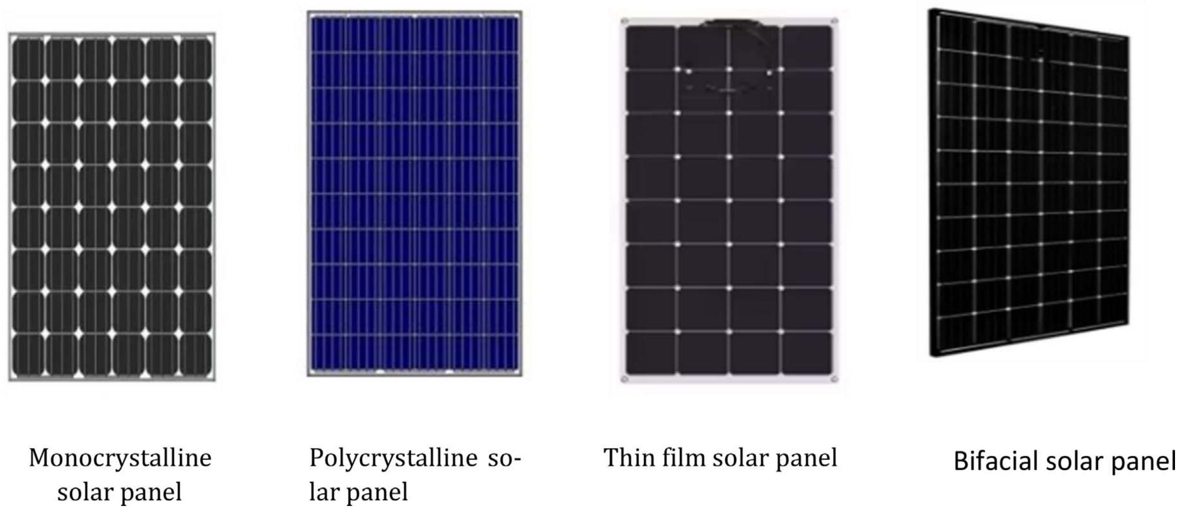


Fig. 5. Common solar PV panel configurations. (a) Monocrystalline solar panel; (b) Polycrystalline solar panel; (c) Thin film solar panel; (d) Bifacial solar panel.

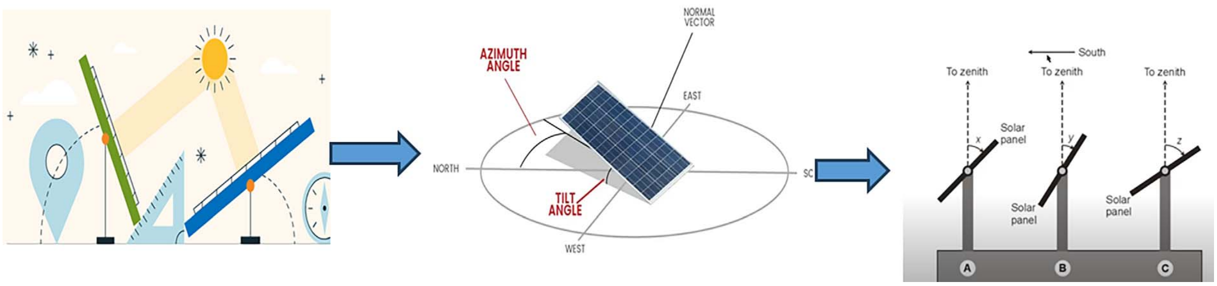


Fig. 6. Optimal tilt angle for floating solar panels.

Table 5. Different types of solar PV technologies for floating solar application.

Panel type	Average efficiency	Typical lifespan	Key advantages	Key disadvantages	References
Monocrystalline	18–24%	25–40 years	Highest efficiency, space-efficient	Higher cost	[55]
Polycrystalline	13–16%	25–30 years	Lower cost	Less efficient	[56]
Thin-Film	7–13%	10–20 years	Flexible, lightweight	Lowest efficiency	[57]
PERC	Up to 25%	25–40 years	Better performance in low light	Higher cost than standard mono	[58]
Transparent	1–10%	~25 years	Aesthetic integration	Very low efficiency	[59]

pc-Si cells achieving efficiencies between 12% and 15% [53]. Thin-film silicon cells offer several key advantages over crystalline cells [54], including (i) a significant reduction in silicon thickness to as low as 50 μm; (ii) deposition capability on low-cost substrates; and (iii) feasibility of module-sized substrate fabrication with integral interconnections. Silicon film thickness could potentially be reduced to as thin as 1 μm, enhancing material efficiency and cost-effectiveness [18, 19]. A general view and classification of silicon-based PV panels are illustrated in Figure 6 and Table 5.

The choice of PV panel type depends on various factors, including efficiency, temperature sensitivity, environmental conditions, and material impact. Monocrystalline panels offer high efficiency but are sensitive to temperature increases, while polycrystalline panels provide a good balance of cost and performance. Though less efficient, amorphous silicon panels perform better in low-light and high-temperature conditions. Understanding these parameters, helps select the optimal PV panel type for specific applications and regions.

Fig. 7. Installed geometric configurations for floating photovoltaic (a) South Korea; (b) Luxemburg; (c) South Africa; (d) Indonesia; (e) Albania; (f) India; (g) China; (h) Chile; (i) Belgium; (j) Russia; (k) Norway; (l) Portugal [63].

b) Panel tilt angle and height parameters

The tilt angle of photovoltaic (PV) panels is critical that should be optimized based on the installation site's geographical latitude to maximize solar irradiance capture, with tilt angles between 10° and 15° proving optimal in tropical regions [60]. For azimuth coordination, panels should face southward in the Northern Hemisphere and northward in the Southern Hemisphere. However, ocean-based installations may require adjustments to compensate for wave motion and current effects (see Fig. 6). Ocean-based floating photovoltaic (FSPV) systems often encounter limitations in precise angle adjustment due to the dynamic impact of tides and waves. The height of PV panels above the water surface is another key parameter, influencing both durability and efficiency [61]. Raising panels above the water mitigates splash risk, which reduces potential corrosion and biofouling [44]. In ocean-based installations, variable-height systems are particularly useful for adjusting to wave height fluctuations, while inland water systems generally require less variation in panel height. Slight elevation of PV panels above the water surface also supports passive cooling by increasing air circulation around the panels, effectively lowering cell temperatures and thereby enhancing system efficiency [38].

2.4.3 Floaters and floating platforms

Standard geometric configurations for floating photovoltaic (FSPV) platforms include circular, rectangular, triangular and modular hexagonal designs, each impacting system stability, wave resistance, and spatial efficiency [62]. The shape and geometry of platforms significantly affect performance, stability, and adaptability to marine environments (see Fig. 7). Various designs have been developed to enhance energy capture while maintaining structural integrity and environmental compatibility. An overview of the primary shapes and configurations of FSPV platforms and design features and applications is shown in Table 6.

2.4.4 Anchoring and mooring system

Effective anchoring and mooring solutions are critical for maintaining the stability and performance of FSPV systems across diverse water conditions. The selection of anchoring and mooring systems should be informed by a comprehensive analysis of environmental factors specific to the site, such as wave dynamics, wind patterns, and water depth. Materials employed such as wire bottom anchors, bank anchors, rigid and taut mooring systems, ropes, and galvanized steel must possess high strength and resistance to corrosion, particularly in saline environments (see Fig. 8 and Tab. 7). Installation processes should be adapted to the water body's unique conditions to secure anchoring placement and ensure adequate mooring line tension. Regular inspections are essential to maintain anchoring system integrity, particularly following extreme weather. Choosing the appropriate anchoring and mooring solution is thus fundamental for ensuring the long-term stability, efficiency, and resilience of floating solar installations in diverse aquatic settings, with each system type offering distinct benefits and challenges based on the specific site characteristics.

Table 6. Comparison of various shapes and geometries of floating solar platforms.

Shape	Design features	Advantages	Applications	Reference
Hexagonal	Maximizes surface area for solar panels, Allows for modular assembly	Wave-friendly design, Easier assembly and connection of multiple units	Large floating solar installations	[64]
Rectangular	Straightforward design accommodating standard panels	Modular and scalable, good stability in various water conditions	Small-scale and large-scale floating solar projects	[65]
Triangular	Elevated above water surface to minimize wave impact	Reduces environmental impact, Lightweight structure	Areas with high wave activity	[66]
Circular	Provides uniform buoyancy distribution	Even buoyancy distribution, Aesthetic integration	Specialized applications where aesthetics is important	[65]
Custom Shapes	Designed for specific environmental conditions	Tailored to meet unique site requirements	Unique site conditions or regulatory considerations	[67]

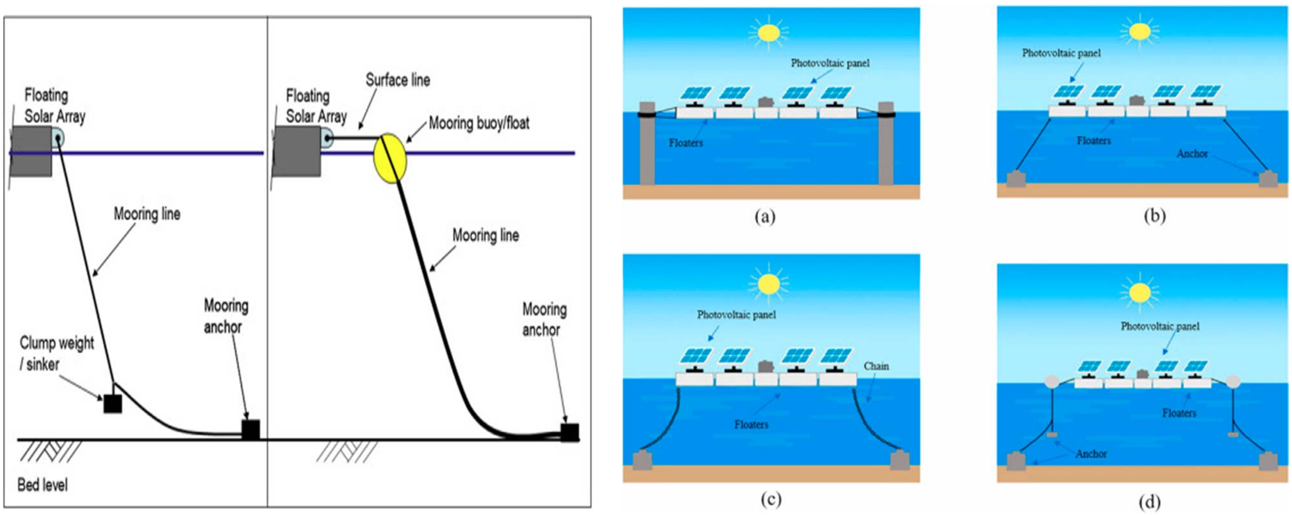


Fig. 8. Examples of various mooring systems for floating photovoltaic systems, including schematic representations: (a) Rigid mooring system; (b) Taut mooring system; (c) Catenary mooring system; and (d) Compliant mooring system [16, 68].

2.4.5 Electrical subsystem

Floating solar PV systems utilize a variety of electrical subsystems that work together to generate and manage electricity effectively. By integrating advanced technologies such as inverters, subsea cables, and monitoring systems, these installations can optimize energy production while addressing the challenges their aquatic environments pose, as shown in Table 8.

3 Research methodology

This study employs a qualitative descriptive approach. Our goal is to gain a deep understanding of the FSPV technology and the factors that influence them. By thoroughly describing these aspects, we aim to establish a solid foundation for developing alternative solutions to the challenges faced in the floating solar energy transition in land and oceans. Figure 9 presents a comprehensive analysis framework for floating solar through the integration of SWOT (Strengths, Weaknesses, Opportunities, Threats), TOWS (Threats, Opportunities, Weaknesses, Strengths), and PESTLE (Political, Economic, Social, Technological, Legal, Environmental) analysis. The analysis underscores the numerous opportunities for FSPV systems, especially in areas such as policy and economic incentives, contributions to SDGs, and ongoing technological advancements. The following method provides a structured approach for evaluating the internal and external factors influencing the adoption and implementation of floating solar technologies on land and ocean.

Firstly, the primary objective of this research is to provide a comprehensive analysis of land-based and ocean-based floating solar projects (FSPs). For this study on FSPV systems on land and ocean, the primary objective

Table 7. Common anchoring and mooring systems for floating solar PV installations [68, 69].

Type	Description	Applications	Advantages	Disadvantages
Bottom Anchoring	Utilizes dead weights (such as concrete blocks) or helical anchors drilled into the lakebed.	Common in stable water bodies with minimal fluctuations.	Simple design, effective for stability.	Required significant installation effort.
Bank Anchoring	Anchors the floating platforms to the bank or shoreline using cables or ropes.	Suitable for reservoirs and lakes with accessible banks.	Easy to install and maintain, reduces material costs.	Limited to areas with suitable bank access.
Piled Anchoring	Involves driving piles into the bed of the water body to secure platforms.	Useful in deep waters or areas with strong currents.	Provides strong resistance against waves and wind loads.	Higher installation costs and complexity.
Elastic Mooring Systems	Incorporates elastic materials that absorb environmental forces, allowing for movement while maintaining stability.	Effective in dynamic environments with variable conditions.	Reduces stress on components, improves longevity.	Requires careful design to ensure proper elasticity.
Sunken Anchors	Heavy anchors placed at the bottom, often combined with ropes or chains for added stability.	Used where water level variations are minimal (less than 1 meter).	Reliable for shallow waters, easy to implement.	Limited effectiveness in deeper waters or strong currents.
Counterweight Systems	Utilizes counterweights that can be adjusted to maintain balance and stability of the floating platform.	Ideal for varying water levels and wave action.	Allows flexibility in design and installation.	Requires careful management of counterweight placement.

is to generate valuable insights by comparing these technologies' strengths, weaknesses, opportunities, and threats. Data was gathered through extensive literature reviews of peer-reviewed journal articles, technical reports, and case studies from reliable sources like Google Scholar, Scopus, and Web of Science to achieve this. In addition, expert interviews with industry professionals and stakeholders were conducted to gain practical insights. Data on solar energy generation, land, water utilization, and government reports were also compiled from reliable public sources. This comprehensive data collection approach provided a robust foundation for the analysis. Secondly, The SWOT analysis method was employed to evaluate the core strengths of FSP, such as reduced land-use requirements and higher energy efficiency due to water-cooling, while identifying challenges like high initial costs and environmental concerns. Moreover, building on the SWOT analysis, the TOWS matrix explores how floating solar internal Strengths and Weaknesses can be strategically utilized to address external Opportunities and Threats (Fig. 10).

A comprehensive assessment of floating solar projects requires the integration of strategic analysis frameworks such as SWOT, TOWS, and PESTLE, enabling stakeholders to evaluate internal and external factors that influence the feasibility and sustainability of these systems (Tab. 9). Simultaneously, identifying threats such as extreme weather conditions or regulatory challenges is crucial for mitigating risks through strategic planning. Finally, the PESTLE analysis complements this by examining the broader political, economic, social, technological, legal, and environmental factors shaping the future of floating solar (Fig. 11). Together, these analytical frameworks provide a comprehensive approach to understanding the multifaceted challenges and opportunities surrounding the deployment of floating solar systems, aiding in the development of effective strategies for sustainable implementation.

4 Result and discussion

This section provides a comprehensive analysis of the FSPV on land and ocean based on SWOT, TWOS, and PESTLE analysis.

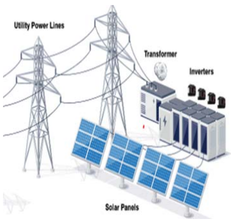
4.1 SWOT analysis

This technology offers significant strengths and opportunities for sustainable energy generation; it also faces notable weaknesses and threats that must be addressed through comprehensive policy support, technological innovation, and environmental management. A SWOT analysis is precious in identifying the strengths of floating solar, such as reducing land-use conflicts and minimizing water evaporation, while also recognizing opportunities for expansion into land-constrained regions. However, weaknesses like higher upfront costs and potential environmental impacts must also be considered to ensure informed decision-making.

Strengths

FSPV systems offer significant advantages over traditional land-based solar installations. These systems have

Table 8. Floating solar electrical subsystem components and functions.

Subsystem type	Description	Components	Parameters	Functionality	Reference
Inverters 	Convert the DC electricity produced by PV modules into AC electricity for grid compatibility.	Central inverters, string inverters, microinverters.	– Efficiency: 95–98% – Power rating: Up to several MW	Facilitate connection to the power grid and optimize energy output.	[70]
Power management systems 	Manage the flow of electricity between the PV modules, inverters, and the grid.	Controllers and monitoring systems.	– Response time: Real-time monitoring – Communication protocols: Modbus, CAN	Ensure efficient energy distribution and system performance monitoring.	[71]
Subsea cables 	Underwater cables used to transmit electricity from floating solar arrays to onshore connections.	High-voltage AC or DC cables.	– Voltage rating: Up to 36 kV – Waterproofing: IP68 rated	Enable long-distance power transmission while minimizing losses.	[65]
Connectors and junction boxes 	Components that connect individual PV modules and facilitate safe electrical connections.	Weatherproof connectors, junction boxes.	– Current rating: Up to 30 A – IP rating: IP67 or higher	Protect electrical connections from water and environmental damage.	
Energy storage systems 	Batteries or other storage technologies to store excess energy generated by the system.	Lithium-ion batteries, flow batteries, *etc.*	– Capacity: Varies (kWh) – Cycle life: 3000–5000 cycles	Provide backup power and stabilize energy supply during low production periods.	[71]
Monitoring systems 	Systems that track performance metrics of the floating solar installation in real-time.	Sensors, data loggers, and software interfaces.	– Data logging frequency: Every minute to hourly Communication range: Up to several kilometers via wireless protocols	Enable proactive maintenance and performance optimization through data analysis.	[72]

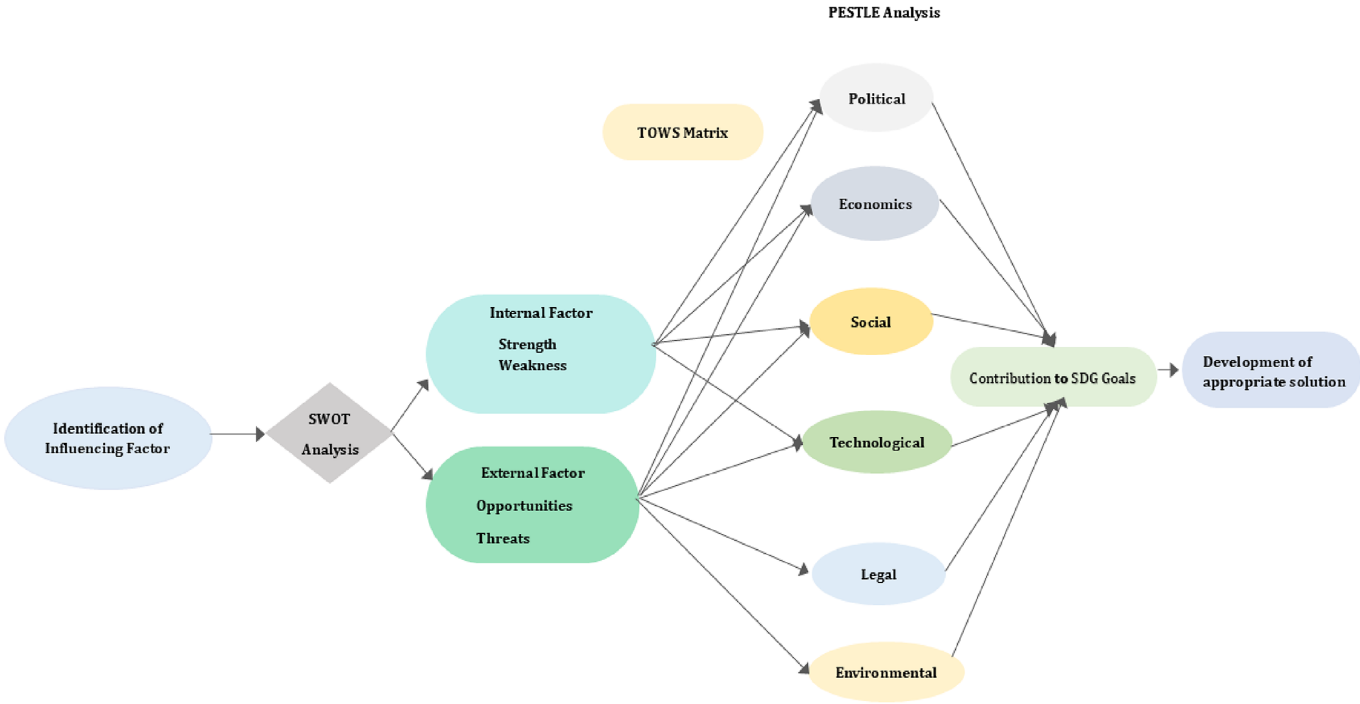


Fig. 9. Identification of factors in the SWOT, TOWS, and PESTLE analysis framework.

demonstrated higher energy generation efficiency, as evidenced by a techno-economic analysis that showed a 10.2% increase in generating capacity for a 10 MW FSPV plant [73]. Moreover, FSPV systems contribute to environmental sustainability by reducing carbon emissions and conserving water resources. A study in Malaysia revealed that a large-scale FSPV system can reduce CO_2 emissions by 11,135.2 tons annually [6]. The integration of FSPV with other renewable energy sources, such as hydropower and hydrogen production, further enhances system efficiency and sustainability, making FSPV a promising solution for clean and reliable energy generation [35].

Weaknesses

Implementing FSPV projects presents a spectrum of OSH (Occupational Safety and Health) risks, primarily from exposure to heat, solar radiation, and hazardous substances. These risks necessitate the integration of ergonomic design principles to ensure a safe and healthy working environment [74]. While FSPV technology offers the advantage of lower investment costs, its nascent stage in the market demands ongoing innovation and policy support to mitigate risks and foster investor confidence [75].

Opportunities

The growth of FSPV systems is contingent upon strong government support, technological advancements, and their contribution to sustainable development. Governments can significantly stimulate FSPV development by implementing clear policies and providing financial incentives, attracting large-scale investments [76]. Moreover, FSPV systems can play a pivotal role in achieving SDGs by providing clean energy, reducing water evaporation, and supporting ecosystem services [77]. The development of hybrid FSPV systems, such as those combined with pumped storage hydropower, holds immense potential for enhancing the water-energy-food nexus, especially in arid regions [78].

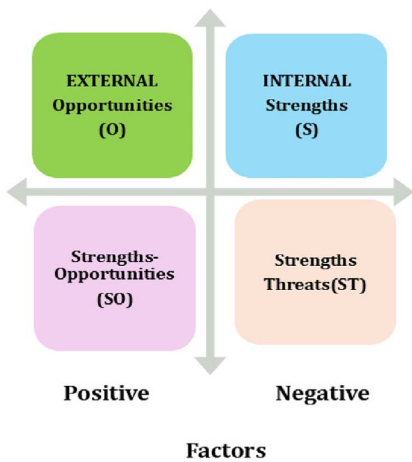


Fig. 10. Schematic of TWOS matrix.

Threats

The sustainability of FSPV systems is contingent upon their ability to mitigate potential negative impacts on water bodies, such as alterations in water chemistry and deoxygenation [77]. To ensure the long-term viability of these systems, it is imperative to implement rigorous monitoring and management strategies to address these concerns. Furthermore, the performance of FSPV systems is influ-

Table 9. Comparison of SWOT, TOWS, and PESTLE analysis.

Analysis	Description	Focus
SWOT	Strengths, Weaknesses, Opportunities, and Threats	Evaluates the internal strengths and weaknesses of FSPV systems, as well as the external opportunities and threats that can impact its development and adoption.
TOWS	Threats, Opportunities, Weaknesses, and Strengths	Builds upon the SWOT analysis by exploring strategic options to leverage strengths and opportunities to overcome weaknesses and threats.
PESTLE	Political, Economic, Social, Technological, Legal, and Environmental	Examines the broader macro-environmental factors that can influence the development and adoption of FSPV systems.

Fig. 11. Schematic of PESTLE analysis.

enced by climatic conditions and weather patterns, which may introduce challenges in specific regions. Consequently, a comprehensive understanding of these dependencies is essential for optimizing the design and operation of FSPV systems [79].

Figure 12 summarizes the strengths, weaknesses, opportunities, and threats identified from the literature. The strategic assessment of floating solar technology using SWOT analysis reveals several key insights into its sustainability on land and ocean.

4.2 TOWS matrix analysis

This analysis utilizes a TOWS matrix to explore strategic options for maximizing the potential and overcoming challenges associated with floating photovoltaic (FSPV) systems, considering both land-based and ocean-based applications.

External opportunities (O)

The global demand for renewable energy sources presents a propitious market for advancing FSPV technology. The need for efficient and cost-effective energy solutions becomes paramount as the world shifts away from fossil fuels to more sustainable alternatives. FSPV technology, with its potential to optimize renewable energy systems and reduce operational costs, emerges as a promising candidate to meet this growing demand. The integration of FSPV-enabled drones into various renewable energy applications, such as solar farm inspections, wind turbine maintenance, and hydroelectric plant monitoring, offers significant benefits in terms of efficiency, safety, and overall system performance [15]. Government Incentives: Financial support from governments through subsidies, tax breaks, or feed-in tariffs can accelerate FSPV development and adoption [80]. Advancements in solar panel technology have significantly improved their efficiency and cost-effectiveness, making them increasingly viable for both land and ocean-based floating photovoltaic (FSPV) systems [81]. The enhanced efficiency of solar panels allows for more significant energy generation per unit area, while reduced costs make FSPV systems more economically attractive [82]. These improvements can benefit both land and ocean-based FSPV systems, offering a sustainable and renewable energy solution. Furthermore, land-based FSPV systems can be integrated with existing water uses like recreation or irrigation, maximizing resource utilization. Additionally, ocean-based FSPV systems can be co-located with offshore wind farms, creating hybrid renewable energy systems that leverage the complementary strengths of both technologies [81].

External threats (T)

The development of floating photovoltaic (FSPV) systems faces several challenges. High initial investment costs, stringent environmental regulations, and limited research on long-term environmental impacts pose significant barriers to widespread adoption. Additionally, land-based FSPVs may contribute to black water, while ocean-based systems could conflict with navigation, fishing, and marine conservation. Addressing these challenges requires careful planning, technological advancements, and ongoing research to ensure the sustainable and effective deployment of FSPV systems.

Internal strengths (S)

Land-based FSPV systems offer several advantages over traditional solar installations. By utilizing existing water

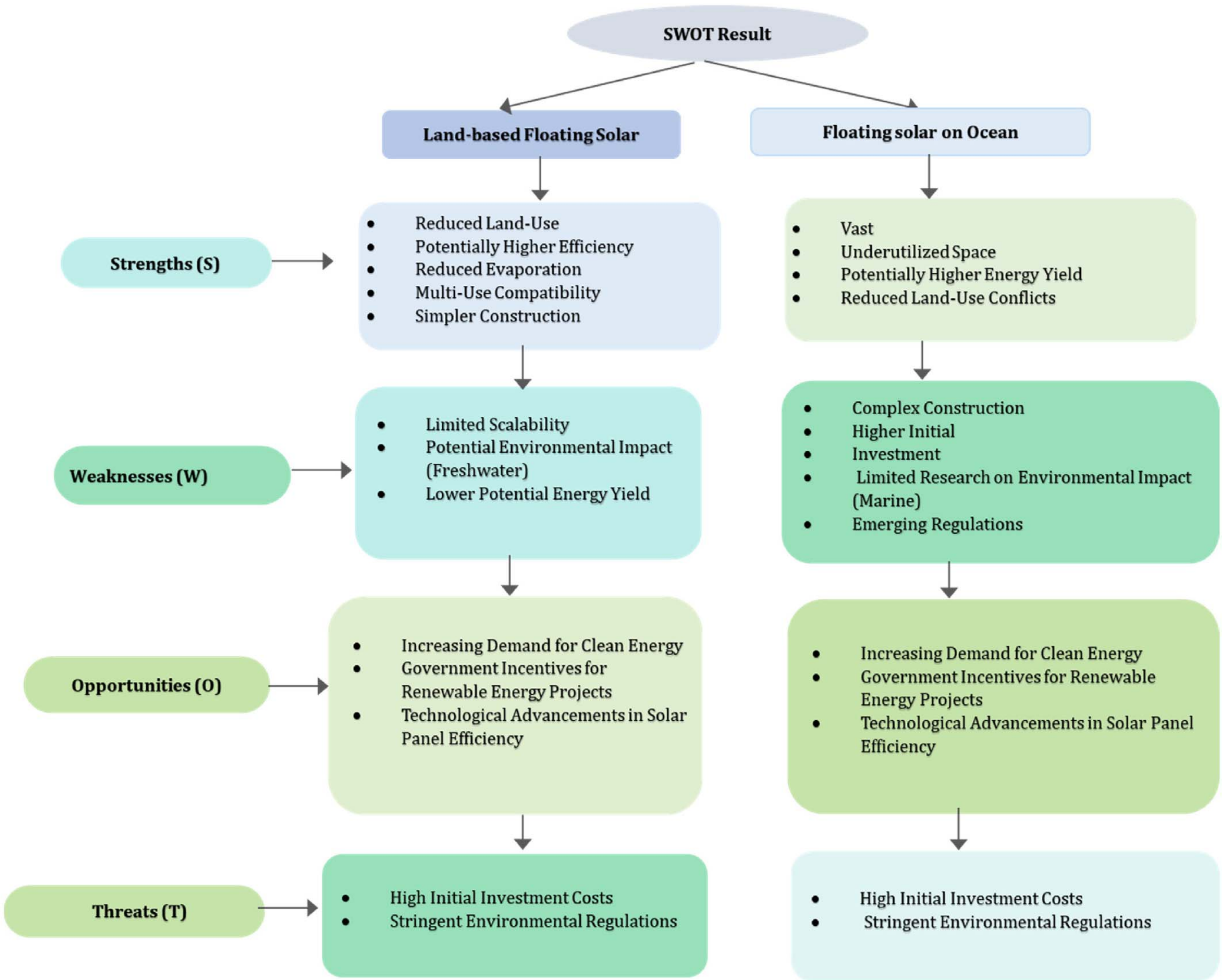


Fig. 12. SWOT results of floating solar on land and ocean.

bodies, they minimize competition for valuable land resources. Additionally, water-cooling can enhance solar panel efficiency and increase power generation, potentially leading to higher energy yields. Furthermore, land-based FSPVs can provide shade, reducing water evaporation rates from reservoirs, especially in drought-prone regions. The modular design potential of FSPV systems allows for more accessible transport, installation, and maintenance. Ongoing advancements in anchoring systems, materials, and remote monitoring technologies further contribute to the feasibility and efficiency of land-based FSPV systems.

Internal weaknesses (W)

The feasibility of FSPVs as a sustainable energy source faces several challenges. Land-based FSPVs are limited by the size and shape of water bodies, restricting their scalability. Ocean-based FSPVs, while potentially offering vast energy potential, require robust designs and advanced anchoring systems to withstand harsh marine conditions, leading to higher construction costs. Maintenance and access to offshore platforms can be challenging, weather-dependent, and potentially increase operational costs. Additionally, the potential environmental impact of ocean-based FSPVs on marine life and ecosystems needs careful assessment. Furthermore, the regulatory landscape for ocean FSPV deployment is still evolving, creating uncertainty for project development.

Strengths-Opportunities (SO) strategies

A multifaceted strategy is necessary to capitalize on the strengths of FSPV technology and address its weaknesses. By investing in battery technology, simplifying the user interface, and advocating for supportive regulations, FSPV systems can become more accessible, reliable, and widely adopted. Additionally, leveraging the high-quality video transmission capability to enter new markets like real estate and media production while integrating the latest technological advancements can significantly enhance the user experience and attract a broader audience. These strategic initiatives will solidify FSPV technology's position in existing markets and pave the way for its successful penetration into new sectors.

Weaknesses-Threats (WT) strategies

To enhance the reliability and accessibility of FSPV systems, this research aims to investigate and implement robust signal interference mitigation techniques. By developing innovative solutions, such as advanced filtering algorithms and adaptive transmission protocols, we can minimize the impact of external factors on video transmission quality, ensuring consistent performance even in challenging environments. Additionally, diversifying the product offerings to include FSPV systems with varying levels of complexity and price points will cater to a broader range of users, from hobbyists to professionals. This strategic approach will strengthen the market position of FSPV technology and drive further advancements in the field. Table 10 presents a TOWS Matrix, which explores strategic planning for both deployment scenarios. By systematically analysing how each environment's Strengths and Weaknesses can be exploited to capitalize on Opportunities and mitigate Threats, the TOWS Matrix offers valuable guidance for maximizing the potential of floating solar technology.

4.3 PESTLE analysis

This analysis examines the key political, economic, social, technological, legal, and environmental (PESTLE) factors influencing the future of floating solar technology. Table 11 presents a PESTLE analysis framework precisely dissecting the Political, Economic, Social, Technological, Legal, and Environmental factors that can significantly influence the development and future of floating solar systems. Understanding these macro-level influences is crucial for formulating effective strategies and navigating the potential challenges and opportunities that lie ahead.

Political factors

The adoption of floating solar power (FSP) is influenced by a complex interplay of factors, including government policies, international relations, and governance frameworks. Supportive policies, such as feed-in tariffs and tax credits, can significantly drive FSPV adoption, while changes in political leadership or energy policy priorities can create uncertainty and hinder investment. Trade agreements and tariffs on solar panels or other FSPV components can affect the cost and availability of materials, influencing project feasibility. International cooperation on research and development can accelerate technological advancements in FSPs. Moreover, the governance of multi-use platforms at sea for energy production and aquaculture presents significant political challenges, requiring adequate governance arrangements to facilitate their development. Policy recommendations emphasize the importance of a governance regime that can address the competing claims at sea and support the integration of various economic activities [83].

Economic factors

Various economic factors influence the feasibility of floating solar technology (FSPs). The initial cost of FSPs, including platform materials, anchoring systems, and solar panels, is a significant barrier to widespread adoption. However, cost reductions through economies of scale and technological advancements are expected. The price of traditional energy sources and the overall electricity demand will influence the economic viability of FSPs. Fluctuations in energy prices can make renewable energy sources like floating solar more competitive. Access to financing options like loans, grants, and public-private partnerships is crucial for project development. Government initiatives and innovative financing models can be vital in attracting investment in FSPs. Multi-Purpose Platforms (MPPs) can potentially economize capital expenditure (CAPEX) and operational costs for the offshore energy and aquaculture industry. By sharing infrastructure and spatial planning, MPPs can reduce costs and enhance economic efficiency. This economic synergy is essential for the sustainable growth of the Blue Economy [84].

Social factors

The successful implementation of Floating Solar Power (FSP) projects hinges on a multifaceted approach that addresses both public perception and technological challenges. Public awareness campaigns emphasizing the environmental benefits of clean energy are essential for fostering social acceptance and support. Addressing potential concerns about environmental impacts through transparent communication and rigorous assessments is crucial to building trust with local communities. Additionally, highlighting the economic benefits, such as job creation and increased energy security, can further encourage community support. Technological advancements, including improvements in solar panel efficiency, cost reductions, and the development of robust anchoring systems, are vital for ensuring the safe and reliable operation of FSPs, especially in offshore environments. Furthermore, advancements in remote monitoring and maintenance technologies can optimize operational efficiency and minimize costs associated with accessing offshore platforms. By addressing these key factors, the widespread adoption of FSPV contributed significantly to sustainable energy production and mitigated the impacts of climate change.

Legal factors

The development and deployment of Marine Underwater Platforms (MUPS) in freshwater and marine environments necessitate a comprehensive regulatory framework to address environmental concerns and ensure sustainable resource utilization. Existing regulations for water bodies and evolving guidelines for ocean deployments play a crucial role in the permitting process and project feasibility. Clear and streamlined regulations are essential to promote investment and development. Furthermore, thorough environmental impact assessments are required to minimize ecosystem disruption and comply with environmental

Table 10. TOWS matrix of FSPV for land and ocean.

Factor	Land-based FSPV	Ocean-based FSPV
Strengths (S)	• Reduced land-use footprint, • Potentially higher energy yield, • Reduced water evaporation, Modular design potential, • Technological advancements.	• Vast, • Underutilized space, potentially higher energy yield, • Reduced land-use conflicts, • Co-location potential, • Technological advancements.
Weaknesses (W)	• Limited scalability, • Potential algorithmic blooms.	• Complex construction, • Limited maintenance access, • Uncertain environmental impact, • Emerging regulatory landscape.
Opportunities (O)	• Increasing demand for clean energy, • Government incentives, • Advancements in solar panel, • Technology, Multi-use compatibility.	• Increasing demand for clean energy, • Government incentives, advancements in solar panel technology, • Co-location potential
Threats (T)	• High initial investment costs, • Stringent environmental regulations, • Limited research on long-term impact, • Potential algorithmic blooms.	• High initial investment costs, • Stringent environmental regulations, • Limited research on long-term impact, • Conflicts with existing uses.

Table 11. PESTLE analysis of floating solar.

Factor	Description	Potential impact
Political	• Government policies and incentives, international relations	• Supportive policies can drive adoption, Trade agreements can affect costs.
Economic	• Cost of FSPV technology, • Energy market dynamics, • Financing mechanisms.	• High initial costs can be a barrier, • Competitive energy prices Favor FSPs, • Innovative financing is needed.
Social	• Public perception, • Environmental concerns, • Community benefits.	• Public acceptance is crucial, Transparent communication is needed, • Local benefits can foster support.
Technological	• Advancements in solar panels, • Anchoring systems, • Remote monitoring.	• Increased efficiency and lower costs, • Improved safety and reliability for ocean deployments, • Optimized maintenance.
Legal	• Regulations for freshwater/ocean deployments, • Environmental impact assessments	• Clear regulations promote investment, • Assessments ensure environmental compliance.
Environmental	• Water scarcity, • Climate change mitigation, • Potential impact on ecosystems.	• Reduced water evaporation is a benefit, • Contributes to the clean energy transition, • Potential negative impacts require mitigation strategies.

regulations. The governance of MUPS demands a robust legal framework to manage competing claims and ensure the sustainable use of marine resources. The article on governance arrangements in European seas offers valuable insights into the legal challenges and the need for policy recommendations to facilitate the development of MUPS. A well-defined legal framework is indispensable for the successful deployment of floating solar and other multi-use platforms [83].

Environmental factors

Floating Solar Power Systems (FSPs) offer a promising solution for regions grappling with water scarcity. By harnessing solar energy on the surface of reservoirs, FSPs can generate clean electricity while simultaneously reducing water evaporation. This dual benefit is particularly advantageous in arid or semi-arid regions with limited water resources. Additionally, FSPs contribute to climate change

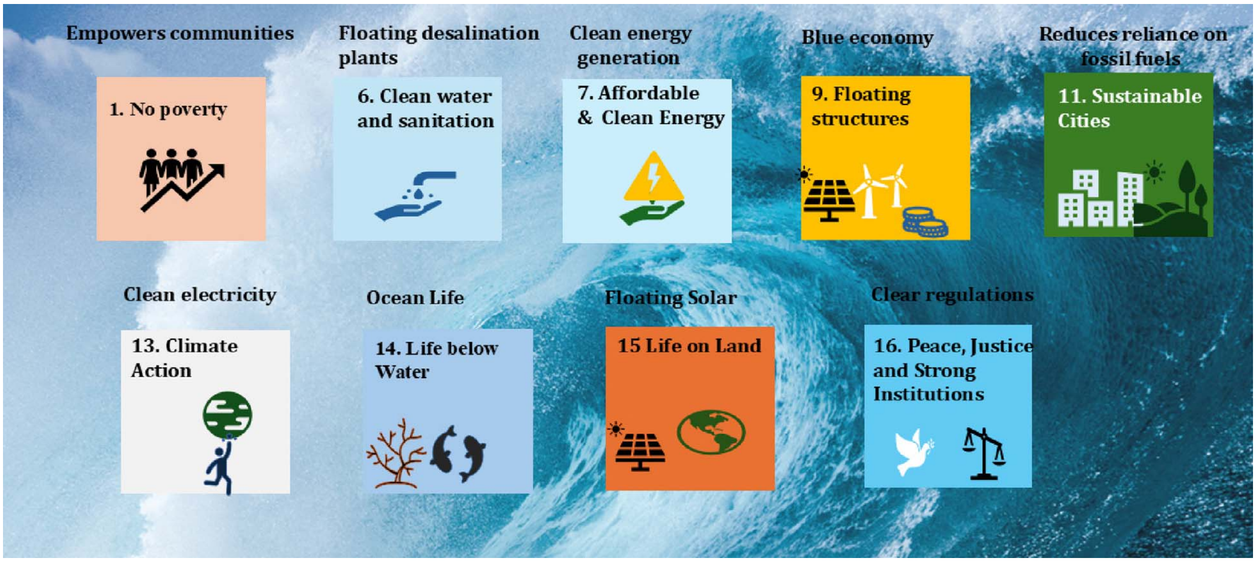


Fig. 13. Contribution of Floating solar towards sustainable development goals.

mitigation by reducing reliance on fossil fuels and generating renewable energy. However, the potential impact of FSPs on aquatic ecosystems must be carefully considered. Factors such as shading, changes in water temperature, and introduction of new materials into the reservoir environment could affect fish populations, marine life, and overall water quality. Therefore, responsible deployment strategies that prioritize environmental sustainability and minimize negative impacts are crucial to ensure the long-term viability and benefits of FSPs in water-scarce regions.

For instance, government policies, economic incentives, public acceptance, technological innovations, legal frameworks, and environmental considerations all play pivotal roles in advancing the adoption of floating solar technologies.

4.4 Floating solar on land and ocean contribution to SDG

Floating solar panels deployed on reservoirs, lakes, and oceans offer a promising path towards a sustainable future. Floating solar offers a range of benefits that directly contribute to achieving several SDGs, including 1, 6, 7, 9, 11, 13, 14, 15, and 16 [77, 85]. The following insights from the referenced articles highlight the potential and contributions of floating solar technologies (Fig. 13).

SDG 1 (No Poverty): Floating solar can provide affordable and clean energy essential for economic development and poverty alleviation. Deploying floating solar systems can create job opportunities and stimulate local economies, particularly in regions with limited access to electricity.

SDG 6 (Clean Water and Sanitation): Floating solar panels can reduce water evaporation from reservoirs, conserving water resources. This is particularly beneficial in arid regions where water scarcity is a significant issue. The reduction in evaporation helps maintain water levels, ensuring a stable supply for drinking, irrigation, and other uses.

SDG 7 (Affordable and Clean Energy): Floating solar technology provides a sustainable and renewable source of energy. It can be integrated with existing hydropower infrastructure to enhance energy production and reliability. The hybrid systems of FSPV and hydropower can act as a virtual battery, balancing energy supply and demand.

SDG 9 (Industry, Innovation, and Infrastructure): The development and deployment of floating solar systems drive innovation in renewable energy technologies. The integration of FSPV with other renewable energy sources, such as wave energy and hydrogen production, showcases the potential for innovative hybrid systems that can enhance energy efficiency and resilience.

SDG 11 (Sustainable Cities and Communities): Floating solar systems can be deployed in urban water bodies, providing clean energy without occupying valuable land space. This contributes to the development of sustainable cities by reducing the carbon footprint and promoting the use of renewable energy sources.

SDG 13 (Climate Action): By reducing reliance on fossil fuels, floating solar technology helps mitigate climate change. The reduction in CO2 emissions from FSPV systems contributes to global efforts to combat climate change and its impacts.

SDG 14 (Life Below Water): The deployment of floating solar panels in marine environments can be designed to minimize environmental impacts. Research into the environmental effects of marine FSPV systems is essential to ensure that these installations do not harm marine ecosystems.

SDG 15 (Life on Land): Floating solar systems help conserve land resources by utilizing water surfaces for energy production. This reduces the need for land-based solar installations, preserving natural habitats and agricultural land.

SDG 16 (Peace, Justice, and Strong Institutions): The development of floating solar projects requires strong governance and regulatory frameworks to ensure their sustainable and equitable implementation. Effective policies and institutions are necessary to manage competing interests and ensure the benefits of FSPV systems are widely shared.

5 Discussion

The SWOT and TOWS analyses have highlighted key strengths and weaknesses of land-based and ocean-based FSPV systems, while the PESTLE analysis has shed light on the political, economic, social, technological, legal, and environmental factors influencing their future development. Based on these insights, several recommendations can be made to advance floating solar technology.

Balancing Scalability with Environmental Impact: Land-based FSPs offer easier scalability but require careful environmental monitoring, particularly of freshwater ecosystems. While promising, energy production from FSPV technologies has been lower than expected, ranging from 0.31% to 2.59% depending on location and technology.

Optimizing Ocean FSPs: Ocean-based systems need cost-effective anchoring and advanced remote monitoring technologies for success. Offshore FSPs present significant opportunities, as demonstrated by projects in Singapore.

Public Perception and Regulation: Addressing public concerns and establishing clear regulatory frameworks for freshwater and ocean deployments are crucial for broader adoption. Malaysia's successful floating solar projects show its potential for gaining public acceptance.

Collaboration and Innovation: Partnerships among governments, researchers, and private investors are essential. A case study of offshore FSPV in the North Sea illustrates the benefits of collaboration.

Government Support: Governments must offer performance-based incentives, streamline permitting processes, and invest in research to lower costs and reduce environmental impacts.

Technological Advancements: Standardized platforms improved solar panel efficiency, and remote monitoring for harsh environments are critical for future success. Technological progress will be key for scaling FSPV systems.

Public Engagement: Public awareness campaigns and open communication with local communities are necessary for fostering acceptance, as highlighted by environmental reviews of floating solar projects.

Financial Innovation: Innovative financing models like public-private partnerships and incentives such as carbon credits will help address the high initial costs of FSPV projects, as shown by techno-economic studies of offshore FSPV integration with wind parks.

6 Conclusion

Floating Solar Projects (FSPs) present a transformative approach to renewable energy generation, offering unique advantages and challenges. A comprehensive analysis utilizing SWOT, TOWS, and PESTLE frameworks reveals that while land-based FSPs are easier to implement, ocean-based FSPs offer significant potential for large-scale energy production and reduced land-use conflicts. Land-based FSPs excel in ease of implementation, potentially lower environmental impact in freshwater environments, and water conservation benefits. However, their scalability is limited by available water bodies. Ocean-based FSPs, on the other hand, boast vast potential for large-scale energy generation and potential synergy with offshore wind farms. However, they face hurdles in complex and expensive construction, limited access to maintenance, and the need for rigorous environmental assessments. Land-based FSPs are ideal for regions with suitable freshwater resources and a need for efficient land-use solutions that align with social acceptance. Ocean-based FSPs are prime candidates for countries with vast coastlines and ambitions for large-scale clean energy generation.

Key strengths of FSPs include increased energy efficiency, environmental benefits, and the potential for hybrid integration with other renewable sources. However, challenges such as occupational safety risks, initial costs, and market entry barriers must be addressed. Opportunities for FSPs lie in policy support, contributions to SDGs, and technological advancements. Governments can play a pivotal role in fostering the growth of FSPs through clear policies and financial incentives. Nevertheless, threats such as environmental impacts and climate dependencies pose significant challenges. Careful monitoring and management of potential negative impacts on water bodies are essential. Additionally, the performance of FSPs can be affected by climatic conditions and weather patterns. Finally, innovative financing models are needed to overcome the initial investment hurdles.

Addressing these challenges through targeted policy support, technological innovation, and environmental management is crucial for successfully deploying FSPs. By leveraging their strengths and opportunities, FSPs can play a vital role in the transition towards a sustainable energy future and contribute significantly to achieving the SDGs. The key to unlocking the full potential of floating solar lies in a multi-pronged approach. The insights provided in this paper offer valuable guidance for stakeholders interested in developing and deploying FSPs, paving the way for their strategic implementation in the global renewable energy landscape. As technology advances, costs decrease, and strategic implementation, FSPs are poised to play a transformative role in the global clean energy transition and become attractive options for energy producers and consumers alike.

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