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The Role of Floating Photovoltaics in Sustainable Regional Energy Planning: A Systematic Literature Review

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ABSTRACT

Floating photovoltaic (FPV) is increasingly recognised as a strategic option for expanding renewable energy in regions facing land scarcity, rapid urbanisation, and growing pressure on water resources. Yet its broader implications for sustainable regional energy planning remain insufficiently conceptualised and systematically synthesised in the academic literature. This study presents a systematic review in the academic literature of 49 Scopus indexed studies to assess how FPV contributes to regional energy planning objectives and to identify thematic and institutional gaps that shape its deployment. Using the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) 2020 guidelines, this review synthesises evidence across technical performance, environmental interactions, spatial planning, socio-economic feasibility, and governance readiness. The findings confirm that FPV provides consistent performance advantages over ground-mounted systems, offers significant water conservation benefits through evaporation reduction, and demonstrates strong suitability across reservoir networks that are often overlooked in planning processes. However, integration of FPV into spatial plans, basin management strategies, and energy transition roadmaps remains limited. Governance emerges as the most critical barrier, characterised by fragmented institutional mandates, unclear water surface rights, and the absence of FPV-specific environmental permitting procedures. Socio economic insights highlight the need for participatory engagement and equitable consideration of reservoir users. Building on these findings, the study develops a planning oriented conceptual framework grounded in the land-water energy nexus, emphasising the interdependence of hydrological conditions, ecological safeguards, system integration, and governance design. The review concludes that FPV can play a transformative role in sustainable regional development, provided that institutional reforms, planning instruments, and environmental assessment protocols evolve to support its responsible and coordinated deployment.

1. INTRODUCTION

The global shift toward cleaner and more resilient energy systems has increased the demand for renewable technologies that can generate substantial energy while minimizing pressure on land resources [1, 2]. This challenge is particularly evident in regions where urban expansion, agricultural development, and environmental conservation compete for limited land area [3, 4]. Within this context, floating photovoltaics (FPV), referring to solar FPV systems installed on water surfaces such as reservoirs, lakes, hydropower basins, and irrigation ponds have gained increasing attention. They offer an emerging option to support renewable energy expansion without intensifying land use competition [5-7].

FPV offers several potential advantages. Water-based installation may improve electrical performance through natural cooling, and the shading provided by the floating structures can reduce evaporation from reservoirs, an important co-benefit in areas facing rising water stress [8, 9]. These attributes have contributed to growing interest in FPV as part of broader renewable energy strategies [10]. However, despite increasing technological progress, the role of FPV within regional energy planning frameworks remains insufficiently examined. Much of the existing literature focuses on specific technical or environmental aspects, while systematic connections to planning practice, governance, and integrated sustainability considerations are still uncommon [11-13].

Regional energy planning itself involves a wide set of interconnected tasks: ensuring reliable energy supply, managing land and water efficiently, protecting environmental quality, and engaging with local communities all while pursuing long-term decarbonization objectives [14-16]. In practice, planners often confront land scarcity, competing land uses, and fragmented institutional responsibilities among water, energy, and environmental authorities [17, 18]. Ground-mounted PV competes with high-value land uses, and many regions face increasingly strict environmental constraints. At the same time, diversifying renewable energy sources and identifying hybrid solutions have become more important. FPV sits at the intersection of these challenges because it enables renewable energy deployment on managed water bodies that are often underutilized in planning discussions [19-21].

The FPV research landscape reflects considerable diversity. Technical and operational studies address buoyancy systems, anchoring methods, hydrodynamic behaviour, electrical configurations, and performance drivers [22]. Environmental research examines evaporation, water temperature changes, ecological interactions, and water quality implications, with results varying by reservoir type, climate, and FPV coverage. Spatial and planning-oriented contributions investigate siting suitability and synergies with existing hydropower infrastructure, though most remain limited to case-specific analyses [20]. Socio-economic studies, while fewer in number, explore public acceptance, interactions with local livelihoods, and cost considerations. Work on policy and governance highlights regulatory uncertainty, overlapping mandates, and the need for improved coordination between water and energy sectors. Despite this growing body of knowledge, few studies offer an integrated perspective that brings these domains together in a manner directly relevant to regional planning.

Several gaps emerge from this literature. Conceptually, FPV is seldom examined through a land-water energy nexus lens, even though its deployment spans all three resource domains [20]. Planning concepts developed for land-based renewables offer limited guidance for water-based infrastructure. Methodologically, much of the research remains siloed, with little integration of technical, environmental, social, and governance considerations into coherent planning frameworks. In practice, fragmented institutional arrangements, unclear licensing pathways, and limited stakeholder engagement often hinder FPV deployment. These gaps collectively suggest the need for a consolidated assessment that synthesizes evidence across domains and identifies how FPV can more effectively support regional planning objectives.

Against this backdrop, a systematic literature review (SLR) offers a structured and transparent approach to organizing the diverse body of FPV research [23]. An SLR enables the integration of insights across technical, environmental, spatial, socio-economic, and governance dimensions, thereby providing a more complete understanding of FPV's potential role in regional energy systems. Applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines adds methodological clarity and reduces selection bias. Beyond synthesizing existing knowledge, the review is intended to provide planners and policymakers with actionable insight into where FPV can be deployed, what constraints are most critical, and what enabling conditions may be required. It also supports the development of an integrative perspective for incorporating FPV into regional planning processes [24].

The overall aim of this review is to clarify how FPV research can inform sustainable regional energy planning. Specifically, the study seeks to identify the main research themes relevant to planning; examine how FPV contributes to land-water optimization, energy diversification, and decarbonization; identify major technical, environmental, socio-economic, and governance barriers to FPV deployment; and develop an integrated perspective to support the inclusion of FPV in planning and policy processes. These aims are pursued through four guiding questions: (1) Which thematic domains dominate FPV research in relation to regional planning? (2) How does the existing evidence describe FPV's potential role in regional energy systems? (3) What barriers constrain FPV deployment across technical, environmental, socio-economic, and institutional dimensions? and (4) What integrative perspective can support planners and policymakers in incorporating FPV into regional energy strategies?

2. METHODOLOGY

2.1 Review design and protocol

This study adopts an SLR approach guided by the PRISMA 2020 framework [25], ensuring transparency, reproducibility, and methodological rigor. The protocol follows established SLR procedures commonly applied in interdisciplinary planning and sustainability research [23]. The review protocol was developed to ensure a transparent, traceable, and replicable process for identifying and analyzing studies related to FPV in the context of regional energy planning. Because FPV research spans several disciplines, engineering, environmental sciences, water resource management, spatial planning, socio-economic analysis, and governance, the protocol was designed to accommodate a wide range of study types while maintaining consistent methodological standards.

The overall procedure consisted of defining the review scope, selecting an appropriate academic database, constructing the search strategy, applying eligibility criteria, screening the results following PRISMA steps, extracting key data from the selected studies, performing a quality assessment, and finally synthesizing the findings using predefined analytical domains.

2.2 Search strategy and database selection

To ensure a systematic, transparent, and manageable literature retrieval process, Scopus was selected as the sole database for this review. Scopus offers comprehensive coverage across engineering, environmental science, sustainability, and planning-related journals [23], making it particularly suitable for capturing the interdisciplinary nature of research on FPV. The use of a single, high-quality database enhances consistency in indexing, minimizes duplication of records, and improves the traceability of the search process, in line with PRISMA 2020 principles of transparency and reproducibility [25].

The search strategy was designed to systematically identify studies that explicitly link FPV systems with planning and sustainability contexts. To achieve this, FPV-specific terminology was combined with planning-oriented keywords to avoid bias toward purely technical or engineering-focused studies. Variations of "floating photovoltaic", "floating solar", "floating PV", and "floatovoltaic" were paired with terms such as "regional energy planning", "energy planning", "sustainable planning", "spatial planning", "renewable energy planning", "energy transition", "resource planning", and "water energy nexus". The search was applied to the title, abstract, and keyword fields (TITLE-ABS-KEY), ensuring both breadth of coverage and thematic relevance. This approach enables the inclusion of studies addressing environmental, spatial, socio-economic, and governance dimensions associated with FPV deployment.

However, it is acknowledged that this keyword combination may limit the inclusion of studies that focus exclusively on technical or engineering aspects of FPV without explicit reference to planning or sustainability contexts. For example, studies examining module efficiency, hydrodynamic behaviour, or anchoring system design without broader system or planning implications may not be captured within the defined search scope. This reflects a deliberate boundary in the review design, prioritising planning-relevant literature while recognising that certain technically detailed studies may fall outside the inclusion criteria. Consequently, the review does not aim to exhaustively cover all engineering developments in FPV, but rather to synthesise research that directly informs regional energy planning and sustainability considerations.

To enhance methodological transparency and ensure reproducibility, all search parameters and the complete query are explicitly documented. Table 1 presents the database configuration and the exact search string used in this review. Providing full details of the search strategy allows for traceability of the retrieval process and facilitates replication in future studies, consistent with PRISMA requirements for reporting information sources and search procedures. The literature search was conducted in January 2026, ensuring that the dataset reflects the most recent studies available at the time of the review. Together with the subsequent screening, eligibility, extraction, and synthesis stages, this documentation establishes a transparent and comprehensive audit trail across the entire review process.

Table 1. Search string and database parameters

Database	Scopus
Search String	(TITLE ABS KEY("floating photovoltaic*" OR "floating solar" OR "floating PV" OR "floatovoltaic*" OR "FPV system*" OR "reservoir solar")) AND (TITLE ABS KEY("regional energy planning" OR "energy planning" OR "sustainable planning" OR "spatial planning" OR "renewable energy planning" OR "energy transition" OR "resource planning" OR "water energy nexus"))
Filters	peer reviewed journal publications; research articles; English language documents; open access sources

In addition to the search query, predefined filtering criteria were applied directly at the database level to ensure alignment with the scope and objectives of the review. These criteria included restricting results to peer-reviewed journal publications, research articles, English language documents, and open access sources. Applying these filters within the database ensures consistency in study selection, reduces reliance on subjective screening decisions, and strengthens the reproducibility and methodological rigor of the review.

The selection of Scopus as a single data source also supports methodological consistency and reduces redundancy across multiple indexing systems [26]. Previous interdisciplinary reviews in energy planning, water energy systems, and sustainability studies have successfully relied on Scopus as a standalone database, demonstrating that this approach remains robust and appropriate for SLR conducted in accordance with PRISMA guidelines [27].

2.3 Inclusion and exclusion criteria

Eligibility criteria were established to filter the studies retrieved from Scopus and ensure that only publications with sufficient methodological depth and thematic relevance were included in the review. The criteria prioritised peer-reviewed journal articles, substantial analytical content, and explicit relevance to one or more FPV domains: technical performance, environmental effects, spatial or planning considerations, socio-economic dimensions, or governance and policy issues.

Publications restricted to laboratory-scale testing without broader contextual interpretation were excluded, along with non-journal sources such as conference proceedings, theses, and book chapters. Only English language, full-text articles were retained to ensure analytical completeness and consistency across the evidence base.

Before presenting the final criteria, it is important to situate their role within the overall review protocol. Table 2 provides a structured summary of the inclusion and exclusion parameters applied at the screening stage, ensuring transparency and reproducibility in accordance with PRISMA standards [25]. The table also clarifies the rationale behind the selection boundaries, which were designed to maintain methodological rigor while capturing the full multidisciplinary scope of FPV research relevant to regional planning.

Table 2. Inclusion and exclusion criteria

Category	Inclusion Criteria	Exclusion Criteria
Source Type	Peer-reviewed journal articles	Conferences, books, theses
Relevance	Floating photovoltaic (FPV) with technical, environmental, spatial, socio-economic, or governance implications	Purely technical laboratory studies
Language	English	Non English
Availability	Full text accessible	Full text unavailable

These criteria ensured that the final pool of studies adequately represented the multidisciplinary perspectives essential for analysing FPV within sustainable regional energy planning frameworks.

2.4 Preferred Reporting Items for Systematic Reviews and Meta-Analyses screening procedure

All records retrieved from the Scopus database were initially exported and organized using a reference management tool to ensure systematic handling of the dataset. Duplicate entries were identified and removed where applicable to maintain data consistency prior to screening.

The study selection procedure was conducted in accordance with the PRISMA 2020 framework and followed four sequential stages: identification, screening, eligibility assessment, and inclusion, as illustrated in Figure 1. This structured approach was adopted to ensure methodological transparency, consistency, and reproducibility throughout the selection process.

Following the identification stage, predefined filtering criteria, as described in Section 2.2, were applied directly at the database level. These criteria included restricting the dataset to peer-reviewed journal publications, research articles, English language documents, and open access sources. The application of these filters at the database stage ensured that only studies aligned with the scope and objectives of the review were retained for further evaluation, thereby reducing potential bias in subsequent screening steps.

Subsequently, the filtered records were subjected to a structured screening process based on titles and abstracts. The screening was conducted independently by two reviewers to minimise potential selection bias and enhance the reliability of the inclusion process. This stage was designed to assess the relevance of each study to the focus of the review, specifically the integration of FPV systems within regional energy planning contexts. Any discrepancies in study selection were resolved through discussion and consensus, ensuring consistent application of the predefined eligibility criteria. Studies that were clearly unrelated to planning dimensions or that focused solely on narrow technical aspects of photovoltaic systems were excluded during this stage.

The remaining records were then evaluated through a full-text eligibility assessment using predefined inclusion criteria. These criteria emphasized the relevance of each study to planning-oriented aspects of FPV, including spatial integration, environmental considerations, socio-economic implications, and governance frameworks. This step ensured that all selected studies contributed meaningfully to the analytical objectives of the review.

The combination of database-level filtering and structured screening procedures enhances methodological rigor by minimizing reliance on subjective decision-making. Furthermore, the use of clearly defined criteria at each stage improves the traceability of the selection process and supports the reproducibility of the review, in accordance with PRISMA 2020 guidelines.

The detailed progression of records through each stage of the selection process, including identification, filtering, screening, eligibility, and inclusion. This structured reporting approach strengthens both the transparency of the methodology and the clarity of its presentation.

This documentation provides a clear record of how studies were filtered and selected according to PRISMA guidelines [25].

2.5 Data extraction process

The studies selected through the PRISMA process were analyzed using a structured data extraction framework. The extraction procedure captured key information from each article, including publication details, study location and context, the type of water body examined, FPV system characteristics, research methods used, major findings, barriers identified, and implications for regional planning.

2.6 Thematic coding and analytical domains

After extraction, the studies were analyzed using a hybrid thematic coding approach. Deductive coding was based on five analytical domains identified from prior research on FPV and sustainable planning, technical and operational characteristics, environmental and water body impacts, spatial and planning considerations, socio-economic aspects, and governance or policy-related dimensions. Inductive coding was applied to incorporate new or unexpected themes emerging during the review [26].

The analytical domain structure is represented conceptually in Figure 1.

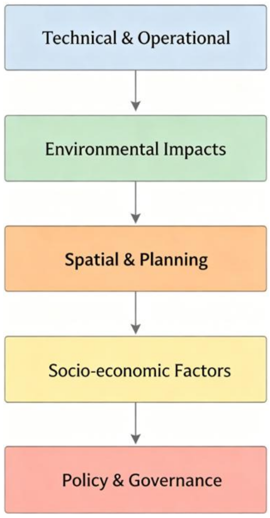

Figure 1. Analytical domain structure

This framework provided a consistent lens for interpreting the diverse findings and ensured that the synthesis reflected both technical and contextual perspectives. Figure 2 presents the analytical coding framework used to classify the reviewed studies into five core domains. This framework guided the systematic categorisation of each study and forms the methodological foundation for the thematic synthesis presented in Section 3. By structuring the evidence across consistent analytical dimensions, it enhances both transparency in classification and coherence in the interpretation of findings.

2.7 Quality assessment

To ensure that the synthesis relied on reliable and methodologically sound evidence, each included study underwent a quality assessment. The assessment considered clarity of objectives, methodological rigor, data validity, relevance to FPV and planning, and transparency in reporting limitations.

This approach is consistent with SLR best practices, which recommend presenting quality assessment outcomes in the results section rather than within the methodology [25]. To ensure full transparency and reporting completeness, all stages of the SLR process, including search strategy, screening procedures, eligibility criteria, data extraction, and synthesis methods, are explicitly documented in accordance with PRISMA 2020 guidelines. This structured approach enhances the reproducibility, traceability, and clarity of the review.

2.8 Synthesis approach

The synthesis of findings followed two complementary layers. The descriptive synthesis summarizes key characteristics of the included studies, such as geographic distribution, FPV system scale, water body types, and research methods employed. The thematic synthesis organizes insights across the five analytical domains, identifying recurrent patterns, methodological tendencies, and cross-cutting barriers relevant to FPV deployment at the regional planning scale.

Because the included studies vary substantially in design, parameters, and objectives, a quantitative meta-analysis would not be appropriate. Instead, the review uses a qualitative synthesis approach that preserves contextual nuance while allowing integration across diverse study types [25].

3. RESULTS

3.1 Overview of the evidence base

The study selection process resulted in a final dataset of 49 peer-reviewed studies, as illustrated in Figure 2.

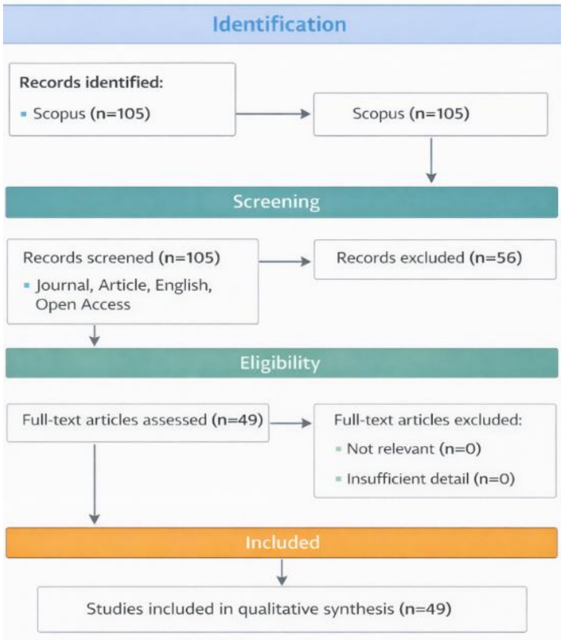

Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for study selection

These studies were derived from an initial set of 105 records identified through the Scopus database, which were subsequently refined using predefined filtering and screening procedures described in Section 2.

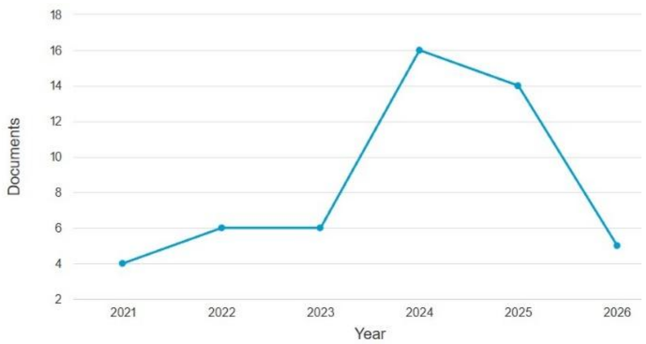

Figure 3. Documents by year

Figure 3 presents the PRISMA flow diagram detailing the study selection process, including the number of records identified, screened, excluded, and retained at each stage. The diagram has been explicitly updated to reflect all screening decisions and exclusion steps in accordance with PRISMA 2020 guidelines, thereby ensuring full transparency, traceability, and reproducibility of the review process.

The temporal distribution of publications is presented in Figure 3. The results indicate a marked increase in research activity after 2022, reaching a peak in 2024, followed by a moderate decline in subsequent years. This trend reflects the growing global interest in FPV systems as part of broader renewable energy transitions and sustainability agendas.

The geographical distribution of publications is shown in Figure 4. The results reveal a concentration of FPV research in specific regions, with strong representation from European countries, particularly the Netherlands and the United Kingdom, alongside contributions from Asia, including Indonesia. Additional studies are distributed across the United States, France, Germany, Brazil, and Sweden, indicating a geographically diverse yet regionally concentrated research landscape.

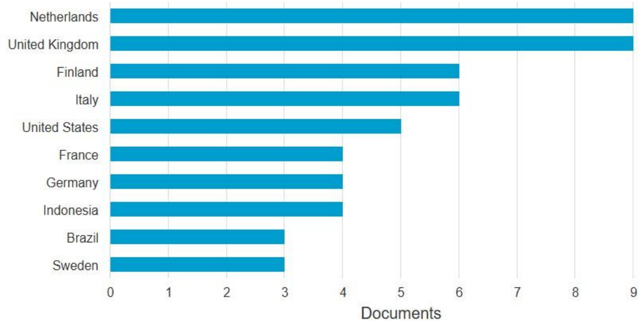

Figure 4. Documents by region

This distribution reflects the regional dynamics of FPV development, particularly in areas characterized by high solar potential, increasing energy demand, and strong policy support for renewable energy transitions. It also indicates that empirical and applied FPV research is more established in regions where deployment is already underway.

In terms of methodological approach, a quantitative overview is presented in Table 3. The evidence base is strongly dominated by technical and operational analyses, which are present across the vast majority of studies. Spatial and planning-oriented approaches are also highly represented, followed by environmental assessments.

In contrast, socio-economic dimensions and governance-related analyses appear less consistently, indicating that institutional, regulatory, and social aspects remain comparatively underexplored within the current literature.

Table 3. Distribution of floating photovoltaic (FPV) studies by analytical domain

Analytical Domain	Number of Studies (n)	Percentage (%)
Technical/operational	49	100.0
Spatial/planning	36	75.0
Environmental	32	66.7
Socio-economic	23	47.9
Governance/policy	22	45.8

In terms of application context, reservoir-based FPV systems dominate the evidence base. This predominance reflects the technical and operational advantages associated with reservoir environments, including hydrological stability, multi-purpose water use, and established grid connectivity [28-30]. In contrast, a smaller number of studies examine FPV deployment in lakes, coastal waters, and offshore environments [31-33], suggesting that these contexts remain relatively underexplored and represent emerging directions for future research.

The distribution of studies by water-body type is summarised in Table 4. Reservoir-based FPV systems represent the dominant application context, followed by marine and offshore environments, while lakes and other water bodies are less frequently investigated. This pattern reflects the practical advantages of existing reservoir infrastructure, including grid accessibility and water surface availability, while also indicating limited exploration of alternative aquatic settings.

Table 4. Distribution of floating photovoltaic (FPV) studies by water body type

Water-body Type	Number of Studies (n)	Percentage (%)
Reservoirs	27	54.2
Marine / offshore	12	25.0
Lakes	5	10.4
Others (ponds, estuary, etc.)	5	10.4

The selected studies also demonstrate considerable diversity in their analytical focus and methodological approaches. The literature spans technical modelling, spatial analysis, environmental impact assessment, and policy-oriented research, underscoring the interdisciplinary nature of FPV studies. This diversity highlights the importance of integrating technical, environmental, spatial, socio-economic, and governance perspectives in order to comprehensively assess the role of FPV systems in regional energy planning.

The characteristics of the selected studies vary considerably in terms of geographical setting, water body type, deployment scale, and analytical focus. Understanding these variations is essential for interpreting the thematic patterns identified in the subsequent analysis. To support this, Table 5 provides a consolidated summary of the key descriptive attributes of the included studies, serving as a structured foundation for the multi-domain synthesis presented in Sections 3.2 to 3.6.

Overall, the evidence base reflects both the maturity of FPV research in regions with established deployment and the emergence of new research directions in less explored contexts. This combination provides a robust and balanced foundation for analysing the role of FPV systems in sustainable regional energy planning. This progression from descriptive mapping to thematic interpretation strengthens reporting completeness and maintains analytical coherence throughout the manuscript.

The descriptive patterns presented in Figures 4 and 5, together with the domain distributions in Tables 3 and 4, provide the empirical basis for the thematic synthesis developed in Sections 3.2~3.6 and the conceptual integration presented in Figure 5. These figures, therefore, function not only as descriptive summaries but as analytical inputs that directly inform the interpretation of cross-domain relationships and the construction of the proposed framework.

3.2 Thematic synthesis

The 49 studies were coded into five thematic categories. While some studies span multiple domains, each includes a dominant analytical emphasis. The synthesis below reflects convergent findings and their relevance for sustainable regional planning.

Table 5. Overview of floating photovoltaic (FPV) study characteristics

Dimension	Categories (Examples)	Description in Evidence Base	Illustrative Focus Areas
Region	East/Southeast Asia; Europe; Africa/MENA; Americas; Global	Asia dominates, followed by Europe and emerging studies in Africa/MENA.	Reservoir FPV clusters; national scale modelling.
Water body type	Hydropower reservoirs; irrigation reservoirs; lakes; multipurpose reservoirs; coastal/offshore	Reservoirs are most frequently analysed due to stability and grid proximity.	Reservoir prioritisation; lake pilots; offshore analysis.
Deployment scale	Pilot; utility scale; regional portfolios; national scenarios	Evidence spans demonstrations to national assessments.	Reservoir networks; performance monitoring.
Primary focus	Technical; environmental; planning; techno economic; socio-economic; governance	Technical and planning studies dominate; governance least represented.	Cooling effects; evaporation reduction; multi-criteria decision analysis (MCDA) siting; LCOE evaluation.

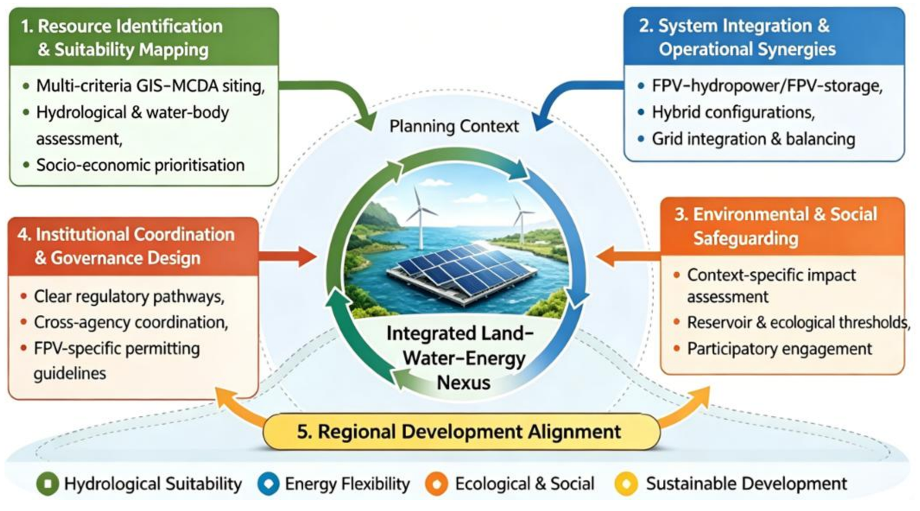

Figure 5. Planning-oriented conceptual framework for integrating floating photovoltaic (FPV) into sustainable regional energy development

3.2.1 Technical performance and system design

Technical investigations constitute the most substantial portion of the FPV literature, and they provide a clear picture of how system behaviour is shaped by engineering configuration and site-specific conditions. Several patterns can be observed across the studies.

First, many authors report measurable improvements in electrical performance when PV modules are installed on water surfaces. These gains are commonly attributed to enhanced convective cooling, lower surface temperatures, and reduced dust accumulation [34-37], all of which help stabilise output in environments that would otherwise favour thermal degradation or soiling losses on land-based arrays [38].

Second, research on system design repeatedly shows that mooring layout, anchoring type, and hydrodynamic stability are critical determinants of long-term operability [39]. The configuration of these components is strongly affected by reservoir geometry, depth profiles, wind fetch, and seasonal water level variation. Studies emphasise that overlooking these parameters can lead to increased mechanical stress, accelerated fatigue, or compromised energy yield [40-42], underscoring the need for location-specific engineering assessments.

Third, an emerging strand of literature explores hybrid configurations that integrate FPV with hydropower plants, battery energy storage, or, in more experimental work, hydrogen production systems [43]. These hybrid setups are valued for their potential to improve ramping capability, dispatchability, and peak load support [44-47], thus widening FPV's relevance beyond standalone generation toward a more strategic role in regional energy system management [48].

3.2.2 Environmental interactions and water body impacts

Environmental assessments of FPV installations reveal that interactions between the floating structures and the underlying water body are both multifaceted and highly dependent on local conditions. A number of recurring findings can be distilled from the literature.

Several studies point to reduced evaporation as one of the most consistent co-benefits of FPV deployment [30, 37, 49, 50]. The shading effect generated by the array surface slows evaporative loss, with particularly notable reductions observed in reservoirs exposed to high temperatures or sustained solar radiation.

In contrast, the influence of FPV on thermal stratification, temperature regimes, and ecological indicators shows greater variability. Hydrodynamic responses depend strongly on water depth, mixing potential, wind exposure, and coverage ratio [31, 41, 51]. Mild thermal shifts are often reported at modest coverage levels, whereas larger or morphologically sensitive reservoirs may experience altered mixing layers or changes in vertical temperature structure. These divergent outcomes underscore the importance of site-specific environmental assessment rather than assuming uniform responses.

Ecological effects documented to date tend to be limited in magnitude at moderate FPV densities. Most studies report minimal change in dissolved oxygen, primary productivity, or broad water quality metrics, though localised shading and reduced wind mixing have been associated with different outcomes in shallow or eutrophic systems [29, 35]. This suggests that ecological sensitivity is tied more to baseline conditions than to FPV presence alone.

Life cycle assessment (LCA) research provides a complementary perspective: FPV reduces land use pressure, yet typically requires higher material inputs for floats, mooring lines, anchoring, and associated hardware [33, 52]. These material demands temper some of the perceived environmental advantages but remain manageable when integrated into broader sustainability evaluations.

3.2.3 Spatial and regional planning perspectives

Spatially oriented studies, many employing GIS-based multi-criteria decision analysis (MCDA), repeatedly identify reservoirs as suitable candidates for FPV deployment [28, 53-55]. These assessments typically emphasise the advantages of utilising existing water infrastructure and highlight the compatibility of FPV with broader regional development goals. When viewed collectively, several planning-relevant opportunities become evident [30, 56].

A recurrent theme is FPV's potential to contribute to renewable energy diversification, particularly in regions where land availability or landscape protection limits the expansion of ground-mounted systems [32, 57]. Another line of work explores how FPV can support basin-scale water management, including evaporation control, reservoir performance optimisation, and the coordinated operation of water energy systems. Complementing this, a smaller but growing set of studies investigates FPV within multi-reservoir portfolio planning, illustrating how strategically distributed arrays across interconnected basins might improve flexibility and strengthen long-term resource planning [49].

Despite these promising insights, most suitability analyses remain disconnected from formal planning instruments. Only a limited number of studies explicitly link FPV to regional development plans, zoning provisions, strategic siting regulations, or river basin governance frameworks [58, 59]. This gap suggests that while spatial analyses can demonstrate where FPV may be feasible, the translation of technical findings into actionable planning practice is still at an early stage [60].

3.2.4 Socio-economic dimensions

Although socio-economic analyses make up a smaller share of the FPV literature compared with technical or environmental studies, they provide important insights into the conditions that shape feasibility, affordability, and social acceptance. A number of recurring themes emerge from this body of work.

Several studies point to the techno-economic advantages of FPV in contexts where land is scarce, contested, or subject to strict protection measures [34, 36, 37]. Under these circumstances, FPV can reduce pressure on terrestrial land uses and help alleviate disputes over agricultural or conservation areas. Its competitiveness therefore derives not only from generation cost but also from avoided land use conflict.

Economic assessments also highlight the sensitivity of FPV project viability to tariff regimes, equipment prices, and financing structures [32, 61, 62]. Fluctuations in the cost of floats, anchoring systems, and grid integration components can meaningfully affect levelised cost outcomes. Likewise, access to concessional finance, blended capital, or performance-based incentives plays an important role in shaping investor appetite and overall project bankability [63].

Social acceptance emerges as a further dimension. Findings indicate that community responses are often conditioned by existing uses of the water body, including fisheries, recreation, transport, and cultural or aesthetic values. In areas where such uses are deeply embedded, early consultation, transparent communication, and co-design processes appear critical for reducing contestation and strengthening legitimacy [51, 59].

3.2.5 Governance and institutional readiness

Governance-focused studies, while fewer in number, offer important insights into the institutional conditions that influence FPV development. Across the available literature, several recurrent governance challenges can be observed.

One persistent issue concerns the absence of regulations tailored to FPV systems. Without technology-specific guidance, project developers and regulators often rely on frameworks designed for floating structures or land-based solar installations, leading to uncertainty in permitting processes and inconsistent interpretations of compliance requirements. This uncertainty can translate into delays or fragmented oversight [58, 64].

Another challenge highlighted in the literature relates to dispersed institutional mandates across agencies responsible for water resources, energy, and environmental protection. FPV projects located on multipurpose reservoirs commonly intersect with several jurisdictions, and limited coordination among these authorities can complicate project evaluation, approval, and monitoring [59, 65].

Questions around water surface rights, custodianship, and operational safety further contribute to institutional ambiguity. In many settings, responsibilities for water bodies are shared or poorly defined, which slows the establishment of clear rules governing access, liability, and long-term operation.

A further theme concerns the weak incorporation of FPV into strategic energy and water planning instruments. Although FPV appears in technical assessments and suitability studies, it is rarely embedded in national energy strategies, basin-level water management plans, or subnational zoning frameworks. This disconnect limits policy continuity and reduces the predictability of future deployment pathways [54, 66].

3.3 Methodological patterns

The methodological diversity of the 49 studies reflects FPV's multidisciplinary character. Before presenting Table 4, it is important to clarify its analytical purpose. The table is not merely descriptive, but identifies methodological clusters that shape how FPV is studied and how these methods inform planning-relevant insights. Table 6, therefore, categorises the main methodological families and highlights their relevance for regional planning and sustainability assessment.

Table 6. Methodological families in floating photovoltaic (FPV) research

Methodological Family	Typical Tools	Main Functions	Planning Relevance
GIS MCDA	AHP, TOPSIS, FUCOM, EDAS, ELECTRE	Suitability mapping; multi-criteria prioritisation	Supports structured spatial and reservoir-based planning.
Techno-economic modelling	LCOE, NPV, IRR	Project feasibility; tariff analysis	Informs investment and policy settings.
Hybrid & energy system modelling	FPV hydropower, FPV battery, FPV hydrogen models	Dispatch optimisation; storage integration	Key for grid and energy system planning.
Environmental monitoring	Water quality sensors; thermal profiling	Assessment of environmental impacts	Supports permitting and safeguards.
Hydrodynamic & structural analysis	CFD; mooring simulations	Platform stability and design	Essential for exposed reservoir and coastal/offshore FPV.
Life cycle assessment (LCA)	Process-based LCA	Embodied carbon; material footprints	Supports sustainability and decarbonisation strategies.

3.4 Cross-domain insights

The integrative analysis highlights several cross-cutting themes that help explain how FPV interacts with wider energy water systems and why its development trajectory varies across regions.

A prominent insight concerns the role of reservoir networks as a primary spatial resource for FPV expansion. Their extensive surface areas, relatively predictable hydrodynamics, and established grid connections make them more suitable than most natural water bodies, particularly for medium to large-scale installations. This consistency across studies signals that reservoirs will likely remain the backbone of near-term FPV deployment [55, 57].

Another recurrent theme is the contrast between technological maturity and institutional readiness. While engineering advances have improved system performance, design tools, and hybridisation options, the surrounding regulatory and governance frameworks have not evolved at the same pace. This asymmetry suggests that institutional constraints rather than technical limitations may shape future scalability more significantly [58, 64].

Environmental outcomes appear far less uniform. Variability in thermal, hydrodynamic, and ecological responses across different settings reflects the influence of reservoir morphology, climatic conditions, and coverage ratios. Such heterogeneity reinforces the importance of detailed environmental assessment and cautions against assuming generalisable impact patterns [31, 37].

Despite the growth of spatial suitability and GIS-based assessments, integration with formal planning processes remains limited. Few studies link technical findings with established zoning mechanisms, basin-level strategies, or regional development plans. This gap indicates an opportunity to reposition FPV within coordinated planning frameworks, rather than treating it solely as a technical siting exercise [54, 66].

3.5 Implications for regional energy planning

The cross-domain synthesis points to several implications for how FPV could be positioned within regional energy planning frameworks. These implications emerge from converging evidence across technical performance, environmental response, socio-economic conditions, and governance readiness [36, 37].

One clear implication concerns FPV's ability to expand solar generation without intensifying land use competition. This attribute is particularly relevant in regions where agricultural demand, settlement growth, or conservation priorities limit the availability of suitable sites for ground-mounted systems. By shifting deployment to reservoirs, FPV can relieve pressure on land resources while supporting renewable energy targets.

FPV also shows potential to enhance coordination between water and energy systems at the basin scale. In hydropower reservoirs, FPV can complement existing infrastructure by providing additional generation capacity, helping reduce evaporative losses, and enabling more flexible operation during periods of fluctuating inflow or demand. These interactions suggest a role for FPV within integrated resource management, rather than as an isolated technology [29, 44].

A third implication relates to diversification and resilience of regional energy portfolios. The ability to distribute FPV installations across multiple reservoirs creates spatial redundancy and reduces dependence on land-based siting. When combined with storage or hydropower hybridisation, FPV can also contribute to system flexibility and may help moderate peak demand pressures [46, 49].

Finally, the literature indicates that FPV's strategic contributions will depend on the strengthening of governance and institutional arrangements. Clearer regulatory guidance, improved coordination across agencies, and robust environmental and social safeguards are essential to translate technical feasibility into durable planning outcomes. Without these institutional foundations, the advantages identified in technical and environmental studies may not be fully realised in practice [58, 59].

3.6 The role of floating photovoltaic in sustainable regional energy planning

Across the thematic domains, FPV emerges as a strategic nexus technology linking land, water, and energy systems. It enables solar expansion without occupying land, supports water conservation through evaporation reduction, and enhances operational flexibility when hybridised with hydropower or storage systems. Reservoir-based FPV systems, in particular, illustrate how FPV can function not only as an engineering solution but as a planning asset capable of advancing sustainable regional development. Realising these benefits requires coherent integration within spatial plans, basin management strategies, socio-economic frameworks, and governance reforms, positioning FPV as an important component of long-term sustainable regional energy planning [30, 35, 67].

4. DISCUSSION

4.1 Floating photovoltaic as a strategic resource in regional energy systems

The evidence shows that FPV is not merely a technological alternative to land-based solar power; its strategic value arises from its position at the intersection of energy expansion, land scarcity, and reservoir availability. FPV unlocks new spatial opportunities by utilising underperforming or underused water surfaces, especially hydropower, irrigation, and multipurpose reservoirs.

Its ability to hybridise with hydropower operations provides operational benefits, improving load balancing, reducing curtailment, and enhancing system flexibility, thus positioning FPV as a resource with regional energy system value, rather than as isolated generation units.

4.2 Environmental and water system implications

FPV's water-related interactions form a critical dimension of sustainability. Evaporation reduction emerges as a major co-benefit, while environmental impacts such as changes in thermal stratification, dissolved oxygen, and ecological indicators are site and reservoir-specific. These insights underline the need for context-sensitive environmental assessments rather than generic prescriptions.

Within regional planning, FPV must be aligned with basin-scale water management strategies to ensure that ecological thresholds are respected while benefits such as water conservation and dual-use functions are realised.

4.3 Spatial planning challenges and opportunities

Spatial planning studies highlight FPV's capacity to relieve pressure on land resources by relocating solar development to reservoirs and water bodies. GIS MCDA studies consistently identify reservoir networks as FPV priority zones, yet incorporation into formal spatial plans, zoning systems, and provincial-scale development instruments remains limited.

This gap suggests a need to strengthen institutional mechanisms that translate suitability mapping into deployable planning decisions.

4.4 Socio-economic and equity considerations

Socio-economic analyses show that FPV can be cost-competitive in contexts where land is scarce or expensive. However, acceptance depends on local reservoir uses, including fisheries, recreation, tourism, and cultural values. Regional planning must therefore incorporate stakeholder engagement, equity considerations, and livelihood impact assessments, ensuring that FPV deployment supports rather than disrupts local socio-economic systems.

4.5 Governance and institutional requirements

The analysis shows that governance-related issues constitute some of the most influential constraints on FPV deployment. Across the 49 studies, several institutional challenges recur, including uncertainty over water surface rights, overlapping or fragmented regulatory mandates, and the lack of FPV-specific permitting and operational standards. These gaps introduce ambiguity during project evaluation and can deter investment even where technical, economic, and environmental conditions appear favourable.

Addressing these constraints requires a more coherent governance architecture. A priority is the development of clear regulatory pathways that define responsibilities, approval steps, and compliance expectations for FPV projects. Clarity in this domain reduces administrative bottlenecks and enables agencies to apply consistent criteria during screening and licensing.

Improved coordination among water, energy, and environmental authorities is also essential. FPV installations often sit at the intersection of multiple mandates, particularly on multipurpose reservoirs, and weak interagency communication can slow decision-making or results in contradictory regulatory requirements. Establishing joint review mechanisms or integrated permitting procedures would help streamline oversight.

In addition, environmental guidelines tailored to FPV technologies would support more consistent assessment of hydrodynamic, ecological, and safety considerations. Current practices often rely on frameworks designed for unrelated structures, resulting in variable requirements and review outcomes. FPV-sensitive guidelines could help harmonise expectations across jurisdictions.

Longer-term institutional readiness will depend on the formal inclusion of FPV within regional and national planning instruments, such as energy transition roadmaps, basin-level water management strategies, and zoning or siting regulations. Embedding FPV in these frameworks enhances policy continuity, reduces procedural ambiguity, and provides clearer signals to developers and financiers [68].

4.6 The need for a land-water energy nexus framework

The cumulative evidence from this review indicates that FPV interacts with land systems, water resources, and energy infrastructures in ways that cannot be fully understood through single-sector analysis. These interdependencies highlight the importance of adopting a land-water energy nexus framework when evaluating or planning FPV deployment.

From a land use perspective, FPV offers an alternative to ground-mounted solar in settings where agricultural demand, settlement growth, or conservation priorities constrain available space. Yet its deployment depends on the characteristics and management of the water bodies on which it is placed. FPV can influence and be influenced by reservoir operations, hydrodynamic behaviour, and environmental thresholds, reinforcing the need to view water system dynamics as integral to its planning and assessment.

On the energy side, FPV contributes to renewable expansion, diversification, and flexibility, especially when combined with hydropower operations or energy storage. These energy benefits intersect with societal considerations, including livelihood uses of reservoirs, cultural practices, and distributional questions that shape local acceptance and long-term social legitimacy.

Institutional arrangements further mediate these interactions. Fragmented responsibilities, gaps in regulatory guidance, and uneven integration of FPV into long-term policy frameworks can create misalignments across sectors. A nexus-oriented approach provides a mechanism to align decision-making, reduce cross-sector trade-offs, and reinforce governance coherence.

4.7 Planning-oriented conceptual framework for floating photovoltaic integration

Building on the synthesis of technical, environmental, spatial, socio-economic, and governance dimensions, this study develops a planning-oriented conceptual framework to guide the integration of FPV into sustainable regional energy strategies. The framework comprises five interlinked components that reflect the multi-sectoral nature of FPV deployment:

a. *Resource Identification and Suitability Mapping* This component integrates spatial multi-criteria assessment with hydrological and ecological analysis to identify priority sites while accounting for reservoir characteristics, environmental sensitivities, and socio-economic conditions. The objective is to locate FPV in areas where technical feasibility aligns with environmental and social context.
b. *System Integration and Operational Synergies* FPV deployment is considered in relation to existing energy and water infrastructures, including hybrid FPV–hydropower configurations, grid connection opportunities, and operational optimisation across reservoirs. This component highlights the potential for FPV to contribute to flexibility, dispatchability, and basin-scale resource coordination.
c. *Environmental and Social Safeguarding* Context-specific evaluation of thermal, hydrodynamic, ecological, and livelihood impacts forms the basis of this component. It emphasises the need for adaptive environmental thresholds, ongoing monitoring, and participatory engagement with affected communities to ensure socially legitimate and environmentally responsible development.
d. *Institutional Coordination and Governance Design* This component addresses the institutional architecture required for FPV deployment, including clear licensing procedures, harmonised standards, and coordinated roles across water, energy, and environmental authorities. Strengthening governance coherence is essential to ensure predictable and transparent approval processes.
e. *Alignment with Regional Development Objectives* FPV is positioned within broader planning instruments such as land use plans, basin management strategies, and regional energy transition policies. This alignment anchors FPV within long-term development pathways rather than treating it as a technology implemented in isolation.

Figure 5 presents the planning-oriented conceptual framework proposed in this study for integrating FPV into sustainable regional energy planning. The framework is directly derived from the synthesis of evidence across the reviewed studies. In particular, it reflects the strong concentration of research in technical, environmental, and spatial domains, while explicitly incorporating governance and socio-economic dimensions that were identified as comparatively underrepresented.

By translating the empirical distribution of research domains into an integrated planning structure, the framework operationalises the findings of this review and provides a coherent basis for bridging technical feasibility with institutional and policy implementation requirements.

The framework thus provides a structured basis for embedding FPV within regional planning processes and guiding policymakers toward coherent, multi-sectoral implementation pathways. Each component of the framework is directly grounded in the thematic synthesis presented in the preceding sections, reinforcing the transparency, interpretability, and internal consistency of the study.

4.8 Synthesis: Floating photovoltaic as an enabler of sustainable regional development

The findings position FPV as a key enabler of sustainable regional development. Its ability to expand renewable capacity without additional land, support water conservation, and interact synergistically with hydropower and storage systems makes FPV uniquely suited for regions facing land scarcity, water constraints, or energy diversification needs.

However, FPV's transformative potential can only be realised through integrated planning, robust governance, environmental stewardship, and participatory processes, situating FPV not merely as a technological option but as a strategic resource for long-term sustainable development.

5. CONCLUSION

This study conducted a SLR of 49 peer-reviewed studies to examine the role of FPV in sustainable regional energy planning. Using the PRISMA 2020 approach, the review synthesised evidence across technical, environmental, spatial planning, socio-economic, and governance dimensions. The findings underscore FPV's potential as a strategic resource for regions seeking to balance renewable energy expansion, land use constraints, and water system sustainability.

5.1 Conclusion

The review demonstrates that FPV is emerging as a multi-functional, planning-relevant technology capable of contributing to sustainable regional development. FPV's significance arises not only from its ability to generate renewable energy on underutilised water surfaces but also from its broader system-level advantages:

a. Land-efficient energy expansion
   FPV enables solar development without competing for agricultural, urban, or conservation land making it particularly valuable in densely populated or land-constrained regions.
b. Synergies with hydropower and water systems
   FPV hydropower hybridisation can enhance operational flexibility, reduce variability, and optimise reservoir operation. FPV can also contribute to evaporation reduction, supporting water conservation objectives.
c. Spatial planning and regional portfolio potential
   GIS MCDA studies show that reservoir networks represent high potential FPV portfolios, offering opportunities for basin-scale energy planning and integrated land-water energy strategies.
d. Environmental and socio-economic benefits
   When designed responsibly, FPV can minimise ecological disturbance while providing economic advantages such as reduced land acquisition costs and opportunities for rural energy development. Social acceptance is achievable when stakeholder needs are addressed.
e. Governance as a key enabling or limiting factor
   Institutional challenges remain the primary barrier to widespread FPV deployment. Clear permitting pathways, cross-agency coordination, and FPV-specific environmental guidelines are essential for translating technical potential into implementable projects.

These findings reinforce the need to reposition FPV not merely as a technological option, but as a strategic planning resource within integrated land-water energy systems.

5.2 Limitations

While this review followed PRISMA 2020 guidelines, several limitations must be acknowledged:

a. Database scope
   The study relied solely on Scopus-indexed literature. Relevant studies from Web of Science, IEEE, or regional journals may not be included.
b. Language and publication bias
   The review included only English-language peer-reviewed articles, which may underrepresent local or policy-oriented FPV research.
c. Heterogeneity of methodologies
   The included studies employed varied analytical, modelling, and assessment approaches, limiting the ability to perform quantitative meta-analysis.
d. Limited governance and socio-economic evidence
   Although technical and environmental domains are well represented, governance and social dimensions remain relatively underexplored, creating data asymmetries.
e. Rapidly evolving technology
   FPV is a fast-developing field. New materials, anchoring systems, and hybrid models continue to emerge, potentially outpacing academic literature.

These limitations do not undermine the validity of the findings but highlight areas where further empirical work is needed.

5.3 Future research directions

Based on the synthesis, several opportunities for future research are identified:

a. Integrated land-water energy nexus modelling
   Future work should develop integrated modelling approaches that capture hydrological, energy, environmental, and socio-economic interactions. This would support more robust scenario planning and basin-level decision-making.
b. FPV hydropower operational optimisation
   There is a need for studies that simulate joint reservoir operations under varying climatic and energy demand conditions, including multi-reservoir coordination.
c. FPV governance frameworks and policy pathways
   Research should explore regulatory reforms, water rights allocation, permitting processes, and institutional coordination mechanisms to support FPV deployment.
d. Socio-economic and community acceptance studies
   Empirical research is required on community perceptions, equity impacts, livelihood implications, and benefit-sharing models, particularly in regions where reservoirs serve multiple purposes.
e. Long-term environmental monitoring
   More field-based monitoring is needed to understand ecological responses over longer time horizons, including water temperature, biodiversity, and water quality effects.
f. Advanced FPV materials, resilience, and climate adaptation
   Studies should explore FPV resilience to extreme weather, floating platform materials, mooring technologies, and climate adaptation strategies.
g. Regional-scale planning tools and decision support systems
   Future research should develop planning tools that integrate FPV within spatial plans, provincial development guidelines, and national energy transition roadmaps.

By advancing research in these areas, FPV can be more effectively incorporated into sustainable regional planning and long-term energy strategies, contributing to water security, energy diversification, and climate-resilient development.

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